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Konstantinos TSANAKAS [1*], Efthimios KARYMBALIS [1], Andrew CUNDY [2], Kalliopi GAKI-PAPANASTASSIOU [3], Dimitris PAPANASTASSIOU [4], Hara DRINIA [3], Efterpi KOSKERIDOU [3] & Hampik MAROUKIAN [3]

# LATE HOLOCENE GEOMORPHIC EVOLUTION OF THE LIVADI COASTAL PLAIN, GULF OF ARGOSTOLI, CEPHALONIA ISLAND, WESTERN GREECE

**Abstract:** Tsanakas K., Karymbalis E., Cundy A., Gaki-Papanastassiou K., Papanastassiou D., Drinia H., Koskeridou E., Maroukian H., *Late Holocene geomorphic evolution of the Livadi coastal plain, Gulf of Argostoli, Cephalonia Island, western Greece.* (IT ISSN 0391-9838, 2019).

This study deals with the late Holocene evolution of the coastal swampy Livadi plain, which is located on the northern part of the Gulf of Argostoli (Cephalonia Island). Cephalonia Island is located at the northwest edge of the Hellenic Arc in a tectonically and seismically highly active area. For the purposes of the study, a detailed DEM, produced by topographic sheets (at the scale of 1:5000), was utilized for geomorphological mapping together with extensive fieldwork. In addition, four shallow boreholes, varying in depth from 3 to 5 m, were drilled using a portable vibratory corer. The stratigraphy has been described in detail and four samples (peat - plant material, foraminifera assemblages and shell material) were collected for radiocarbon dating. Additionally, sedimentological and micro/macrofaunal identifications of forty-five sediment samples from the various stratigraphic units were performed to reconstruct the palaeoenvironments of deposition. The results suggest that cores L1 and L2, which are located close to the present day shoreline, are marine/coastal dominated while cores L3 and L4 have a shallowing-upward sedimentary sequence since the lower units correspond to a marine environment of shore-face conditions, which progressively becomes a backshore brackish environment that gradually changes upwards to a terrestrial environment. The dated sea-level indicators (samples of peats, foraminifera and shells) from 5000-4000 BP are too high compared to local relative sea-level curves, indicating local coseismic uplift(s) of around 1 m before 1200 BP and after 4800 BP. This uplift idea is supported by recent (ca. 0.2 m) uplift observed clearly along the beach face at Livadi caused by the recent Cephalonia earthquake in 2014.

**Key Words:** Palaeogeography, boreholes, Holocene evolution, radiocarbon dating, geomorphological evolution, lagoon, Cephalonia, Greece.

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## INTRODUCTION

Coastal lowland plains are excellent geological archives to reconstruct coastal evolution and relative local sea-level fluctuations through sedimentological analyses and micro/macro-faunal identifications. Chronostratigraphy along with facies identification contribute to the reconstruction of coastal landscape evolution and late Holocene sea-level fluctuations caused by eustatism and local tectonics. Reconstructing recent (Holocene) shoreline evolution and related sea-level changes in coastal areas is a well-developed topic on both the Aegean and Ionion coasts. Ghilardi & *alii* (2014, 2018) reconstructed coastal landscapes of the broader area along the south Euboean Gulf (Euboea Island, Greece) during the Holocene based on both geoarchaeological techniques and sedimentological analyses along with micro/macrofaunal identifications of shallow boreholes drilled in the lowlying coastal plains. Different facies have been identified in the cores revealing typical features of deltaic progradation. At the same area Karymbalis & *alii* (2018) reconstructed the recent palaeogeographic evolution of a palaeolobe of the Lilas River fan delta. Gaki-Papanastassiou & *alii* (2011) examined the relative role of fluvial and tectonic controls in the sedimentary and geomorphic evolution of the small, active-fault-bounded fan delta of the Asopos River in eastern Attica (Greece), over the late Holocene. They recognized an earlier phase (pre-thirteenth century AD) of fluvially controlled progradation in the western part of the delta and extremely low recent rates of (vertical) sediment accumulation consistent with sediment starvation.

Evelpidou & *alii* (2012) utilizing similar techniques reconstructed the Holocene palaeogeographic evolution of the western part of Naxos island. They concluded that the former coastal area of the western island was wider with many active lagoons and embayment changing from a shallow marine environment to a coastal environment frequently alternating with a brackish mesohaline system. The former sea-level position in western Naxos island should be between -1.5 m and -2 m during the last 2000 years, which may partly reflect eustatic processes and partly a gradual or coseismic land subsidence. Another palaeogeographic approach regarding the Cycladic Archipelago is the paper by Karkani & *alii* (2018) in which the palaeolandscape of the Paroikia Bay (Paros Island) during the Late Holocene has been investigated. The authors showed that a semi-enclosed lagoon existed in the northeastern part of Paroikia from at least 2915-2551 BC, which was gradually infilled after 780-436 BC, while a subsidence observed on Paros Island is linked to long-term subsidence in combination with vertical seismic displacements. Kraft & *alii* (1977) used subsurface geological analyses to elucidate palaeogeographic coastal settings of major archaeological sites around the Aegean Sea. Desruelles & *alii* (2009) investigated recent changes in relative sea-level of the central part of the Cyclades archipelago by a combination of a geoarchaeological approach and dating of submerged beachrock of Delos and the nearby islands of Mykonos and Rhenia suggesting that the sea level was at about -2.5 m (± 0.5 m) around 400 BC. In order to identify vertical land movements and sea level changes along the coast of Crete since Late Holocene Mourtzas & *alii* (2016) conducted a geomorphological survey along the coasts of Crete which revealed widespread evidence of uplifted and submerged tidal notches, different phases of beachrock formation, and many relics of ancient coastal constructions.

In western Greece Vött & *alii* (2007a, b) reconstructed the deltaic environment of the Acheloos River delta since the middle Holocene. Facies discrimination and determination of palaeoenvironmental settings was based on sedimentological and micro- and macrofaunal analyses of sediments encountered in vibracores along with palaeobotanical, micromorphological and geophysical studies while geochronology allowed to establish a relative sea-level curve for the area. Vött & *alii* (2006) identified Holocene coastal changes of the Astakos plain in Akarnania, NW Greece based on the analysis of the lateral and vertical distribution patterns of sedimentary facies. Koster & *alii* (2015) investigated *tsunami* deposits in the environs of the Agoulinitsa peatland, Kaiafas Lagoon and Kakovatos, along the coast of Gulf of Kyparissia, in the western part of the Peloponnese. Vött & *alii* (2011) studied the palaeoenvironments of ancient Pheia, one of the harbour sites of Olympia in western Peloponnese, and found allochthonous high-energy deposits of marine origin repeatedly intersecting autochthonous deposits in terrestrial or quiescent water environments indicating that the ancient harbour site has been destroyed by a *tsunami* event. Emmanouilidis & *alii* (2018) conducted a middle to late Holocene palaeoenvironmental study of Gialova Lagoon located in the SW Peloponnese through a multi proxy analysis (including sedimentological, high resolution geochemical and micro- and macro faunal analysis) carried out on the sediment sequence of a 8 m deep vibracore.

A significant amount of research has been conducted along the coasts of the Ionian Islands aiming at the Holocene palaeogeographic evolution of lowlying plains focusing on *tsunami* landfalls. Based on its deposits, recurrent impacts of extreme wave events, which should have influenced the Lefkada barrier system, have been reconstructed by May & *alii* (2012). Finkler & *alii* (2018) reconstructed the palaeoenvironmental setting of the harbour facilities at the Pierri site at Corfu Island, including the analysis of the local sedimentary record in order to detect and differentiate natural and man-made triggers that caused environmental shifts.

Storm events have also been reorganized as major factors responsible for coastal morphological changes (Ferreira & *alii*, 2006; Ghionis & *alii*, 2015; Paskoff & Kelletat, 1991; Pirazzoli & Tomasin, 2002; Ullmann & *alii*, 2007). Investigations on the effects of sea storms have been conducted on Greek and Mediterranean coasts for the cases of the Lefkada lagoon as well as the north Italian Adriatic coast of Catalan and the French coasts of the NW Mediterranean (Ghionis & *alii*, 2015; Costas & *alii*, 2005; Jiménez & *alii*, 2009; Mendoza & Jiménez, 2008; Mosso & *alii*, 2011; Pirazzoli & Tomasin, 2002)

The aim of this paper is to reconstruct the recent (late Holocene) evolution of the coastal swampy Livadi plain, located in the northern part of the Gulf of Argostoli (Cephalonia Island), and to evaluate possible seismically-induced elevational changes based on the position of sea-level indicators in the recent core stratigraphy. For this purpose, previous studies of palaeogeographic reconstruction related to the research area were taken into consideration while four shallow boreholes, varying in depth from 3 to 5 m, were drilled and described. Additionally, selected samples (peat - plant material, foraminifera assemblages and shell material) were collected for radiocarbon dating and particle size and micropalaeontological analyses of forty five sediment samples from the various stratigraphic units was performed in an attempt to reconstruct the *palaeoenvironments* of *deposition*. One of the main objectives of the present study is to answer several questions related to landscape and shoreline evolution during the late Holocene, a period of quasi-static sea-level trend.

Willershäuser & *alii* (2013) reconstructed the palaeogeographic evolution of the Livadi coastal plain focusing on the detection of potential *palaeotsunam*i events in the coastal sedimentary record. Additionally they proposed an event-geochronostratigraphy and provided insight in the local Holocene relative sea-level changes.

## REGIONAL SETTING - STUDY AREA

Cephalonia Island occupies an area of 781 km$^2$ and is located at the north-west edge of the Hellenic Arc in a tectonically and seismically highly active area (fig. 1). The tectonic situation of the broader area of the Ionian Islands is highly complex because collision, subduction, transform faulting and spreading mechanisms are concentrated in a small region (Sachpazi & *alii*, 2000). The evolution of the island is dependent mainly on the behavior of the Hellenic

Arc, which lies offshore just west of Cephalonia. Geodynamic processes in the region are related to the active subduction of the African lithosphere beneath the Eurasian plate, which progressively becomes continental convergence in northwestern Greece (fig. 1). The transition occurs along the Cephalonia fault zone, a prominent dextral strike slip fault, located offshore, west of the island (Louvari & *alii*, 1999; Scordilis & *alii*, 1985).

