



## **Palaeoenvironmental changes of the Lefkada Sound (NW Greece) and their archaeological relevance**

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### **Abstract**

Lefkada Island is separated from the Greek mainland by the Lefkada Sound, a shallow lagoonal environment. Ancient accounts report that the Corinthians cut a navigable canal across a former isthmus in the 7<sup>th</sup> century BC. A nowadays submerged Corinthian mole at the southern end of the sound closed off a protected harbour area.

The main objectives of our studies were to detect environmental changes throughout the Holocene and to reconstruct the palaeogeographical evolution of the Lefkada Sound for different points in time based on the analysis of the sedimentary record encountered in various geoarchives. Geomorphological, geochemical, microfaunal, archaeobotanical and geochronological methods as well as earth resistivity measurements were applied.

From the northern Lefkada Sound and adjacent regions, severe tsunamigenic impact is known. Vibracore data shows considerable influence of extreme events on the development of the northern subarea in historical times.

In the central part of the sound, our results revealed a terrestrial connection of Lefkada Island with the Greek mainland, which is gradually displaced by a limnic and later lagoonal environment. At least twofold high energy impact disturbed the quiescent lagoonal conditions at or after Hellenistic times. The marginal parts of the lagoon have been affected by siltation due to alluvial or anthropogenic deposition.

In the area of the presumed harbour of ancient Lefkada, our results indicate an early marine transgression sometime before ~2800-2700 cal BC. Subsequently, open marine conditions prevailed for a long time, however showing temporary influence of high energy events. Layers with numerous artefacts probably reflect the period during which the harbour was in use and are subsequently covered by alluvial sediments.

Several relative sea level indicators document a remarkably rapid relative sea level rise in the inner sound, partly due to tectonic subsidence. In more lateral parts, tectonic uplift is observed. Thus, distinct local variations in tectonic movements have to be considered.

### **1 Introduction**

Postglacial sea level rise and delta formation since the mid-Holocene have caused enormous landscape changes and thus have strongly influenced human activity and settlements in coastal areas. Additionally, catastrophic events like seismic movements, storms or tsunami waves are assumed to have considerably affected the coastal evolution. In the eastern Mediterranean, coastline changes and their implications for archaeological sites are well studied in various regions. For the Lefkada Sound, detailed palaeogeographical analyses did not exist so far. This paper presents first results of our research on palaeoenvironmental changes of the area.

### **2 Topographic and tectonic setting**

Lefkada Island is separated from the Greek mainland – the Plaghia Peninsula – by the Lefkada Sound, a shallow lagoonal environment (Fig. 1). Towards the north, the lagoon is cut off from the open Ionian Sea by an extended barrier beach system. Its partly destroyed and drowned section is called Plaka. To the south, the sound is bordered by a submerged mole, the so-called “Mole of the Corinthians”. Across

the shallow lagoon runs an artificial (navigable) canal. Lefkada city lies at the north-eastern corner of Lefkada Island at around 1-5 m above present mean sea level (m a.s.l.), while the archaeological remains of ancient Lefkada are located in a higher position further south. A bridge, today completely ruined and covered by sediments, connected Lefkada Island and the Plaghia Peninsula during Hellenistic to Roman times.



Figure 1: Overview of the study area and location of the presented sedimentary and archaeological archives

Tectonically, the area of the Lefkada Sound is part of the Ionian Zone of the outer Hellenides (Monopolis & Bruneton 1982) and is located close to the triple junction of the African, the Aegean and the Adriatic microplates (Haslinger et al. 1999). The study area belongs to the tectonically and seismically most active regions of the Mediterranean. Especially the Cefalonia Fault, situated directly to the west of Lefkada Island, is responsible for severe earthquakes (Galanopoulos 1952, 1954, Hatzfeld et al. 1995). The last strong earthquake ( $M_w$  6.2) occurred on August 14, 2003, causing mass movements and extensive damages especially along the western coast of the island (Benetatos et al. 2005, Parcharidis et al. 2006). The high seismic and tectonic activity indicates a considerable tsunami hazard for the region.

The sound lies in a tectonic depression and is flanked by tectonic horsts. Severe differences in the vertical tectonic movement are represented by findings of Eemian sea level indicators in different elevations, ranging between around 14 m below present mean sea level (m b.s.l.; PER 5, Fig. 3) and up to 8.65 m a.s.l. at the northern coast of Lefkada Island (IOA 1, Fig. 1). Here, ESR-dating of *in-situ* branches of corals provided an age of 130 +/- 15 ka BP.

### 3 Historical background

The palaeogeographical setting in the area of the Lefkada Sound was discussed in a controversial way already at the end of the 19<sup>th</sup> century. Was Lefkada always an island or was it connected to the Akarnanian mainland in the past? The ancient historians Livius, Strabo and Plinius report that an isthmus existed east of the ancient town of Lefkada in Archaic-Classic times, just where an ancient bridge crossed the sound during the Hellenistic to Roman epoch (Négris 1904, Fig. 1). However, Partsch (1889, 1907), von Marées (1907), Lehman-Hartleben (1923) and von Seidlitz (1927), for instance, suggest that the described isthmus was located further northward, either close to the fortification of Aghia Mavra or at the so-called “Canali Stretti”. Anyway, historical tradition says that an isthmus was cut through by the Corinthians in order to get a navigable canal. The nature of

Lefkada, island or peninsula, was of particular interest for the archaeological research trying to solve the question whether Lefkada possibly was the Homeric Ithaka, the homeland of Odysseus (Goessler 1904, Lang 1905, Dörpfeld 1927).

