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Traces of Holocene tsunamis across the Sound of Lefkada, NW Greece

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ABSTRACT

This paper gives evidence of multiple tsunami inundation of the Sound of Lefkada (NW Greece) since the mid-Holocene based on the analysis of sediment cores by means of geomorphological, sedimentological, geochemical, micromorphological and micropalaeontological methods. Layers of sand, gravel and shell debris, mostly unsorted, were found intersecting autochthonous lagoonal muds of the sheltered and quiescent inner-sound environment. They are further characterized by erosional unconformities at their base, rip-up clasts from the underlying sediments, fining upward sequences and an upward increase in sorting. The coarse grained high energy deposits include macro- and microfaunal remains typical of open-marine, partly even deep-water conditions which underlines their allochthonous character. Several distinct event layers indicate multiple tsunami passage across the sound. Earth resistivity measurements and vibracore transects revealed that the entire sound has been affected by catastrophic wave events. Thin sections of tsunami-influenced sediments found in lateral parts of the sound show a mixture of marine, lagoonal and terrigenous material. The inner Sound of Lefkada, well protected against storms, thus represents an excellent trap for tsunamigenic deposits. A preliminary local tsunami geochronology is based on 9 radiocarbon dates and diagnostic ceramic fragments. Several early tsunami impacts hit the sound between the 6th and 3rd millennium BC. Younger events seem to be consistent with tsunami landfalls that hit adjacent areas around 1000 cal BC, 395–247 cal BC as well as in Roman and medieval times. Vibracore data document an isthmus-like shallow-water environment which existed in the central sound and which was repeatedly inundated by tsunami wave action. Multiple tsunami passage eroded a natural channel which, we suggest, is the precursor of the famous waterway excavated by the Corinthians in the 7th century BC. Based on historical data, it is concluded that the navigable channel across the sound was repeatedly choked with sediments by tsunamigenic inundation during the following centuries. This study reveals a high tsunami risk for the Sound of Lefkada with at least one strong event in every 500–1000 years.

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1. Introduction

Numerous geomorphological and geological studies revealed that the eastern Mediterranean has been subject to repeated large-scale tsunami impact since the mid-Holocene. The tsunami hazard of this region — belonging to the seismo-tectonic most active areas of the world and, at the same time, attracting millions of tourists every year — must not be underestimated. Evidence of tsunami landfall is given by a variety of different tsunamigenic deposits encountered in near-coast geological archives ranging from fine grained sandy to mega block deposits and showing a large variability in terms of thickness and dimension.

In Italy, tsunamigenic sediments were identified along the Gargano and Apulian coasts (Gianfreda et al., 2001; Mastronuzzi and Sansò, 2004) and around Stromboli Island (Maramai et al., 2005). Dominey-Howes (2002) showed that the Aegean Sea has been repeatedly affected by tsunamis, most recently, for example, by the one which hit Astypalaea Island in 1956 (Dominey-Howes et al., 2000a). Further studies dealt with the tsunami induced by the Bronze Age eruption of the Santorini volcano (Dominey-Howes et al., 2000b; McCoy and Heiken, 2000; Minoura et al., 2000). In central Greece, tsunami deposits were found in Lokris (Pirazzoli et al., 1999; Gaki-Papanastassiou et al., 2001) and along the shores of the Gulf of Corinth (Kortekaas, 2002; Kontopoulos and Avramidis, 2003; Alvarez-Zarikian et al., in press). Tsunami influence is also known from Crete (Scheffers, 2006; Scheffers and Scheffers, 2007), Cyprus (Kelletat and Schellmann, 2002; Whelan and Kelletat, 2002), the Turkish (Kelletat, 2005) and the Levantine coasts (Morhange et al., 2006;

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Reinhardt et al., 2006). In the north African coastal zone, tsunami traces were identified in the Nile delta (Goiran, 2001; Stanley and Bernasconi, 2006).

Apart from field findings, modelling approaches for the eastern Mediterranean helped to better understand flow dynamics of tsunami waves, the potential distribution of tsunami sediments and possible triggering factors (Tinti and Armigliato, 2003; Alasset et al., 2006; Hamouda, 2006; Pareschi et al., 2006a,b; Stefatos et al., 2006).

Tsunami catalogues show that western Greece is characterized by the highest number of tsunami events reported from all over the Eastern Mediterranean with a re-occurrence interval of 11–14 years only (Soloviev et al., 2000; Camilleri, 2006). A series of different tsunami deposits was encountered, for instance, in the coastal zone between Preveza and Lefkada Island. These sediments, partly interrelated, attest to multiple tsunami landfall and comprise, among others, dislocated mega-blocks both on land and under water, washover fan deposits (chevrons), runup/backwash layers, a break-through channel and suspension deposits in a freshwater lake environment. The Preveza–Lefkada sequence offers ideal sediment traps for high-resolution studies on extreme events and their effects on coastal dynamics (Vött et al., 2006, 2007a,b). This paper focuses on the quiescent lagoonal waters of the nearby Sound of Lefkada which is separated from the open sea by a beach barrier. Our main objectives are (1) to present geo- and bio-scientific evidence of multiple tsunami influence on the sound, (2) to provide a local geochronological frame, (3) to compare tsunami findings from the inner sound with those known from the Preveza–Lefkada outer-sound area, and (4) to decipher the influence of repeated tsunami passage across the sound on its Holocene evolution.

2. Regional setting and historical background

The shallow lagoonal environment of the Sound of Lefkada is closed off from the open Ionian Sea by a beach ridge system, reaching around 3.5 m above present mean sea level (a.s.l.). The base of the beach ridge is made up of beachrock, up to at least 6–10 m thick. The lagoon, separating Lefkada Island from central mainland Greece, is approximately 4.7 km long and narrows southward from 4.8 km around Fort Santa Maura to only 300 m around Fort Alexandros (Fig. 1). Water depth ranges between 0.1 m and 0.7 m except some 5 m along the narrow artificial channel which was excavated in the 19th/20th century and connects the Bay of Lefkada in the north with the Bay of Drepano in the south. The contemporary sedimentary environment in the Sound of Lefkada is characterized by quiescent, locally even anoxic conditions. Typically fine grained, clayey to silty sediments are brought in by alluvial fan deltas mostly from the Plaghia Peninsula shore. Due to its sheltered position, the sound is protected from open sea wind and wave activity. In times of prevailing winds from northern direction, however, considerable parts of the sound may fall dry so that mudflats are exposed to subaerial conditions.

Lefkada Island and the Plaghia Peninsula belong to the seismically most active regions in the eastern Mediterranean (Galanopoulos, 1952, 1954; Scordilis et al., 1985; Papazachos and Papazachou, 1997; Louvari et al., 1999) and thus show a high tsunami risk (Papazachos and Dimitriu, 1991, Fig. 4). Both is due to the right-lateral strike slip Cefalonia transform fault (CF) and its northern prolongation, the Lefkada transform fault (LF), trending in a SSW–NNE direction offshore some 15 km to the west of the study area (Karakostas et al., 2004, Fig. 4). The last strong earthquake along this fault zone occurred on August 14, 2003 (Papadopoulos, 2003; Papathanassiou et al., 2005; Papadimitriou et al., 2006), triggering a 0.5 m tsunami south of Nidri (EERI, 2003) and causing large scale ground failures on the island (Karakostas et al., 2004). Part of the Hellenic Arc, the area represents a triple junction where collision, subduction, transform faulting, and spreading of the African, the Adriatic and the Aegean plates take place (Sachpazi et al., 2000, p. 303). To the north and west of the CF and LF, crustal motion is almost null whereas towards the south, rates are up to 40 mm/a (Cocard et al., 1999; Kahle et al., 2000). In addition, van Hinsbergen et al. (2005) and Broadley et al. (2004) found an average 40–90° clockwise rotation of northwestern Greece since Oligocene–Miocene times.

According to Strabo's interpretation (Strabo, Geography, 10, 2, 8), Homer described the Mycenaean Lefkada as a part of the western Greek mainland, i.e. as peninsula (Homer, Odyssey, 24, 377; Partsch, 1889; Funke and Freitag, in press). Corinthian settlers are suggested to have founded the ancient polis of Lefkada at the northeastern flank of the modern island in the 7th century BC when, according to historical sources, a natural isthmus still existed close to the city and connected the island to the Plaghia Peninsula (Partsch, 1907, p. 273). Strabo (Geography, 10, 2, 8) also reports that the Corinthians were the first to cut through the isthmus and created a navigable channel. A large mole, now submerged under around 1.4 m of sea water, was built south of Fort Alexandros probably in the 5th/4th century BC in order to close off a harbour basin protected from the open waters of the Bay of Drepano (Murray, 1982, 1988). Shortly afterwards, during the Peloponnesian War, in 427/425 BC, the channel was impassable and warships had to be dragged over the isthmus (Thukydides, The Peloponnesian War, 3, 81; 4, 8). At some time before 348/347 BC, the waterway was re-dredged (Pseudo-Skylax, Periplus, 34), and, in 218 BC, the Makedonian king Philip V used it as shortcut for his fleet (Murray, 1982, p. 246 ff.). By 197 BC, the canal was not usable due to sandy shallows east of ancient Lefkada (Livy, 33, 17, 6; Lehmann-Hartleben, 1923, p. 266f.). However, the canal must have been restored before 50 BC when Cicero sailed through the sound on a merchant coaster (Murray, 1982, p. 246; Schweighardt and Schmid, 1995; Wirbelauer, 2002). During the Augustean period, local pilots and tugboats were needed for the passage (Murray, 1982, p. 246ff.) and for the 1st century AD, Pliny (HN, 4, 1, 5) reports from sandy shallows plugging the sound. In the 2nd century AD, wooden sticks marked the navigable route (Oberhummer, 1887, p. 13; Partsch, 1907, p. 275f.). Further information is missing until 1844 and 1902 when British and Greek authorities excavated the new ship canal (von Marées, 1907; Naval Intelligence Division, 1945, p. 337). In summary, historical data reveal at least three periods during which the waterway was blocked by sandy sediments — a phenomenon which may not be explained by the present-day sedimentary dynamics known from the inner sound. The latter are those of a quiescent shallow-water environment characterized by clayey to silty deposits partly accumulated under anoxic conditions (section 2). Storms are not known to have ever influenced the inner sound.

In terms of sea level fluctuations, the remains of a Hellenistic to Roman bridge covered by sediments (Négris, 1904; Goessler, 1904, p. 25; Lang, 1905) and the submerged mole of the Corinthians document a relative rise in sea level of about 2.5–3 m during the last 2500 years (Murray, 1988; Vött, 2007).

3. Materials and methods

We studied the stratigraphic sequences of 51 vibracores drilled by means of an engine driven Atlas Copco mk1 coring device. Coring was carried out down to maximum 15 m below ground surface (b.s.) with core diameters of 6 cm and 5 cm. Vibracores in the Sound of Lefkada were arranged in transects. The position and elevation of each coring site were measured using a Leica SR 530 differential GPS. In the field, facies discrimination was achieved by geomorphological, sedimentological and palaeontological criteria such as grain size distribution, grade of sorting, sediment colour, and origin and state of preservation of macrofossil remains. Vibracores were cleaned, photographed and sampled for further studies in the laboratory. High resolution facies detection is mainly based on microfauna analysis. Especially ostracods and foraminifers are useful ecological indicators of the palaeo-environment (Frenzel and Boomer, 2004; Murray, 2006) and helped