The dominant long-term vertical movement of the island during the Quaternary is uplift (Sorel, 1976; Stiros & *alii*, 1994). Gradual uplift from the beginning of the Pleistocene has left its imprint on the landscape of Cephalonia. The existence of a series of uplifted marine terraces, which have been carved mainly on Pliocene formations along the coasts of the southern part of Cephalonia, in addition to the presence of fragmented erosional – dissolutional planation surfaces at various elevations on the carbonate rocks of the Alpine bedrock, indicate the importance of neotectonics in the geomorphic evolution of the island (Karymbalis & *alii*, 2013).

Along the northeastern coasts of the island at the broader area of the Fiscardo peninsula fossil shorelines produced by recent co-seismic movements have been identified (Evelpidou & *alii*, 2016). A tidal notch slightly submerged below present mean sea level exists at various sites. The depth of this "modern" notch is now at -20 ± 10 cm has been submerged by the global sea-level rise during the 19th and 20th centuries. The existence of this notch at the same depth on east and west sides of the Ionian Thrust suggests that both areas were not affected by the co-seismic vertical movements that occurred in 1953 (in the wider area). On the east coast of the Fiscardo peninsula impacts of ancient earthquakes have left some marks of emergence at about +18 and +44 ± 5 cm, and of submergence at about -25 (modern), -45, -60, -75, -82, -100, and -230 cm, with even some evidence of past uplift and subsidence at the same sites (Evelpidou & *alii*, 2016). During the strong earthquake (Ms = 7.2) in 1953, the eastern part of the Cephalonia Island as well as the eastern coast of the Gulf of Argostoli experienced sudden co-seismic uplift up to about 70 cm (Stiros & *alii*, 1994) documenting that there is a direct relation between coastal evolution and earthquake activity. This is evident from the existence of a continuous tidal notch for 14 km along the southeastern coastline of the Island (Pirazzoli & *alii*, 1994; Stiros & *alii*, 1994; Evelpidou & Pirazzoli, 2016) which was uplifted +50 ± 10 cm as a consequence of the 1953 earthquake.

According to Willershäuser (2013), the Island was hit by almost 5 *tsunami* -events, which were dated to 5700 cal BC (I), 4250 cal BC (II), the beginning of the 2nd millennium cal BC (III), 1st millennium cal BC (IV) and 780 cal AD (V).

The Livadi coastal plain is located at the northernmost part of the Gulf of Argostoli. It is a low-lying swampy-marshy environment with a maximum elevation of 2.8 m a.s.l. separated from the Gulf of Argostoli by a barrier beach consisting of coarse sand (fig. 2). To the north and east the swampy area is bounded by Upper Cretaceous limestones of the Paxos geotectonic unit while to the northwest it is bounded by Pleistocene formations (mainly sandstones and conglomerates). To the west the coastal plain progressively gives its position to coastal fan deposits.

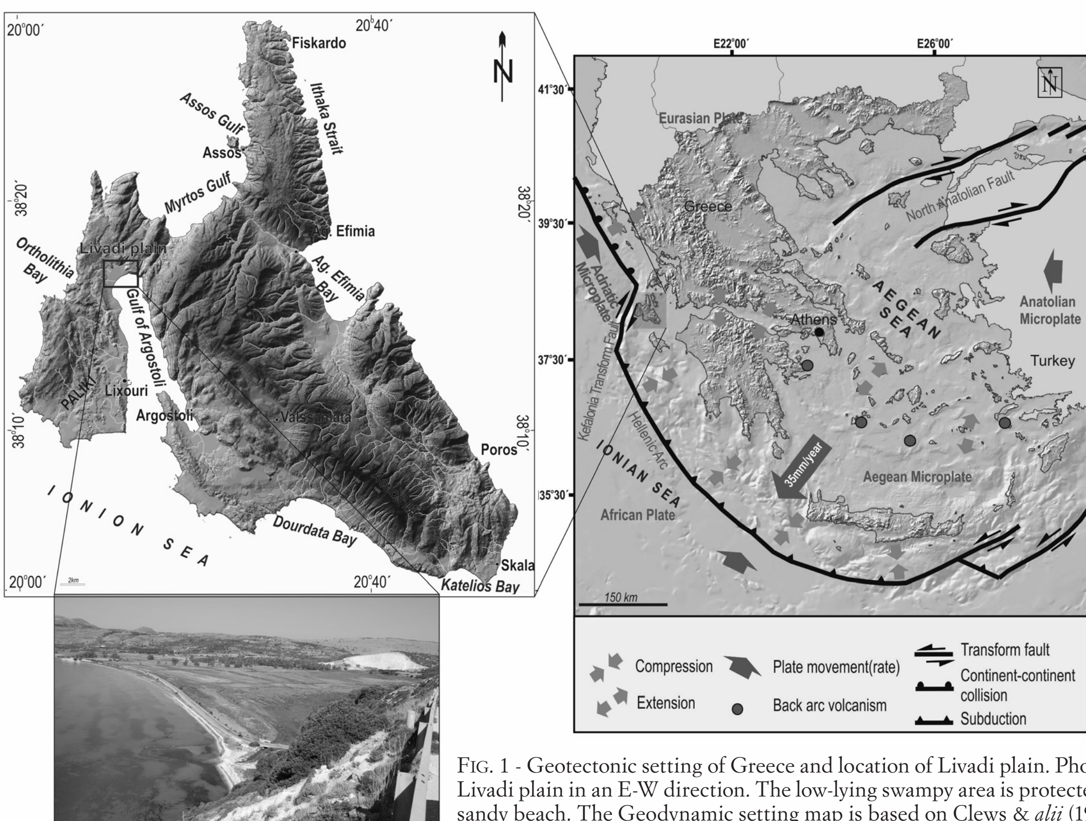


FIG. 1 - Geotectonic setting of Greece and location of Livadi plain. Photo depicts the Livadi plain in an E-W direction. The low-lying swampy area is protected by a barrier sandy beach. The Geodynamic setting map is based on Clews & *alii* (1989), Sachpazi & *alii* (2000), Vött & *alii* (2007) and Willershäuser & *alii* (2013).

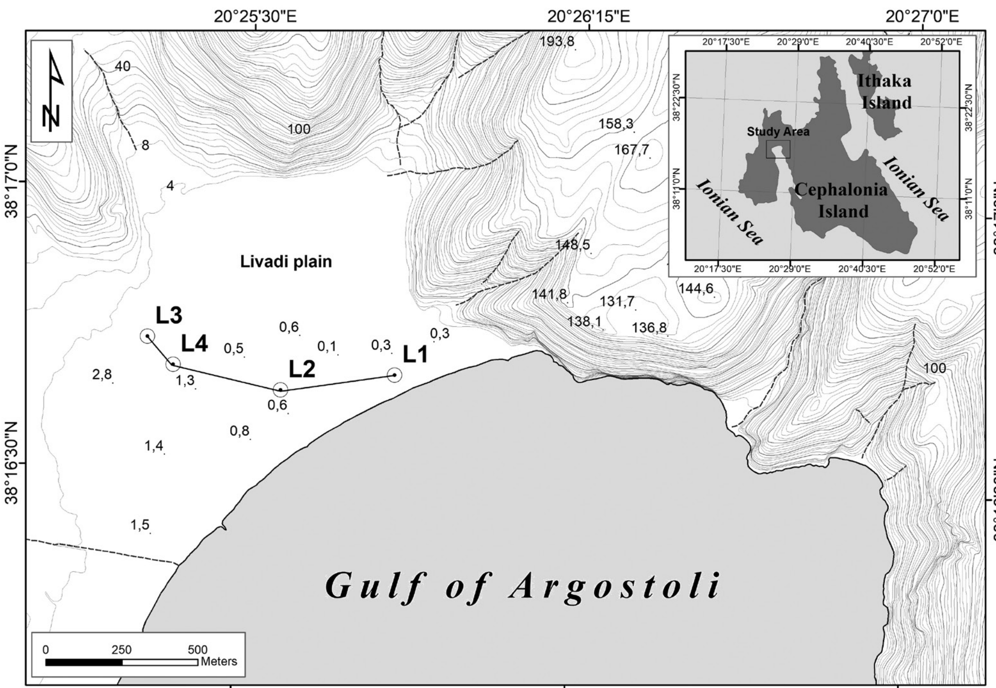


FIG. 2 - Topographic map of the Livadi plain. Red dots L1-L4 represent the boreholes locations.

The north-south trending Gulf of Argostoli separates the main island in the east from the Paliki Peninsula in the west (fig. 2). The bathymetry of the Gulf reveals that it is a shallow submarine valley with a maximum depth of about 25 m east of cape Ag. Georgios. Its western submarine slopes are less steep than the eastern ones probably due to structural reasons since the strata on the western Paliki peninsula are dipping toward the Gulf as well as due to the deposition of sediments supplied by the drainage networks of the Paliki Peninsula. The present Gulf of Argostoli was a valley during the early Holocene with a channel of almost N–S direction flowing along its eastern side. This was the main channel of a large drainage pattern which was active during the last glacial period up until the early Holocene while the three major drainage networks of the present Paliki peninsula were its major tributaries (Karymbalis & *alii*, 2013).

## MATERIALS AND METHODS

A detailed 2x2 m cell size DEM produced by detailed topographic sheets (at the scale of 1:5,000) with a good contour density (4 m contour interval, as well as 1 m in the relatively flat low-lying regions) obtained from the Hellenic Military Geographical Service, was utilized for geomorphological mapping together with extensive fieldwork. In addition series of aerial photos taken in 1945 and 1996 along with google earth images were used for the identification of the main landforms.

Stratigraphic data were collected in July 2011 using a portable vibratory corer, 50 mm in diameter. To obtain information about the late Holocene stratigraphy under the recent alluvial cover, four cores were collected from the back barrier beach swampy area of the Livadi coastal plain (fig. 2, tab. 1) extending down to a depth of 3 m (L1 and L3), 3.3 m (L2) and 5 m (L4).