Ancient Lefkada was probably founded in the 7<sup>th</sup> century BC by Corinthian settlers. Négris (1904) suggests that the Mole of the Corinthians (Fig. 1) was constructed to protect the southern entrance of the canal. Murray (1982, 1988) found that the harbour mole of ancient Lefkada did not only serve as protection, but also as a loading pier. Murray (1988) found fragments of Corinthian amphora and concludes that the harbour was in use between the 5<sup>th</sup>/4<sup>th</sup> century BC and the 4<sup>th</sup>-6<sup>th</sup> centuries AD. According to Murray (1988), the submersion of the mole started shortly after the 6<sup>th</sup> century AD. Its remains – in parts the original mole surface is preserved in a minimum depth of 1.40 m b.s.l. – represent a reliable relative sea level indicator. With an assumed original surface elevation of 0.5-1.5 m a.s.l., a minimum relative sea level rise of ~2.4 meters is assumed. Murray (1982: 240) even gives an average value of 3.4 meters. Based on his investigation of the remains of the Hellenistic to Roman bridge, Négris (1904: 24) suggests a relative sea level rise of ~3.0 m in the course of the last 2000 years.

In antiquity, the navigable canal through the sound was a safe shortcut along the way between Greece and Italy and therefore the control over the strait was a both lucrative economic and strategic factor. According to historical data, compiled e.g. by Murray (1982: 247f.), the navigability of the sound was interrupted at least three times during Archaic and Roman times. Murray (1982) suggests that the natural tendency of the sound is to silt up and that whenever possible, the strait was dredged and the canal reopened, because that was essential for the prosperity of the city. Vött et al. (2007c, d) propose that tsunami impact might also have influenced the navigability of the sound.

#### 4 Objectives and methods

The prior aim of our research is to reconstruct the palaeogeographical evolution of the sound for different points in time since the late Pleistocene/early Holocene based on the analysis of sedimentary and archaeological records encountered in vibracores and profiles.

Geomorphological, geochemical, microfaunal, archaeobotanical and geochronological methods as well as thin section analyses and earth resistivity measurements were applied. The results were compared to both historical and archaeological data. Our geoarchaeological approach is summarized e.g. by Brückner (2003), the benefits resulting from interdisciplinary landscape research are exemplary shown by Lang et al. (2007).

Table 1: Radiocarbon dates from vibracores LEF 2 and LEF 12. Abbreviations: b.s. – below ground surface; b.s.l. – below sea level; artic. sp. – articulated specimen; 1 $\sigma$  max; min cal BP/BC (AD) – calibrated ages, 1 $\sigma$ -range; lab. no. – laboratory number, Erl – University of Erlangen; UtC – University of Utrecht

sample name	depth (m b.s.)	Depth (m b.s.l.)	sample description	lab. no.	$\delta^{13}\text{C}$ (ppm)	$^{14}\text{C}$ age (BP)	1 $\sigma$ max; min (cal BP)	1 $\sigma$ max; min (cal BC)	calibration
LEF 02/07 M	2.36	2.36	<i>Tellina</i> sp. (artic. sp.)	UtC 13691	0.3	2574 +/- 37	2308; 2197	358; 247	marine
LEF 02/14 M	5.53	5.53	<i>Dosinia</i> sp. (artic. sp.)	UtC 13690	0.0	6257 +/- 37	6752; 6654	4802; 4704	marine
LEF 12/07 M	2.48	1.43	<i>Dosinia exoleta</i> (artic. sp.)	Erl-9808	0.1	2370 +/- 50	2064; 1924	114 cal BC; 26 cal AD	marine
LEF 12/10 PR	3.77	2.72	seaweed	Erl-9809	-17.8	2436 +/- 42	2133; 2008	183; 58	marine
LEF 12/18 PR	7.28	6.23	seaweed	Erl-9810	-14.6	4504 +/- 48	4797; 4640	2842; 2690	marine

In the surroundings of the Lefkada Sound, more than 50 sediment cores were retrieved with core diameters of 6 cm and 5 cm and a maximum recovery depth of 15 m. On-site, the sedimentary facies was determined based on sedimentological features and macrofossil remains. Samples were taken for systematic micro- (foraminifers, ostracods) and macrofaunal studies, for pollen analyses and for detailed geochemical analyses of various parameters such as electrical conductivity, pH-value, loss on ignition, contents of carbonate, orthophosphate as well as several (earth-)alkaline and heavy metal ions. Moreover, artificial trenches given by earthen cisterns were studied.

The exact position and elevation of vibracoring sites and trenches were determined by means of a differential GPS.  $^{14}\text{C}$ -AMS dates and diagnostic ceramic fragments as well as ESR-dating of several pre-Holocene coral fragments were used for establishing a local geochronology.

In this paper, we present two vibracores from the northern and southern parts of the lagoon and a vibracore transect across the central part of the sound (Fig. 1).

Radiocarbon ages given in Table 1 are calibrated using the software “Calib” by Stuiver et al. (2006). Marine samples are corrected for an average reservoir effect of 402 years (Reimer & McCormac 2002) because of the lack of detailed information on the palaeo-reservoir effects in the Lefkada Sound.