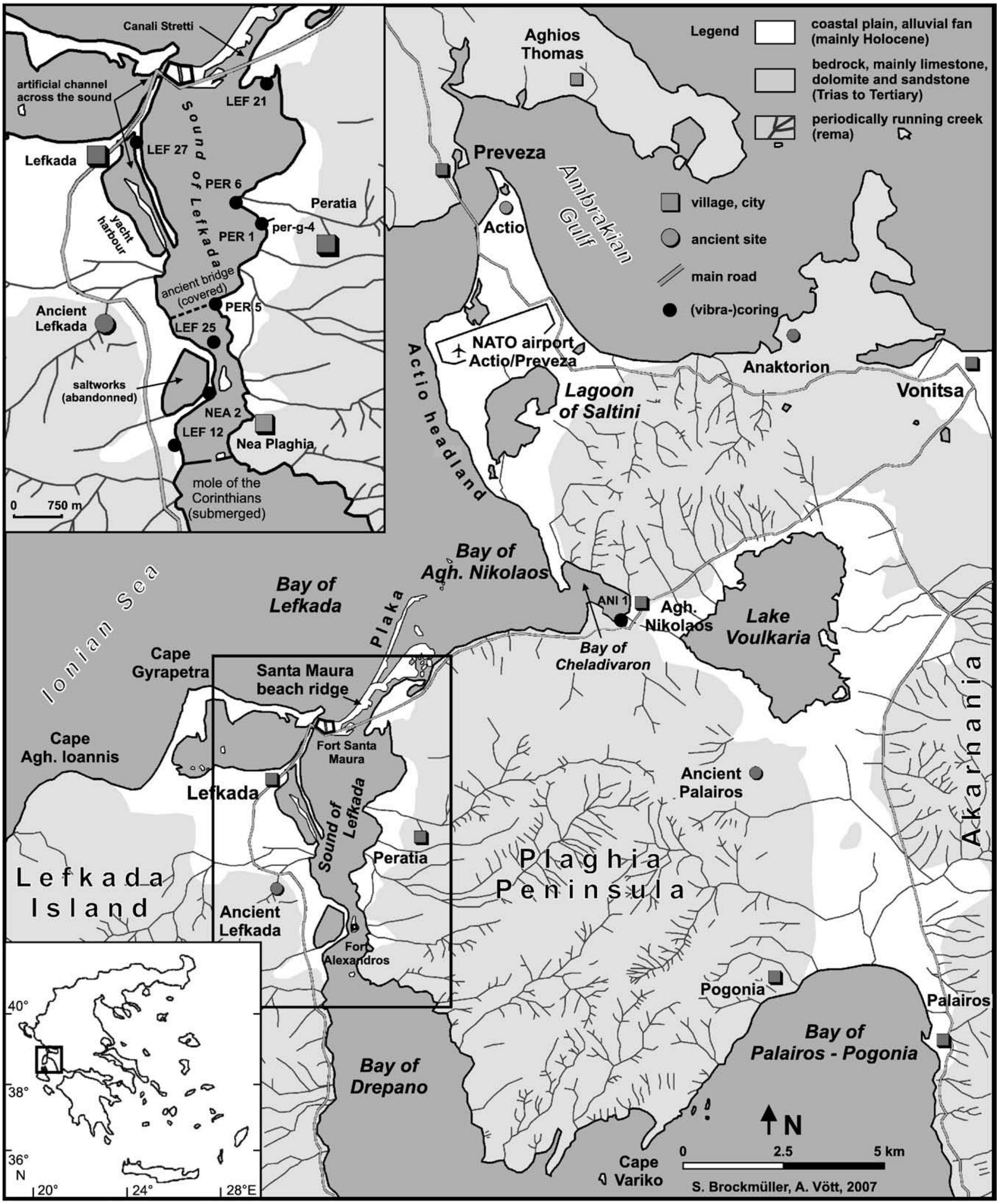


Fig. 1. Topographic overview of the Sound of Lefkada and location of selected vibracores.

to detect allochthonous species indicating fully marine and/or deep-water conditions from environments outside the Sound of Lefkada (see Marriner and Morhange, 2007, p. 168ff.). Selected species underwent scanning electron microscope (SEM) analysis. Thin sections of sediment samples allowed to check the general state of preservation of microfossils and the sediment structure. Palynological studies were conducted in search of a tsunami signature in the pollen record. We also determined standard geochemical parameters of sediment samples such as electrical conductivity, pH-value, loss on ignition, and concentrations of (ortho-)phosphate, calcium carbonate, (earth) alkaline and heavy metals. Statistical analyses of geochemical parameters helped to detect intra-facial variabilities such as temporary interferences of the environment (Vött et al., 2002, 2003). Earth resistivity tomography, using a multi-electrode Syscal R1 plus instrument and the RES2DINV inversion model, was applied to study subsurface structures and for the spatial interpolation of vibracore data. Chronological information is mainly based on ^{14}C-AMS analyses of organic samples or bio-chemically produced calcium carbonate. Where possible, we preferred sampling of undisturbed pre- or post-tsunami core sections as dating of samples out of tsunamigenically reworked material yield simple maximum ages and may result in age inversions in the geochronostratigraphy. All ages were calibrated using the software Calib 5.0.2. It has to be assumed that the marine palaeo reservoir effect was not constant through time and was subject to local variations (see Geyh, 2005, p. 69ff.). However, we corrected marine samples for an average reservoir effect of 402 years (Reimer and McCormac, 2002). In few cases, diagnostic ceramic fragments found in vibracores allowed to cross-check radiocarbon datings.

4. Results

4.1. Evidence of tsunami impacts to the north of the Sound of Lefkada

Since 2005, different types of tsunami deposits have been identified along the northern margin of the Sound of Lefkada, in the Bay of Aghios Nikolaos and along Actio headland (Fig. 2; see Vött et al., 2006, 2007a,b). We found geomorphological, sedimentological and geoarchaeological traces, partly interrelated, of several tsunami impacts which document considerable palaeogeographical changes and coastline displacements. Based on radiocarbon datings, tsunami landfalls between the cities of Preveza and Lefkada were dated to the time periods 2870–2350 cal BC, around 1000 cal BC, 395–247 cal BC, around 430 cal AD, around 840 cal AD, and 1000–1400 cal AD (Vött et al., 2006, 2007a,b). The findings thus revealed strong tsunami impact already in pre-historic times not covered by tsunami catalogues (section 2).

The local susceptibility to tsunami events may be explained by the high seismicity of the region, by its being exposed to the open Ionian Sea, to the northern end of the Hellenic trench and to the highly active triple junction around the nearby CF and LF. Moreover, tsunami waves on their way landward toward Aghio Nikolaos seem to have been enhanced by the smoothly rising bathymetry and the funnel-like contour of the coast. Concerning the influence of storm waves, offshore sea level data from buoys indicate maximum storm sea levels in the open Ionian Sea around 4 to 7 m (http://www.idromare.com; http://www.poseidon.hcmr.gr; see also Scicchitano et al., 2007, Fig. 9). However, due to the wave breaking Plaka beachrock ruin and the low water depths towards the coast, the Bay of Aghios Nikolaos and the Lake Voulkaria are not at all or only slightly influenced by storm wave dynamics and thus represent ideal tsunami sediment traps (for further details, see Vött et al., 2006, 2007a,b).

The 1.2 km-long tsunamigenic washover fan near Cape Gyrapetra (Vött et al., 2006) as well as the washover plain to the east of the Canali Stretti (Fig. 1, Vött et al., 2007a) implicate strong sediment transport

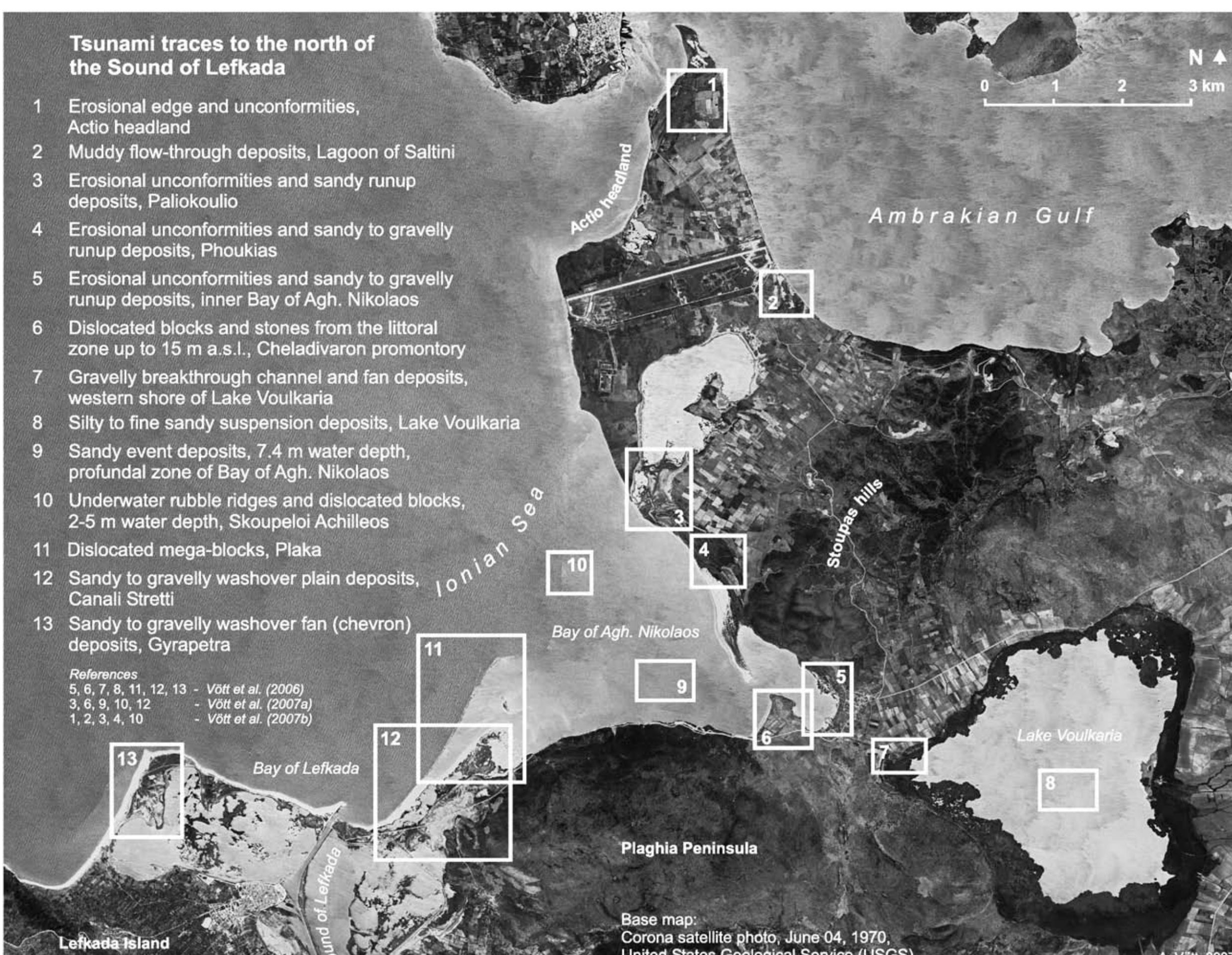


Fig. 2. Evidence of multiple tsunami impact on the bays of Lefkada and Aghios Nikolaos, the Lake Voulkaria and Actio headland known from previous studies (Vött et al., 2006, 2007a,b).

and tsunami water flow into the lagoonal waters of the Sound of Lefkada and suggested further investigations in the inner sound.

4.2. Tsunami traces in the inner Sound of Lefkada

4.2.1. Geomorphological and sedimentological evidence

We present detailed stratigraphic information for a transect of seven cores along the Sound of Lefkada (Figs. 1 and 3).

Vibracore LEF 27 (N 38°50.128′/E 20°42.867′) was drilled some 300 m east of Lefkada city on top of an artificial bank out of material excavated from the modern canal. The lower part of the core is made up of fine sandy littoral deposits including fragments of a marine fauna and is both intersected and covered by a palaeosol with abundant carbonate nodules. The upper palaeosol is followed by silty deposits of a limnic environment (up to 4.88 m b.s.l.). According to fragments of a marine fauna found in the following similar unit (4.88–4.81 m b.s.l.), conditions were then influenced by saltwater. However, on top of a clear erosional unconformity the subsequent silty to sandy material (4.81–4.69 m below present sea level (b.s.l.)) includes abundant shell debris from *Cerastoderma glaucum*, *Cerithium* sp., *Dosinia exoleta*, and *Gibbula* sp. indicating a sudden high energy event from the seaside which struck the quiescent environment. The following stratum of clayey to silty lagoonal deposits (4.69–1.53 m b.s.l.) is intersected by another four and covered by a fifth (1.53–0.94 m b.s.l.) sand layer rich in shell debris. The top of LEF 27 shows well sorted fine sand with remains of a marine fauna (0.94–0.59 m b.s.l.), covered by artificial canal bank deposits.