Core elevations were determined using a DGPS Topcon GMS-2 with an accuracy of ± 0.03 m. Topographic measurements were performed perpedincular to the coastline across the minimum elevation of the beach barrier using a Leica Disto A8 laser distance meter in order to determine the tangential beach slope. Maximum elevations of the wave run-up (R) with respect to the mean sea level were calculated using the Komar's (1998) equation:

$$R=0.36*g^{0.5}*S*H_{so}^{0.5}*T$$

where S is the tangential beach slope, T is the wave period and $H_{so}$ the maximum significant offshore wave height. The wave period (T) and the maximum significant offshore wave height ($H_{so}$) were calculated using Cerc (1984) equations adopting wind and wave characteristics for SE direction winds (120°-150°) from the Hellenic Center for Marine Research (Soukisian & *alii*, 2007). All elevations are reported here as either above or below mean sea-level. Cores were described and logged, and then sub-divided in the field.

The cores were granulometrically and palaeontologically analyzed in order to determine the depositional evolution and the palaeoenvironmental history of the coastal plain. Forty five sediment samples were taken from selected layers at decimeter intervals. Dry mechanical sieving was performed on all sediment samples. Eight sieves were used, ranging in diameter from 4 mm for the coarser particles to 45 μm or 0.045 mm for the finer ones and percentage distribution by weight of silt-clay (< 0.63 μm), sand (0.63 μm - 2 mm) and gravel (> 2 mm) particles of the matrix material was estimated for each sample.

TABLE 1 - Geographic characteristics of the four boreholes within the Livadi plain.

| Core ID | Coordinates | Surface elevation (cm) | Core max. depth (cm) | Setting description |
|---|---|---|---|---|
| L1 | N 38º 16.856′<br>E 20º 25.943′ | + 30 | 300 | Back barrier depression<br>Veg. Patchy *Suaeda maritima* |
| L2 | N 38º 16.804′<br>E 20º 25.538′ | 50 | 330 | Channel depression<br>Veg. Patchy *Suaeda maritima* |
| L3 | N 38º 16.862′<br>E 20º 25.395′ | 230 ± 10 | 440 | Slight depression |
| L4 | N 38º 16.832′<br>E 20º 25.429′ | 150 ± 10 | 500 | |

The palaeontological analysis was aimed at the determination of the depositional environment. For that purpose, selected samples were studied from the collected cores to assess their environmental character and stratigraphic position. These samples were processed using traditional macro and micropalaeontological techniques for calcareous macro and microfossils (mollusks and foraminifera). The material > 125 µm of the washed residue was semi-quantitatively picked for all biogenic components under a light microscope. At least 100 benthic specimens were counted for each sample, where sufficient concentration was present, and they were identified with reference to Cimerman and Langer (1991), Sgarrella and Moncharmont Zei (1993). Selected species were photographed by using a JEOL JSM-6500F thermal field emission scanning microscope (FESEM). Differently from the benthic foraminifera, the planktonic assemblage was very poor and badly preserved; consequently it was counted simultaneously to the benthic assemblage, but examined only qualitatively.

The chronostratigraphy of the cores was established by $^{14}$C dating of 4 samples (two sub-samples of plant and peat material, one shell sample and one mixed assemblage foraminifera sample) collected from core material. $^{14}$C dating via accelerator mass spectrometry has been undertaken by Beta Analytic Radiocarbon Dating Laboratory, Florida, USA).

Accelerator Mass Spectrometry (AMS) method was applied on four samples (plant material, mixed assemblage foraminifera sample, one shell and peat deposition), counting directly the radiocarbon ($^{14}$C) atoms (Stuiver et. al, 1998) in order to establish the corresponding ages (tab. 2). The $^{13}$C/$^{12}$C ratio has been used to monitor the ionization detection efficiency and improve the accuracy of the radiocarbon dating. Based on the assumption that the production of radiocarbon is not constant, the measured age of the samples had to be converted to calendar years. $^{14}$C measured ages have been calibrated using IntCal04 calibration curve, applying 2σ (95.4%) probability using OxCal version 4.3 software.

Since we selected four different types of samples (peat, plant and shell material, forams) for dating there is a wide variety of unknown factors that may have influenced the $^{14}$C concentration found in each sample. Samples with a marine component, in coastal regions, require an additional consideration because of the reservoir age of the ocean (e.g. Reimer & Reimer, 2001). A number of authors have used δ13C values as indicators of palaeovegetation change, and notably in coastal environments as indicators of palaeosalinity, due to an increased dominance of C-4 plants as salinity increases (e.g. DeLaune, 1986; Chmura & Aharon, 1995; Mackie & *alii*, 2005; Wilson & *alii*, 2005). Sample Liv4-pt was a bulk sample out of peat with a terrestrial delta $^{13}$C signature. On the other hand samples Liv2-sh and Liv1-fr are of marine origin and Marine Reservoir Effect must be considered while sample Liv1-pl seems to represent terrestrial plant material but the delta $^{13}$C value indicates that marine influence cannot be excluded. Hence for three of the samples we used a reservoir correction and calibrated ages were attained based on Intcal 7.1, web version, 2 sigma interval.

## RESULTS

### *Geomorphology of the Livadi coastal plain.*

The Livadi plain is a typical coastal swamp confined in a sheltered environment in the Gulf of Argostoli. In terms of composition it consists of unconsolidated sediments, mostly fine grained and sands. The geomorphological configuration of the plain is the outcome of the interaction of land and marine processes during the Holocene (fig. 3). It is characterized as a low lying almost flat and extensive area with a shallow topographic depression observed at its easternmost part, acting as a perennial swamp.

The fine sediments along the plain, observed not only surficially but also in the core samples are indicative of a coastal lagoon which has been enclosed by spits and bars as the plain has evolved during the Holocene.

Livadi plain's formation is dominantly affected by marine processes and a recent propagation towards the sea is indicated by the presence of group of advancing beach ridges. At least one generation of beach ridges has been recognized via linear topographic depressions with an almost E-W orientation alternated with ridges (< 50 cm ridge and swale topography) as well as changes in vegetation. Beach ridges are only visible at the lower part of the plain along the modern shoreline, indicating former limits of the lagoon during the late Holocene.

At least seven tributaries of 2$^{nd}$ and 3$^{rd}$ order discharge in the study basin. Three alluvial cones have been formed along the western and northwestern boundaries of the plain by the deposition of alluvial sediments deriving from ephemeral streams at the northeastern part of Paliki peninsula which discharging into the Gulf of Argostoli. These drainage networks were tributaries of a much larger

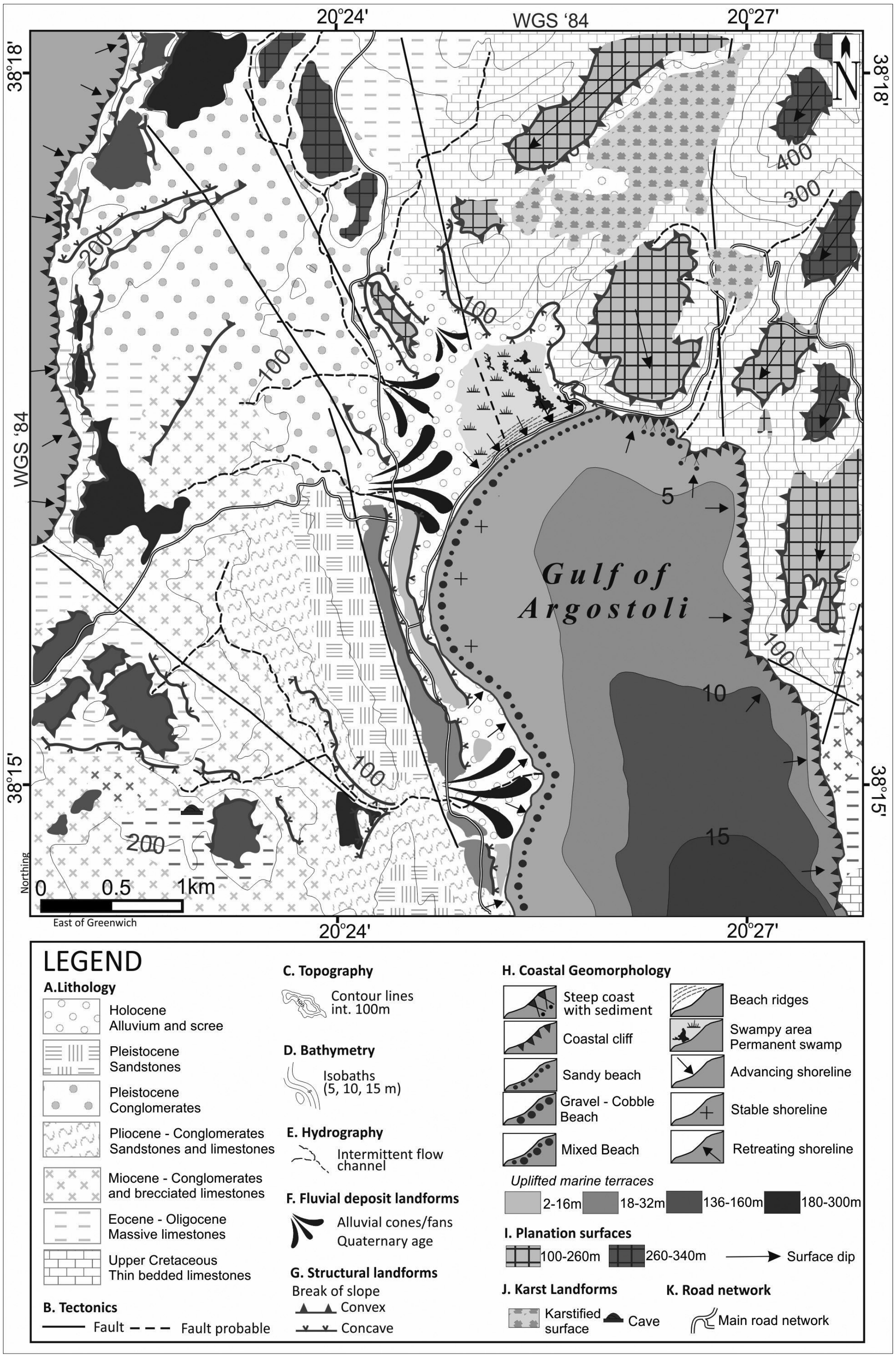


Fig. 3 - Geomorphological map of the broader Livadi plain investigated area.

