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Palaeotsunami impact on the ancient harbour site Kyllini (western Peloponnese, Greece) based on a geomorphological multi-proxy approach

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with 12 figures and 1 table

Abstract. Geoscientific and geoarchaeological studies carried out at the ancient harbour site of Kyllini (western Peloponnese, Greece) revealed distinct evidence of repeated tsunami landfall. Located in the westernmost part of the Peloponnese, the Kyllini harbour site is situated at a narrow stretch of coastal lowland along the northeastern edge of Cape Kyllini. Directly exposed to the Ionian Sea and the Hellenic Trench, the harbour holds a considerably high risk for tsunami events and thus represents a valuable geo-archive for palaeotsunami research. While the inner harbour basin is merely preserved as a near-coast swamp, partially submerged installations like moles, quays, breakwaters and towers clearly define the outer harbour basin.

Geoscientific studies carried out at the Kyllini harbour site comprised on-shore and coastal vibracoring, sedimentological, geochemical and microfossil analyses of the recovered sediments as well as electrical resistivity measurements. The overall geochronological framework is based on radiocarbon dating of biogenic material and age determination of diagnostic ceramic fragments. The stratigraphical record of the harbour site reveals an autochthonous pre-harbour marine embayment on top of Pliocene bedrock. Following a first high-energy impact, a coastal lake was established that was subsequently used as harbour basin and fortified by man. Following a period of siltation, the harbour sequence is abruptly overlain by a massive layer of coarse grained marine sand, indicating a sudden high-energy impact to the harbour site. Partly preserved as geoarchaeological destruction layer and post-depositionally cemented, the layer forms beachrock-type calcarenitic tsunamites. Our results suggest that the harbour site of Kyllini was affected by two tsunami events. A first event occurred between the late 7th and early 4th cent. BC prior to the harbour foundation while it seems as if at least parts of the harbour basin were later destroyed by a second tsunami event between the 4th and 6th cent. AD.

Keywords: tsunami, ancient harbour, Greece

1 *Introduction*

Induced by the collision of the African and European lithospheric plates, the eastern Mediterranean and especially Greece belong to the seismo-tectonically most active regions worldwide. Along the Hellenic Arc, where the northward moving African Plate is being subducted under the Aegean microplate, movement rates reach up to 40 mm/a (Hollenstein et al. 2008). As a result, strong earthquakes occur with high frequency and are a well-known factor for triggering tsunamis (Papazachos & Dimitriu 1991). Throughout the eastern Mediterranean, the tsunami hazard belongs to the highest worldwide since large water depth, narrow shelf zones and short distances from shore to shore encourage major events (Tselentis et al. 2010). Concerning western Greece, coastlines that are exposed to the Hellenic Arc must be considered as particularly threatened by tsunami hazard. Accordingly, geo-scientific studies provide convincing evidence,

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that coastal areas along the Ionian Islands or the western Peloponnese have repeatedly been affected by major tsunami events (e.g. Scheffers et al. 2008, Vött et al. 2009a, 2009b, 2011a, Röbke et al. 2013, Willershäuser et al. 2013).

Historic accounts such as the one by Ammianus Marcellinus, who reports on the 365 AD tsunami, repeatedly describe tsunami impact along the Peloponnesian shores (Amm. Mar. 26.10.15-19 after Rolfe 1940). Compared to adjacent areas, however, the historical record especially for the northwestern Peloponnese is sparse and merely comprises younger events and/or those that had more or less devastating effects on larger settlements (Hadler et al. 2012). In order to better assess the hazard potential of an area and to prepare for future events, it is however inevitable, to gather sufficient data on the frequency and effects of palaeotsunami events. Investigations on recent tsunami impacts (e.g. Japan 2011) revealed that areas once affected by palaeotsunami impact are highly prone to future events (Goto et al. 2011). Thus, to better understand the historically known tsunami risk for an area, it is necessary to fill in the gaps in the historical record by geo-scientific studies.

In this respect there is the need to search for geo-archives that show high-quality and preferably complete conservation of sedimentary traces of previous events. Ancient harbour basins have turned out to be such suitable geo-archives since they provide sheltered and quiescent near-coast environments that act as efficient sediment traps for tsunami deposits.

Geo-scientific evidence of palaeotsunami impact is well documented for the ancient harbour at Caesarea Maritima (Israel, Reinhardt et al. 2006), Alexandria (Egypt, Bernasconi et al. 2006), Leptis Magna (Libya, Pucci et al. 2011) or Yenikapı (Istanbul/Turkey, Bony et al. 2012). In Greece, palaeotsunami impact, for instance, affected the ancient harbour sites of Phalasarna (Crete, Pirazzoli et al. 1992), Palairos-Pogonia (Akarnania, Vött et al. 2011a), Pheia (western Peloponnese, Vött et al. 2011b), Krane (Cefalonia/Ionian Islands, Vött et al. 2012), Helike (Gulf of Corinth, Soter & Katsonopoulou 2011) or Lechaion (Gulf of Corinth, Hadler et al. 2013).

With regard to the tsunami hazard of the northwestern Peloponnese and to allow a reliable risk assessment and mitigation strategies, the main objectives of our study were (i) to establish a stratigraphical record for the Kyllini harbour site in order (ii) to decipher potential palaeo-tsunami impacts and (iii) to assess their effects on the ancient settlement as well as on the coastal evolution. Within the context of palaeotsunami impact, we additionally aimed at (iv) reconstructing the evolution of the harbour site through space and time and (iv) correlating geoarchaeological data on the harbour evolution with archaeological remains and historical reports.

2 *Natural setting and geoarchaeological background*

The Kyllini peninsula is the westernmost promontory of the entire Peloponnese (Maroukian et al. 2000). The hilly landscape of the area consists of alternating Pliocene marine, brackish and freshwater deposits that are uplifted by salt diapirism since the Miocene (IGME 1969, Kowalczyk & Winter 1979). The headland is connected to the mainland of the Peloponnese by the low-lying floodplains of the Peneios River, consisting of Holocene alluvial deposits (IGME 1969, Maroukian et al. 2000).

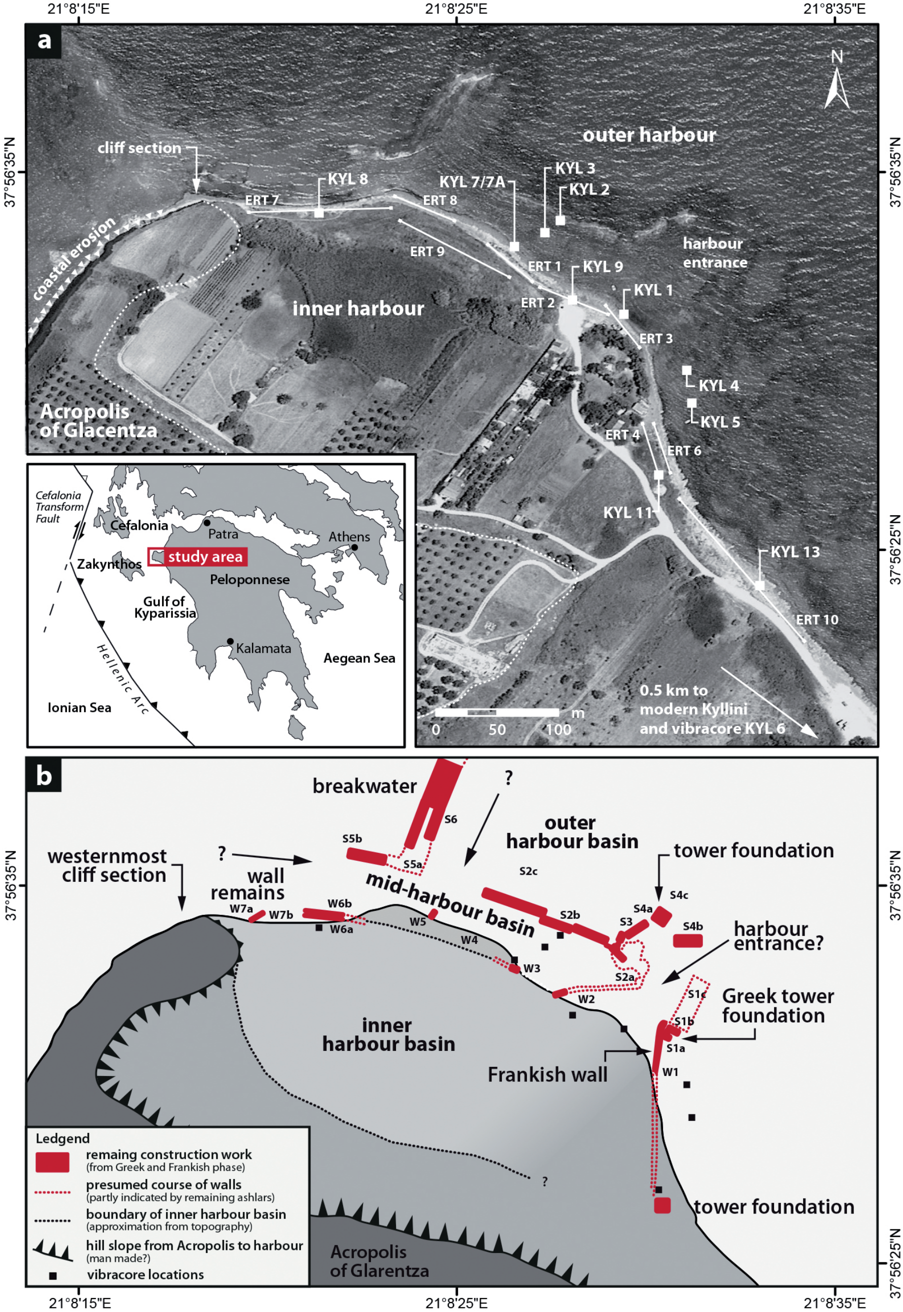

Fig. 1. Overview of the Kyllini harbour site including locations of vibracores and ERT transects (a) as well as archaeological remains of the Classical and Frankish harbour (b). The local topography provides sheltered conditions and makes the site a favourable anchorage. Maps modified after Google Earth, 2009 and Morgan, 2009.