Vibracoring site LEF 21 (N 38°50.584′/E 20°157′) is located on a sandy flat some 400 m south of the main road. The profile shows littoral deposits (7.95–4.51 m b.s.l.) which are covered by lagoonal

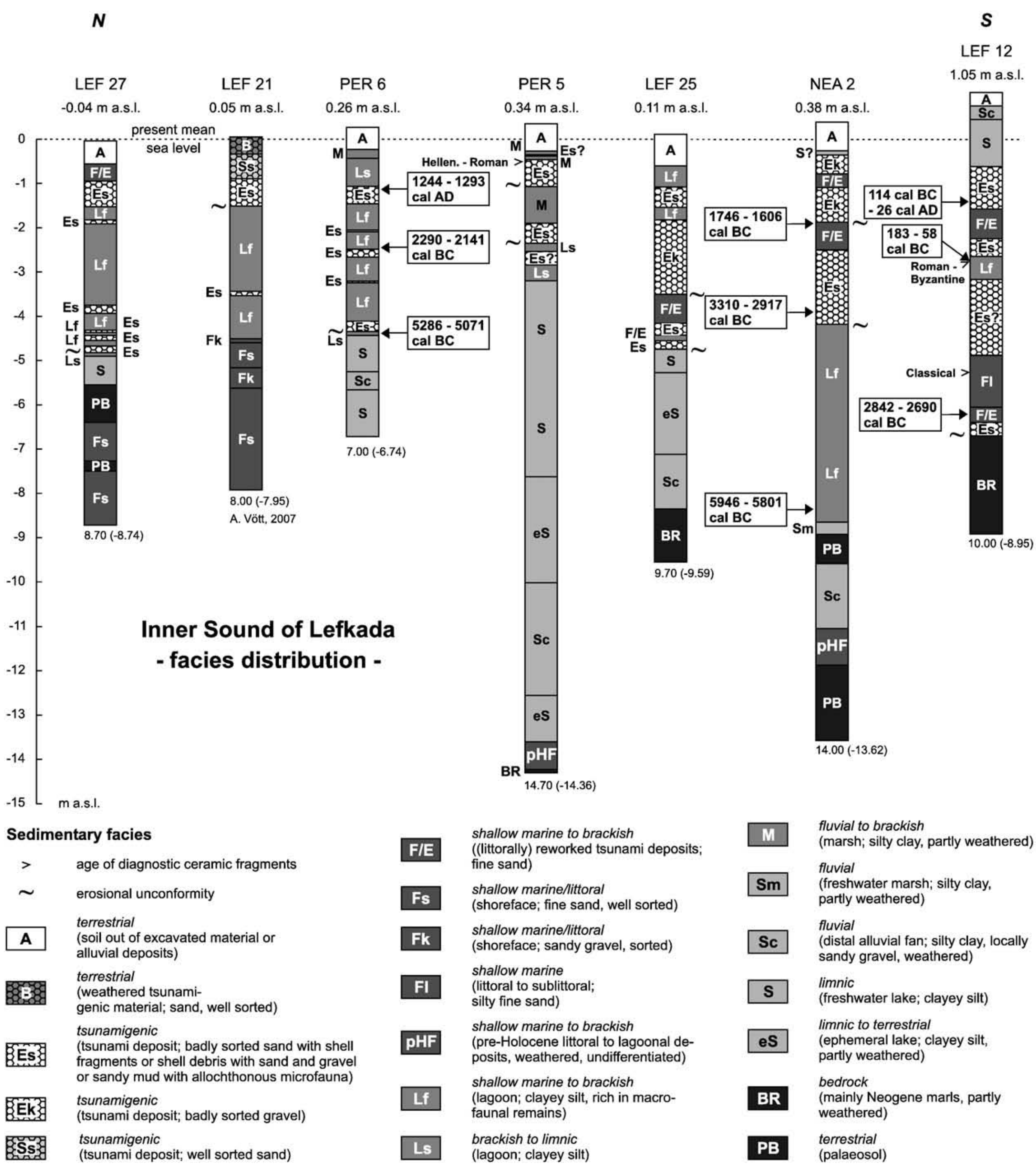


Fig. 3. Stratigraphy, facies distribution, and high energy event layers of selected vibracores across the Sound of Lefkada. For location of vibracoring sites: see Fig. 1.

mud (4.51–1.57 m b.s.l.). The latter contains indistinct shell debris layers difficult to separate from the overall sedimentary structure. However, the top of LEF 21 consists of a thick package of marine sand (1.52 m b.s.l.–0.05 m a.s.l.), clearly laminated and fining upward from coarse to middle to fine sand. The uppermost part of the sand layer, exposed to subaerial conditions during low tide, is weathered to a brownish soil.

Vibracore PER 6 (N 38°49.666′/E 20°43.875′) was retrieved at the eastern shore of the sound near the end of an abandoned quai west of Peratia. Its base is made up of clayey to silty limnic (6.74–4.44 m b.s.l.) and later slightly saltwater influenced sediments (4.44–4.30 m b.s.l.) which are partly intersected by fluvial sand and grus. On top of a clear erosional contact, a fine sandy to silty layer covered by shell debris from bivalves and gastropods (4.30–4.13 m b.s.l.) was found. Similar to LEF 27, the erosional contact marks the final change from freshwater to brackish conditions. This following lagoonal facies is documented by clayey to silty mud with fragments of a brackwater fauna dominated by *Cerastoderma glaucum* (4.13–0.45 m b.s.l.). There are four more distinct layers of partly fine sandy shell debris which indicate temporary moderate to high energy influence to the system. The upper part of the profile shows that the lagoon gradually turned limnic and its sediments were covered by marsh and, later, by anthropogenic material excavated from the nearby canal.

Coring site PER 5 (N 38°48.890′/E 20°43.662′) lies on the very tip of a fan delta southwest of Peratia close to the archaeological remains of a tower which belongs to the Hellenistic to Roman bridge across the sound (Négris, 1904; section 2). On top of the bedrock, pre-Holocene, probably MIS 5 marine to brackish deposits were found (14.28–13.66 m b.s.l.), covered by a thick sequence of fluvial and ephemerally limnic deposits (13.66–7.66 m b.s.l.). The subsequent silty to clayey limnic sediments (7.66–3.21 m b.s.l.) show singular findings of a brackish fauna in their upper part (3.21–2.37 m b.s.l.) and are intersected by clayey silt with few sandy and gravelly components (2.86–2.56 m b.s.l.). On top of a sharp erosional contact, we encountered a layer of fine sand with pieces of grus and gravel and abundant shell fragments of a marine to brackish macrofauna (2.37–1.91 m b.s.l.). This documents abrupt and short-term high energy influence. The following marsh sediments are again partly eroded and covered by sandy, badly sorted event deposits including, for instance, *Cyclope neritea* (1.08–0.47 m b.s.l.). Towards the top, further sandy to gravelly high energy deposits were found embedded in marsh sediments (0.47–0.28 m b.s.l.), but they are, however, less distinct.

Vibracore LEF 25 (N 38°48.584′/E 20°43.661′) was retrieved from the central inner sound some 600 m south of PER 5. The lower and middle parts of the profile are similar to LEF 27, PER 6, and PER 5 showing deposits of a quiescent environment being abruptly eroded by a high energy event. In the course of this event, sandy to gravelly unsorted sediments, rich in macrofauna fragments, were deposited (4.76–4.57 m b.s.l., Fig. 4). Freshwater-dominated conditions encountered in the mid-core section (7.15–4.76 m b.s.l.) were irreversibly replaced by a marine to brackish environment characterized by fine sandy to silty sediments (4.57–4.45 m b.s.l.) including, for instance, valves of *Dosinia exoleta*. This indicates moderate water flow that allowed the partly reworking of the underlying event deposits. At least another three periods of temporary high energy input of coarse material can be distinguished in the upper part of the profile (4.45–4.18 m, 3.52–1.84 m, 1.55–1.09 m b.s.l.) each of them separated by more or less quiescent marine to brackish conditions during which fine-grained sediments were accumulated.

Vibracore NEA 2 (N 38°48.152′/E 20°43.502′) was drilled some 800 m to the south–southwest of LEF 25 on the northern fringe of a ridge-like spit extending from Lefkada Island into the sound towards Fort Alexandros. The base of NEA 2 shows a palaeosol covered by silty to fine sandy deposits of a brackish to marine environment (11.92–11.09 m b.s.l.) of probably pre-Holocene age. Subsequent alluvial fan sediments and another palaeosol (9.62–8.96 m b.s.l.) are followed by silty marsh deposits and thick clayey to silty lagoonal mud (8.95–4.48 m b.s.l.) including fragments and articulated specimens of *Cerastoderma glaucum*, *Dosinia exoleta*, and *Cyclope neritea* as well as an indistinct shell debris layer (7.24 m b.s.l.). On top of a subsequent erosional unconformity, we found unsorted sand (4.20–2.52 m b.s.l.) with pieces of gravel and a stone fragment with bioerosion features (3.17 m b.s.l.) which give evidence of high energy influence to the environment; then

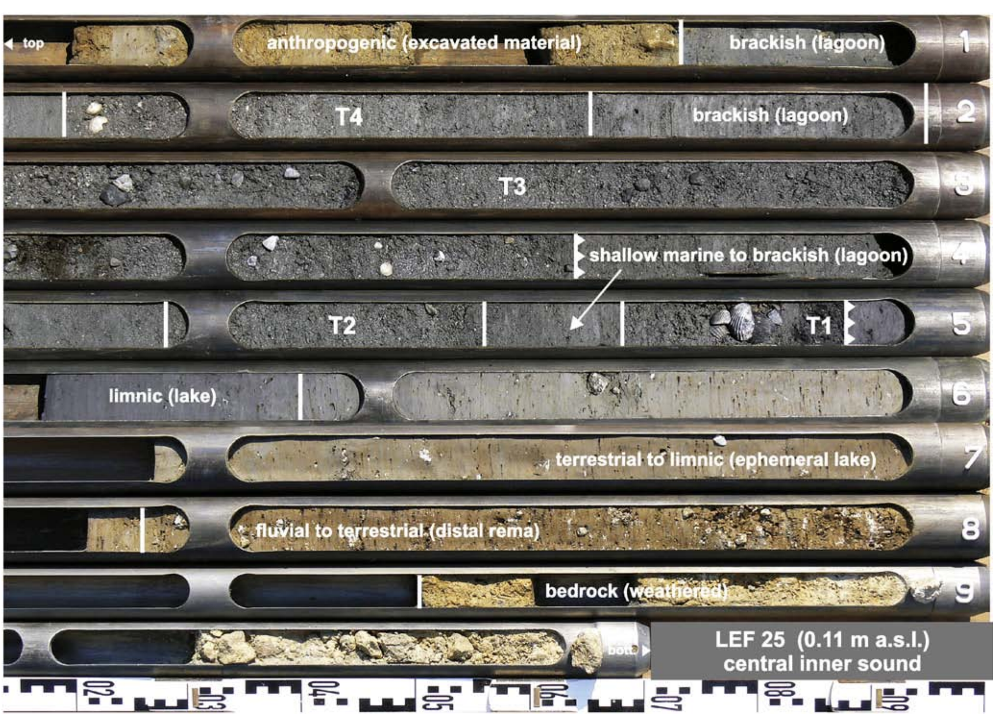


Fig. 4. Facies profile of vibracore LEF 25 from the central inner sound showing a sequence of autochthonous lagoonal mud deposits intersected by four coarse grained tsunami layers out of sandy to gravelly material of marine origin (T1 to T4). The bases of T1 and T2 are characterized by erosional unconformities. Photo taken by M. May, 2006.

follows comparatively well sorted fine sand indicating the partly reworking of the underlying unit. However, considerable contents of hydrogen sulphide (H_2S) document post-depositional anoxic conditions. The subsequent layer of sandy gravel (1.89–1.11 m b.s.l.) contains abundant marine shell fragments and is characterized by another erosional contact at its base. These high energy deposits seem to have been partly reworked and covered by a third coarse-grained stratum of marine origin (0.79–0.37 m b.s.l.). Finally appear probably limnic (0.37–0.27 m b.s.l.) and anthropogenic deposits.

Vibracoring site LEF 12 (N 38°47.682′/E 20°43.278′) is located close to the shore of the inner Bay of Drepano some 150 m north of the submerged mole of the Corinthians. At the base of the profile, we encountered weathered Neogene marls which, at their top, showed clear signs of erosion. The following unsorted sandy to gravelly high energy deposits (6.73–6.43 m b.s.l.) contain numerous marine shell fragments and also rip-up clasts, up to 4 cm large, from the underlying marls. The subsequent fine sand layer (6.43–6.08 m b.s.l.) showed shell debris and some badly rounded stones and documents reworking dynamics. Then, a sublittoral environment was established and silt-dominated deposits were accumulated (6.08–4.89 m b.s.l.). On top of the latter and overlain by lagoonal mud, we found fine to mean sand with fragments of a marine macrofauna (4.89–3.18 m b.s.l.) which possibly reflects temporary high energy conditions or a shift towards a littoral environment. Comparable to NEA 2, the top of the profile shows again high energy deposits. They are made up of sand and include numerous pieces of gravel (2.66–2.26 m, 1.59–0.62 m b.s.l.). These deposits are intersected by a layer of well sorted fine sand and covered by limnic and alluvial fan sediments.