TABLE 2 - Accelerator Mass Spectrometry dates and cal ages (OxCal 4.3).

| Core ID | Depth (cm) | Sample type | Dating method | Lab ref. | Measured age | 13C/12C | 2σ Calibration (IntCal04 curve) |
|---|---|---|---|---|---|---|---|
| L1-pl | 166-180 | Plant material | AMS | 311090 | 1130 ± 30 BP | -14.5 °/$_{oo}$ | 1172-631 cal BP |
| L1-fr | 265 | foraminifera | AMS | 311086 | 4090 ± 30 BP | +0.8 °/$_{oo}$ | 4241-4008 cal BP |
| L2-sh | 300-305 | shell | AMS | 311089 | 4110 ± 30 BP | +0.1 °/$_{oo}$ | 4280-4060 cal BP |
| L4-pt | 342-348 | peat | AMS | 311087 | 4410 ± 30 BP | -25.9 °/$_{oo}$ | 5257-4866 cal BP |

drainage network with a N-S direction (present Argostoli Gulf) which was active during the last glacial period up until the early Holocene (Gaki-Papanastasiou & *alii*, 2011). The large size of the alluvial cones in relation to the size of the depression indicates that the streams contribute not only to the filling of the basin but also to erosional procedures during flooding events.

The broader area surrounding the Livadi plain is characterized by a mountainous relief with elevations exceeding 400 m at the northeastern part. Planation surfaces have been recognized and mapped throughout mainly the northern part of the broader study area representing remnants of older, fewer and more extensive erosional surfaces. These surfaces, elevated at 100-260 m and 260-340 m were formed by the combined action of erosion and dissolution. Their development probably reflects the gradual tectonic uplift of the island while their local separation by stream valleys in the form of distinct erosional escarpments is indicative of a rejuvenating relief. Smaller karst depressions are also visible at the northern part of the study area, occurring in association with the highly soluble carbonate rocks of Cretaceous age.

Active tectonics has played an important role not only in the sediment accumulation within the plain but also in its recent configuration. Tectonic activity during the Late Quaternary is further suggested by the presence of several uplifted geomorphological features across the whole island, including marine terraces, marine notches, beachrocks and aeolianites (Karymbalis & *alii*, 2013) In particular, uplifted marine terraces have been recognized at the western part of the Gulf of Argostoli, imprinted into pre-existing Mio-Pliocene marine formations, and elevated at 2-16 m, 18-32 m and 136-160 m.

The coastal geomorphology is quite contradictive in the Gulf of Argostoli. The eastern part is characterized by steep coastal cliffs (slopes > 50%) and relatively stable shoreline as opposed to the western part of the Gulf where the deposition of fluvial sediments resulted in an advancing shoreline and the subsequent formation of beaches consisting of mixed sediments. The morphological differentiation of both sides of the Gulf could be attributed to the increased sediment supply due to the erodible lithology of the drainage basins at the west as opposed to the hard to erode limestones to the east.

### *Dating*

Liv1-pl sample (plant material) was collected from a depth of 170 cm in the L1 borehole and gave an age of 1172-631 cal BP indicating the time of the lagoonal occupation of the plain within the Holocene. A mixed assemblage of foraminifera (Liv1-fr) was collected from a depth of 265 cm from the same borehole and gave an age of 4241-4008 cal BP. The marine shell from a clast horizon in L2 coring, at a depth of 300-305 cm gave an age of 4280-4060 cal BP constraining the age of a marine inundation (possible *tsunami* or storm event) in the Gulf of Argostoli. Finally, sample Liv4-pt was collected from a peat deposit layer (borehole L4) at a depth of 342-348 cm. It gave an age of 5257-4866 cal BP indicating the vertical position of the shoreline at that time, as peat is considered to serve as a credible sea level index point.

### *Sedimentary stratigraphy and palaeontological analysis*

*Borehole L1* - Borehole L1, located about 93 m from the present day shore at an absolute elevation of 0.3 m was drilled down to a depth of 3 m. The core is mainly characterized by sand deposits while the upper layers consist also of silt and clay (fig. 4).

From the bottom of the core up to 2.74 m a peat layer is found rich in well-preserved agglomerated *Posidonia* debris. At a depth of 2.84 m the peat layer is interrupted by a thin, approximately 5 cm thick, layer consisting of coarse to medium sand. From 2.74 up to 1.87 m a layer of gray medium to coarse sand with comminuted shell debris and intact valves (up to 5 mm) was observed. Fragments of bivalves (*Nucula* and *Tellina*), gastropods (Cerithiids, Rissoids, *Gibbula* and *Bittium*, *Truncatella hammersmithi*), benthic forams, spines of echinoids and sponges were found. Additionally, rare *Donax trunculus*, which is usually found 0-2 m in depth in the Mediterranean Sea, and unfragmented but few Tellinids were encountered. The benthic foraminifera fauna is dominated by marginal marine environment assemblages represented mainly by *Ammonia beccarii*, *Elphidium crispum*, *Uvigerina sp.*, *Cibicides lobatulus gr.*, *Amphistegina sp*, *Planulina ariminensis.* At 2.49 m the sandy layer is interrupted by a 3 cm thick peat layer with well-preserved agglomerated *Posidonia* debris. A sample of mixed foraminiferal assemblage collected from the depth of 2.6-2.65 m was dated at 4810-4390 cal BP.

From 1.87 up to 1.23 m the stratigraphy consists of gray coarse sand and rounded to sub-rounded grit, with common comminuted shell debris, and few intact gastropods (up to 4 mm). As in the underlying sand layer fragments of bivalves (*Donax venustus*, *Donacila cornea*), gastropods (*Nassarius* sp., *Bittium*, *Rissoa ventricosa*, *Truncatella subcylindrica* and *Truncatella hammersmithi*), and spines of sponges are frequent. Benthic foraminifera fauna is similar to the one described at the underlying layer. In particular foraminiferal assemblages are dominated by *Ammonia beccarii*, *Cibicides lobatulus gr*, *Elphidium spp. Planulina*

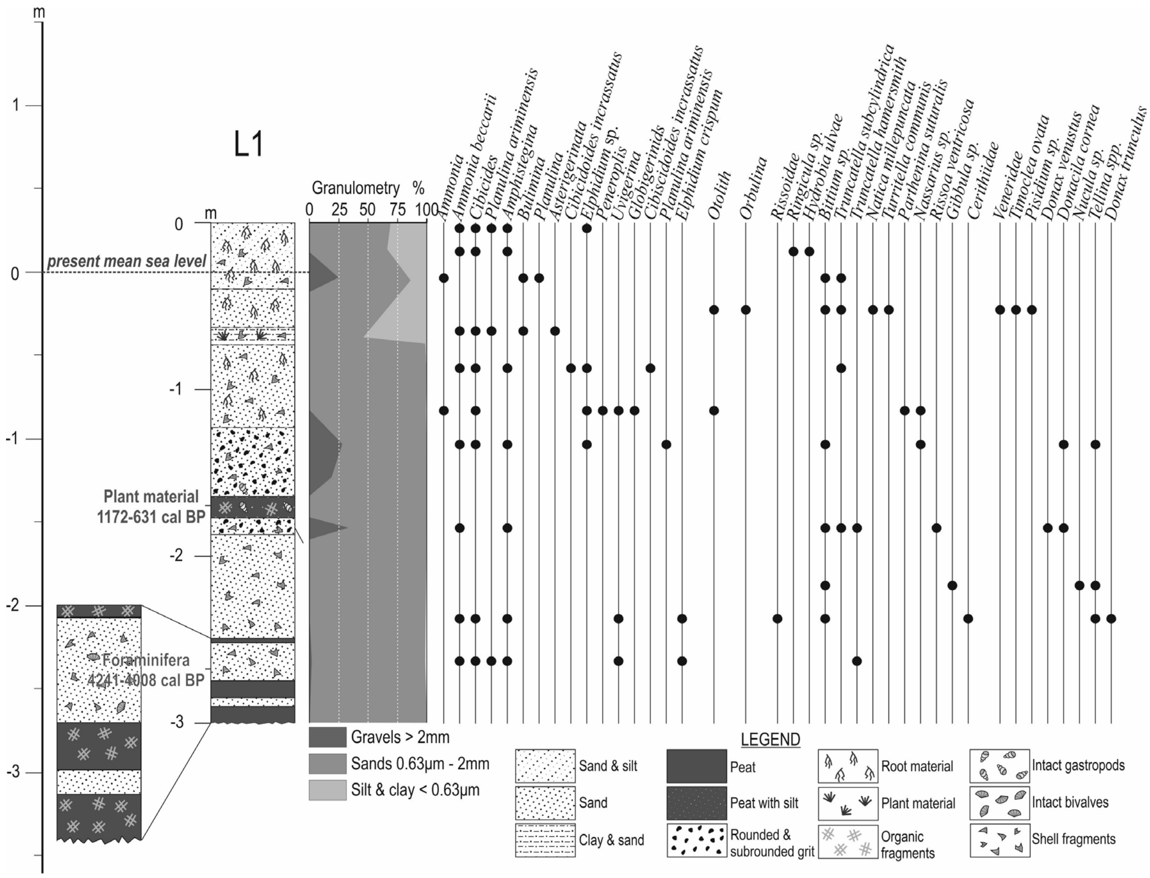


FIG. 4 - Borehole L1 log and results of grain size and palaeontological analysis.