## 5 Results: Sedimentological archives revealing the landscape history

### Tsunamigenic impact on the northern part of the sound

Vibracore LEF 2 (Fig. 2) exemplifies tsunamigenic impact on the northern part of the Sound of Lefkada (see Vött et al. 2006, 2007a). Several meters of shallow marine to littoral sediments (sand and gravel rich in marine mollusc fragments) at the base of the core are covered by 3.5 meters of lagoonal deposits. The lagoonal mud, mostly silty and rich in marine fossils, indicates the existence of a seaward barrier from ~4750 cal BC to ~300 cal BC, as  $^{14}\text{C}$ -AMS datings suggest (see Table 1).

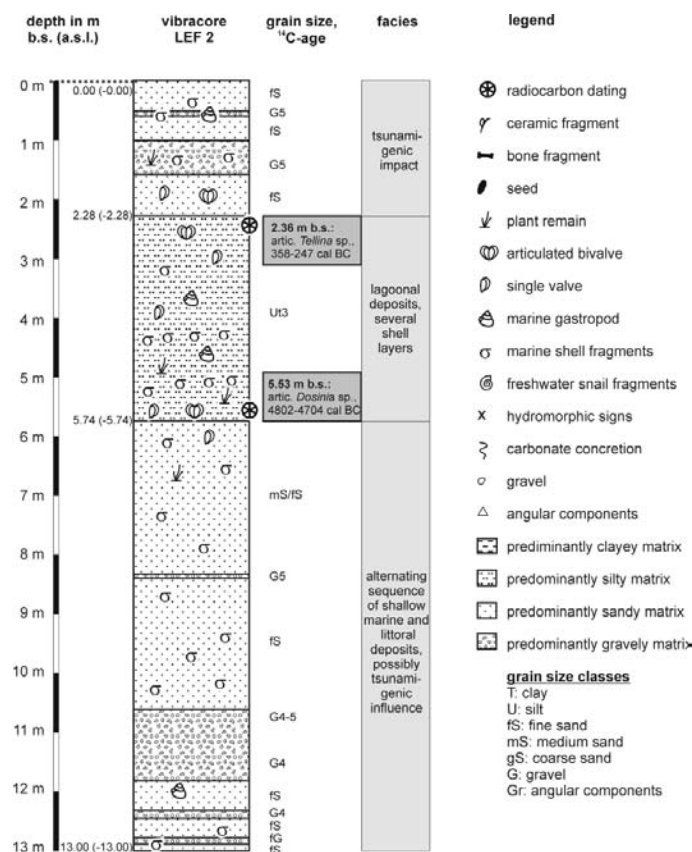


Figure 2: Stratigraphic sequence of vibracore LEF 2. Note: Legend is also applicable for Fig. 4.

On top of the lagoonal sediments, high energy impact is represented by alternating layers of sand and gravel, slightly weathered in the uppermost part of the sequence. The seaward barrier must have been overflowed by tsunami waves at or after ~300 cal BC. There are further geomorphologic and sedimentologic findings in the area that prove multiple tsunami impact to the Lefkada coastal zone (Vött et al. 2006, 2007a, b, c, May et al. 2007). It is suggested that tsunamis had a considerable influence on the development of the inner Lefkada Sound (Vött et al. 2007d).

### Geoarchaeological aspects of the evolution of the central sound

In the central part of the sound (Fig. 3), thick packages of alluvial deposits, partly covered by (ephemerally) limnic sediments prove a former terrestrial connection of Lefkada Island with the Greek mainland up to a depth of around ~3.55-3.00 m b.s.l., where first saltwater-borne sediments occur in LEF 24 and PER 5. In both cases, we found lagoonal sediments on top of the limnic sedimentary unit.

The vibracores also show signs of high energy impact. Vibracore LEF 24 revealed a fourfold input of coarse material (mainly shell debris and sand) in the quiescent lagoonal environment, namely in depths of 2.62-2.29 m, 1.87-1.46 m, 1.36-1.30 m and 1.14-0.66 m b.s.l. In vibracore LEF 38, chaotic layers showing a mixture of clayey sandy silt, gravel, stones, ceramic fragments, marine molluscs and shell fragments as well as plant remains were encountered in 1.95-1.59 m and in 1.10-0.43 m b.s.l. They are covered by a thick anthropogenic layer with a lot of ceramic fragments. In vibracore PER 5, high energy impact is recorded in 2.08-1.91 m and 1.08-0.47 m b.s.l., represented by mostly sandy sediments containing marine gastropods and bivalves as well as shell debris and gravel. Clear erosional unconformities mark the onset of some of the described layers, which seem to result from strong water currents. The marginal parts of the lagoon are affected by siltation due to alluvial or anthropogenic deposition, locally very rich in ceramic fragments.

The  $\text{Ca}^{2+}/\text{Mg}^{2+}$ - and the  $\text{Fe}^{2+/3+}/\text{Na}^{+}$ -ratios of sediment samples are, among others, reliable geochemical indicators for facies changes. High concentrations of  $\text{Fe}^{2+/3+}$  indicate *in-situ* weathering or fluvial input of weathered terrestrial material, whereas high  $\text{Na}^{+}$ -contents originate from marine saltwater influence, or, in case of high evaporation, from the precipitation of NaCl (Schroll 1976, Vött et al. 2002).  $\text{Ca}^{2+}$ - and  $\text{Mg}^{2+}$ -ions derive from Ca- or Mg-rich bedrock. High  $\text{Ca}^{2+}$ -values may also indicate a high biochemical production of calcium carbonate. The  $\text{Ca}^{2+}/\text{Mg}^{2+}$ -ratio, however, is a good indicator for sediments deposited under marine conditions (Vött et al. 2002).