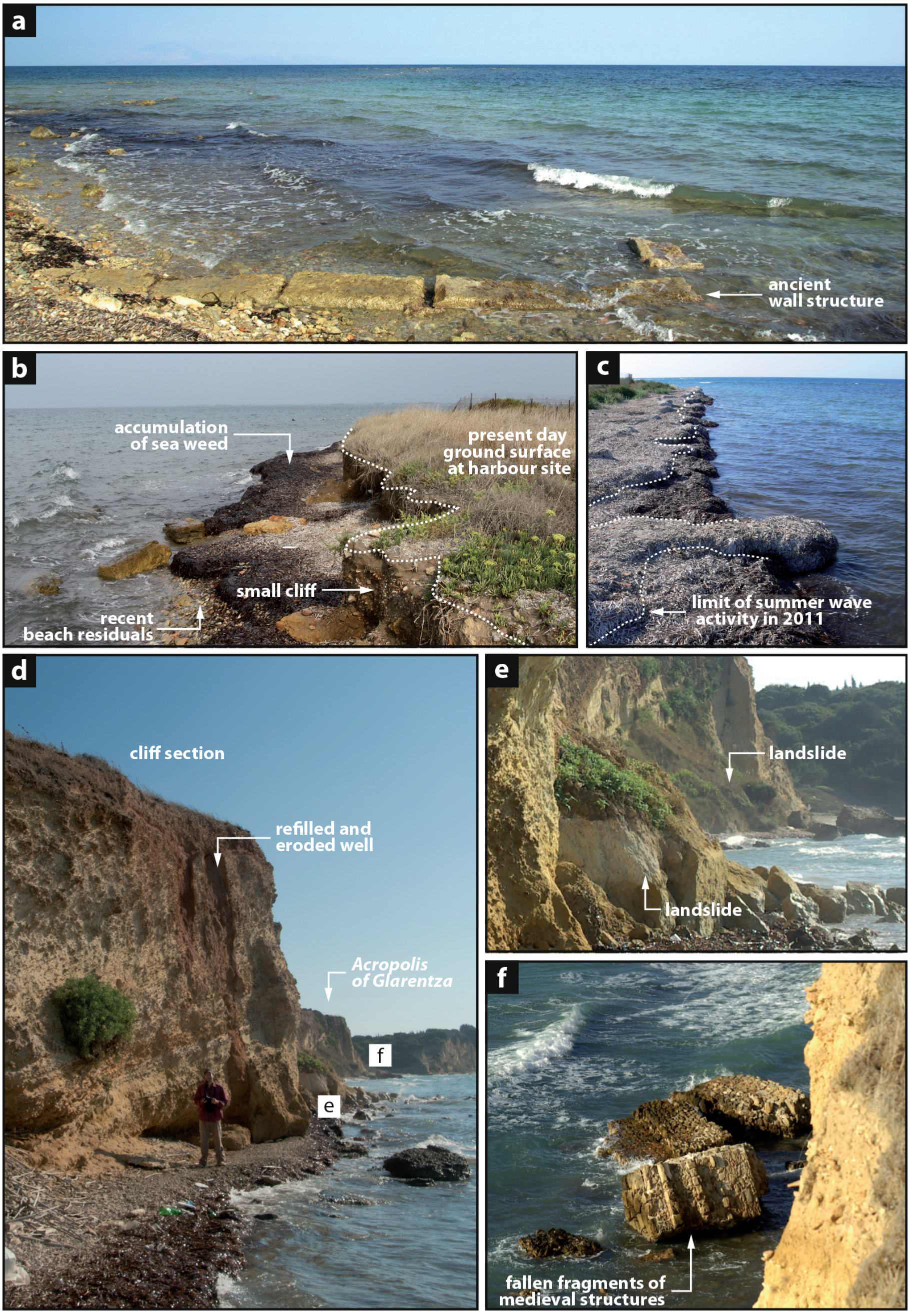

Fig. 2. Recent coastal dynamics at the Kyllini harbour site (a). Constant erosion has formed a small cliff (0.5–1.0 m high), that is mostly inactive during summertime (b). The annual accumulation of seaweed along the shores of Kyllini protects the harbour area from erosion (c). West of the harbour, the Kyllini peninsula is bound by a steep cliff coast (d). Strong erosion and rapid cliff retreat are visible from numerous landslides (e) which also affect the medieval fortress of Glarentza (f).

The ancient harbour of Kyllini is located at the northernmost point of the Kyllini Peninsula, directly adjacent to the modern village and harbour (Fig. 1). Remains of the medieval fortified settlement are located on top of the bedrock ridge to the southwest of the harbour. At several locations along the coastline, dune fields and beachrock-type consolidated sediments occur (IGME 1969). Especially during winter storms, the accumulation and erosion of seaweed leads to rapid changes in the coastal constellation. To the northwest of the harbour, high cliffs with narrow beaches face the Ionian Sea. Since dominating wave dynamics easily erode the poorly consolidated soft Pliocene rocks, the recent cliff retreat is fast and already affects the archaeological site, as documented by fallen wall fragments scattered at the foot of the cliff (Fig. 2d–f., Maroukian et al. 2000).

Due to the topographic constellation (Fig. 1), Kyllini has been a favourable strategic spot for a long time. While only few locations along the coastline of the western Peloponnese provide a sheltered anchorage for ships, the sheltered embayment at Kyllini offers both a well defendable settlement site and a protected harbour which, by archaeological and literary evidence has been used at least since the 5th century BC.

2.1 *Historical accounts on the Kyllini harbour site*

The Greek harbour of Kyllini belongs to the territory of Elis that was controlled by the powerful eponymous poleis. Among others, Elis held the sanctuary of Olympia and thus hosted the Olympic Games (Hansen & Nielsen 2004). The Greek and the Frankish Kyllini, named Glarentza, are well known from archaeological finds of coins that come from the Hellenistic to Roman and from the Medieval period, respectively (EBA 2005).

While *Κυλληνιον* is already mentioned in Homer's Iliad (Hom. 15.515 after Murray 1924), Thukydides is the first to report on the Classical harbour in the mid-5th cent. BC (Thuk. 1.30 after Landmann 2010). According to his descriptions, Kyllini was the main *επινειον* of Elis (engl. *epineion*, Thuk. after Jones & Powell 1942) used as a Spartan naval station, which implies that the harbour facilities were strongly fortified and may also have comprised shipshed complexes.

During Classical to Hellenistic times, the harbour maintains a significant strategic role, still being one of only few locations along the western Peloponnesian shoreline that *"affords ships a suitable anchorage"* (Strabo 8.3.4. after Jones 1927). As a consequence, Kyllini is quite often affected by military conflicts (e.g. Paus. 3.8.5 after Jones et al. 1918, Xen. 3.2.30 after Brownson 1921, Diod. Sic. 19.66.1/2, 19.87.3 after Geer 1954, Thuk. 2.84/86, 3.69 after Landmann 2010). As the major port for Elis, it must also be assumed that Kyllini served as a landing for a great number of spectators visiting the Olympic Games (Hansen & Nielsen 2004, FIA 2013).

In Roman times, historical accounts of Strabo and Pausanias still refer to Kyllini as *επινειον* – probably a naval station of Elis – but also note a considerable trading activity (Pausanias 6.26.4-5, 8.6.8 after Jones et al. 1918, e.g. Strabo 8.3.5 after Jones 1927).

Hereafter, not much is known about Kyllini until in the early 13th century AD, when the site came under Frankish possession and the castle of Glarentza was built (Traquair 1906/07, Bon 1969, Tzavara 2004). According to archaeological investigations, the harbour facilities were then partly re-established as demonstrated by Greek foundations below Frankish walls (Pakkanen et al. 2010). For about two centuries, Kyllini again was a flourishing harbour of major economic as well as strategic importance (Bon 1969, EBA 2005). At the beginning of the 15th cent. AD, however, Glarentza was repeatedly conquered (Traquair 1906/07, FIA 2013). In order to prevent it from falling into the enemy's hands again, the Byzantine emperor Constantinos Palaiologos ordered the slighting of Kyllini's fortification wall in 1431 AD (Sphrantzes after Phillipides 1980). Although the destruction of walls and towers probably also implies a destruction of the Frankish harbour facilities, historical accounts document on-going trading activity. However, without fortification the significance of Kyllini gradually declined towards the mid-15th AD century when it was replaced by the nearby and well-fortified fortress of Chlemoutsi (Schmitt 1995).

2.2 *Recent archaeological studies*

Recently, coastal and underwater investigations at the ancient harbour site of Kyllini are conducted within the Kyllene Harbour Project, carried out by the Finnish Institute at Athens in collaboration with the Department of Underwater Antiquities of the Hellenic Ministry of Culture (FIA 2013).