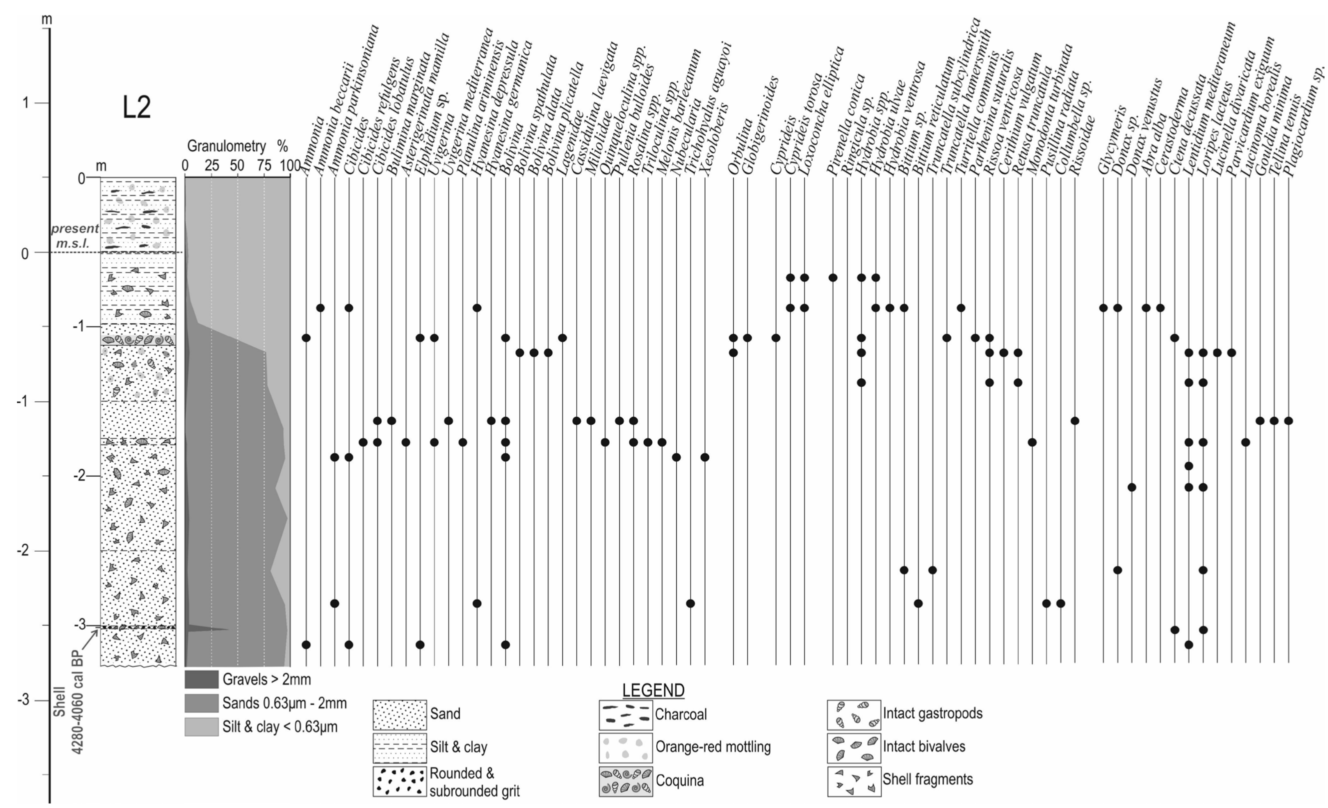


FIG. 5 - Borehole L2 log and results of grain size and palaeontological analysis.

*ariminensis* and *Amphistegina sp*. In general, planktonic foraminifera are very scarce in this layer while the tests of foraminifera found in the sandy interval are fairly well preserved except for some of them that are rather smooth and sometimes difficult to classify even at genus level. Within this layer a 14 cm thick poorly humified peat layer consisting of stem material and well preserved agglomerated *Posidonia* debris was found at 1.66-1.80 m. The peat also includes gray coarse sand with shell debris and intact gastropods (up to 1-2 mm). A sample consisting of plant material revealed an age of 1290-1180 cal BP.

From 1.23 m up to 0.72 m there is a 0.55 m thick layer of medium to coarse sand, slightly finer than the underlying unit, rich in poorly humified root material and comminuted shell debris. The macrofauna is dominated by spicules of echinoids, fragments of bivalves and gastropods (*Truncatella subcylindrica*, which is found in marine coastal environments near or just above the high tide line, *Parthenina suturalis* - parasitic in Polychaete Annelids). Microfossil analysis indicates that assemblages are dominated by displaced marine benthic foraminifera (*Ammonia beccarii*, *Elphidium* spp., *Amphistegina*, *Cibicides lobatulus gr*, *Cibicidoides incrassatus*, *Peneroplis sp*, *Uvigerina sp and Globigerinidae*). The lower part of this unitis characterized by the presence of otoliths (*Ceratoscopelus maderensis*, *Diaphusholti* and *Myctophum punctatum*) and some terrestrial gastropods.

Above the previous layer, a 10 cm thick layer of gray medium sand with clay with poorly comminuted shell debris, rich in humified plant materials, is recorded between 0.72 and 0.62. It contains scattered rather displaced transported marine benthic foraminifera (*Ammonia beccarii*, *Planulina ariminensis*, *Cibicides lobatulus sp.*, *Asterigerina taplanorbis*, *Bulimina sp.*).

From 0.62 up to the top of the core the stratigraphy consists of beige medium to coarse sand which progressively becomes black gray medium to coarse sand with silt upwards. It is rich in poorly humified root material and comminuted shell debris. At the depth of 30 cm some angular limestone clasts are present. Macrofossil analysis of samples from the lower part revealed the presence of *Truncatella subcylindrica*, a brackish water gastropod which lives on marine foreshores or salt marshes. At the lower part of this unit an intact *Bittium* and a small *Pisidium* (a freshwater bivalve) are identified. Fragments of gastropods (*Truncatella subcylindrica*, which are indicative of marine coastal environments near or just above the high tide line, *Bittium*, *Natica millepunctata*, *Turritela*) spines of echinoids and very fragmented shells of bivalves (*Veneridae*, *Timoclea*) are common. The microfossils of the lower part include many benthic forams both fragmented and in good condition (*Ammonia*, *Bulimina*, *Planulina*) and planktonic forams (mainly *Orbulina*).

The benthic microfauna of the upper part of this unit also consists of benthic foraminifera (*Ammonia beccarii*, which is a typical marine species abundant in infralittoral bottoms and can tolerate a moderate concentration of organic matter, *Cibicides lobatulus gr*, *Planulina ariminensis*, which is an indicator of bottom current activity, *Amphistegina sp*). A significant number of the benthic foraminifera are epiphytic. Planktonic foraminifera are very scarce. The abundance of epiphytic species suggests a coastal environment of high water temperature, shallow depths and well oxygenated and vegetated sea floor. A sample from 15-20 cm depth showed the existence of benthic forams along with a mixed marine and back barrier brackish - salt marsh gastropod shell assemblage (*Ringicula and Hydrobia ulvae respectively*).

*Borehole L2* - The core was drilled at the center of the coastal swampy Livadi plain about 500 m west of the location of L1 and 350 m from the coastline. The core reached a depth of 3.27 m. The lower half of the core (up to 1.5 m) is dominated by sand deposits (sands represent approximately 85% of the total sediment texture) while the upper 1.5 m consist also of silt and clay (mud represents 95% of the total sediment texture).

From the bottom of the core up to 2.5 m the stratigraphy consists of waterlogged fine to medium gray sand with finely comminuted shell debris and spicules of sponges. The basal section of this unit contains angular to subangular terrigenous quartz grains. A 2 cm thick pebble clast horizon consisting of rounded and oblate limestone clasts (1-3 cm diam.) and numerous shell fragments in a sand matrix is recorded at the depth of 3 m.

The macrofauna of this unit is dominated by bivalves (such as *Lentidium mediterraneum*, which corresponds to fine sands of the infralittoral zone, *Ctena decussata* which is indicative of shallow shelf environments, *Loripes lacteus*, characteristic of sheltered settings, *Donax sp.*) and gastropods (*Bittium* sp., *Bittium reticulatum*, *Pusillina radiata* - epiphytes- assemblage and fragments of *Collumbella* and *Truncatella subcylindrica*, which are indicative of a brackish environment). Microfossil assemblages are mainly dominated by benthic foraminifera and rare planktonic foraminifera. *Haynesina depressula* shows a marine environment of low salinity due to fresh water input, while the oligohaline character of the depositional environment is further supported by the presence of *Trichohyalus aguayoi*, a brackish foraminiferal species which dominates in oligohaline conditions under an influence of fresh water input (Bronnimann & *alii*, 1992).

From 2.5 m up to 1.5 m the stratigraphy consists of fine to medium gray sand with finely comminuted shell debris and frequently intact valves of bivalve as the underlying layer. The macrofauna of this unit includes bivalves (such as *Lentidium mediterraneum*, *Donax venustus*, *Loripes lacteus*, *Gouldia minima*, *Tellinatenius*, *Plagiocardium*, *Lucinoma borealis*) and gastropods (*Monodonta turbinata*, Rissoidae). The microfossil analysis showed the presence of various benthic foraminifera (*Ammonia parkinsoniana*, *Cibicides*, *Nubecularia*, *Quinqueloculina* spp., *Elphidium* spp., *Cibicideslobatulus*, *Rosalina* spp., *Uvigerina* spp., *Triloculina* spp., *Asterigerina tamamilla*, *Cibicides lobatulus gr.*, *Melonisbarleeanum*, *Planulina ariminensis*, *Bolivina* sp., *Bulimina marginata*, *Uvigerina mediterranea*, *Cassidulina laevigata*, *Cibicides lobatulus*, *Haynesina germanica*, *Miliolidae*, *Pullenia bulloides*) together with many planktonic foraminifera. Among the ostracods, Xestoleberis and few Cyprideis are also found.