Fig. 3 shows the  $\text{Fe}^{2+/3+}/\text{Na}^{+}$ - and the  $\text{Ca}^{2+}/\text{Mg}^{2+}$ -graph for the transect across the sound via vibracores LEF 24 and PER 5. Near the base of vibracore PER 5, carbonatic (marine) sands show a high  $\text{Ca}^{2+}/\text{Mg}^{2+}$ -ratio. Intensely weathered bedrock or phases of alluvial and (ephemerally) limnic deposition are represented by high  $\text{Fe}^{2+/3+}/\text{Na}^{+}$ -values, while phases of brackish or marine conditions are reflected by a high  $\text{Ca}^{2+}/\text{Mg}^{2+}$ -ratio. The following lagoonal deposits as well as the high energy event layers are reflected by a high  $\text{Ca}^{2+}/\text{Mg}^{2+}$ -ratio. The event layers, in most cases extraordinarily rich in marine shell debris, generally offer higher values than the lagoonal muds.

### Palaeoenvironmental changes in the area of the ancient harbour of Lefkada

Vibracore LEF 12 was drilled in the southwestern part of the sound, close to the area where the harbour of ancient Lefkada is presumed (Fig. 1). The encountered sediments (Fig. 4) and the related ages both of organic samples and potsherds show that the change to marine conditions took place before 2700 cal BC, first in terms of a high energetic littoral (or even tsunamigenic) and later of a more quiescent shallow marine environment. During historical times, the place, protected by the Mole of the Corinthians, offered open marine conditions and represented an ideal harbour site. Many artefacts such as pottery fragments, bones, plant remains (e.g. *Olea* sp.) or stones suggest strong human influence. The chaotic findings in the upper part of our core might also result from catastrophic events like tsunami impact (Vött et al. 2007d) or from severe torrential runoff. Finally, siltation affected the area.

Detailed microfauna analyses help to determine the sedimentary facies (Handl et al. 1999). Selected samples of vibracore LEF 12 were examined for their content of foraminifers, ostracods, molluscs, plant remains, and for sedimentary attributes as composition, rounding, grain size, and other distinctive features. A sample from 7.58-7.48 m b.s. (below surface) shows a population of (partly detrital) foraminifers, rich in species, and, to a lesser extent, ostracods in a mainly sandy sediment. This sediment is typical of a turbulent shallow marine (littoral) environment or even of tsunamigenically affected conditions (Vött et al. 2007d).