Archaeological remains that are still visible at the harbour site allow a rough visualisation of the ancient facilities (Fig. 3, Morgan 2008). From its basic structure, the harbour was separated into different basins. While the existence of an inner basin can merely be expected from the present-day topography and swamp-like conditions in the lowland embayed between the acropolis of Glarentza and the recent coastline (Fig. 3a), an outer harbour is well defined by remaining harbour installations. In the shallow water off the modern coastline, submerged walls, moles and tower foundations are well preserved (Fig. 3b–c). In the north-western harbour area, a massive mole runs perpendicular to the recent beach, while narrower structures that parallel the coastline form some kind of mid-harbour basin (Morgan 2009, FIA 2013). It seems, though, as if these walls separate the mid-basin from the inner harbour (Figs. 1 and 3e). No archaeological remains are visible in the central area of the inner harbour basin. Its maximum extension is merely defined by the rising terrain of the surrounding slopes. While the outer harbour is mostly submerged, the present day surface of the inner basin lies about 1 m a.s.l. (above sea level) along the present beach but slightly declines in landward direction.

The harbour basins were probably accessible by three different entrances (Fig. 1b), whereby only the northeastern entrance seems to be ascertained since it was secured by towers and additional walls, creating an entrance channel opening towards the inner basin (Morgan 2009). Assuming a mid-harbour basin, it is likely that further entrances existed to the north and/or the west.

Regarding the age of the archaeological remains, most visible structures date to the Frankish period and indicate a well-fortified harbour site during Medieval times (EBA 2005). Many facilities are, however, constructed on top of ancient Greek harbour remains. At the north-eastern harbour entrance for instance, a Frankish wall connects a polygonal Frankish tower (Fig. 3f), with an ancient Greek tower foundation (Fig. 1b, S1a), built-over by Frankish constructions (S1 b) (Morgan 2009, FIA 2013).

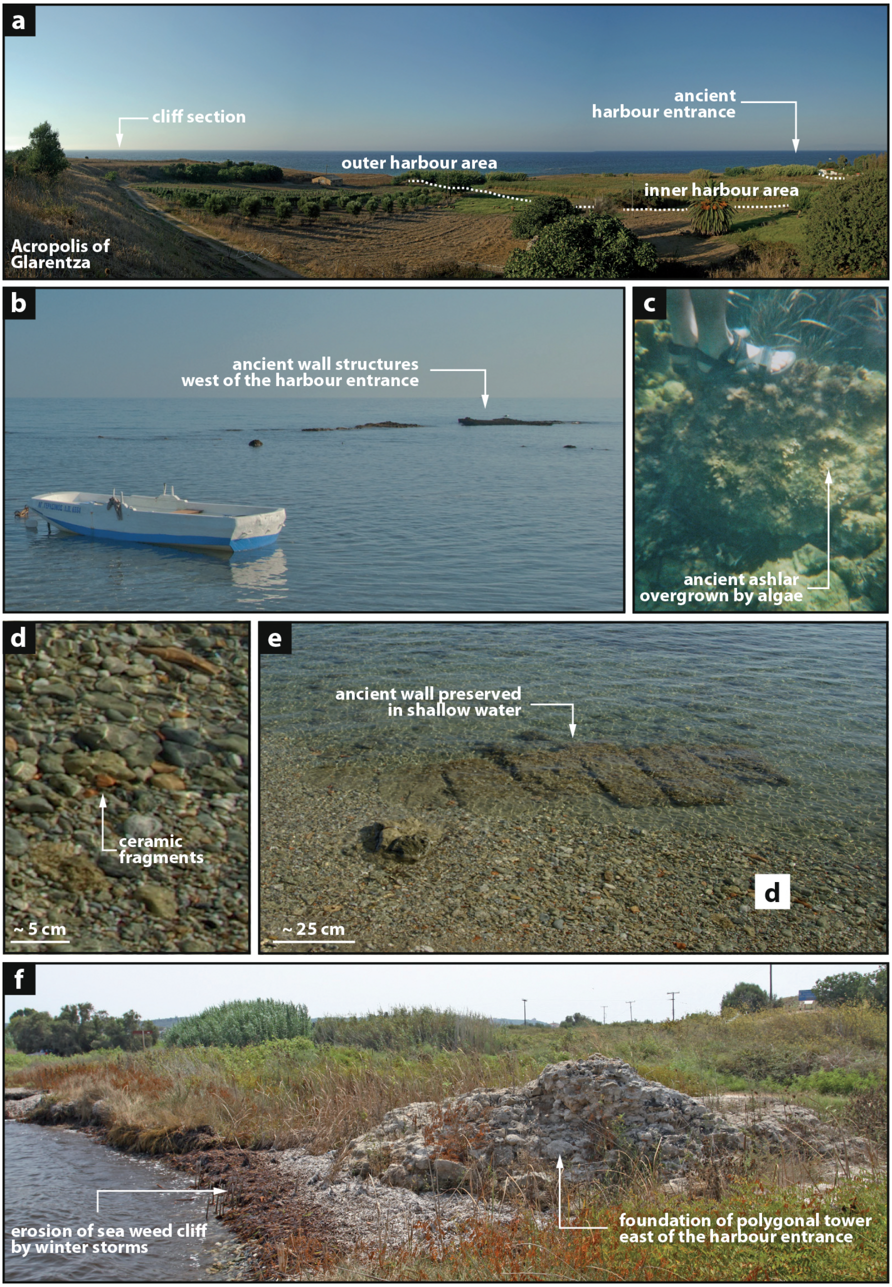

Fig. 3. Visible remains of the ancient Kyllini harbour site. Today, the inner harbour basin appears as coastal lowland (a), while remains of the outer harbour lie off the recent coastline in shallow water depth (b, c). Along the recent coastline, numerous ceramic fragments are incorporated to the gravely beach (d). Remaining walls that run in landward direction are covered by those beach deposits (e). The foundation of an polygonal tower marks the eastern fortification of the harbours that has equally been connected to the city wall (f).

3 *Methods*

This study is based on a multidisciplinary approach combining a broad variety of geo-scientific methods in the context of archaeological observations.

Field work

On-site geo-scientific studies are based on vibracoring using an Atlas Copco Cobra mk pro coring device with core diameters of 3 cm, 5 cm and 6 cm. In total, 11 vibracores with a maximum coring depth of 9 m below surface (m b.s.) were drilled along the recent coastline (beach), partly also in the shallow water of the outer harbour basin. Vibracores were photographed, described and sampled with regard to different stratigraphical units. The core description considers grain size, colour of sediment and content of calcium carbonate as well as macrofossil and plant remains, ceramic fragments and further sedimentological and pedological features (Ad-hoc-Arbeitsgruppe Boden 2005). Position and elevation data for each vibracoring site were measured using a Topcon HiPer Pro DGPS device (handheld type FC-200).

Laboratory analyses

Sediment samples were analysed for standard geochemical parameters such as pH-value, electrical conductivity, loss on ignition and content of calcium carbonate. Additionally, a handheld XRF spectrometer (type Niton XL3t 900s GOLDD, calibration mode SOIL) was used to determine a detailed geochemical profile for each stratigraphical unit. In order to eliminate potential influences of moisture, grain size or inhomogenities, sediment samples from vibracore KYL 7 A were dried, finely grounded using a ball mill and prepared in sample cups. To obtain mean values for element concentrations, samples were then measured three times for 30.5 sec with an average resolution of 5 cm. Magnetic susceptibility measurements were carried out by means of a Bartington Instruments MS3 Magnetic Susceptibility meter and a MS2 K Surface Sensor (24.5 mm^2 response area, 8 mm response depth). Samples were measured in situ for 1 sec and deviations were controlled by means of a standard sample.

Grain size analyses were conducted for selected vibracores in order to characterize the depositional environment of each stratigraphical unit. The proportion of each grain size fractions was determined.

Microfossil analyses were carried out for vibracore KYL 7 A to better distinguish between freshwater, brackish or marine environments. Sediment samples of 15 ml were extracted from each stratigraphical unit, partly pre-treated with H_2O_2 (3 %) and fractioned by wet-sieving (< 125 µm, 125–250 µm, 250–400 µm and > 400 µm). Foraminifera were then picked from residual sediments using a stereo microscope (type Nikon SMZ 745 T) and photo-documented using a light-polarizing microscope (type Nikon Eclipse 50 i POL with digital camera type Digital Sight DS-FI2). Photos were processed using the NIS Elements Basic Research 4 software. Finally, foraminifera were identified to group or – if possible – to species level. Identification is mainly based on Loeblich & Tappan (1988) and Cimerman & Langer (1991).

Dating approach

The local geochronostratigraphy is based on ^{14}C-AMS dating of plant remains or biogenic calcium carbonate. Radiocarbon dating was accomplished by the Leibniz-Laboratory for Radiometric Dating and Isotope Research, Christian-Albrechts-University, Kiel (KIA). Archaeological age determination of diagnostic ceramic fragments as well as architectural remains provided further data for the chronostratigraphy of the harbour evolution.

4 *Results*

4.1 *The stratigraphical record of the Kyllini harbour basin*

Along the recent coastline and in the area of the outer harbour basin, 6 vibracores were drilled (KYL 1–3, 7–9). Five additional cores were drilled along the south-east trending beach (KYL 4, 5, 11 and 13) and close to the modern settlement (KYL 6). In the following, we present detailed data of selected stratigraphical records retrieved from different vibracoring sites in the exterior of the main archaeological protection zone (for vibracore locations see Fig. 1). The sedimentary sequence of the Kyllini harbour site provides distinct evidence that the area has repeatedly been affected by the impact of high-energy wave events.

Vibracore KYL 8 (ground surface at 0.65 m above sea level [a.s.l.], N 37° 56′ 32.2″, E 21° 08′ 24.4″) was drilled in the western part of the harbour area, close to the uprising coastal cliff. As derived from the stratigraphical record, the vibracore – although located directly at the recent coastline – obviously represents the outermost seaward area of the inner harbour basin.