From 1.5 m up to 0.98 m the stratigraphy is dominated by blue gray sand with a black and orange staining with abundant sponge spicules and common intact bivalves and gastropods as well as shells fragments. Bivalves include *Lentidium mediterraneum*, *Loripes lacteus*, *Lucinella divaricata* and few *Parvicardium exiguum*. The gastropod fauna is dominated by *Retusa truncatula*, *Rissoa ventricosa*, *Cerithium vulgatum*, and rare *Hydrobia*. Microfossil analysis showed common to abundant planktonic foraminifera (mainly represented by *Orbulina*), marine ostracods and many benthic forams (*Bolivina spathulata*, *Bolivina alata*, *Bolivina plicatella*) indicative of a poorly oxygenated sea floor. In the upper part of this unit (between 1.05 and 1.12 m) there is a 7 cm thick coquina layer rich in both intact and fragmented gastropod (*Rissoa ventricosa*, *Parthenina suturalis*, *Truncatella hammersmithi*, *Hydrobia*) and bivalve (mainly *Ctena decussatea*) shells and spicules of sponges as well as spines of echinoids. The coquina layer contains also planktonic foraminifera (*Orbulina*, *Globigerinoides*), benthic forams (*Ammonia*, *Elphidium*, *Uvigerina*, *Bolivina*, Lagenidae) and Ostracods (juvenile *Cyprideis* and many adult marine ostracods).

From 0.98 m up to 0.5 m the stratigraphy consists of chocolate-brown silty clay with few intact gastropods (*Hydrobia* spp., abundant *Hydrobia ulvae* and *Hydrobia ventrosa*, *Pirenella conica*) and comminuted shell fragments of bivalves (*Glycymeris*, *Donax*, *Abra alba*, *Cerastoderma*), gastropods (Turritelidae, *Bittium*) and echinoderms. The microfauna is dominated by a monospecific assemblage of well-preserved autochthonous ostracods *Cyprideis torosa*, as well as by few *Loxoconcha elliptica* indicating a brackish lagoonal environment. Benthic foraminifera include *Ammonia beccarii*, *Haynesina depressula* and *Cibicides*. Planktonic forams are also present.

Overlying the lagoonal unit there is a 0.5 m thick layer composed of chocolate-brown silty clay with appearances of charcoal, and orange-red mottling. Sediment in this unit is lightly dessicated and cracked, reflecting its occurrence in a sheltered, seasonally-flooded, swampy area.

*Borehole L3* - The borehole was located about 700 m from the present day shore at an absolute elevation of 2.3 m. Although the core reached a depth of 4.47 m, no appropriate dating material was found. The stratigraphy is mainly characterized by silt and clay deposits.

From the bottom of the core up to 4.2 m there is a layer of brown fine sand with silt and clay with highly comminuted shell fragments. The microfaunal analysis showed that the autochthonous assemblage is made up of ostracods (such as *Candona* sp.) typical of a freshwater or brackish environment. A few well-preserved planktonic foraminifera of small and equal size indicative of an autochthonous assemblage are also recorded. Benthic foraminifera are very rare (*Ammonia tepida*, *Bolivina*).Above this layer there is a 0.3 m thick layer of yellowish-brown silty fine sand with occasional subrounded limestone grit. It includes fragments of bivalves, spines of echinoids and benthic foraminifera (Lagenidae).

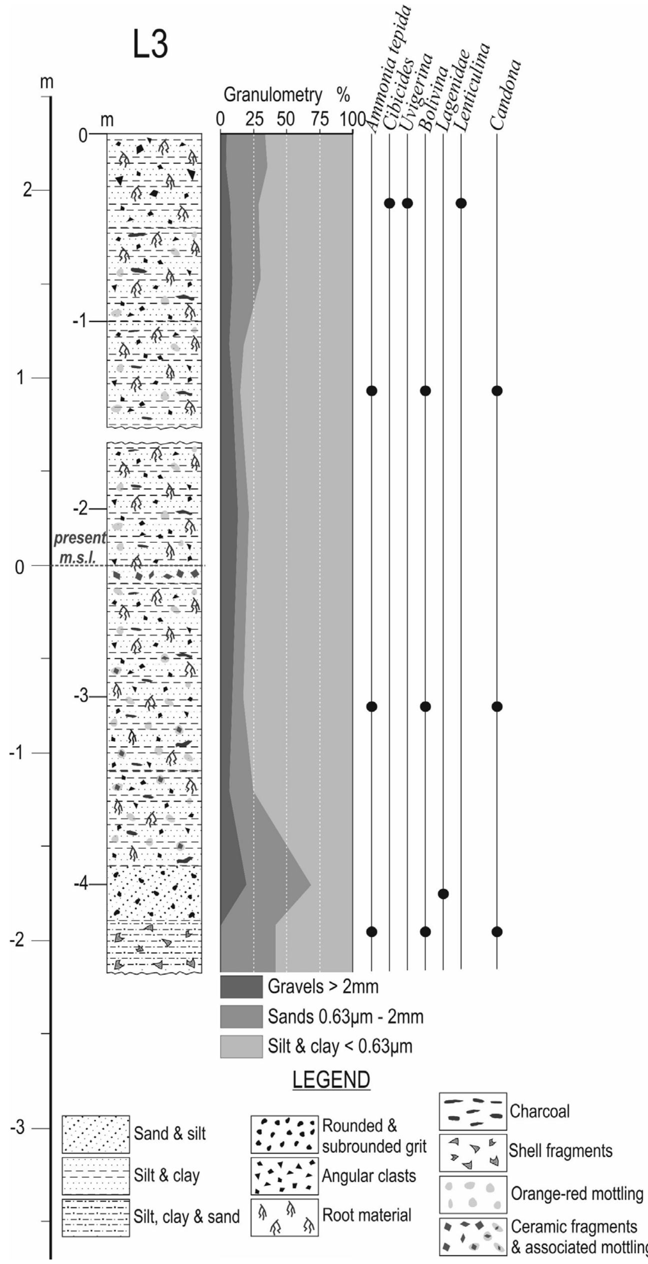


FIG. 6 - Borehole L3 log and results of grain size and palaeontological analysis.

From 3.9 m up to 0.5 m the stratigraphy is dominated by chocolate-brown silty clay. It is rich in poorly humified root material, contains angular limestone grit (of about 1 cm diam.) with common orange-red mottling and apparent charcoal (about 1-2 mm). Within this unit a 10 cm thick layer of ceramic fragments is recorded between 2.3 and 2.4 m, which could possibly correspond to a common occupation horizon. Below this horizon and up to the base of the unit very common orange-red mottling partly from ceramic fragments is observed.

The top 0.5 m of the core consists of chocolate-brown silty clay, highly desiccated and cracked at the surface (0-5 cm), rich in poorly humified root material, with a friable structure that becomes less friable with depth. It contains volcanic glass, quartz grains, angular limestone clasts and grit (of about 1 cm diameter). The palaeontological analysis showed a few equally sized planktonic foraminifera and subrounded fragments of terrestrial gastropods.

*Borehole L4* - Borehole L4 was drilled in between boreholes L2 and L3, about 560 m from the present day coastline at an absolute elevation of 1.5 m. The core reached a depth of 5 m and consists of alternations of silt, clay and fine sand with occasional grid and pebble clasts.

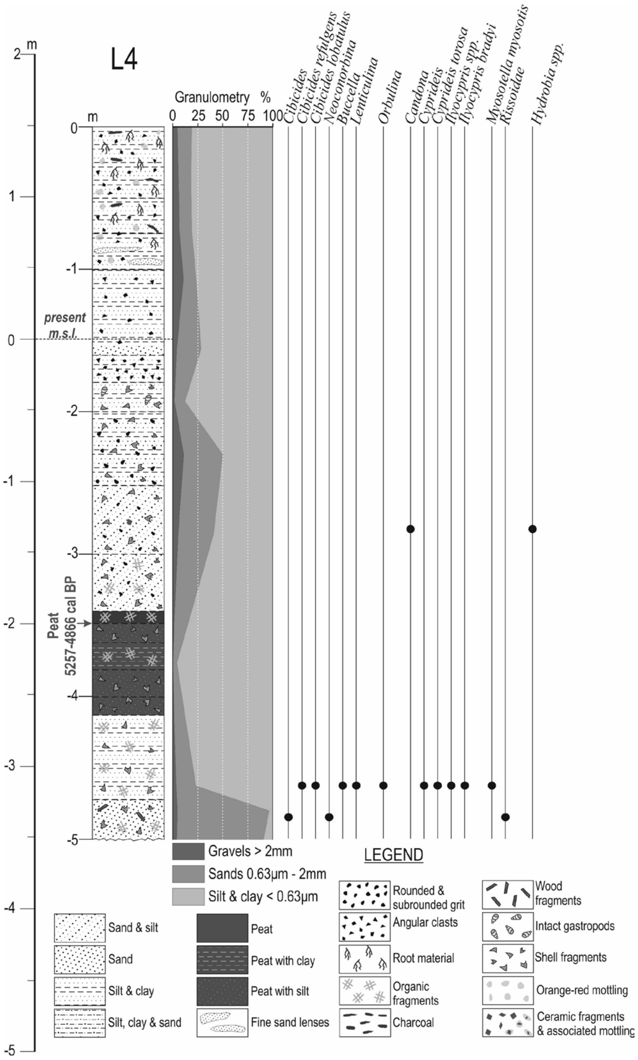


FIG. 7 - Borehole L4 log and results of grain size and palaeontological analysis.

From the bottom of the core up to 4.72 m there is a layer of gray black medium sand with mollusks shell fragments, well humified organic matter and wood fragments up to 1 cm long. The macrofauna analysis showed fragments of the gastropod *Rissoidae* and tiny fragments of bivalves. Planktonic forams are rare while a low density of benthic foraminifera (mainly *Cibicides* and *Neoconorbina*) is observed.

Between 4.72 and 4.12 m there is a unit consisting of gray silt with clay and medium sand with humified organic fragments and common finely comminuted shell debris. The macrofauna of this unit is dominated by *Myosotella myosotis* (Draparnaud, 1801), a gastropod found in the highest parts of a brackish water salt marsh. The sedimentary analysis showed aragonite as granular aggregates (up to 1 mm in size) of very fine grained crystals. The ostracod fauna revealed the presence of *Ilyocypris bradyi*, a globally distributed freshwater genus, together with *Cyprideis*, *Cypriteis torosa* and *Ilyocypris* spp., indicating an environment influenced by freshwater. Benthic foraminiferal species (*Cibicides lobatulus*, *Lenticulina* sp., *Buccela* sp.) are rare, broken commonly rounded and poorly preserved. At the lower part of this unit the presence of planktonic foraminiferal specimens (mainly *Orbulina*) is prominent.