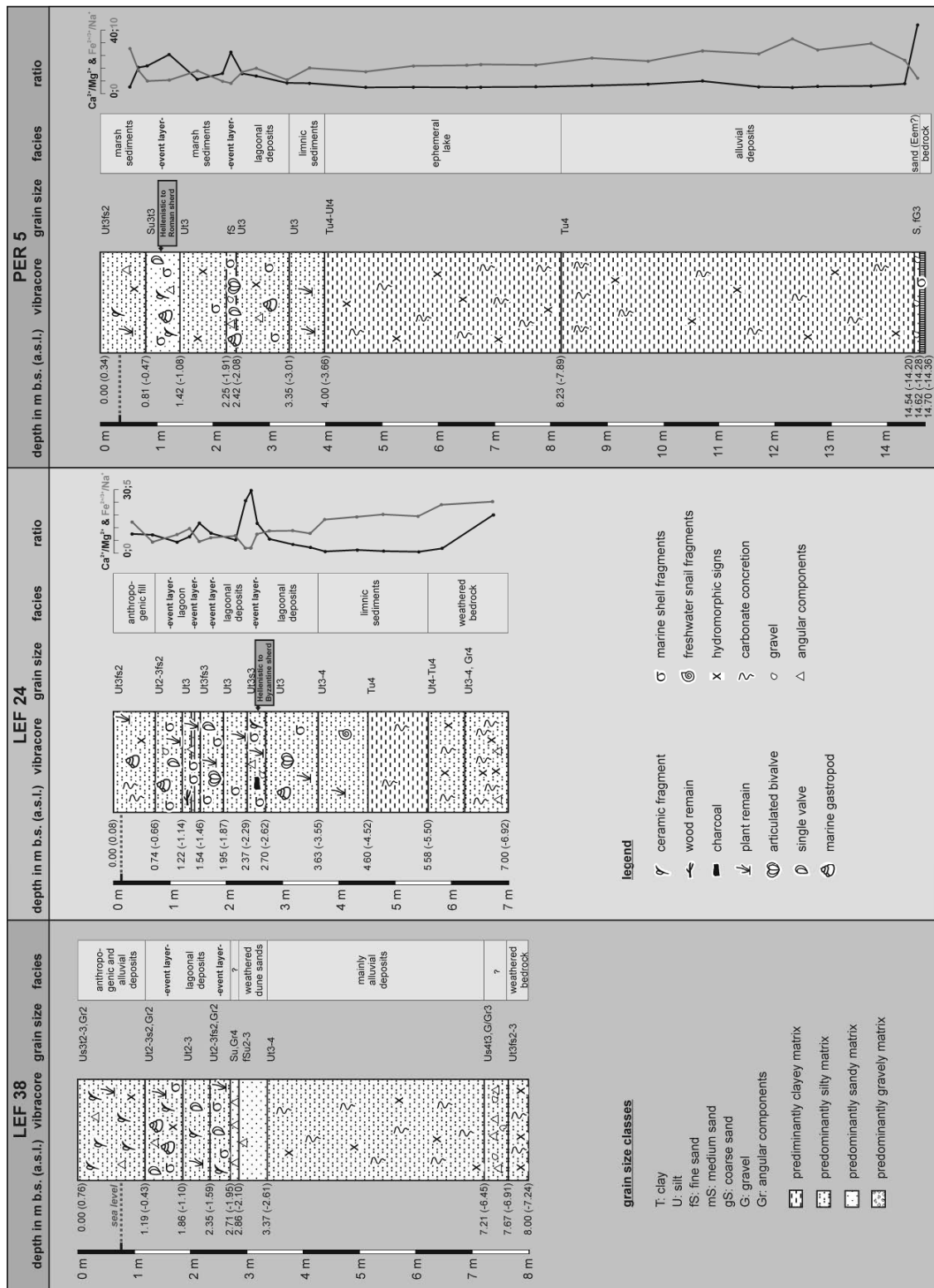


Figure 3: Vibracore transect LEF 38 – LEF 24 – PER 5 across the central sound.

A sample from 6.60–6.50 m b.s. revealed abundant seaweed remains and a moderate content of (partly detrital) foraminifers and mollusc fragments. Seaweed requires oxygen-rich, temperate turbulent water and a silty-(fine)sandy sediment, as it is found here. The relative frequency of *Ammonia beccarii* and *Elphidium crispum* indicates slight variations of salinity. Altogether, the findings point at a shallow marine setting with at least temporary surf.

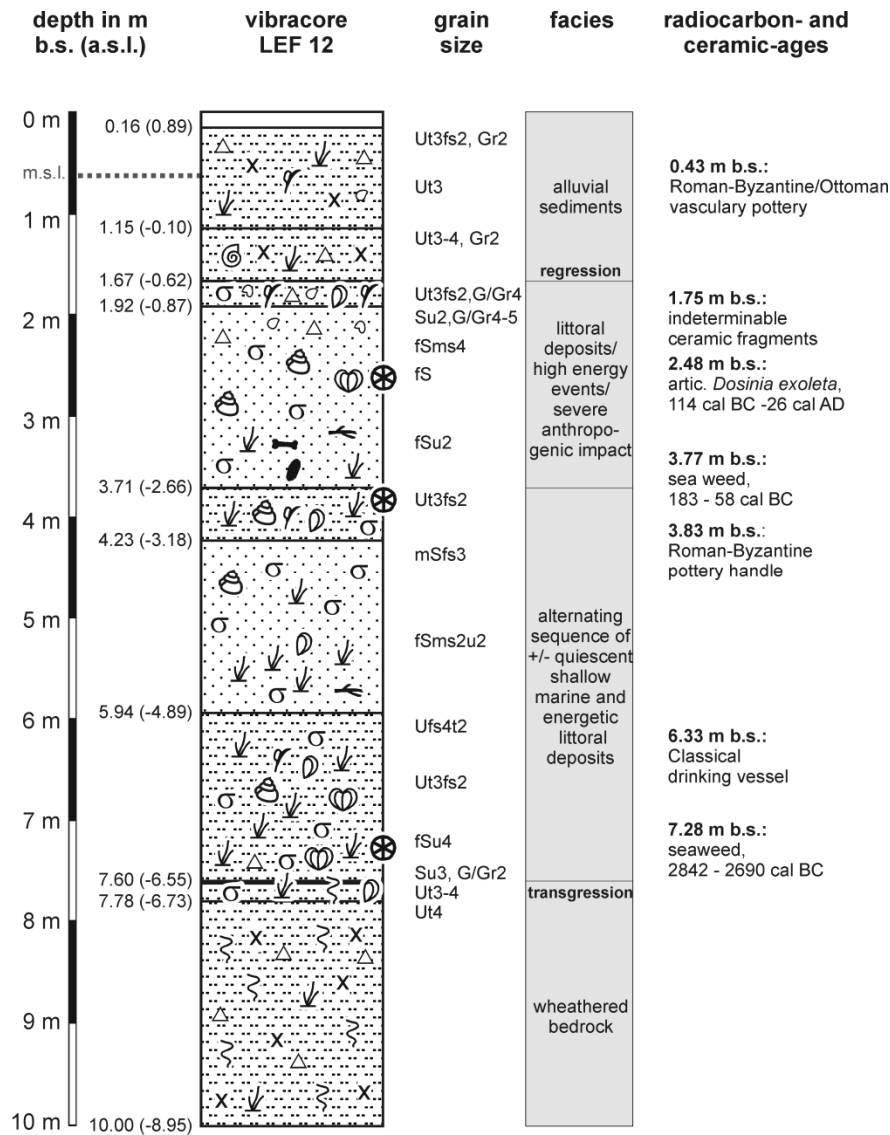


Figure 4: Stratigraphic sequence of vibracore LEF 12. Legend: See Fig. 2.

At 5.45–5.35 m b.s., a mostly sandy sediment with predominant (sub)angular grains, some organic material, sporadic marine mollusc-fragments, numerous planktonic and sessile foraminifers and divers, to some extent freshwater adapted ostracods, partly damaged, point to more or less turbulent shallow marine conditions.

A sample from 4.45–4.35 m b.s. shows a similar composition. However, the sediment, mostly medium sand, is a little bit coarser and contains less ostracod remains. What is striking, is the different degree of conservation of the microfossils – some are rounded or even broken. Besides an event-like influence, it has to be considered that a nearby river could have transported fossil microfauna remains, possibly even of pre-Quaternary age, into the sound which do not originally belong to the (sub-)recent biocoenosis.