The basal unit of KYL 8 is dominated by partly lithified, sandy bedrock (6.00–4.78 m below ground surface [b.s.]). Subsequently, medium grey sand documents the establishment of marine conditions (4.78–3.74 m b.s.) associated with a shallow embayment. At the site of a nearby test core, marine deposits even reach down to 7.50 m b.s.

An increasing silt content at both coring sites indicates more quiescent conditions (KYL 8: 3.74–3.68 m b.s.). In the test core stratigraphy, a unit of homogeneous sand again documents marine influence associated to increased sedimentary dynamics. An abruptly following unit of light-grey, sandy to clayey silt indicates the establishment of a quiescent, probably limnic environment. The sharp basal contact of the unit documents a rapid closure of the marine embayment and a cut-off from shallow marine conditions. Subsequently, clayey-silty sediments including seaweed remains and marine macrofossils testify to the gradual transition to a lagoonal environment that corresponds well with the depositional conditions typical of harbour basins. At site KYL 8, a sharp contact also marks the abrupt onset of lagoonal conditions (3.68–2.94 m b.s.) subsequently to the quiescent marine environment. Plant and animal remains like olive pits, nutshells or pincers, as well as ceramic sherds or wooden plank fragments with attached calcified worm tubes were found incorporated into the lagoonal facies. A constantly growing amount of seaweed and increasing content of organic substance in the upper lagoonal unit documents the gradual siltation of the inner harbour basin (KYL 8: 2.94–2.70 m b.s.).

Following a sharp erosional contact, the quiescent harbour deposits are covered by coarse-grained marine sand (2.70–0.55 m b.s.) indicating a sudden environmental change towards high-energetic conditions. At the base of the sand unit, underlying lagoonal deposits were

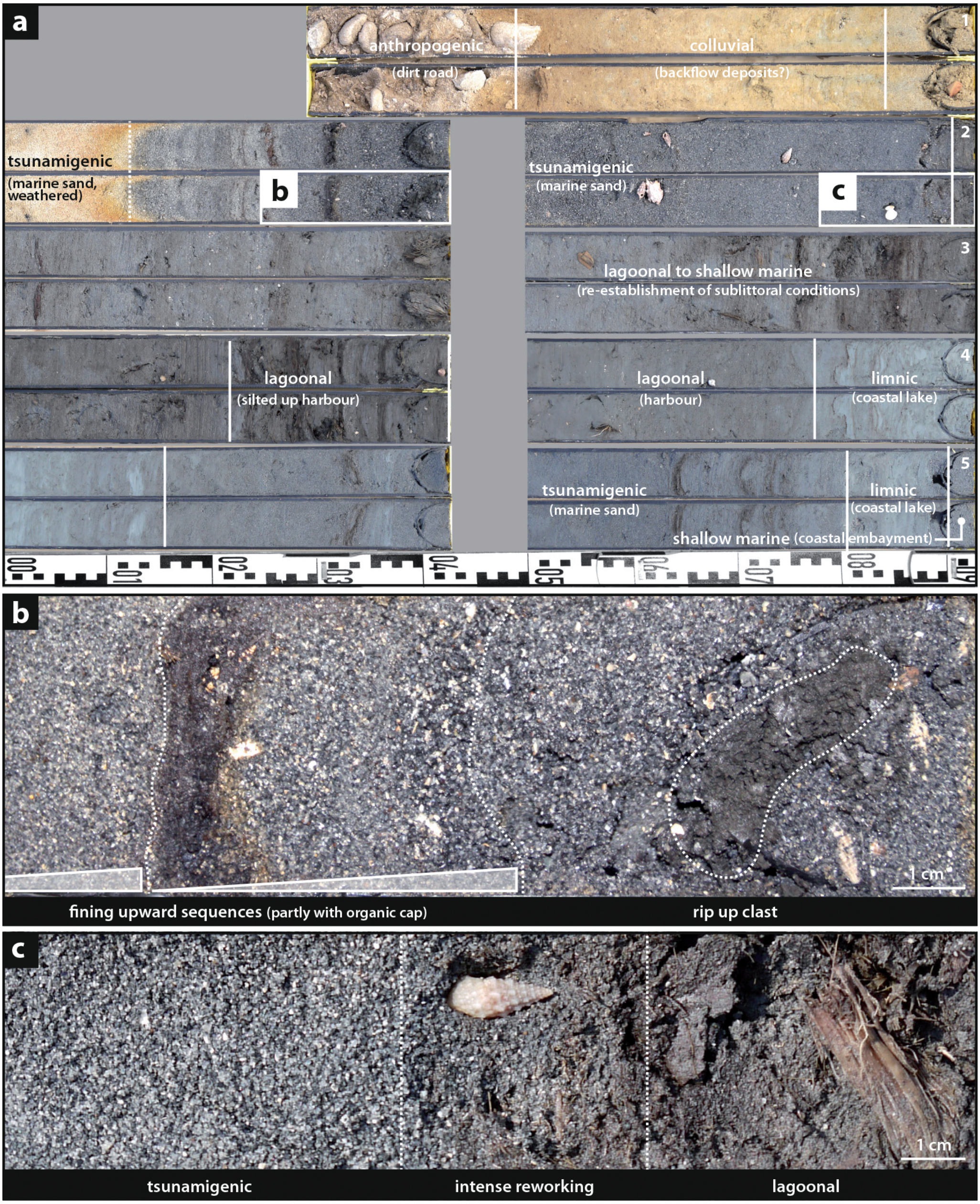

Fig. 4. Simplified facies profile of vibracore KYL 7 A drilled in the mid-harbour basin (a). The detailed view shows rip up clasts incorporated to the high-energy event deposit (b) by erosion of underlying shallow marine to lagoonal deposits (c). Multiple fining upward sequences document repeated inflow and subsequently decreasing flow velocities. Note that the lower two meters (5.00–7.00 m) are not depicted in the photo.

found strongly reworked partly appearing as rip up clasts. The entire unit incorporates numerous *Cerithium* sp. gastropods and shows a fining upward grain size distribution. Towards the top, the sand unit passes over to silt-dominated colluvial deposits (0.55–0.00 m b.s.).

Vibracores drilled within the submerged harbour area show a quite similar stratigraphical record. Here, stratigraphic details of core KYL 7/7 A (ground surface at 0.77 m a.s.l., N 37° 56′ 32.7″ E 21° 08′ 25.7″) are presented (Fig. 4a).

The base of core KYL 7/7 A is dominated by grey, fine to medium sand deposited in a shallow marine environment (7.00–4.88 m b.s.). Subsequently, light grey silt indicates the formation of quiescent conditions (4.93–4.80 m b.s.l.). This unit is, however, covered by alternating sequences of sand, clayey silt and organic material documenting a temporary and cyclic alternation of high- and low-energetic depositional conditions (4.80–4.16 m b.s.). On top of this sequence, light grey clayey to silty limnic deposits were found that indicate the rapid formation of a coastal lake (4.16–3.80 m b.s.), covered by lagoonal mud corresponding to harbour deposits (3.80–3.50 m b.s.). Towards the top, abundant seaweed and organic material indicates a short period of siltation (3.43–3.22 m b.s.). Then, silty sand with shell debris and seaweed document a gradual change from lagoonal back to low-energy shallow marine conditions (3.22–1.90 m b.s.). Subsequently follows, on top of an erosional contact (Fig. 4c) and following a thin shell debris layer (1.93–1.85 m b.s.), grey, medium to coarse marine sand including numerous specimens of *Cerithium* sp. (1.90–0.82 m b.s.). While the lower part of the unit is characterized by quite homogenous sand (1.85–1.57 m b.s.), the middle section contains rip up clasts and reveals repeated fining upward sequences (Fig. 4b) from coarse sand to organic rich layers (1.57–1.13 m b.s.). The sediment colour changes from grey to rust-coloured, thus indicating that the material was partly deposited above sea level (1.13–0.82 m b.s.). Successively, the sandy unit is covered by colluvial deposits (0.82–0.50 m b.s.). Gravel on top of the profile is assumed to be associated to a gravel road along the beach (0.50–0.31 m b.s.).

4.2 *Stratigraphical correlation of high-energy deposits*

Along vibracore transects A (Fig. 5) and B (Fig. 6), an event-stratigraphical approach allows to correlate high-energy event facies. According to the presented data, Kyllini was hit by at least two high-energy impacts.

A first event generation (I) affected the site prior to the foundation of the harbour site. At sites KYL 3 and KYL 7/7 A, autochthonous conditions were abruptly interfered by high-energy impact; multiple fining-upward sequences that consist of alternating layers of sand, silt, clay and organic substance were suddenly deposited in the quiescent environment documenting repeated rapid inflow of a sediment-loaded mass of water and a fast decline in flow velocity. Well-developed mud-caps (Fig. 4a) reflect short-term stagnation of the water prior to backflow. The underlying low-energy deposits have been reworked due to increasing flow dynamics.

All along transect A, the upper limit of the event layer is characterized by a sharp contact. Subsequent to event generation I, the former shallow marine embayment was abruptly disconnected from the open sea and transformed into a coastal lake. As major consequence for the Kyllini harbour site, the high-energy event-related reorganisation of the coastline obviously created the initial conditions that subsequently led to the foundation of the harbour.