In summary, considerable sections of the presented vibracores from the Sound of Lefkada are characterized by a facies which is not typical of the prevailing quiescent sedimentary conditions in the present shallow-water lagoonal environment (section 2). Geomorphological and sedimentological traces such as the occurrence of (1) unsorted sandy to gravelly deposits with marine shell fragments, (2) fining upward phenomena and laminated structures within gravel and sand sheets, (3) sandy shell debris layers intersecting homogeneous lagoonal mud deposits, (4) sharp erosional contacts between autochthonous fine grained sediments and coarse grained material, (5) rip-up clasts from the underlying stratum found in sand and gravel layers thus document event-like temporary high energy influence to the Sound of Lefkada originating from open-marine, i.e. outer-sound areas. Based on the facts that (a) the sound is well protected against storm wave dynamics of the open Ionian Sea and (b) there is evidence of (past) tsunamigenic influence on the adjacent coastal zone between Lefkada and Preveza (section 4.1), we conclude that these traces document multiple tsunami impact on the sound.

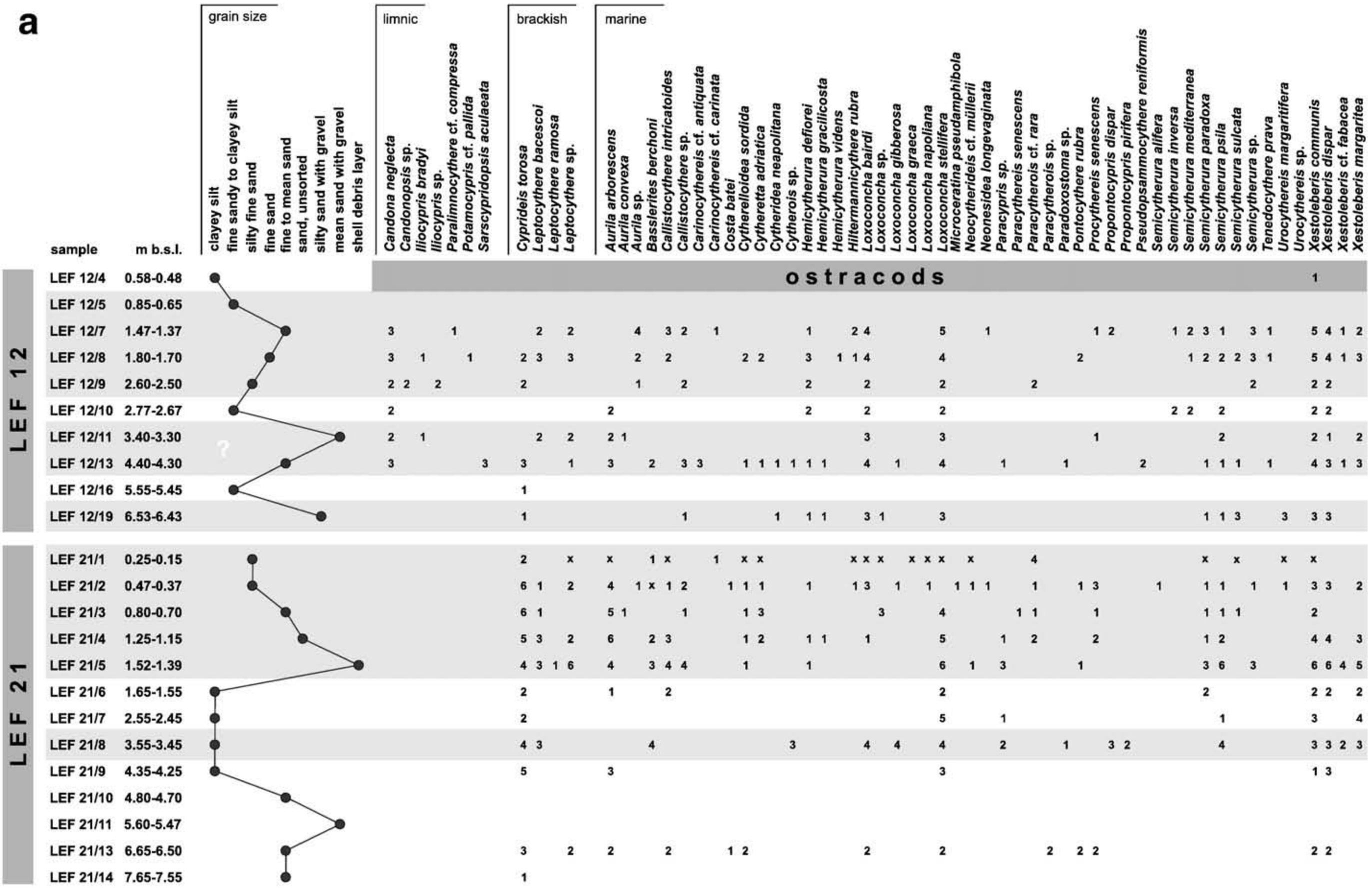
4.2.2. Microfaunal and palynological indicators

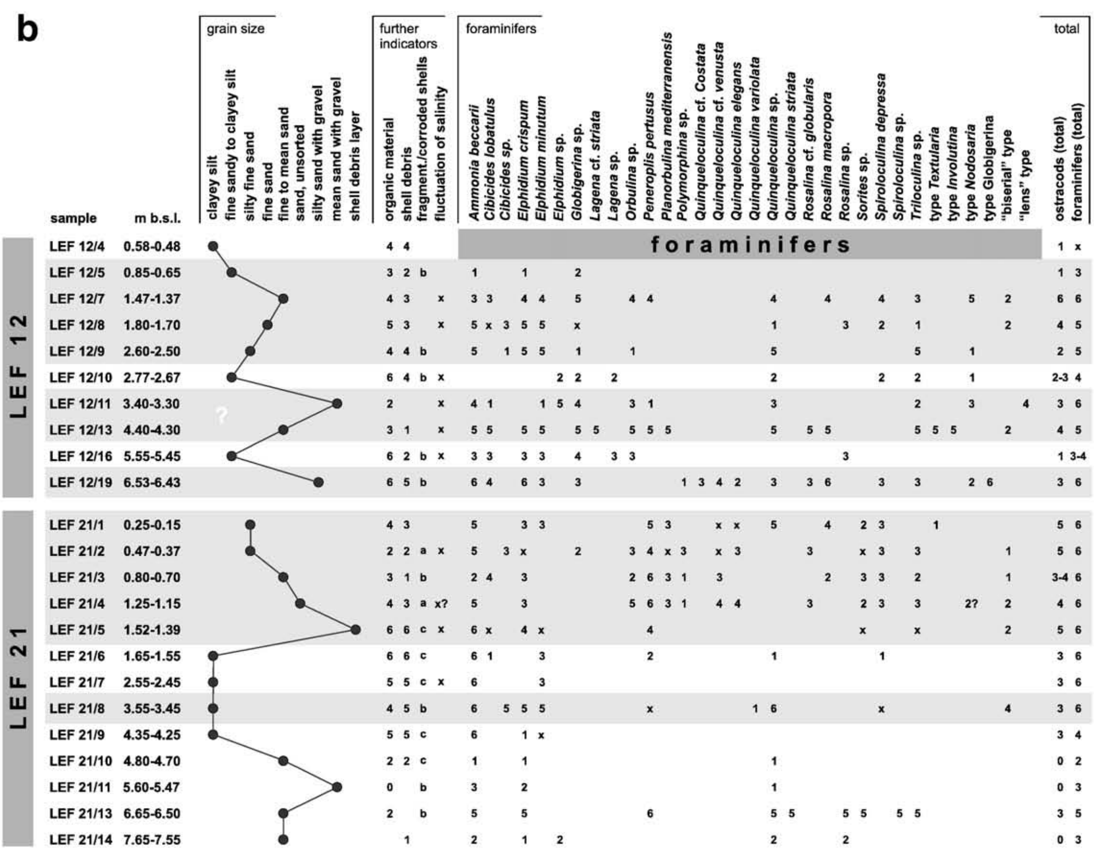
We present detailed results of microfauna analyses for vibracores LEF 12 and LEF 21 (section 4.2.1). Fig. 5a and b summarize ostracod and foraminifer species or genera encountered in selected sediment samples. Those layers which, according to geomorphological, sedimentological and geochemical criteria, were identified as tsunami sediments are shaded in light grey. Ostracods typical of ex-situ (open-) marine outer sound environments are restricted to sandy and gravelly substratum, i.e. to coarse-grained high energy event deposits. In some cases, these deposits may be partly reworked. Autochthonous lagoonal deposits are, however, characterized by a considerably lower bio-diversity and low abundances of the encountered species (e.g. samples LEF 12/16, LEF 12/10, LEF 21/11-9, and LEF 21/7-6). Foraminifers represent the dominating microfauna group and occur in almost every sample. Autochthonous associations typical of lagoonal conditions are dominated by *Ammonia beccarii* and *Elphidium* sp. In coarse grained event deposits in the lower and uppermost sections of LEF 12 and LEF 21 (e.g. samples LEF 12/19, LEF 12/9-7, LEF 21/13, LEF 21/5-1), however, we encountered a highly bio-diversified foraminifera fauna typical of (open-) marine and partly also of deep-water environments. The spectrum is quite inhomogeneous and seems to represent a mixture of different associations. According to Murray (1973, 2006), *Cibicides lobatulus*, *Cibicides* sp., *Planorbulina* sp., *Quinqueloculina* sp., *Textularia* sp., *Triloculina* sp. are characteristic for detrital environments at 40–100 m water depth, *Peneroplis* sp., *Planorbulina* sp., *Quinqueloculina* sp., *Rosalina* sp., *Textularia* sp., and *Triloculina* sp. also for deep-water mud environments down to 150 m water depth. Further fully marine species are, for instance, *Sorites* sp., and *Spiroloculina depressa*. Found inside the Sound of Lefkada and especially in sediments close to the present sea level (e.g. samples LEF 21/5-1), they do not represent an in-situ assemblage.

Fig. 6 illustrates SEM photographs of selected ostracod and foraminifer species encountered in sediment samples from LEF 21 which are not typical of quiescent lagoonal but rather of strong autochthonous influence from outer sound areas. Please note that, for doubtless identification, more or less intact specimens were chosen. However, Fig. 6a shows an almost intact and Fig. 6d a damaged specimen of *Carinocythereis* cf. *carinata*; Fig. 6c depicts a specimen of *Hiltermannicythere rubra*, Fig. 6o a specimen of a *Textularia*-type foraminifer both of which are reworked and rounded; the specimens of *Xestoleberis cf. fabacea* (Fig. 6h), *Planorbulina mediterranensis* (Fig. 6k) and *Sorites* sp. (Fig. 6m) are also partly broken; it is also remarkable that the aperture of *Quinqueloculina* sp. shown in Fig. 6p is completely filled with mineral grains up to the size of fine sand. It is suggested that these characteristics are due to intense stress during transport and do not reflect in-situ conditions. Moreover, allochthonous sand layers are characterized by high amounts of macrofauna shell debris, abundant broken foraminifers and ostracods and, in some cases, even appear as bio-arenitic sediment (Fig. 5b). In contrast, autochthonous lagoonal or limnic deposits show highest contents of organic material, microfauna remains are often corroded, and pyrite crystals indicate partly anoxic sedimentary conditions.