Between 3.82 m and 3.72 m b.s., a slight change in the facies is apparent. The environment is still shallow marine, but the sediment is finer (clayey, fine sandy silt) and both abundance and biodiversity of the foraminifers and ostracods strongly decrease. The occurrence of terrestrial organic matter and of some freshwater ostracods as well as the differences in particle rounding document nearby freshwater input.

Abraded or damaged foraminifers, encountered in a sample taken from 3.65-3.55 m b.s., reflect intensive processes of relocation in a turbulent environment (Fig. 5, c-e). A similar indication is given by mollusc shell fragments, almost absent ostracods as well as the more or less rounded mostly fine sandy material (with sporadic content of silt and gravel) and an increased content of terrestrial organic matter.

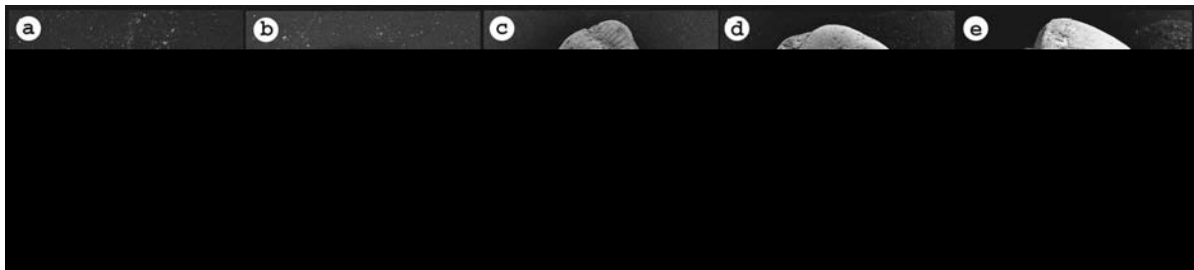


Figure 5: Scanning electron microscope photographs of selected ostracods (a-b, 2.52-2.42 m b.s.) and foraminifers (c-e, 3.65-3.55 m b.s.) from vibracore LEF 12

Between 2.85-2.75 m b.s., well-sorted fine sand was encountered, showing different grades of abrasion. Abundant foraminifers and ostracods as well as fragments of marine molluscs document ongoing shallow marine conditions, or, at least, marine influence to the site. Moreover, numerous terrestrial plant remains as well as the sporadic occurrence of freshwater ostracods (*Candona neglecta*, *Iliocypris bradyi*, *Potamocypris cf. pallida*, Fig. 5, a-b) and stonewort-oogons from *Chara* sp. indicate temporary freshwater influence.

At 2.52-2.42 m b.s., a high biodiversity of foraminifers and ostracods indicates favourable living conditions in a littoral environment or tsunamigenic influence. The fine and medium sand grains are mostly angular-subangular. However, several limestone particles are well rounded and some pieces of gravel occur. Associated with sporadic freshwater ostracods, the latter might indicate fluvial imprint.

A sample from 1.90-1.70 m b.s. documents a severe facies change. Clayey to fine sandy silt, combined with coarse gravel, contains several fragments of marine molluscs, only few foraminifers and very few ostracods. Several ceramic fragments and shell debris are also included. The occurrence of coarse gravel is either due to anthropogenic activity or to a strong water current. Possibly, a catastrophic event like an extreme flood is responsible for the high transport energy. Intense freshwater input seems to be responsible for the replacement of the marine ostracods by freshwater species as well as for the appearance of fragments of freshwater gastropods. Strong sediment input caused a considerable progradation of the coastline. This is either due to intense alluvial deposition or due to tsunamigenic backwash.

A sample taken from 1.63-1.53 m b.s. contains clayey to silty sediment, hardly any ostracods and no foraminifers at all. Instead, it shows abundant organic matter and fragments of terrestrial snails. The marine to brackish environment is thus replaced by a fluvial-terrestrial freshwater environment due to proceeding siltation.



## 6 Discussion: Geochronology of the environmental changes and their geoarchaeological implications

In the northern part of the sound (vibracore LEF 2), open marine to littoral conditions were replaced by a lagoonal environment around 4700 cal BC (Vött et al. 2006). Furthermore, we found evidence of severe tsunamigenic impact after ~300 cal BC.

High energy impact is also visible in the upper parts of the cores of the vibracore transect which runs along the ruins of the ancient, Hellenistic to Roman bridge. Strabo (10.2.8), who lived around 64 BC-24 AD, reports that the bridge crosses a “porthmos” (= strait), which is supposed to be situated in the area of a former “isthmus” east of the ancient city of Lefkada. The same localisation of an “isthmus” is given by Thucydides (3.94.2), a contemporary witness of the period between ~460 and 395 BC. Our results confirm a relatively high position of the intense weathered bedrock, representing a former gentle topographic elevation in the central part of the sound. This sill marks the longest existing terrestrial connection between Lefkada and the Plaghia Peninsula, narrowed by the post-glacial sea level rise from both a northern and southern direction. Possibly, this isthmus was cut through by Corinthian settlers before the sea level finally reached it. The tsunamigenic impact to the northern sound at or after ~300 cal BC might be responsible for the erection of a bridge where an isthmus still existed in the Classical period.

First saltwater-borne sediments in the presented vibracores of the central transect were found at ~3.55-3.00 m below the recent mean sea level. The profiles give evidence for multiple catastrophic flooding of the sill. However, it seems as if vibracoring sites LEF 24 and PER 5 gradually got under lagoonal conditions before. At least two (four in the middle of the sound) high energy events disturbed the quiescent lagoonal conditions. In the lowermost distinct event layer in vibracore LEF 24 (2.62-2.29 m b.s.l.), a Hellenistic to Roman-Byzantine pottery fragment marks a *terminus ad* or *post quem* for the deposition of the related sediments.