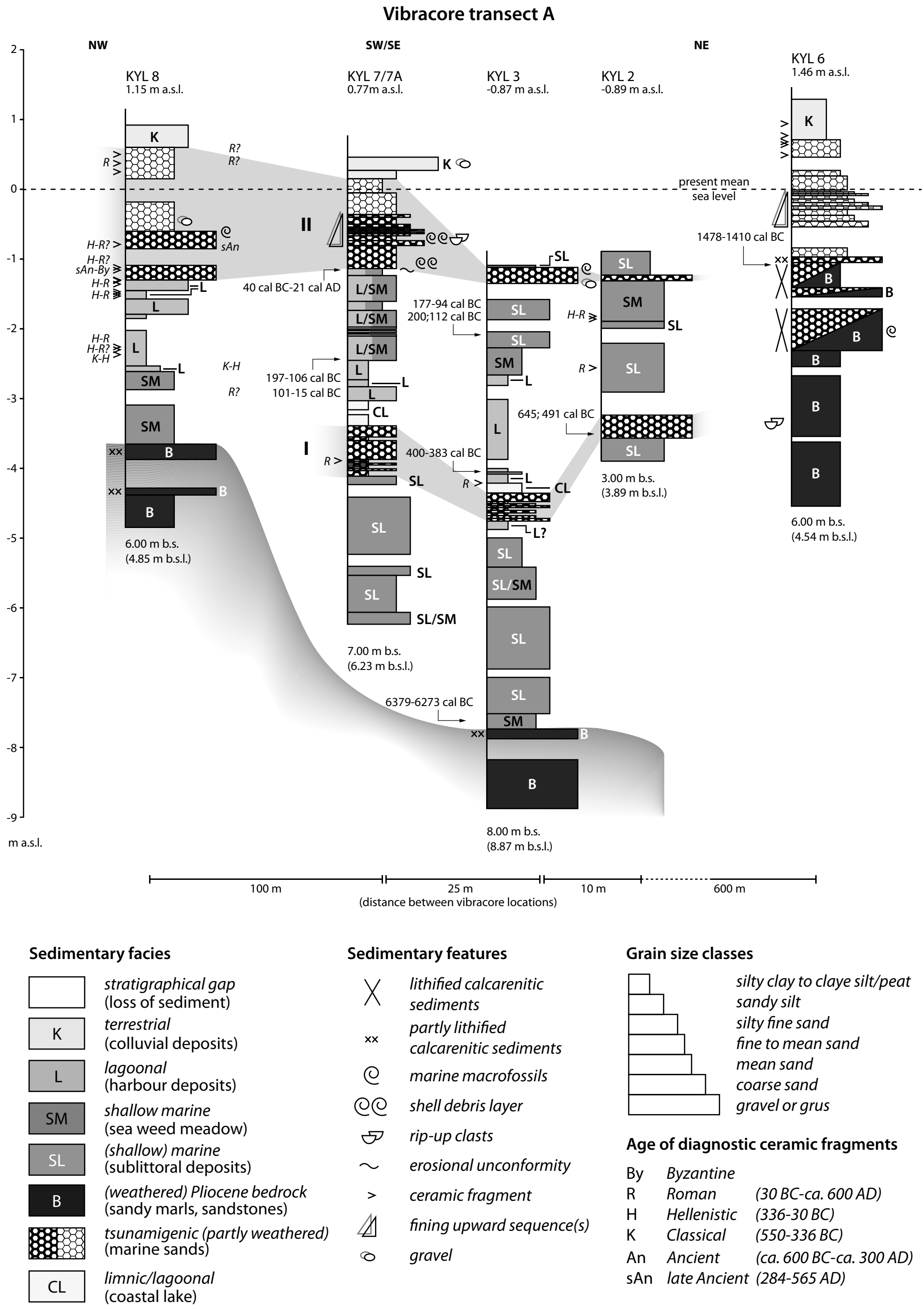

Fig. 5. Stratigraphies, facies distribution and geochronostratigraphy for vibracore transect A. For location of vibracores see Fig. 1. Details on radiocarbon ages are presented in Table 1.

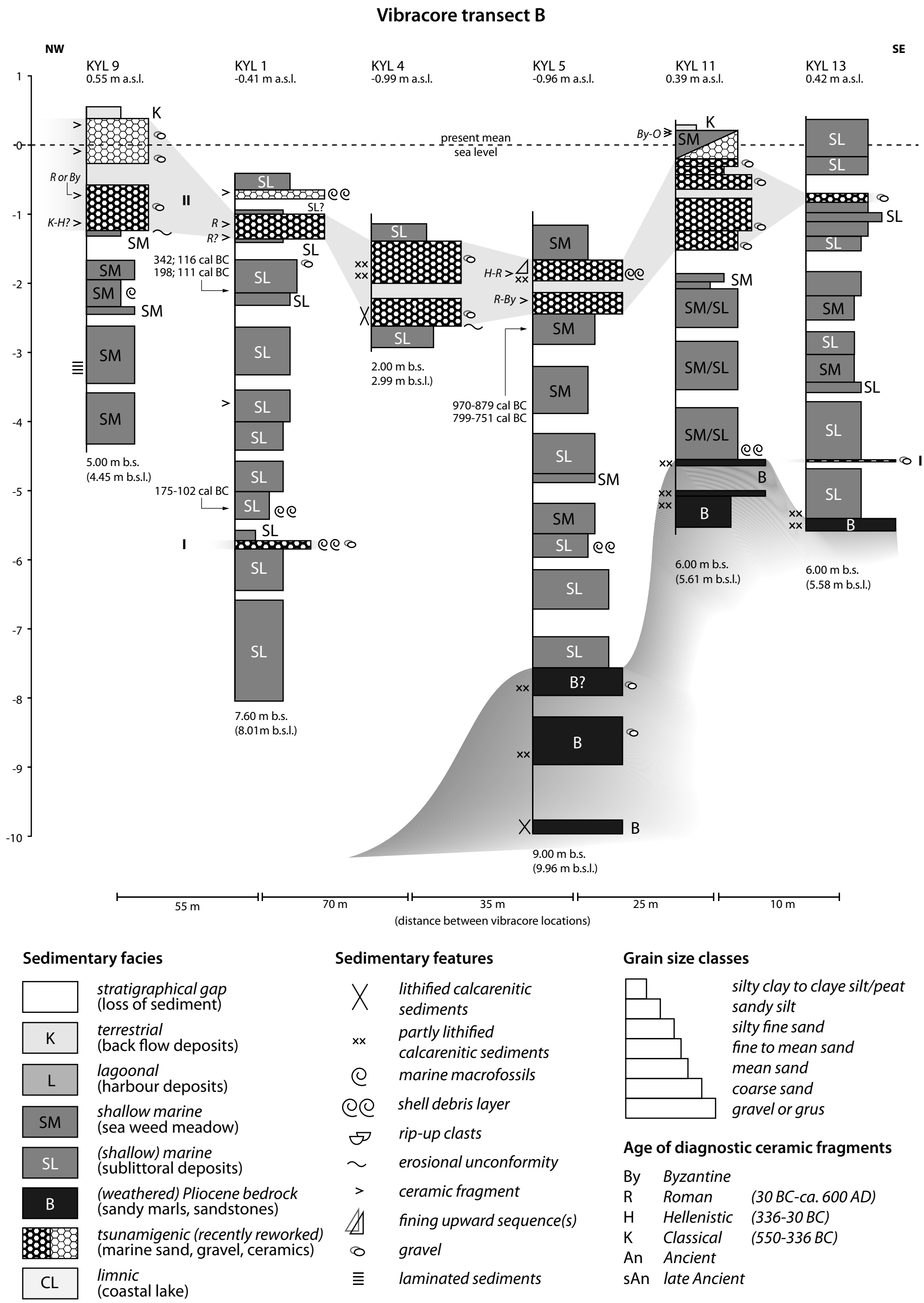

Fig. 6. Stratigraphies, facies distribution and geochronostratigraphy for vibracore transect B. For location of vibracores see Fig. 1. Details on radiocarbon ages are presented in Table 1.

The high-energy layer associated with event generation I is hardly traceable along vibracore transect B. Here, the event affected already more or less wave-dominated environments that impede the identification of event-related allochthonous sediments. Only vibracores KYL 9 and KYL 1 allow an event-stratigraphical correlation with transect A.

Across the entire Kyllini harbour site, the impact of a second high-energy event (II) is evident from the stratigraphical records. Along transect A, event generation II interferes semi-terrestrial conditions of the silted up inner harbour basin as well as shallow marine conditions in the seaward basin. For this younger high-energy impact, the sedimentary record at site KYL 7/7 A reveals a similar deposition pattern as the one found for event generation I. Low-energetic silty to sandy deposits associated with growing up seaweed meadows are unconformably overlain by a thick layer of marine sand, attesting an abrupt environmental change towards temporary high-energetic conditions. The upper limit of the autochthonous fine-grained deposits exhibits sedimentary features of strong erosion and significant reworking. At site KYL 7/7 A, a basal shell debris layer additionally marks the erosional contact. Following homogeneous sand, rip up clasts are embedded in the sediment (Fig. 4b). The overall content of marine macrofossil fragments is high, especially incorporating numerous specimens of *Cerithium vulgatum* that do not appear in the autochthonous shallow marine deposits. Since *C. vulgatum* prefers shallow water but sandy sediments (Poppe & Goto 1991), it can be assumed that the allochthonous deposits originate from the nearby offshore coastal area outside the harbour and were dislocated by high-energy wave impact. Alternating layers of fining upward sequences from coarse to fine sand and organic substance again indicate repeated inflow and subsequent stagnation of a sediment loaded mass of water. As the *επινειον* of Kyllini was fortified with massive walls and thus acted as a sediment trap, successive high-energy waves eventually "swashed" into the basin and led to sediment deposition. The remaining harbour facilities then prevented rapid water run off so that mud-caps and layers of organic substance were deposited and conserved. At sites KYL 2 and KYL 3, the deposits of event generation II are thin, which may either be explained by erosion due to recent wave action or by dredging activities.