From 4.12 m up to 3.4 m a peaty unit is found. Most of this unit consists of peat with clay rich in shell fragments and large (between 3 and 5 cm) poorly to medium humified stem material with a heavy sulfidic smell overlaid by dark gray organic silt, rich in highly comminuted shells. The upper 10 cm of this unit is a strongly humified black peat. A sample of peat from this layer was dated at 5050-4870 cal BP.

From 3.4 m up to 2.5 m the stratigraphy is dominated by gray silt with fine sand with frequently comminuted shell fragments and occasional subrounded limestone grit (< 5 mm) clasts. Highly degraded ceramic fragments (1-2 mm) are common in the middle of this unit while at the lower half large well humified organic fragments (4-5 mm) are present. The macrofauna is dominated by *Hydrobia*, a brackish water mud gastropod, while microfossil analysis indicates that assemblages are dominated by *Candona* which is a brackish/freshwater genus of ostracods.

Between 3.4 m and 1 m there is a unit composed of brown silty clay with fine sand. It contains large (4 cm diam.) subrounded limestone clasts and numerous comminuted shell fragments throughout while intact shells of *Hydrobia* sp. is found.

From 1.5 towards 1.6 m there is an apparent increase in fine sand.

From the surface down to a depth of 1 m the core is composed of chocolate-brown to red silty clay highly desiccated and cracked at surface (0-10 cm) with poorly humified root material and angular limestone grits (< 1 cm diam.), orange-red mottling and some apparent black charcoal fragments (1-2 mm).

*Interpretation – Identification of biosedimentary units*

Facies identification of the four boreholes provided clear lithostratigraphical sequences. It should be noted here that there are many similarities compared to the microfossil analyses conducted by Willershäuser & *alii* (2013) for sediment samples recovered from the landward fringe of the plain. Both the sedimentologial and the faunal analyses allowed us to distinguish six biosedimentary units, which can be described as follows:

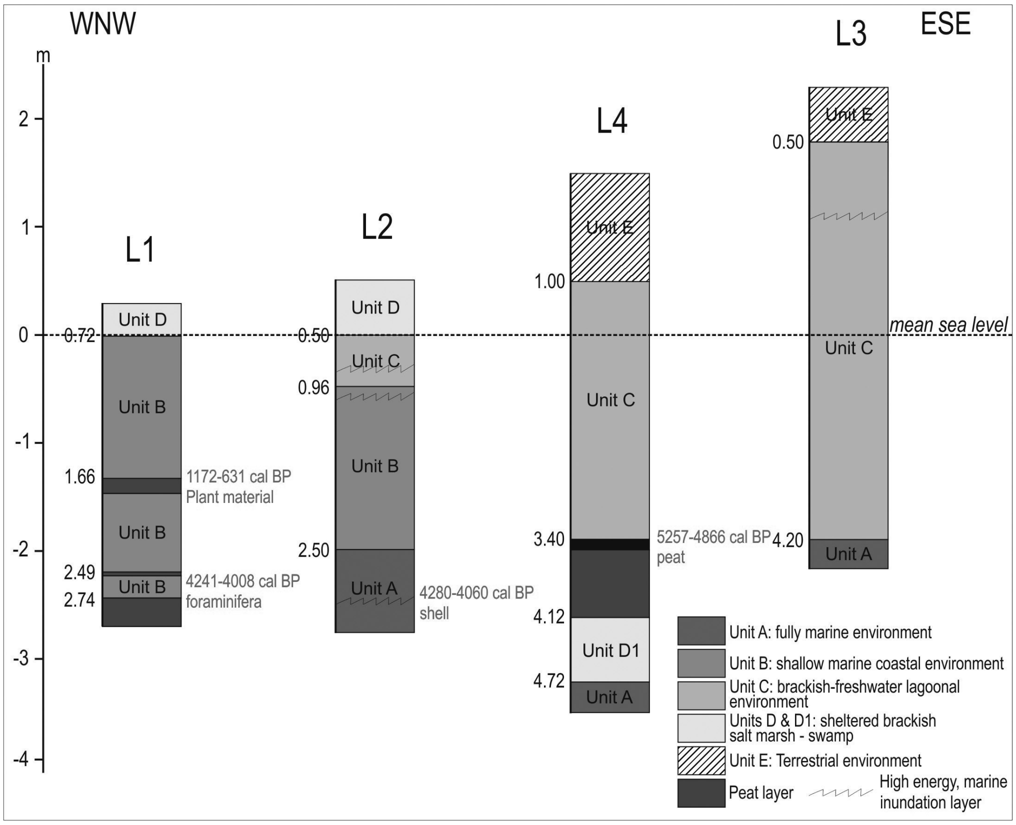


FIG.8 - Palaeoenvironmental units as identified by grain size and micropalaeontological analysis.

*Unit A: a basal marine unit* - This first unit is found in the lowermost part of boreholes L2, L3 and L4 (fig. 8) but is not recognized for L1. For L2, the unit is found from the bottom of the core up to 2.5 m. The base of this unit was not reached and the total depth is thus unknown. The micro and macrofaunal identification confirms the existence of a marine environment of low salinity due to freshwater input. The presence of angular and subangular terrigenous quartz grains at the basal section of this unit as well as a 2 cm thick pebble clast horizon with numerous shell fragments in a sand matrix are evidence of high energy events. Input of angular quartz and feldspar material is a common feature due to *tsunami* backwash (Willershäuser & *alii*, 2013; Vött & *alii*, 2014). For L4 this basal fully marine depositional environment, which probably corresponds to shore face conditions, is recorded from the bottom of the core up to 4.72 m while in L3 it is found from the base of the core up to 4.2 m. The age of this sequence has been determined through a radiocarbon date on an intact valve of a marine bivalve preserved in the middle of this unit in L2 which yielded an age of 4280-4060 cal BP. Since this shell was collected from the pebble clast horizon its age is also indicative of the high energy inundation event (although providing a maximum age).

*Unit B: a shallow marine – coastal environment of high energy.* This unit is only identified in cores L1 and L2 which are the closer to the present day coastline (fig. 8). For both cores this unit overlays the marine unit (Unit A) and has a thickness of 0.94 m and 1.54 in cores L1 and L2 respectively. The sedimentological and faunal analysis indicate that the lower part of this unit in core L1 is characteristic of a fully marine shallow marginal marine environment (infralittoral zone) with a well oxygenated vegetated sea floor, where many elements were transported due to wave activity. The depositional environment thus corresponds to a shallow fully marine one of high hydrodynamic energy possibly along the coastline. In core L1 within unit B three peat layers were found varying in thickness from a few centimeters to a few tens of centimeters. Peat formation indicates a more protected depositional environment for short periods of time, and a tendency for positive, but also fluctuating sea-level for this time period. Macrofossils and marine ostracods from this unit in core L2 show also a shallow marine environment possibly along the coastline while the absence of autochthonous ostracods advocates poor stability of the water masses. The chronology of Unit B is determined by radiocarbon dates of two samples from core L1. A sample of mixed foraminiferal assemblage collected from the depth of 2.60-2.65 m was dated at 4241-4008 cal BP while a sample consisting of plant material embedded within a poorly humified peat layer revealed an age of 1172-631 cal BP. According to the radiocarbon results the dating of Unit B is earlier than 4241-4008 cal BP. The presence of a coquina layer within this unit from core L2 which contains mixed material from different environments (deep marine, shallow marine, coastline and lagoonal) enhances the hypothesis that the Livadi plain has been affected by the influence of past high energy events which according to Willershäuser & *alii* (2013) are *tsunami* waves.

*Unit C: a brackish – freshwater lagoonal environment.* This unit is found in cores L2, L4 and L3. In core L2 it overlies the shallow marine – coastal unit (Unit B) while in core L4 it is found overlying a black peat layer (fig. 8). In core L3 this lagoonal unit has a thickness of about 3.7 m and overlies the basal marine unit (Unit A). Sedimentological analysis and micro and macro faunal identification point to a protected freshwater – brackish lagoonal depositional environment. In core L2 this unit has a thickness of 48 cm and the palaeontological analysis showed mixed faunal levels indicating abrupt palaeoenvironmental changes related to salinity fluctuations attributable to flooding caused by high energy marine inundation event. Unit C in core L3 shows a shallowing upward tendency with a gradual change of the depositional environment to one dominated by terrestrial processes. The presence of angular washed material, quartz and feldspars at the upper part of the unit up to a depth of 1.2 m possibly indicates a high energy marine inundation event backwash. According to (Willershäuser & *alii*, 2013; Vött & *alii*, 2014) input of angular quartz and feldspar material is a common feature due to *tsunami* backwash. It is possible these high energy events correspond to *tsunami* since according to Willershäuser & *alii* (2013) and Vött & *alii* (2014) Cephalonia island has been repeatedly impacted by *tsunami*s during the Holocene. A radiocarbon date of a sample collected from the underlying black peat layer reveals an age of 5257-4866 cal BP in the lowermost part of this unit in core L4.

*Unit D and D1: a sheltered brackish - salt marsh-swamp.* Unit D consists the uppermost part of cores L1 and L2 while in core L4 unit D1 overlies the basal marine unit and underlies a 72 cm thick layer of poorly to medium humified peat (fig. 8). The sedimentological and faunal analyses of samples from L4 showed supersaturated conditions in the water column and freshwater influence. Additionally, at the lower part of Unit D1 the presence of planktonic foraminiferal specimens (mainly *Orbulina*) is prominent evidence of a backshore trace of a high energy marine inundation event. The age of the upper part of the overlying peat layer is 5257-4866 cal BP. Hence for core L4 the age of this unit D1 is earlier (diachronous). On the other hand the age of this marshy – swampy unit (Unit D) in cores L1 and L2 is recent since it is recorded at the uppermost part of the sedimentary sequence. In core L1 the microfauna analysis suggests a very shallow back barrier brackish – salt marsh of high water temperature with a well oxygenated and vegetated floor.

*Unit E: an environment dominated by terrestrial processes.* Unit E is recorded at the uppermost part of the sedimentary sequence of cores L4 and L3 which are the cores drilled at the inner part of the coastal plain of Livadi (fig. 8).