In general, the event layers are documented by coarse (mostly sandy) sediments rich in shell fragments, which sometimes contain gravel or ceramic fragments. It seems plausible to parallelise some of the layers which result from strong water currents. With regard to our findings from the northern sound their tsunamigenic origin seems most probable (Vött et al. 2007d).

The area of the presumed harbour of ancient Lefkada, represented by vibracore LEF 12 in the very south of our working area, was first affected by shallow marine conditions at some time before ~2800-2700 cal BC. Subsequently, a long period of open marine conditions – combined with layers of high energy impact and/or strong anthropogenic influence – occurred, followed by a local regression due to the increased input of alluvial sediments. A clear distinction between anthropogenic and catastrophic deposits remains, however, difficult.

The most recent siltation of the formerly more extended marine or lagoonal environment, as documented in vibracores LEF 12, LEF 38 and PER 5, took place in spite of a relative rise in sea level and is probably due to human impact. Clearing and overuse at the adjacent slopes might have intensified soil erosion.

In the research area, several relative sea level indicators appear, e.g. the submerged Mole of the Corinthians, the Hellenistic-Roman bridge, now covered by sediments, drowned Venetian salt works, etc., all representing a remarkably rapid rise of the relative sea level during the Holocene due to eustatic sea level rise, intense tectonic subsidence and further triggers. At the northern coast of Lefkada Island, however, an Eemian cliff documents strong tectonic uplift. The local differences in tectonic movements, including both subsidence and uplift, have to be considered carefully throughout the interpretation.

## 7 Conclusions

Various sedimentary and archaeological archives helped to decipher the landscape evolution and the interaction between men and environment in the area of the Lefkada Sound. Different methods, combined in an interdisciplinary approach, serve to understand palaeogeographical changes.

The northern part of the sound, represented by vibracore LEF 2, revealed open marine to littoral conditions before ~4700 cal BC. Severe influence of high energy events is evident at least for the time around or after ~300 cal BC.

In the central part of the sound, our results prove a topographical elevation, probably reflecting the former “isthmus” between Lefkada Island and the Plaghia Peninsula. According to historical tradition, this “isthmus” existed until the Classical period and became a “porthmos” (strait) in Hellenistic times. Vibracores LEF 24 and PER 5, located in this area, document the initial existence of a lagoonal environment, which has then been disturbed by multiple high energy impact. While the marginal vibracores show two event-layers, the central vibracore LEF 24 reveals a fourfold impact. Here, the first event seems to have occurred in or after the Hellenistic period as indicated by an included diagnostic ceramic fragment. Against the background of evident tsunami imprint to the northern Sound of Lefkada and adjacent regions, a tsunamigenic interpretation of the encountered event layers in the inner sound seems likely.

According to our findings in vibracore LEF 12, representing the southern part of the sound, open marine conditions set in before ~2800-2700 cal BC. The later harbour situation of ancient Lefkada is reflected by the occurrence of numerous anthropogenic artefacts. Microfossil analyses indicate temporary strong freshwater input, finally resulting in the aggradation of the site after Hellenistic times. Widespread marginal siltation of the Lefkada Sound, also reflected in vibracores LEF 38 and PER 5, is probably attributed to increased soil erosion.

Several relative sea level indicators in our working area show (i) a comparatively rapid rise of the relative sea level and (ii) enormous local differences in tectonic movements.