Another sedimentary feature of event generation II is visible along transect A. High-energy event-related marine sediments were partly deposited above sea level and were subsequently subject to subaerial weathering as attested by the rusty sediment colour (see Fig. 4a, KYL 7A from 1.13 m b.s. onwards). As the geo-scientific data indicates, wide areas of the harbour basin were buried by these sediments.

Event generation II deposits were also recovered from vibracoring site KYL 6 (1.46 m a.s.l., N 37° 56′ 14.2″ E 21° 08′ 34.3″), drilled in the vicinity of modern Kyllini (Fig. 1a) some 600 m distant from the archaeological site. Here, the bedrock is, on top of an erosional unconformity, overlain by a high-energy event deposit including marine macrofossils and ceramic fragments. The upper part features multiple fining-upward sequences. The fact that the upper part of the event deposits are dark yellow to rust-coloured is explained by postdepositional subaerial weathering. Event generation II did thus not only affect the harbour site itself but also the surrounding coastal area.

Along transect B, event generation II is preserved as noticeable interference of the shallow marine environment. While autochthonous conditions are characterized by mean sand including seaweed, the event layer is characterized by abundant gravel, shell debris and ceramic

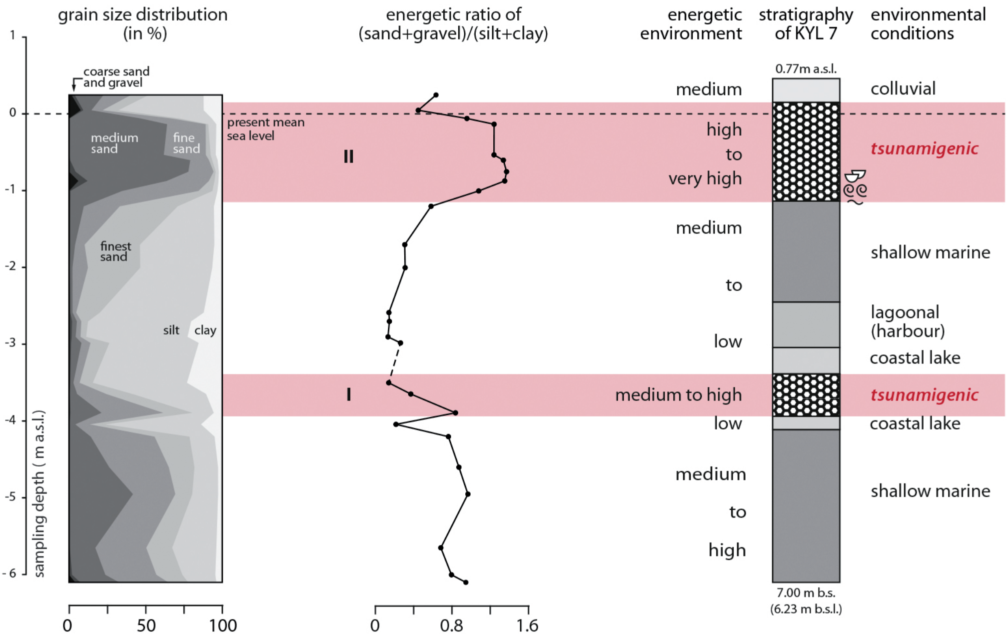

Fig. 7. Results of grain size analyses for samples from vibracore KYL 7. Event deposits are characterized by a sudden shift towards coarser grain sizes, while in situ deposits are mostly silt dominated. The energetic ratio emphasizes the abrupt increase in transport energy that goes along with both event layers.

fragments. For offshore vibracoring sites, a re-establishment of the former environmental conditions is observed (i.e. KYL 1, KYL 4, KYL 5). It remains unclear, though, whether marine conditions naturally recurred posterior to the event or are the result of modern coastal erosion.

4.3 *Multi-proxy analyses of high-energy event deposits*

Different palaeoenvironmental proxies provide significant information on the geochemical fingerprint of sedimentary facies as they help to distinguish between autochthonous and allochthonous sediments. In this study, different methods were applied to to verify high-energy impact to the Kyllini harbour site. Being a key site for both the harbour evolution and reconstruction of event-generations I and II, detailed multi-proxy analyses were carried out for sediments from vibracoring site KYL 7 A.

4.3.1 *Grain size analysis of vibracore KYL 7 A*

The grain size distribution of each facies is directly related to the energetic environment. As a gradual shift of different laterally associated depositional environments will inevitably results in an equally gradual vertical sequence, erosive events must be assumed where unconformities and abrupt alterations occur. Since low-energy marine embayments or harbour basins are characterized by fine-grained deposits (Marriner & Morhange et al. 2007), a high-energy input of allochthonous sediments is supposed to be well traceable in the stratigraphical record. The calculation of an energetic ratio for each facies additionally emphasizes abrupt changes (Willershäuser et al. 2013). Grain size data for vibracore KYL 7 is presented in Fig. 7.

Grain size distributions as well as the calculated energetic ratio of *(gravel+sand)/(silt+clay)* for KYL 7 provide evidence on gradual and abrupt changes of the palaeo-environment at the Kyllini harbour site (Fig. 7). Autochthonous sedimentation conditions of the pre-harbour, harbour and also post-harbour environment are characterized by fine grained sediments and thus show a rather low energetic index. On the contrary, coarse grained high-energy deposits show highest values for the energetic ratio, while the abrupt changes additionally emphasize the temporary character.

4.3.2 *Microfaunal analysis of vibracore KYL 7 A*

Due to their good preservation potential in the stratigraphical record, the analysis of foraminiferal assemblages in sediment samples provides a valuable tool to reconstruct the palaeo-environmental evolution of marine and coastal environments (Gupta 2002). However, rapid or catastrophic alterations of an ecosystem may strongly affect the foraminiferal community (Mamo et al. 2009). In coastal environments, single high-energy events like storm surges or tsunamis can already initiate considerable changes of the environmental conditions. Such events are quite often accompanied by a clear disturbance of the foraminiferal assemblage preserved in the stratigraphical record (e.g. Pilarczyk et al. 2012, Hadler et al. 2013).

With regard to the facies pattern of vibracore KYL 7 A, 29 sediment samples were analysed for their foraminiferal assemblages (Fig. 8). A total number of 75 species were identified according to Loeblich & Tappan (1988) and Cimerman & Langer (1991). Except for the upper weathered part of the profile, all foraminifera appeared to be of recent character.

At the shallow marine base of the profile, the foraminiferal assemblage is characterized by a medium to high diversity but low abundance. Dominating species comprise *Ammonia beccarii*, *Orbulina universa* and *Planorbulina mediterranensis*. The assemblage mirrors a near-coast shallow marine environment (Murray 1991, 2006). Living attached to vegetation, the occurrence of *P. mediterranensis* indicates the increased presence of *Posidonia* and therefore reflects more quiescent conditions. The planktonic *O. universa* reflects slightly increased water depths (Gupta 2002).

Planktonic foraminifera like *Lagena* sp. or *Fursenkonia* sp. found within the overlying marine sand require growing water depth. Moreover, *Quinqueloculina seminula* and also *Elphidium* sp., *Asterigerinata mamilla, Rosalina* sp., *Cibicides* sp. and *Massilina secans* emphasize the fully marine character (Murray 1973, 1991, 2006). Especially the incorporation of planktonic species that do not occur in the upper and lower facies indicates an allochthonous occurrence of sediments rather associated with adjacent seaward environments than a near-coast marine embayment.

Decreasing diversity and abundance of foraminifera mark the event-associated establishment of a quiescent water body. The foraminiferal distribution and the presence of saltwater-bearing species show that it is rather a pre-harbour lagoon, separated from open marine condi-