We selected 11 sediment samples from vibracore LEF 26 from the inner sound in search of a potential tsunamigenic fingerprint in the pollen record. LEF 26 shows limnic (up to 3.81 m b.s.l.), in its uppermost part slightly brackish sediments (3.81–3.68 m b.s.l.) followed by a sandy to silty marine shell debris layer (3.68–3.40 m b.s.l.) on top of an erosional contact. The subsequent lagoonal to marsh unit (3.40–0.59 m b.s.l.) is interrupted by another distinct sandy shell debris layer (2.29–2.09 m b.s.l.) and covered by material excavated from the nearby navigable channel. There seem to be further (indistinct) shell debris layers, possibly affected by bio-turbation. The amount of pollen grains found per sediment unit is extremely low and does not allow quantitative analyses. However, the number of pollen grains seems to be higher in non-disturbed lagoonal sediments (10–19 pollen grains counted per microscopic slide) than in the sandy shell debris layers (6–9 pollen grains per slide). Similar to profiles LEF 25, LEF 27, PER 6 (Fig. 3) and others, the latter represent tsunami deposits. Low pollen content may thus be explained by high sedimentation rates and the input of oxygen during extreme events. It is worth noting that the pollen content of the underlying lake deposits is almost null although there are no signs of oxidation. Pollen from *Olea* sp., *Picea* sp., and *Pinus* sp. appear, for the first time, at 3.79–

Fig. 5. a. Ostracod species and genera found in sediment samples from vibracores LEF 21 in the northern and LEF 12 in the southern part of the Sound of Lefkada, compared to grain size distribution. Abundances: x — not specified; 1 — very rare/singular; 2 — rare; 3 — few; 4 — fairly many; 5 — many; 6 — great many. Light grey shading: samples from tsunamigenic layers. Fig. 5b: Foraminifer species and genera found in sediment samples from vibracores LEF 21 in the northern and LEF 12 in the southern part of the Sound of Lefkada, compared to grain size distribution and further facies indicators. Abundances: x — not specified; 1 — very rare/singular; 2 — rare; 3 — few; 4 — fairly many; 5 — many; 6 — great many. Further symbols: a — type bio-arenite; b — abundant broken shells; c — corroded shells. Light grey shading: samples from tsunamigenic layers.


a
grain size
limnic
brackish
marine
ostracods
sample
m b.s.l.
clayey silt
fine sandy to clayey silt
silty fine sand
fine sand
fine to mean sand
sand, unsorted
silty sand with gravel
mean sand with gravel
shell debris layer
Candona neglecta
Candonopsis sp.
Iliocypris bradyi
Iliocypris sp.
Paralimnocythere cf. compressa
Potamocypris cf. pallida
Sarscypridopsis aculaeata
Cyprideis torosa
Leptocythere bacescoi
Leptocythere ramosa
Leptocythere sp.
Aurila arborescens
Aurila convexa
Aurila sp.
Bassleerites berchoni
Callistocythere intricatoides
Callistocythere sp.
Carinocythereis cf. antiquata
Carinocythereis cf. carinata
Costa batei
Cytherelloidea sordida
Cytheretta adriatica
Cytheridea neapolitana
Cytherois sp.
Hemicytherura defiorei
Hemicytherura gracilicosta
Hemicytherura videns
Hiltermannicythere rubra
Loxoconcha bairdi
Loxoconcha sp.
Loxoconcha gibberosa
Loxoconcha graeca
Loxoconcha napoliana
Loxoconcha stellifera
Microceratina pseudamphibola
Neocytherideis cf. müllerii
Neonesidea longevaginata
Paracypris sp.
Paracythereis senescens
Paracytherois cf. rara
Paracytherois sp.
Paradoxostoma sp.
Pontocythere rubra
Procythereis senescens
Propontocypris dispar
Propontocypris pirifera
Pseudopsammocythere reniformis
Semicytherura alifera
Semicytherura inversa
Semicytherura mediterranea
Semicytherura paradoxa
Semicytherura psila
Semicytherura sulcata
Semicytherura sp.
Tenedocythere prava
Urocythereis margaritifera
Urocythereis sp.
Xestoleberis communis
Xestoleberis dispar
Xestoleberis cf. fabacea
Xestoleberis margaritea
LEF 12
LEF 12/4 0.58-0.48
LEF 12/5 0.85-0.65
LEF 12/7 1.47-1.37
LEF 12/8 1.80-1.70
LEF 12/9 2.60-2.50
LEF 12/10 2.77-2.67
LEF 12/11 3.40-3.30
LEF 12/13 4.40-4.30
LEF 12/16 5.55-5.45
LEF 12/19 6.53-6.43
LEF 21
LEF 21/1 0.25-0.15
LEF 21/2 0.47-0.37
LEF 21/3 0.80-0.70
LEF 21/4 1.25-1.15
LEF 21/5 1.52-1.39
LEF 21/6 1.65-1.55
LEF 21/7 2.55-2.45
LEF 21/8 3.55-3.45
LEF 21/9 4.35-4.25
LEF 21/10 4.80-4.70
LEF 21/11 5.60-5.47
LEF 21/13 6.65-6.50
LEF 21/14 7.65-7.55


b
grain size
further indicators
foraminifers
total
sample
m b.s.l.
clayey silt
fine sandy to clayey silt
silty fine sand
fine sand
fine to mean sand
sand, unsorted
silty sand with gravel
mean sand with gravel
shell debris layer
organic material
shell debris
fragment./corroded shells
fluctuation of salinity
Ammonia beccarii
Cibicides lobatulus
Cibicides sp.
Elphidium crispum
Elphidium minutum
Elphidium sp.
Globigerina sp.
Lagena cf. striata
Lagena sp.
Orbulina sp.
Peneroplis pertusus
Planorbulina mediterranensis
Polymorphina sp.
Quinqueloculina cf. Costata
Quinqueloculina cf. venusta
Quinqueloculina elegans
Quinqueloculina variolata
Quinqueloculina sp.
Quinqueloculina striata
Rosalina cf. globularis
Rosalina macropora
Rosalina sp.
Sorites sp.
Spiroloculina depressa
Spiroloculina sp.
Triloculina sp.
type Textularia
type Involutina
type Nodosaria
type Globigerina
"biserial" type
"lens" type
ostracods (total)
foraminifers (total)
LEF 12
LEF 12/4 0.58-0.48
LEF 12/5 0.85-0.65
LEF 12/7 1.47-1.37
LEF 12/8 1.80-1.70
LEF 12/9 2.60-2.50
LEF 12/10 2.77-2.67
LEF 12/11 3.40-3.30
LEF 12/13 4.40-4.30
LEF 12/16 5.55-5.45
LEF 12/19 6.53-6.43
LEF 21
LEF 21/1 0.25-0.15
LEF 21/2 0.47-0.37
LEF 21/3 0.80-0.70
LEF 21/4 1.25-1.15
LEF 21/5 1.52-1.39
LEF 21/6 1.65-1.55
LEF 21/7 2.55-2.45
LEF 21/8 3.55-3.45
LEF 21/9 4.35-4.25
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LEF 21/11 5.60-5.47
LEF 21/13 6.65-6.50
LEF 21/14 7.65-7.55

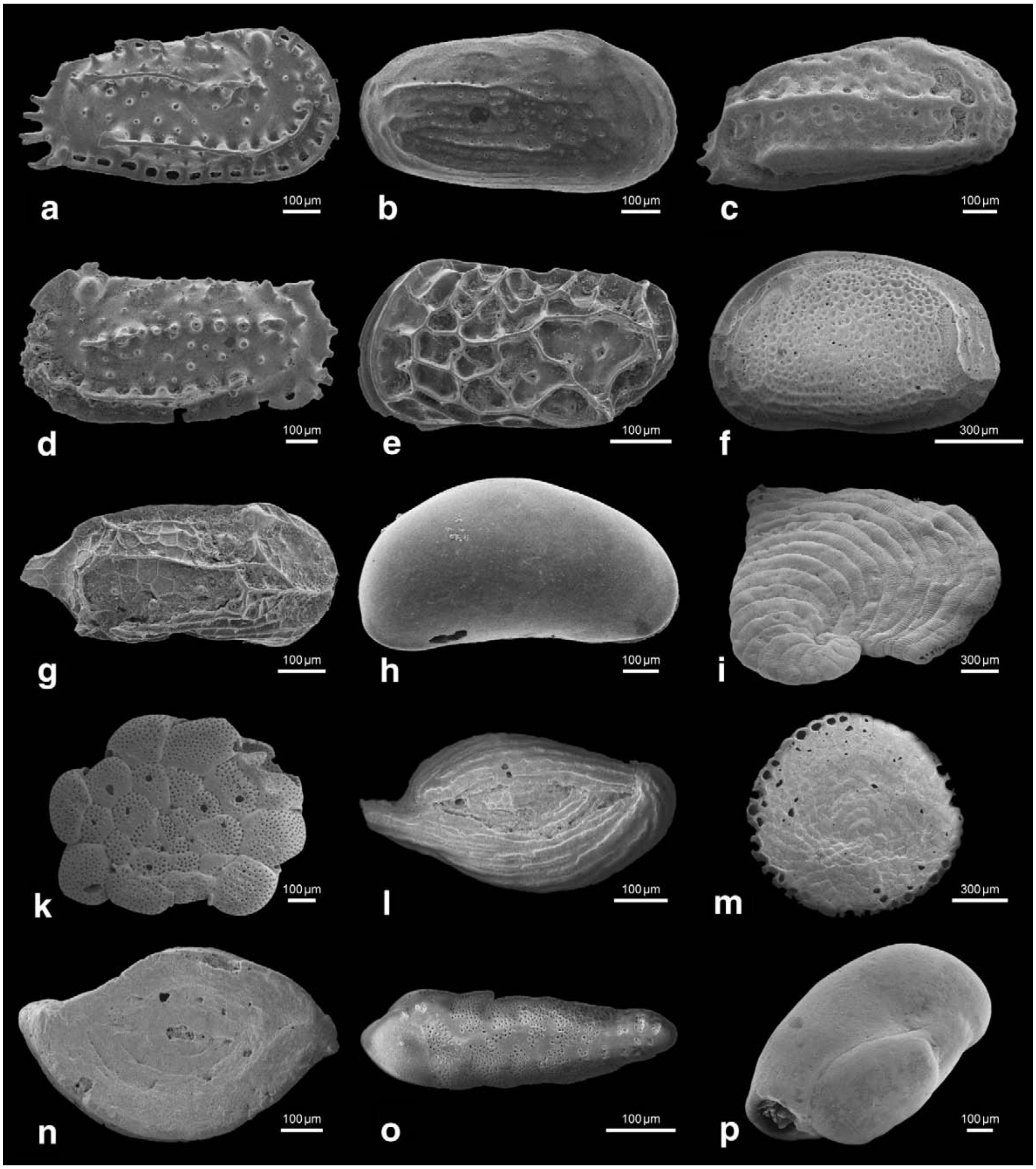

Fig. 6. Scanning electron microscope photographs of selected marine ostracods (a–h) and foraminifers (i–p) retrieved from sediment samples from vibracore LEF 21 indicating high energy transport of allochthonous sediments from open-marine environments into the quiescent lagoonal waters of the Sound of Lefkada by tsunamigenic inundation. (a) *Carinocythereis* cf. *carinata* (LEF 21/1); (b) *Cytheretta adriatica* (LEF 21/1); (c) *Hiltermannicythere rubra* (LEF 21/1); (d) *Carinocythereis* cf. *carinata*, damaged (LEF 21/2); (e) *Loxoconcha* cf. *napoliana* (LEF 21/2); (f) *Aurila arborescens* (LEF 21/5); (g) *Semicytherura psila* (LEF 21/5); (h) *Xestoleberis* cf. *fabacea* (LEF 21/5); (i) *Peneroplis pertusus* (LEF 21/4); (k) *Planorbulina mediterranensis* (LEF 21/4); (l) *Quinqueloculina elegans* (LEF 21/4); (m) *Neocytherideis* cf. *muelleri* (LEF 21/4); (n) *Spiroloculina depressa* (LEF 21/4); (o) *Textularia*-type foraminifer (LEF 21/5); (p) *Quinqueloculina* sp. (LEF 21/8). See text for further explanation.

3.71 m b.s.l. within limnic to slightly brackish deposits. Pollen from *Quercus* sp. was first found within the subsequent shell debris layer.

4.2.3. Traces from earth resistivity tomography and geochemistry

Earth resistivity measurements were carried out along 20 transects at the northern, western and eastern shores of the Sound of Lefkada. In this paper, we present high resolution results from transect per-g-4 that runs in a SW–NE direction perpendicular to the shore some 700 m west of Peratia across vibracoring site PER 1 (Figs. 1 and 7). The upper part of vibracore PER 1 shows predominantly clayey freshwater lake deposits that are, on top of an erosional unconformity, covered by silty mud with fine sand, gravel, and numerous marine shell fragments (2.58–2.21 m b.s.l.) reflecting an abrupt facies change due to an abrupt marine incursion. Subsequently, two sandy shell debris event layers (1.90–1.59 m, 1.31–0.83 m b.s.l.), sandwiched by marsh and alluvial sediments, follow.