## DISCUSSION

The present study focuses on the palaeogeographic evolution of the Livadi plain located at the northern part of the Gulf of Argostoli, Cephalonia Island, through the drilling of four shallow borholes. Facies identification allowed us to distinguish a basal marine biosedimentary unit which gradually gives its place to a unit representative of a low energy lagoonal depositional environment, covered by sediments of a unit dominated by terrestrial processes (fig. 9).

According to the findings of Willershäuser & *alii* (2013) peat formation in the Livadi plain already starts in the 6th millennium BC but in order to have a clear and safe picture for the beginning of the formation of the Livadi swampy plain a complete stratigraphy down to the basement is required. The biosedimentary units are occasionally interrupted by high energy marine inundation layers. This sedimentary stratigraphy is quite similar to the one documented by Willerhäeuser & *alii* (2013) for the same swampy area. For the coastal lowland of the eastern Paliki peninsula, west of the Livadi plain Willerhäeuser & *alii* (2013) describe autochthonous sedimentary conditions represented by shallow marine silty fine sand covered by loam, deposited by colluvial/alluvial processes, interrupted by high energy layers with a clearly marine fingerprint. In addition, for a transect of vibracores located at the northern part of the Livadi plain, the same authors describe autochthonous silt dominated sediments, repeatedly intersecting high energy-sand which according to them is clearly pointing to episodic high energy influence attributed to *tsunami* waves and cannot be interpreted as storm laminae or other regular interferences of the palaeogeographical evolution.

Effectively discriminating storm from *tsunami* deposits is one of the most challenging topics in coastal geoscience (Mariner & *alii*, 2017; Vött & *alii*, 2018; Kaniewski & *alii*, 2016). In stratigraphic terms, storms and *tsunamis* constitute "event deposits," namely, episodic facies of short duration resulting from abnormal high-energy processes. The "storm versus *tsunami*" debate is particularly strong in the Mediterranean, an area that is prone to both multisite seismic activity (e.g. Papadopoulos, 2015) and storm events (e.g. Dezileu & *alii*, 2012). Since ~2000, much of the Mediterranean literature has focused on Holocene records of *tsunami*, whereas archives of storm events have been relegated to a secondary position ( Marriner & *alii* 2010). Marriner & *alii* (2017) reconstructed *tsunami* variability from the Mediterranean based on stratigraphic archives for the past 4500 years and investigated its relationship with climate records and reconstructions of storminess. They provided evidence for h ~1500-year cycles, strongly correlated with climate deterioration in the Mediterranean/North Atlantic, challenging up to 90% of the original *tsunami* attributions and suggesting that most events are better ascribed to periods of heightened storminess. The stratigraphic facies documented in the present study which are associated to high energy marine sedimentation can be safely attributed to temporary sea-water inundation during the upper Holocene. Similar high energy sedimentation influence, documented by Willerhäeuser & *alii* (2013) at the Livadi swampy plain is attributed to repeated *tsunami* landfall. *Palaeotsunami* evidence has also been described by Vött & *alii* (2013) for the protected Koutavos Bay close to the harbour of ancient Krane, at the eastern shore of the Gulf of Argostoli. The relatively limited western wave fetch associated with maximum wave heights (Scicchitano & *alii*, 2007; Soukissian & *alii*, 2008) and the long fetched but less frequent SE waves (Soukisian & *alii*, 2007), make the study area a protected environment from extreme storm events. According to Willerhäeuser & *alii* (2013), the geomorphodynamic potential of storm – wave driven littoral processes in the inner Gulf of Argostoli is low. However, the documented high energy marine inundation deposits are not laterally continuous and may be related to changes in shoreline position within the Holocene. According to the findings of this paper, the possibility of a *tsunami* source cannot be ruled out but shoreline changes may also generate sands, as may storm wave overwash. In addition, the Livadi plain is separated from the Gulf of Argostoli by a beach barrier, consisting of coarse sand, with elevations ranging from 1.1 m amsl at its northeastern edge, to 2.6 m at its southwestern edge. The possibility of the estimated maximum run-up (0.75 m) generated by southeastern winds to overtop the barrier is very low. However, in an extreme event where the astronomical tide (according to Tsimplis (1994) the tidal range of the broader area is 0.25 m) and a storm surge coincide; the possibility of sea waves overtopping the barrier could not be totally excluded. Hence, adding up 0.35 m of storm surge for the Gulf of Argostoli (Krestenitis & *alii*, 2015) and 0.25 m of astronomical tide (Tsimplis, 1994) gives a total of 1.45 m which could overtop at least the northeastern part of the barrier causing marine inundation and deposition of high energy marine sediments in short distances. However, the discrimination of the high energy inundation layers documented in this paper between storm or *tsunami* events lies beyond the methodological approach of this study.

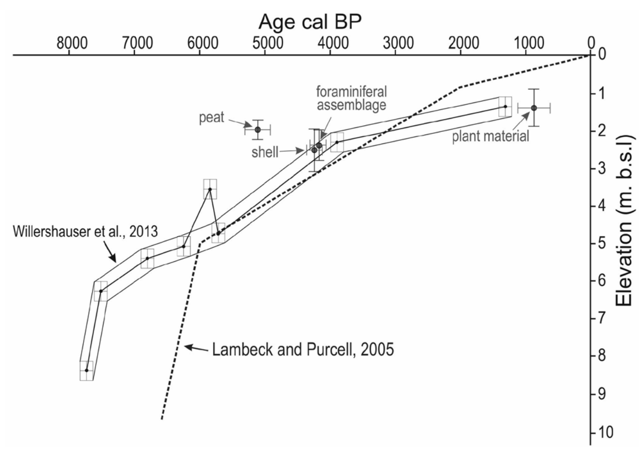


FIG. 9 - Relative local sea-level changes of the Livadi coastal plain. Samples from L1, L2 and L4 cores are plotted against the sea-level curve predicted by the glacio-hydro-isostatic model of Lambeck & Purcel (2005) and the local relative sea-level curve proposed by T. Willershäuser & *alii* (2013). Sample elevation vertical uncertainties are adopted from Vacchi & *alii* (2016).

Radiocarbon dating of the samples presented in the present study from boreholes L1 and L2 (foraminifera, shell and plant material) do not serve as reliable sea level index points and thereby cannot be used as a precise means to estimate the tectonic uplift of the study area during the Holocene. Fig. 9 shows the samples of this study in relation to the sea-level curve predicted by the glacio-hydro-isostatic model of Lambeck and Purcell (2005) and the local relative sea-level curve since the mid-Holocene proposed by T. Willershäuser & *alii* (2013). The diagram suggests that according to the results of this study, when considering the peat radiocarbon date from borehole L4, the sea-level in the inner Gulf of Argostoli was higher than the predicted. An estimation however of an exact uplift rate is considered risky, as intercalated peat beds have only an indirect relation to sea level (Einsele, 1992; Ricken, 1991) and therefore lies beyond the findings of the present study. The coastal layer however (sample L4-pt) is considered to be more reliable in terms of evaluating relative sea-level trends and positions and the fact that it is found above the sea level curve proposed by Willerhäeuser & *alii* (2013), certainly implies a tectonic uplift of the study area during the Holocene. Co-seismic tectonic uplift episodes of the Cephalonia island during the period of the Holocene is supported by many authors. Stiros & *alii*, (1994) describe a co-seismic uplift of 30-70 cm of the central part of Cephalonia island, documented during the 1953 earthquake (M = 7.2), attributed to an east dipping thrust located at the western margins of the Livadi plain. A recent (ca. 0.2 m) uplift has also been clearly observed along the beach face of the Livadi swamp caused by the recent Cephalonia earthquake in 2014 (M = 6.1) (Valkaniotis, & *alii* 2014). Moreover, Willerhäeuser & *alii*, (2013) also report a co-seismic uplift of 1 m documented by an unexpected peak in their RSL band around 3950-3750 cal BC. Additionally, the same authors describe post depositional weathering processes within the upper Holocene sedimentological sequences of the Livadi plain caused by possible co-seismic uplift effects.

## CONCLUSIONS

Our data show a high resolution record of the coastal evolution of the Livadi plain, which is located on the northern part of the Gulf of Argostoli (Cephalonia Island). The sedimentological, macro- and micro-palaeontological analysis of sediment samples collected from four shallow boreholes, along with the radiocarbon dating; suggest that the beginning of the formation of the Livadi plain can be safely put before the fifth millennium BP and probably earlier since peat formation in the Livadi plain already starts in the 6th millennium BC (Willershäuser & *alii*, 2013).

The marine base recorded in the sedimentary sequences is the result of the marine transgression which occurred before the stabilization of the sea-level in the Mid-Holocene.

The formation of a barrier spit which extended towards the east, had confined a lagoon in the north during the period of Mid- to Late Holocene. The spit has advanced eastwards due to the action of a (W-E) longshore drift which led to the formation of one generation of beach ridges with an almost (W-E) orientation.

The formation of the beach barrier has created a more sheltered low energy environment depositing finer sediments after 4280-4060 BP. During this period, a semi-enclosed lagoon functioned in the northern part of the current swamp, but progressively was isolated, and turned into a coastal lagoon environment.

The stratigraphic facies found in the present study are in accordance with the findings of Willerhäeuser & *alii*, (2013). High energy sedimentation layers documented both in the present study as well as by Willerhäeuser & *alii*, (2013) could be attributed to *tsunami* events but storm events, even though of low possibility, cannot be totally excluded. However, the presence of sedimentary layers which contain terrigenous angular and subangular washed material, quartz and feldspars intersecting the sediments of the basal marine unit and the brackish-freshwater lagoonal unit indicates *tsunami* backwash. The sea-level in the inner Gulf of Argostoli was never higher than the present sea level. The peat layer found above the relative sea level curve proposed by Willerhäeuser & *alii*, (2013), implies a co-seismic tectonic uplift of the study area around 5257-4866 cal BP. Estimation however of the precise co-seismic uplift is considered risky, as intercalated peat beds have only an indirect relation to sea level and therefore lies beyond the available data and the methodology applied in the present study.

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