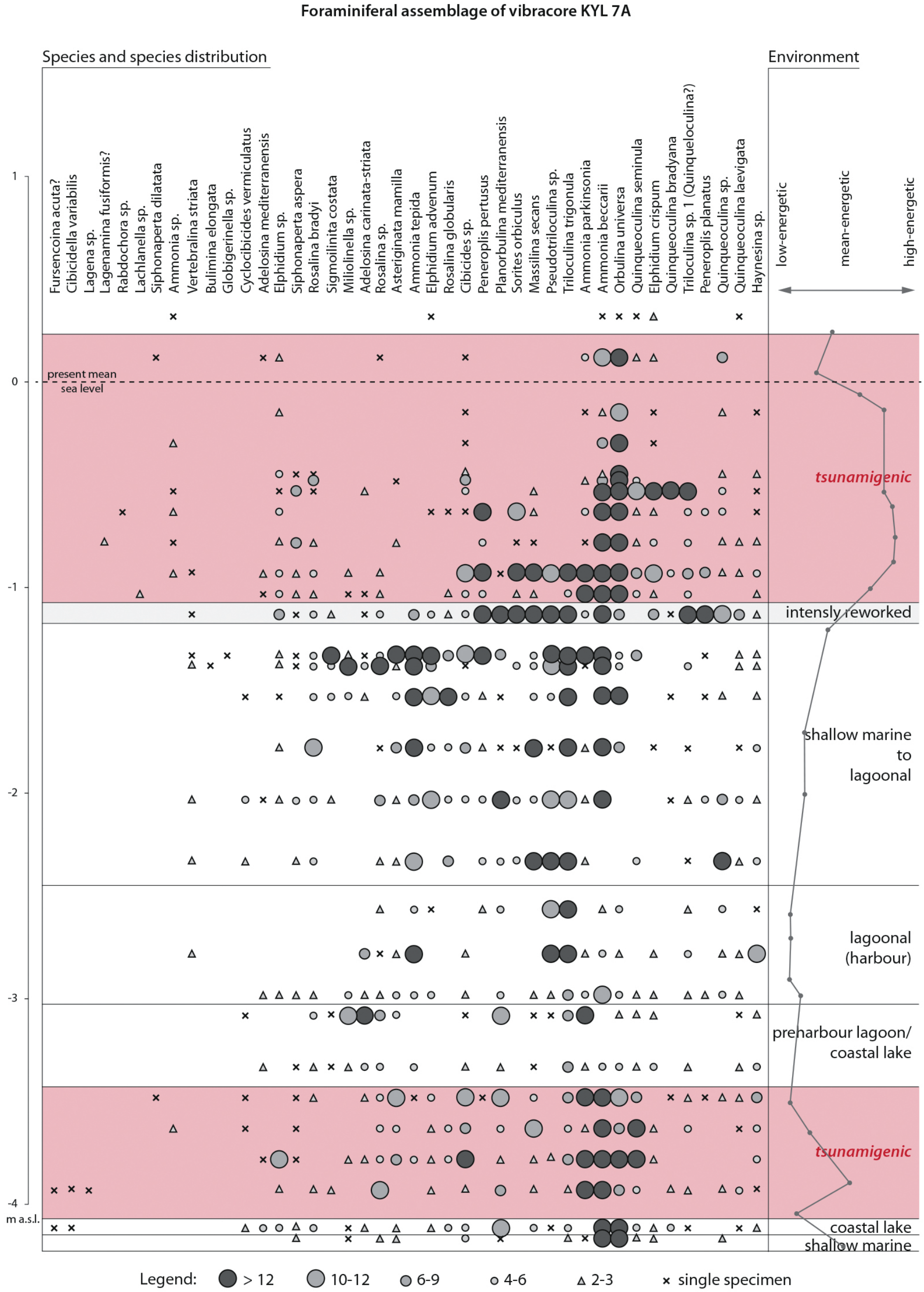

Fig. 8. Results of foraminiferal analyses of selected sediment samples from vibracore KYL 7 A. Some omnipresent specimens of *Adelosina* sp., *Ammonia* sp., *Bolovina* sp., *Brizalina* sp., *Bulimina* sp., *Cibicides* sp., *Cycloforina* sp., *Elphidium* sp., *Fissurina* sp., *Globigerina* sp., *Massilina* sp., *Milliolinella* sp., *Nonion* sp., *Polymorphina* sp., *Quinqueloculina* sp., *Rosalina* sp., *Sigmoilinita* sp., *Siphonaperta* sp., *Spirillina* sp., *Spiroloculina* sp. and *Triloculina* sp. are not regarded as decisively indicative and are not included in the figure.

tions, than a coastal lake. Dominating species are *Adelosina carinata-striata*, *Miliolinella sp.*, *A. parkinsonia* and *A. beccarii* as well as *P. mediterranesis*.

The subsequent harbour facies is marked by the sudden and rapid decrease in diversity. In the lower harbour facies, stress tolerant species like *A. tepida*, *Triloculina trigonula*, *Pseudotriloculina* sp. and *Haynesina* sp. represent about 2/3 of the total assemblage. While *Haynesina* sp. prefers brackish conditions, *A. tepida* also tolerates extreme environmental conditions like temperature changes, hypersaline or anoxic water that often occur in harbour basins (Gupta 2002, Marriner & Morhange 2007). In the upper part of the harbour facies, extreme conditions obviously intensify, as diversity and abundance of *A. tepida* and *Haynesina* sp. decrease. *Triloculina* sp., however, even tolerates hypersaline conditions (Murray 2006). Species associated with normal or shallow marine environments like *Rosalina bradyi* and *Elphidium crispum* are absent (Murray 1991).

Subsequently, microfossil assemblages document the re-establishment of shallow marine conditions. A sudden rise in the diversity is accompanied by the establishment of a shallow marine seaweed habitat. While *T. trigonula* still occurs in large numbers, the presence of *Quinqueloculina* sp. emphasizes the return of marine conditions. Abundant specimens of *Massilina secans* document prevailing shallow water conditions with a water depth of only a few meters (Murray 2006). *Bulimina marginata* documents rather quiescent conditions (Gupta 2002). Warm water planktonic species like *Peneroplis pertusus* or *Rosalina globularis* that browse around seaweed and algae also emphasize a near-shore environment dominated by seaweed meadows (Murray 1991, 2006). The assemblage further includes numerous foraminifera associated with Mediterranean seaweed habitats of slightly increased salinity, like *Asterigerinata mamilla*, *Elphidium advenum*, *Rosalina* sp., *Cibicides* sp., *P. mediterranensis*, *Vertebralina* sp. or *Cyclocibicides* sp. (Gupta 2002, Murray 2006). To the upper part of the facies, a high diversity and overall high abundance of species indicates a fully established marine habitat with stable palaeo-environmental conditions.

Towards the top of the shallow marine facies, a shift in the foraminiferal assemblage documents a sudden increase of sessile species like *Sorites orbiculus*, *Planorbulina mediterranensis* or *Peneroplis planatus* that cling to the leaves or rhizomes of *Posidonia* (Murray 1973, Gupta 2002). Together with sedimentary characteristics, the encountered foraminiferal assemblage thus proves the allochthonous sediment input from nearby shallow marine environments caused by strong overflow dynamics and intense reworking of the seafloor. Omnipresent species like *A. beccarii* or *T. trigonula* still persist.

The foraminiferal assemblage of the facies associated with event generation II provides further evidence for a marine-borne, high-energy impact to the study area as several significant breaks occur in the species distribution. The input of allochthonous sediments is among others marked by the sudden occurrence of *S. orbiculus* and *P. mediterranensis*.

According to Gupta (2002), *S. orbiculus* is generally immobile and attached to *Posidonia*. The species avoids high-energetic conditions and commonly occurs in shallow lagoonal environs (Murray 2006). As indicator for low-energy conditions, the high amount of *S. orbiculus* contradicts the coarse-grained sandy composition of the facies that reflects high-energy conditions. In the upper part of the event deposit, diversity is again low with dominating *A. beccarii* and *O. universa*. A re-appearance of several species associated with seaweed habitats within one sample is due to a layer of organic substance incorporated in the event deposit. Predominance of the planktonic *O. universa* may be related to slightly increased water depths. As the species is predominant, the allochthonous sediments may originate in nearby deeper marine environments. Strong pyritization effects indicate a post-depositional alteration under anoxic conditions. Towards the top of the unit, the total amount of foraminifera strongly declines due to the constant weathering of the deposit.

In a summary view, the assignment of specific foraminiferal species to distinct palaeoenvironments additionally allowed estimating the source areas for event-displaced deposits. Results for both event layers point to a dislocation of sediments from nearby offshore environments and thus indicate short transport distances. It must be emphasized, that the foraminiferal spectra of event-related facies do not necessarily comprise "exotic" species from distal or deep water environments as commonly proposed (e.g. Mamo et al. 2009) but rather reflect the dislocation of reworked sediments from adjacent areas.

4.3.3 *XRF measurements*

As different environmental factors are related to specific chemical components, different sedimentary facies hold characteristic geochemical profiles depending on the local conditions at the time of sediment deposition.

Terrestrial settings are basically influenced by weathering and pedogenic processes so that the concentrations of elements like Fe or Ti are increased, while Ca is affected by rapid dissipation. Marine environs are, on the contrary, influenced by the production of calcium carbonate ($CaCO_3$) by marine organisms (e.g. molluscs, gastropods, foraminifera) so that marine sediments are generally enriched in calcium (Ca). Lagoonal sediments reveal terrestrial as well as marine characteristics and indicators of eutrophication such as the content of sodium (K), related to a high content of clay minerals in lagoonal deposits (Albarède 2009). Since major marine flooding events are often accompanied by a significant landward dislocation of sediments, allochthonous high-energy deposits may leave a distinct geochemical fingerprint in the stratigraphical record of the respective geo-archive (Vött et al. 2011a, 2011b).

Selected element concentrations measured for vibracore KYL 7 A are illustrated in Fig. 9. Autochthonous shallow marine sediments are characterized by medium Ca concentrations and low contents of Fe, Ti and K, whereas autochthonous limnic/lagoonal deposits show inverse concentrations. At the transition from a natural coastal lake to lagoonal environment, the temporary inversion probably marks the opening of the coastal lake during harbour construction. Harbour sediments are characterized by maximum Fe, K and Pb concentrations and a comparatively low Ca content. In Kyllini, the strong Pb increase marks the transition of a natural coastal lake into an artificial harbour basin; once abandoned, shallow marine conditions were re-established and the Pb values decrease. Following the harbour facies, the geochemical signature documents a transition back to shallow marine condition. While terrestrial indicators constantly decline, the increasing marine influence is accompanied by slightly increasing Ca values.