The simplified inverse model resistivity section documents the borders between the tsunamigenically affected core section and the underlying limnic sediments on the one hand and the overlying alluvial deposits on the other hand (Fig. 7). Alternating tsunami and lagoonal deposits show lowest electrical resistivity values as they are infiltrated by salty groundwater from the sound due to their coarser texture. Fig. 7 suggests that the thickness of alluvial sediments increases and the thickness of the tsunamigenically affected sequence decreases in a landward direction. Earth resistivity measurements prove that geomorphological and sedimentological tsunami traces are

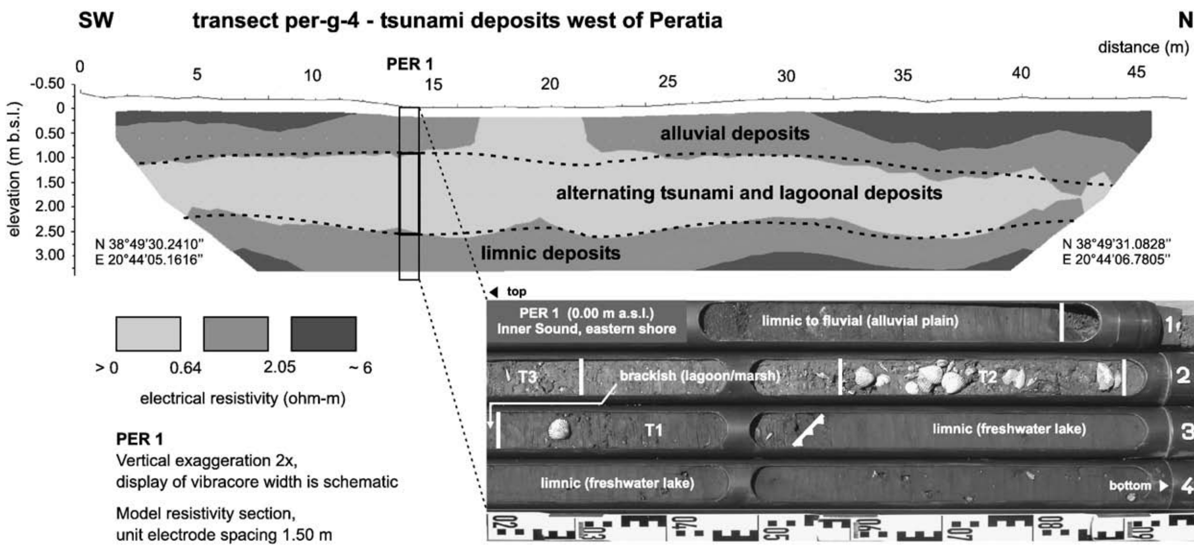

Fig. 7. Simplified model resistivity section for earth resistivity transect per-g-4 at the eastern shore of the Sound of Lefkada and facies profile of the associated vibracore PER 1. For location of resistivity transect and vibracoring site: see Fig. 1. Photo taken by M. May, 2004.

not restricted to local core evidence but continue in a lateral dimension.

Based on multivariate geostatistical analyses of geochemical core data from adjacent coastal plains, it was found that the Ca–Mg ratio is a highly appropriate parameter to discriminate between open-marine, restricted-marine (brackish) and non-marine (limnic, terrestrial) sedimentary environments (Vött et al., 2002, 2003). This may be explained by high calcium carbonate production by organisms in marine environments on the one hand and increased concentrations of magnesium-rich clay and silt where Flysch units were eroded by local torrential streams (Bornovas, 1964; IGME, 1996) and deposited in limnic or lagoonal environments on the other hand. Here, we present Ca–Mg ratios for selected vibracores from the central sound (Fig. 8) compared to simplified logs illustrating tsunami-influenced core sections according to geomorphological and sedimentological criteria. Please note that not every one of these sections was sampled for geochemical analyses. In general, Fig. 8 depicts that tsunamigenic layers are characterized by high Ca–Mg ratios while lagoonal, limnic or alluvial deposits show considerably lower values. However, high Ca–Mg ratios were also found for sand accumulated in the littoral zone of a shallow marine environment as encountered in the lower parts of cores LEF 27 and LEF 26. We conclude that, in the Sound of Lefkada, (1) high Ca–Mg ratios reflect marine deposits and thus can be used to detect tsunami sediments within allochthonous lagoonal mud units, (2) a sequence of several peaks of the Ca–Mg ratio in a vertical profile from the lagoon indicates multiple tsunami impact, and (3) pre-tsunami deposits come closest to the present ground surface or sea level in the central sound around LEF 24 and PER 5 where they form a subterraneous sill. Core sections with tsunami traces below 3 m b.s.l. were only found in the northern and especially in the southern part of the sound.

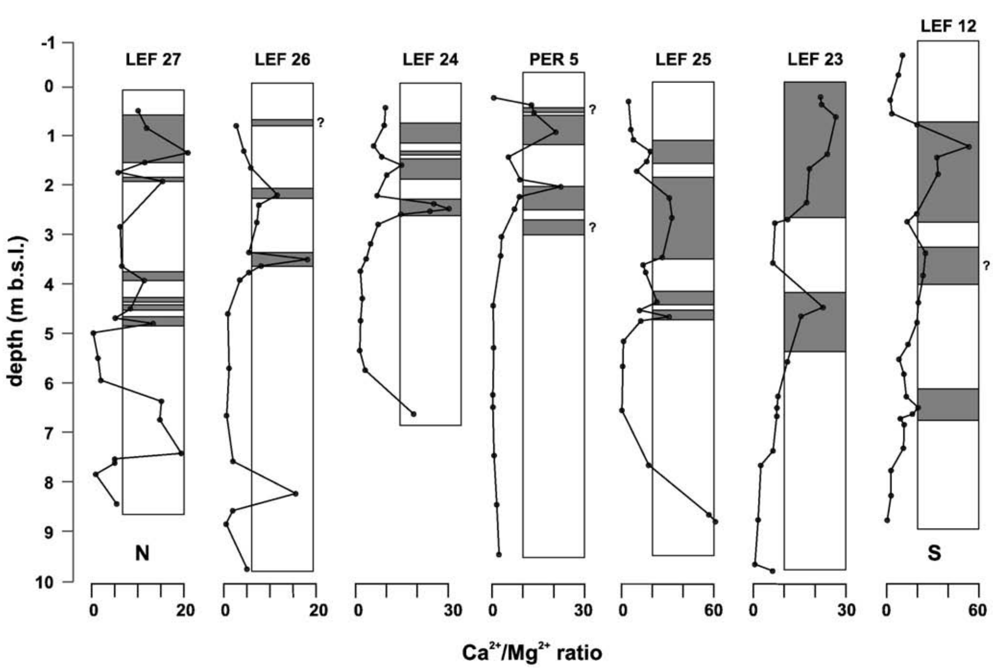

Fig. 8. Vertical profiles of the Ca–Mg ratio of sediment samples from selected vibracores from the inner Sound of Lefkada compared to simplified logs showing allochthonous tsunami deposits (shaded in grey). For location of vibracoring sites: see Fig. 9.

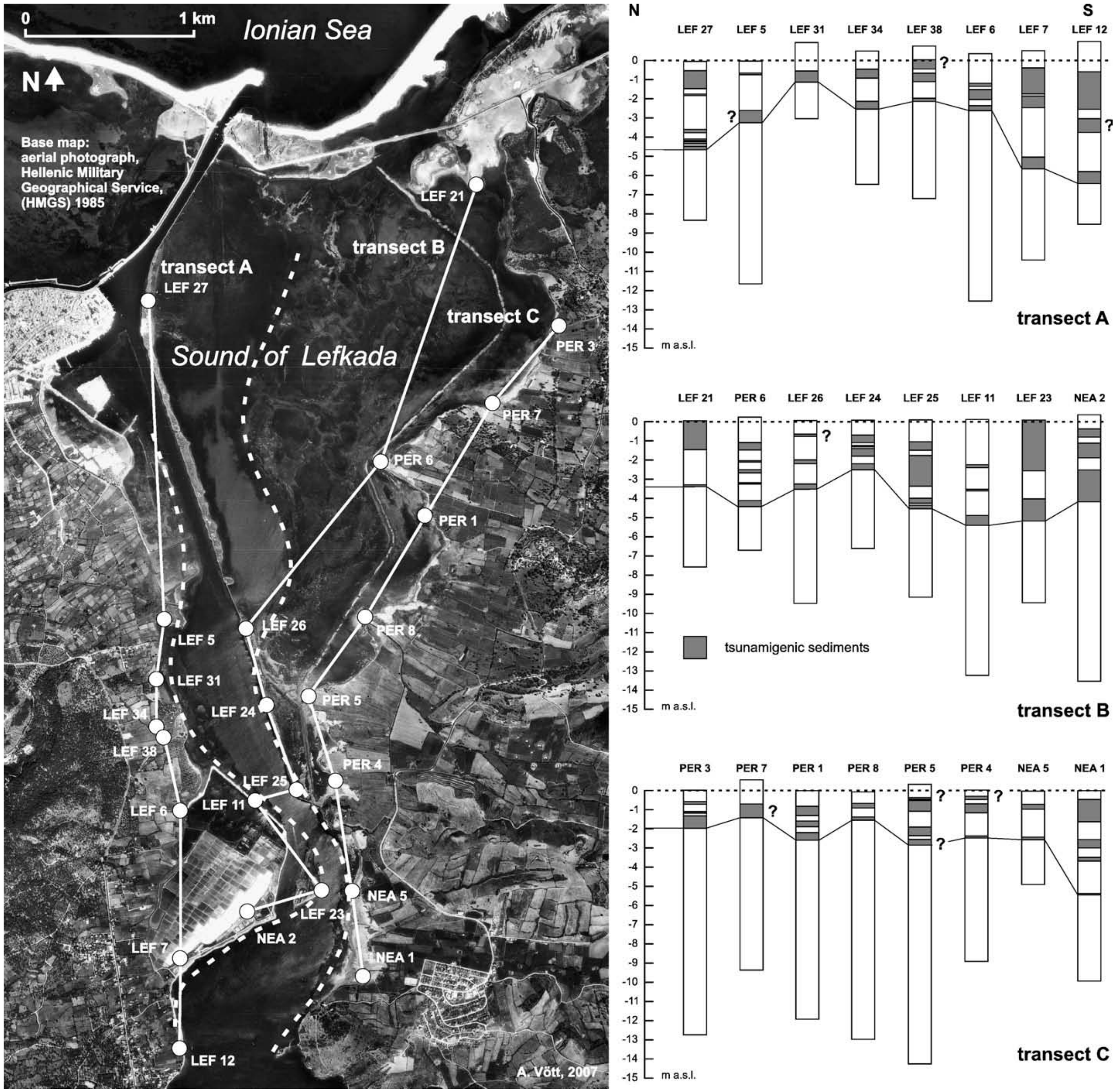

Fig. 9. Simplified logs for 24 cores from the Sound of Lefkada, arranged in transects A, B and C, showing tsunamigenic deposits (shaded in grey). See text for further explanation.

4.2.4. Multiple tsunami passage across the sound

Geomorphological, sedimentological, palaeontological and geochemical criteria (sections 4.2.1 to 4.2.3) helped to detect tsunami deposits in 24 selected vibracores drilled in the Sound of Lefkada. Fig. 9 shows simplified logs illustrating the elevation and thickness of the event layers. Vibracore transect A runs along the eastern flank of Lefkada Island, transect B covers the inner sound, and transect C focuses on the western fringe of the Plaghia Peninsula. The summary view of the tsunami deposits leads to the following results:

(1) Apart from LEF 31 and PER 7, all vibracores are characterized by several allochthonous high energy deposits separated by autochthonous lagoonal sediment layers. The highest number of events (6) was found for LEF 27 lying close to the central part of the Santa Maura beach ridge system and thus being strongly exposed to tsunami impact from the open sea. The average number of event layers is 3.

(2) Tsunami deposits are most strongly condensed in cores of transect C which is the one lying farthest from the open sea. Except for NEA 1 which is located at the shore of the inner Bay of Drepano, event layers along transect C are thinnest and restricted to elevations between 3 m b.s.l. and present sea level. The latter is also the case for cores at the opposite shore of the sound along transect A (LEF 5, LEF 31, LEF 34, LEF 38, LEF 6) which may be explained by decreasing lateral effects of tsunamigenic inundation. On the contrary, tsunami sediments encountered in the central sound (transect B, including LEF 27) and at the western shore of the Bay of Drepano (LEF 7, LEF 12) show the lowest

condensation and therefore the thickest individual event layers (1.68 m at LEF 25; 2.68 m at LEF 23; 2.04 m at LEF 12, including reworked sandy to gravelly sediments).

(3) Pre-tsunami deposits are characterized, in most cases, by erosional contacts at their top. In general, they show highest elevations along the western and eastern shores of the sound and lowest elevations in the inner parts of the lagoon. Our core data therefore indicate a natural channel that was eroded along the inner sound by the passage of tsunami waters. The dashed line in Fig. 9 depicts the edges of a natural channel that can be identified in sea charts (DHI, 1986) and topographic maps (von Marées, 1907) as well as in aerial photographs and satellite images (e.g. Corona, USGS) and that was probably shaped by one of the younger tsunami events which hit the sound.