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## References

- Benetatos, C., A. Kiratzi, Z. Roumelioti, G. Stavrakakis, G. Drakatos & I. Latoussakis (2005): The 14 August 2003 Lefkada Island (Greece) earthquake: Focal mechanisms of the mainshock and of the aftershock sequence. – *Journal of Seismology* 9/2, 171-190.
- Brückner, H. (2003): Delta Evolution and Culture – Aspects of Geoarchaeological Research in Miletos and Priene. – In: Wagner, G.A., E. Pernicka & H.-P. Uerpmann (eds.): *Troia and the Troad. Scientific Approaches*, 121-143.
- Dörpfeld, W. (1927): *Alt-Ithaka. Ein Beitrag zur Homer-Frage.* – 2 vol. München.
- Eros Data Center, USGS (eds.): *ASTER satellite image (2003).*
- Galanopoulos, A. (1952): Die Seismizität der Insel Leukas. I. Allgemeine historische Übersicht. – *Gerlands Beiträge zur Geophysik*, 62/4, 256-263. Leipzig.
- Galanopoulos, A. (1954): Die Seismizität der Insel Leukas. II. Die Erdbeben vom 22. April und 30. Juni 1948. – *Gerlands Beiträge zur Geophysik*, 63/1, 1-15. Leipzig.
- Goessler, P. (1904): *Leukas - Ithaka: Die Heimat des Odysseus.* Stuttgart.
- Handl, M., N. Mostafawi & H. Brückner (1999): Ostracodenforschung als Werkzeug der Paläogeographie. In: Brückner, H. (ed.): *Dynamik, Datierung, Ökologie und Management von Küsten.* – *Marburger Geographische Schriften* 134, 116-153. Marburg.
- Haslinger, F., E. Kissling, J. Ansorge, D. Hatzfeld, E. Papadimitriou, V. Karakostas, K. Makropoulos, H.-G. Kahle & Y. Peter (1999): 3D crustal structure from local earthquake tomography around the Gulf of Arta (Ionian region, NW Greece). – *Tectonophysics* 304, 201-218.
- Hatzfeld, D., I. Kassaras, D. Panagiotopoulos, D. Amorese, K. Makropoulos, G. Karakaisis & O. Coutant (1995): Micro-seismicity and strain pattern in northwestern Greece. – *Tectonics* 14, 773-785.
- Lang, G. (1905): *Untersuchungen zur Geographie der Odyssee.* Karlsruhe.
- Lang, F., K. Freitag, P. Funke, E. Grüger, S. Jahns, L. Kolonas, P. Schwandner & A. Vött (eds.) (2007): *Interdisziplinäre Landschaftsforschung in westgriechischen Akarnanien.* – *Archäologischer Anzeiger* (in press).
- Lehman-Hartleben, K. (1923): Die antiken Hafenanlagen des Mittelmeeres. *Klio-Beiheft* 14.
- Marées, W. von (1907): *Karten von Leukas. Beiträge zur Frage Leukas-Ithaka.* – Berlin.
- May, M., A. Vött, H. Brückner & S. Brockmüller (2007): Evidence of tsunamigenic impact at the Actio headland near Preveza, NW Greece. – In: Gönnert, G., B. Pflüger & J.-A. Bremer (eds.): *Geographie der Meere und Küsten. Coastline Reports* 9. Hamburg.
- Monopolis, D. & A. Bruneton (1982): Ionian Sea (Western Greece): Its structural outline deduced from drilling and geophysical data. – *Tectonophysics* 83, 227-242.
- Murray, W.M. (1982): *The Coastal Sites of Western Akarnania: A Topographical-Historical Survey.* – PhD thesis. University of Pennsylvania.
- Murray, W.M. (1988): The ancient harbour mole at Leukas, Greece. – In: Rabner, A. (ed.): *Archaeology of coastal changes. – Proceedings of the first international symposium "Cities on the sea – past and present"*, Haifa, Israel, September 22-29, 1986. *British Archaeological Reports, International Series*, 404, 101-118.
- Négris, P. (1904): Véstiges antiques submergés. *Athener Mitteilungen* XXIX. 340-369.
- Parcharidis, I., M. Foumelis, E. Lekkas & M. Segou (2006): Implication of Secondary Geodynamic Phenomena on Co-seismic Interferometric Coherence. – European Space Agency, special publication "Fringe 2006", issue 610.
- Partsch, J. (1889): *Die Insel Leukas. Eine geographische Monographie.* – *Petermanns Geographische Mitteilungen, Ergänzungsheft*, 95. Gotha.
- Partsch, J. (1907): Das Alter der Inselnatur von Leukas. – *Petermanns Geographische Mitteilung*, 53, 269-278. Gotha.
- Reimer, P.J. & F.G. McCormac (2002): Marine radiocarbon reservoir corrections for the Mediterranean and Aegean Seas. – *Radiocarbon* 44, 159-166.
- Schroll, E. (1976): *Analytische Geochemie, vol. 2. Grundlagen und Anwendungen.* – Stuttgart.
- Seidlitz, W. von (1927): VIII. section. Geologische Untersuchung der Inselnatur von Leukas. – In: Dörpfeld, W. (ed.): *Alt-Ithaka. Ein Beitrag zur Homer-Frage.* 2 vol. München. 352-372.
- Stuiver, M., P.J. Reimer & R. Reimer (2006): *CALIB Radiocarbon Calibration.* [<http://calib.qub.ac.uk/calib>].

- Vött, A., M. Handl & H. Brückner (2002): Rekonstruktion holozäner Umweltbedingungen in Akarnanien (Nordwestgriechenland) mittels Diskriminanzanalyse von geochemischen Daten. - *Geologica et Palaeontologica*, 36, 123-147. Marburg.
- Vött, A., M. May, H. Brückner & S. Brockmüller (2006): Sedimentary evidence of late Holocene tsunami events near Lefkada Island (NW Greece). – *Zeitschrift für Geomorphologie N.F. Suppl.* Vol. 146, 139-172. Berlin, Stuttgart.
- Vött, A., H. Brückner, M. May, F. Lang & S. Brockmüller (2007a): Strong tsunami impact on the Bay of Aghios Nikolaos and its environs (NW Greece) during Classical-Hellenistic times. – *Quaternary International*. Amsterdam (accepted).
- Vött, A., H. Brückner, M. May, F. Lang & S. Brockmüller (2007b): Late Holocene tsunami imprint on Actio headland at the entrance of the Ambrakian Gulf. – *Méditerranée, revue géographique des pays méditerranéés*, 108, 43-57.
- Vött, A., H. Brückner, S. Brockmüller, M. May, I. Fountoulis, K. Gaki-Papanastassiou, R. Herd, F. Lang, H. Maroukian, D. Papanastassiou & D. Sakellariou (2007c): Tsunami impacts on the Lefkada coastal zone during the past millennia and their palaeogeographical implications. – In: Papadatou-Giannopoulou, H. (ed.): *Proceedings of the International Conference Honouring Wilhelm Dörpfeld, August 6-9, 2006, Lefkada* (in press).
- Vött, A., H. Brückner, S. Brockmüller, M. Handl, S.M. May, K. Gaki-Papanastassiou, R. Herd, F. Lang, H. Maroukian, O. Nelle & D. Papanastassiou (2007d): Traces of Holocene tsunamis across the Sound of Lefkada, NW Greece. – *Global and Planetary Change* (submitted).

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