(4) Fig. 9 also illustrates a W–E-trending subterraneous sill made out of pre-tsunami deposits between the ancient city of Lefkada at LEF 38, the inner sound around LEF 24, and the fringe of the PER 5 fan delta. Against the background of tsunami evidence from the Bays of Lefkada and Aghios Nikolaos and the Actio headland (section 4.1) predominant tsunami wave passage in the sound is assumed to be from north to south. Fig. 9 shows that the event layers increase in thickness southward of the central sill. This seems to be due to the decrease of transport energy once the tsunami water masses had overflowed the sill and diverged into the deeper waters of the inner Bay of Drepano.

(5) Based on our core data, the spit at the southern fringe of the inner sound from LEF 7 via NEA 2 to LEF 23 seems to be made up of tsunami deposits which are partly reworked in the littoral zone of the inner Bay of Drepano. We assume that the northern part of the pre-tsunami bay environment, extending some hundreds of meters further northward than today, was filled up with event deposits. Later, this area was used to establish the saltworks of Lefkada which were abandoned in the 20th century AD.

(6) More lateral parts of the sound, e.g. PER 3 and PER 7, were also affected by tsunami wave action. However, the number of distinctly discernible event layers decreases from the central lagoon towards its shores. This may reflect that more central and exposed sites were hit more frequently than lateral parts which, in turn, were only hit by larger tsunami impacts reaching further inland. Comparing the maximum depth of tsunami layers all over the sound (Fig. 9), lateral sites are characterized by a higher pre-tsunami topographic position and thus suffered from lower tsunami inundation levels. Anomalous wave dynamics from the seaside is also documented in thin sections of tsunami sediment samples from the eastern fringe of the modern sound. The lowermost event layer encountered at PER 3 (1.55–1.51 m b.s.l.), for example, is made up of unsorted material including both rounded and angular mineral grains from coarse sand to clay (Figs. 9 and 10a,b). The sediment is made up of both marine and terrigenous material; its texture is chaotic. PER 3 thin sections show numerous shell ragments of a marine macrofauna (Fig. 10c) as well as foraminiferal remains from open-marine species such as *Globigerina* sp. (Fig. 10c and e), *Orbulina* sp. (Fig. 10d) and *Textularia*-type foraminifers (Fig. 10d). Microfauna remains, mostly broken, were thus transported, reworked and deposited in an ex-situ environment. Moreover, there are signs of secondary calcification most probably due to corrosion by rain water and subsequent re-crystallisation by strong evaporation (Fig. 10c and f).

4.2.5. Geochronological data

Geochronological information on environmental changes and tsunami influence on the inner Sound of Lefkada is based on 9 ^{14}C-AMS radiocarbon ages and few dates derived from diagnostic ceramic fragments found in vibracores (Fig. 3). Radiocarbon dating of tsunami layer material is problematic as the dated sample may represent older reworked material (section 3). Depending on the availability of datable material found in the cores, sampling of pre- and/or post-tsunami deposits was therefore preferred. However, in cases where pre- and post-tsunami units were void of datable material, tsunami layer material was dated yielding a maximum age of the event. Conventional and calibrated radiocarbon ages are summarized in Table 1.

5. Discussion

5.1. Local tsunami geochronology

Table 1 and Fig. 3 show that oldest tsunami traces may go back to the 6th millennium BC. Undetermined plant remains found immediately below tsunami deposits encountered at PER 6 (PER 6/11 PR) date to 5286–5071 cal BC. Additionally, there is sedimentological and chronological evidence of an extreme event, yet unpublished, which hit the inner Bay of Aghios Nikolaos some time after 5984–5895 cal BC. This is the age of in-situ peat found in core ANI 1 at 8.31 m b.s.l. around 500 m to the southwest of the village of Aghios Nikolaos (Fig. 1). Some 55 cm above the dated peat sample and following organic mud, accumulated in a freshwater environment, an almost 50 cm-thick tsunamigenic layer of unsorted sand including abundant marine shell fragments was found. Thus, there is strong evidence of an early tsunami impact on the Lefkada coastal zone. However, further datings especially above the mentioned tsunami layers are necessary in order to estimate the potential hiatus due to tsunamigenic erosion and to better define their mid-Holocene age.

In accordance with geo-scientific criteria mentioned above, the ^{14}C-AMS age of 2842–2690 cal BC determined for plant remains from the lower part of LEF 12 at 6.23 m b.s.l. (LEF 12/18 PR) underlines that the underlying layer of unsorted marine deposits may not be interpreted as storm-borne material or a simple transgressive unit: Compared to Vött (2007) who reconstructed a relative sea level for the adjacent Palairos coastal plain (Fig. 1) of 3.00 m b.s.l. for the time around 2750 cal BC, the LEF 12 high energy deposits lie some 3.5 m deeper, a value which is unrealistic for the low to moderate energy coast around the near-littoral site LEF 12 being sheltered from the open Ionian Sea (Fig. 1). The data given in fact indicate that a tsunami affected the site shortly before 2842–2690 cal BC. This age is consistent with the time period of 2870–2350 cal BC for which Vött et al. (2007b) found strong tsunami influence on Actio headland (section 4.1). Although derived from reworked material, the maximum age of 3310–2917 cal BC determined for the lowermost tsunami sediments encountered at NEA 2 (NEA 2/12 PR) may reflect the same high energy event. However, radiocarbon dating of unidentified in-situ plant remains found in the middle part of LEF 6 (LEF 6/6 PR) suggests that already three tsunamis had passed the sound before 2290–2141 cal BC.

At NEA 2, sea weed remains from the upper core section (NEA 2/8 PR) yielded an age of 1746–1606 cal BC predating strong tsunami influence to the site. Given the fact that the tsunami produced an erosional unconformity, it may be identical with the 1000 cal BC event which hit the Bay of Aghios Nikolaos and the Lake Voulkaria (Vött et al., 2006, 2007b; section 4.1). However, further datings are needed to verify this hypothesis.

The two younger dates analysed for samples from LEF 12 (LEF 12/10 PR, LEF 12/7 M) as well as ceramic fragments found at 5.28 m and 2.78 m b.s.l. (Fig. 3) indicate a (post- or ad-) Classical and pre-Roman tsunami and that at least one of the two younger extreme events occurred during Roman times after 183–58 cal BC. This is also suggested by a high number of *Phillyrea*-pollen grains found in samples of a tsunamigenic shell debris layer (LEF 26/4, 2.23–2.13 b.s.l) and in both over- and

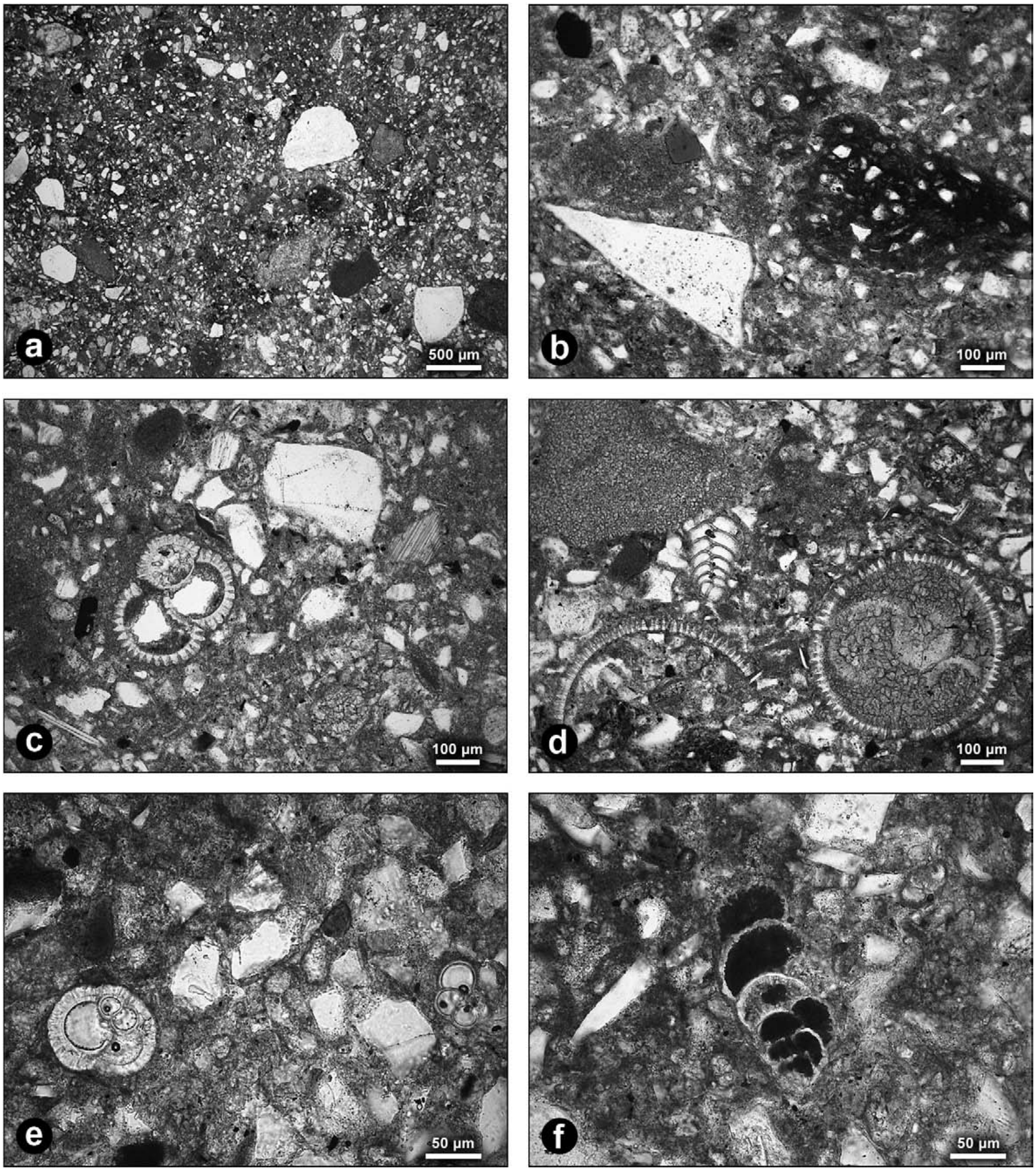

Fig. 10. Thin section photographs from a tsunami sediment sample of vibracore PER 3 (sample PER 3/6+, 1.58–1.54 m b.s./1.55–1.51 m b.s.l.), seen under plain polarized light. See text for further explanation.

underlying lagoonal mud (LEF 26/5, 2.43–2.33 m b.s.l., LEF 26/3, 1.68–1.58 m b.s.l.) taken from the inner-sound vibracore LEF 26. The increase in *Phillyrea* pollen might correspond to the increase of *Phyllirea* sp. found in sediments from the Lake Voulkaria dated to the time between the 8th and 2nd century BC (Jahns, 2005; for recalibrated radiocarbon dates see Vött et al., 2006). These findings fit well with chronological data from the outer-sound area in the environs of the Bay of Aghios Nikolaos where tsunami traces were dated to 395–247 cal BC and also to Roman times (Vött et al., 2006, 2007a).

Plant remains extracted from the uppermost tsunami layer at PER 6 (PER 6/3 PR) further suggest tsunamigenic inundation during or after 1244–1293 cal AD possibly related to the tsunami described by Vött et al. (2006) which hit the nearby Cheladivaron promontory at 1000–1400 cal AD. However, the given radiocarbon date is only a maximum age and regional tsunami catalogues list at least 20 further light to strong tsunamis for the Ionian Sea between 1402 and 1850 AD (Vött et al., 2006, Table 2) so that one of these events might also be responsible for this layer.

5.2. Tsunami deposits and co-seismic crustal movements

In geo-scientific literature there has been a controversial discussion on the discrimination between storm and tsunami deposits (e.g. Nott, 2004; Scheffers et al., 2005; Morton et al., 2006). Consequently, a number of criteria have been defined which are widely accepted for the identification of tsunamigenic imprint on coastal zone sediments (for detailed lists of criteria see Dominey-Howes et al., 2006; Dawson and Stewart, 2007; Kortekaas and Dawson, 2007; see also Dawson, 1994). Recent studies on sediments of the 2004 Indian Ocean tsunami have been most helpful in checking and improving these criteria (e.g. Moore et al., 2006; Hawkes et al., 2007; Morton et al., 2007; Paris et al., 2007).

Table 1
^{14}C-AMS dating results for samples from the Sound of Lefkada

Sample name	Depth (m b.s.)	Depth (m b.s.l.)	Sample description	Lab. no.	δ^{13}C (ppm)	^{14}C Age (BP)	1σ max; min (cal BP)	1σ max; min (cal BC)
ANI 1/22 PR	8.37	8.31	Peat, organic material	UtC 13676	−27.9	7040±41	7933–7844	5984–5895
LEF 12/7 M	2.48	1.43	*Dosinia exoleta*, articulated specimen	Erl 9808	0.1	2370±50	2063–1924	114 BC–26 AD[a]
LEF 12/10 PR	3.77	2.72	Sea weed remains	Erl 9809	−17.8	2436±42	2132–2007	183–58[a]
LEF 12/18 PR	7.28	6.23	Sea weed remains	Erl 9810	−14.6	4504±48	4791–4639	2842–2690[a]
NEA 2/8 PR	2.30	1.92	Sea weed remains	UtC 13694	−13.1	3710±50	3695–3555	1746–1606[a]
NEA 2/12 PR	4.30	3.92	Unidentified plant remains	UtC 13693	−28.3	4410±70	5259; 4866	3310; 2917
NEA 2/21 M	8.75	8.37	*Cyclope neritea*, articulated specimen	UtC 13692	−3.5	7350±60	7895; 7750	5946; 5801[a]
PER 6/3 PR	1.37	1.11	Unidentified plant remains	Erl 9821	−10.4	733±40	706; 657	1244; 1293 AD
PER 6/6 PR	2.74	2.48	Unidentified plant remains	Erl 9822	−9.6	3788±48	4239–4090	2290–2141
PER 6/11 PR	4.64	4.38	Unidentified plant remains	Kia 28880	−13.6	6215±40	7235; 7020	5286; 5071

Note: b.s. — below ground surface; b.s.l. — below sea level; 1σ max; min cal BP/BC (AD) — calibrated ages, 1σ-range; ";" — there are several possible age intervals because of multiple intersections with the calibration curve; Lab. no. — laboratory number, University of Erlangen (Erl), University of Kiel (Kia), University of Utrecht (UtC).
[a] Samples corrected for a marine reservoir effect of 402 years.

Shi et al. (1995), for instance, found sharp unconformities at the bottom of tsunami sediments, sand layers including gravel and rip-up clasts as well as a general fining upward trend and an up-core increase in sorting in deposits of the 1992 Flores event in Indonesia. Nichol et al. (2007) describe similar characteristics of tsunami deposits detected in a backbarrier wetland in northern New Zealand. We encountered the same kind of geomorphological and sedimentological criteria in cores from the Sound of Lefkada (section 4.2.1) which underlines the tsunamigenic influence.

Kontopoulos and Avramidis (2003) identified sandy intercalations in the homogeneous mud of the Aliki Lagoon, Gulf of Corinth, as tsunami-borne deposits. However, the Aliki Lagoon, due to its exposed topographic situation, is much more in danger to be affected by storm wave dynamics than the entirely enclosed Sound of Lefkada where similar deposits were encountered. Based on the principle of uniformitarianism, storm influence can definitely be excluded for our study area (section 2). Switzer et al. (2005) describe widespread sand sheets found onshore in southwestern Australia which seem to be tsunamigenic overwash deposits. Comparable sediments were detected in the Canali Stretti washover plain in the northern Sound of Lefkada (Figs. 1 and 3, Vött et al., 2007b).

Goff et al. (1998), Goiran (2001), Stanley and Bernasconi (2006), Alvarez-Zarikian et al. (in press), and Marriner and Morhange (2007) used ex-situ findings of diatoms and/or marine macro- and microfauna as indicators for tsunami impacts. Using this approach for our studies, microfossil analyses of sediment samples from lagoonal inner-sound cores clearly document tsunamigenic high energy influence from the seaside (Fig. 5a and b).

Pirazzoli et al. (1999) and Dominey-Howes (2002) give examples for tsunami deposits out of allochthonous littoral material found in terrestrial environments and consisting of a mixture of sand and gravel. Such roughly bimodal sediments (see Scheffers and Kelletat, 2004) were retrieved from numerous cores taken from the sound. Also, geochemical criteria accepted as typical of tsunami deposits, such as high concentrations of sodium or calcium (Dominey-Howes et al., 2006, Table 7), were found to be true for inner-sound sediments (Fig. 8).

As to crustal dynamics, Pirazzoli et al. (1994) assume that the northern part of Lefkada Island has been subject to up-and-down tectonic (yo-yo) movements. In fact, *Lithophaga* sp. boreholes and corals which we found up to 12.55 m a.s.l. at Cape Aghios Ioannis, dated by electron spin resonance technique (ESR) to 113,000±9,000 BP, document considerable uplift since the last interglacial sea level high stand. A nearby notch at the present coast of the same site may reflect slight uplift during the Holocene (Pirazzoli et al., 1994). Vött (2007, p. 903) described a submerged notch close to Cape Variko (Fig. 1) which documents co-seismic subsidence in post-Roman times. It thus cannot be excluded that the inner sound area has been subject to sudden co-seismic vertical displacements. The submerged mole of the Corinthians (Murray, 1988) as well as the remains of the Hellenistic to Roman bridge (Négris, 1904), both indicating a relative sea level rise of 2.5–3 m during the last 2500 years and thus being in accordance with the results found for adjacent coastal Akarnania (Vött, 2007), probably also underwent abrupt coastal subsidence. As observed during the 1999 Izmit and the 2004 southeast Asia earthquakes, tsunami landfall may go hand in hand with local crustal uplift or subsidence (Altinok et al., 2001; Meltzner et al., 2006; Searle, 2006). It is highly probable that a considerable number of tsunami events recorded in the sediments of the Lefkada coastal zone were triggered by earthquakes related to the nearby CF and LF Hellenic Arc sections and thus may have been accompanied by vertical crustal movements. In this context, it has to be emphasized that even large order coastal subsidence is not able to induce high energy water flow and the transport of large sediment masses towards or along the coast.

In summary, the Sound of Lefkada represents an ideal sediment trap which exemplarily shows, in one place, all those geo- and bioscientific criteria which are found to be indicative for tsunami deposits. This makes the sound an important model area for the study of multiple strong tsunami impacts and their effects on coastal evolution.

5.3. Palaeogeographical implications

Wilhelm Dörpfeld was convinced that Homer's Odyssey reflects a true episode of the Mycenaean history and identified Lefkada Island as Homer's Ithaca (Dörpfeld, 1927). This famous "Ithaka-Frage" initiated numerous studies on the cultural and coastal evolution of Lefkada Island (see Morris, 2001, p. 287). A main issue was to find the location of the isthmus which, in the 7th century BC, was cut through by the Corinthians (section 2). Goessler (1904), von Marées (1904), Partsch (1907), and Lehmann-Hartleben (1923) were sure that the isthmus must have been located close to the Canali Stretti (Fig. 1, see also Leake, 1835; de Stefani, 1896) and denied any other terrestrial connection further south. von Seidlitz (1927) drilled numerous cores all over the sound down to 3 m b.s.l. but did not penetrate the younger lagoonal deposits. Consequently, he rejected an isthmus east of ancient Lefkada. However, he found thick sand and gravel layers intersecting the lagoonal muds of the inner sound (von Seidlitz, 1927, p. 363f.) without recognizing that these layers represent multiple tsunami impact (section 4).

Based on Négris (1904) who found a relative sea level rise of 2.8–3 m since the 4th/5th century BC, Lang (1905) suggested that large parts of the lagoon were exposed to subaerial conditions in ancient times forming a 4–5 km-long isthmus between Lefkada Island and the Plaghia Peninsula. He was convinced that the ancient bridge described by Négris (1904) span a channel across this isthmus.

Based on geo-scientific evidence, our study revealed highest elevations of pre-tsunami deposits in the inner sound right between ancient Lefkada and the Plaghia Peninsula (sections 4.2.3 and 4.2.4), exactly where archaeological remains document the course of the ancient bridge. Pre-tsunami deposits indicate that this could have represented a kind of isthmus which was made up of a shallow-water limnic to early lagoonal environment strongly influenced by distal dynamics of the alluvial fan systems entering the sound from the Plaghia side. Earliest tsunami influence on this area is dated to the 3rd millennium BC (section 5.1). The highest elevation of pre-tsunami deposits was found at LEF 24 with 2.62 m b.s.l.; compared to local relative sea level data (Négris, 1904; Vött, 2007), this site lay close to or slightly above sea level at least until the 1st millennium BC, most probably even longer due to its partial erosion by younger tsunami activity and possible co-seismic subsidence in post-Roman times (section 5.2). Livy (33, 17) reports that, in 197 BC, the length of the isthmus was still 750 m (Lang, 1905, p. 18; Partsch, 1907, p. 274). This is perfectly consistent with the length of the ancient bridge across the sound. Moreover, Kolbe (1902) describes epitaphs on stelai encountered east of ancient Lefkada at 3 m b.s.l. covered by sediments. Provided that these findings are in-situ, they indicate that adjacent parts of the isthmus may even have been used as Lefkada's necropolis (Lang, 1905, p. 12).

From a palaeogeographical point of view, our results show that (1) a shallow-water limnic, later slightly brackish environment existed between Lefkada Island and mainland Akarnania; (2) these isthmus-like lowlands have been overflowed and partly eroded by multiple tsunamigenic inundation at least since the 3rd millennium BC creating a natural channel across today's Sound of Lefkada (cf. von Marées, 1907, p. 12 and Karte 2); (3) the Corinthians did not have to cut through an isthmus but probably simply re-opened a pre-existing natural channel which was partly filled by coarse tsunamigenic material; they would also have had to excavate the Canali Stretti in the northern sound in order to create a continuous waterway; (4) the history of the navigability of the sound is closely related to repeated tsunami passages by which the strait was partly choked and had to be cleaned from time to time (section 2). Lehmann-Hartleben (1923, p. 267), for instance, reasoned that the sandy shallows reported by Livy (33, 17) must have been formed between the erection of the city wall and the conquest of ancient Lefkada by the Romans in 197 BC. This scenario, based on the interpretation of historical data, fits well with geo-scientific evidence of the 395–247 cal BC tsunami found for the Canali Stretti area (Vött et al., 2006, 2007a; section 5.1). The remarkable fact that the Lefkadians were forced to import cereals from Kyrene, northern Africa, around 330–326 BC (Wacker, 1996, p. 93; see also Vött et al., in press), is possibly associated with this event.

Ancient literature does not mention directly that the Lefkada coastal zone has ever been hit by tsunamis. This may be explained by the little importance of the area due to its low population density and peripheral position, or because historical accounts got lost or need to be revised properly. The only information on the Ionian Islands which may be interpreted in terms of tsunami hazard is given by Strabo (10, 2, 15) saying that where Cefalonia "island is narrowest it forms an isthmus so low-lying that it is often submerged from sea to sea" (Bittlestone, 2005, p. 52, translation by J. Diggle). However, the Sound of Lefkada is the only low-lying site in the region for which repeated tsunamigenic inundation is proven. Further research is therefore required to check for tsunami traces in adjacent areas.

6. Conclusions

Based on the analysis of Holocene deposits from the Sound of Lefkada and against the background of multiple tsunami impact found for adjacent regions (Vött et al., 2006, 2007a,b), the following conclusions can be made:

(1) Vibracores revealed coarse grained sandy to gravelly high energy sediments with abundant fragments of marine macrofauna, mostly related to an erosional unconformity at their base, that intersect inner-sound mud deposited in a quiescent lagoonal environment. These deposits document tsunami influence on the Sound of Lefkada.

(2) Geophysical analyses documented widespread tsunamigenic deposits in the inner sound. Tsunami sediments also show a characteristic geochemical fingerprint. Indicators such as the Ca–Mg ratio helped to detect allochthonous high energy influence. Microfauna studies confirmed the repeated input of ostracods and foraminifers from open-marine, partly even deep-water environments to the shallow lagoonal waters of the inner sound. We found multiple interbedding of ex-situ and in-situ deposits documenting the multiple passage of tsunami waters.

(3) Spatial analysis of vibracore data shows that repeated tsunamigenic inundation eroded a natural channel across a shallow-water limnic to lagoonal environment of an isthmus-like nature which existed in the central inner sound.

(4) Geochronological data indicate that several tsunami events occurred between (at least) the 3rd millennium BC and medieval times and that most of these events are consistent with tsunamis found for the nearby Bay of Aghios Nikolaos and Actio headland. Our data thus documents that tsunami impacts repeatedly affected the wider coastal zone between Preveza and Lefkada and seem to largely dominate the coastal evolution (Vött et al., 2007a,b; see also Dawson, 1994). The inner Sound of Lefkada is subject to a high tsunami hazard with a re-occurrence interval for strong events of less than 500–1000 years.

(5) Our results suggest that the Corinthians, known to have excavated a navigable waterway in the 7th century BC, may just have re-opened or widened a natural tsunamigenic channel. This channel has been repeatedly choked with tsunami sediments in the course of the following centuries.

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