Event generations I and II are clearly distinguishable by their significant geochemical record. Event generation I reflects a geochemical fingerprint, already described for the shallow

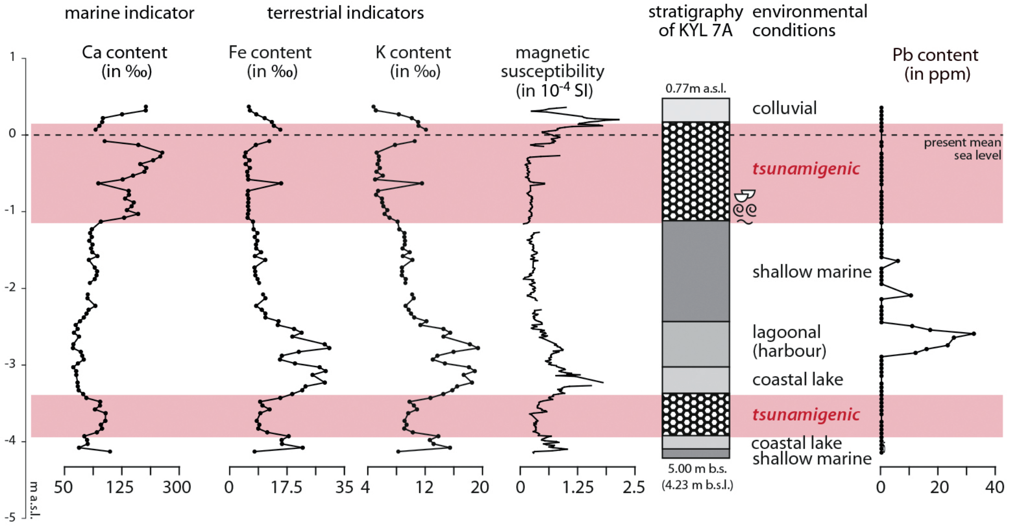

Fig. 9. Results of XRF analyses and magnetic susceptibility measurements for vibracore KYL 7 A. While autochthonous facies document near-shore, quiescent environmental conditions (Fe, K, Ti), allochthonous deposits show a marine fingerprint (Ca). Harbour deposits are detectible by increased Pb values due to anthropogenic influences on the ecosystem.

marine environment at the very base of the profile as event deposits originate from the nearby coastal zone. The geochemical signature of event generation II is characterized by maximum Ca concentrations, while terrestrial indicators (especially Ti) are reduced to low concentrations. At 0.63 m b.s.l., increased geochemical parameters link a rip-up clast to the underlying lagoonal to shallow marine facies. In the upper part of the profile the geochemical signature documents constant weathering due to sediment deposition above sea level. Since vibracoring site KYL 7 A is located directly adjacent to the recent coastline, the uppermost facies is geochemically influenced by spray water due to marine wave dynamics.

4.3.4 *Magnetic susceptibility*

Magnetic susceptibility allows assigning another geochemical fingerprint to different sedimentary facies. Weathered terrestrial or lagoonal deposits usually bear a high magnetisability, while marine sediments are generally enriched in diamagnetic components like quartz sand or calcium carbonate (Dearing 1999).

For the stratigraphical record of vibracore KYL 7 A, the magnetic susceptibility reaches maximum values where quiescent depositional conditions are predominant (Fig. 9). High values are associated with coastal lake, lagoonal and harbour facies. This is mostly due to the high content of Fe-rich clay minerals and magnetic minerals originating from terrigenous weathering. On the contrary, marine facies are characterized by low susceptibility values.

Intersecting coastal lake deposits, event generation I is marked by contrasting low values. Covering a shallow marine facies, event generation II deposits are not well discernible in the

Table 1. Radiocarbon dates of samples from the outer Kyllini harbor site. Note: b.s – below ground surface; b.s.l. – below sea level; Lab.No. – laboratory number; KIA – Leibniz-Laboratory for Radiometric Dating and Isotope Research, Christian-Albrechts-University, Kiel; 1 σ max;min (cal BP, cal BC/AD) – calibrated ages, 1 σ range; ";" – there are several possible ages intervals due to multiple intersection with the calibration curve; * – marine reservoir correction with 408 years of reservoir age; a – comparative measurement of second prepared sample portion; b – significant age differences of > 2 σ between original and comparative measurement; c – δ13 value indicates aquatic plant remain. Calibration based on Calib 6.0 software (Reimer et al. 2009).

Sample	Depth (m b.s.)	Depth (m b.s.l.)	Sample description	Lab. No. (KIA)	$\delta^{13}C$ (ppm)	^{14}C Age (BP)	1 σ max; min (cal BP)	1 σ max; min (cal Bc/AD))
KYL 1/12+ PR	1.70	2.11	unident. plant remain	45997-1	−22.03 ± 0.11	2140 ± 25	2292; 2066	342; 116 BC
KYL 1/12+ PR[a]	1.70	2.11	unident. plant remain	45997-2	−21.69 ± 0.19	2125 ± 25	2148; 2061	198; 111 BC
KYL 1/17+ PR	4.85	5.26	unident. plant remain	45998	−2.680 ± 0.14	2110 ± 20	2125–2052	175–102 BC
KYL 2/8 PR	2.54	3.43	sea weed	45999	−15.52 ± 0.15[c]	2775 ± 25	2595; 2441	645; 491 BC*
KYL 3/4 HR	1.33	2.20	wood fragment	46000-1	−25.04 ± 0.11	2110 ± 25	2127–2044	177–94 BC
KYL 3/4 HR[a]	1.33	2.20	wood fragment	46000-2	−24.25 ± 0.20	2130 ± 25	2150; 2062	200; 112 BC
KYL 3/10 HR	3.29	4.16	wood fragment	46001	−30.41 ± 0.16	2210 ± 25	2350–2333	400–383 BC
KYL 3/20+ PR	6.86	7.73	unident. plant remain	46002	−15.20 ± 0.10[c]	7805 ± 40	8329–8223	6379–6273 BC*
KYL 5/5	1.625	2.585	sea weed	46003-1	−14.40 ± 0.09[c]	3100 ± 25	2920–2829	970–879 BC*
KYL 5/5[a]	1.625	2.585	sea weed	46003-2	−13.15 ± 0.27[c]	2945 ± 30[b]	2749–2701	799–751 BC*
KYL 6/13+ PR	2.545	1.085	sea weed	46004	−16.56 ± 0.21[c]	3510 ± 25	3428–3360	1478–1410 BC*
KYL 7/10 PR	1.98	1.21	wood/bone fragment	46005	−27.10 ± 0.11	2005 ± 25	1990–1929	40 BC –21 AD
KYL 7/12 PR	3.325	2.555	sea weed	46006-1	−14.43 ± 0.12[c]	2460 ± 25	2147–2056	197–106 BC*
KYL 7/10 PR[a]	3.325	2.555	sea weed	46006-2	−14.36 ± 0.17[c]	2380 ± 20[b]	2051–1965	101–15 BC*

magnetic susceptibility curve. Maximum values were only obtained for weathered high-energy deposits and covering colluvisol material.

4.4 *Dating approach*

In order to establish a local event-geochronostratigraphy, 14 radiocarbon ages retrieved from six different vibracore locations are presented in this paper (Table 1). Non-marine plant material was preferred for dating, since the unknown spatio-temporal variability of the local marine reservoir effect still leads to considerable age deviations for marine samples).

Dating samples were taken in maximal approximation to the upper and/or lower stratigraphical contacts. Samples taken from high-energy deposits merely provide a *terminus ad* or *post quem* (maximum age) for the event. If material for dating is retrieved beneath an erosive contact, the sample also yields a *terminus post quem* but the temporal dimension of the erosional hiatus remains unknown.

About half of the samples taken for radiocarbon dating consist of seaweed remains (KYL 2/8 PR, KYL 5/5, KYL 6/13+ PR, KYL 7/12 PR). The unidentified plant remains of samples KYL 3/20+ PR must also be considered as seaweed since plant material from marine aquatic environments exhibits much smaller $\delta^{13}C$ values than known from terrestrial plants (Geyh 2005). For samples that feature marine $\delta^{13}C$ values, a marine reservoir effect was taken into account. Due to the fact that the influence of spatial variations of the sedimentary environment or temporal variabilites of carbonate exchange on the marine reservoir age are still unknown, reservoir ages given in recent databases do only mirror local conditions for a specific time and are thus not transferable to other regions. Therefore, an average marine reservoir age of 408 years was used to calculate calendar ages using the Calib 6.0 software (Hughen et al. 2004, Reimer et al. 2004).

According to Wagner (2010) and Geyh (2005), reservoir effects for samples from C3 land plants, especially wood or charcoal, are negligible. $\delta^{13}C$ values obtained for samples KYL 1/12+PR and KYL 1/17+PR are typical of C3 land plants and therefore indicate a terrestrial origin. Samples KYL 3/4 HR, KYL 3/10 HR and KYL 7/10 PR also provide reliable ages for they comprised macroscopic wood fragments, as approved by the respective $\delta^{13}C$ values. For samples KYL 1/12+PR, KYL 3/4 HR, KYL 5/5 and KYL 7/12 PR, additional radiocarbon ages have been retrieved from comparative measurements of a second prepared portion of the same sample. While samples KYL 1/12+PR[a] and KYL 3/4 HR[a] provide consistent dating results within the fault tolerance, there are significant age differences (> 2 σ) between the original and comparative measurement concerning samples KYL 5/5[a] and KYL 7/12 PR[a].

Across the Kyllini harbour site, 38 ceramic fragments were recovered from 10 different vibracores (Fig. 10). 29 diagnostic sherds were ascribed to historical periods. The majority of ceramic finds date to Hellenistic to Roman times which fits well with the early phase of harbour usage.

4.5 *Geoarchaeological evidence of high-energy impact*

The coast to the west of the Kyllini harbour site is characterized by a cliff, up to 4 m high. Event generation II deposits can be followed from the assumed harbour entrance over 250 m

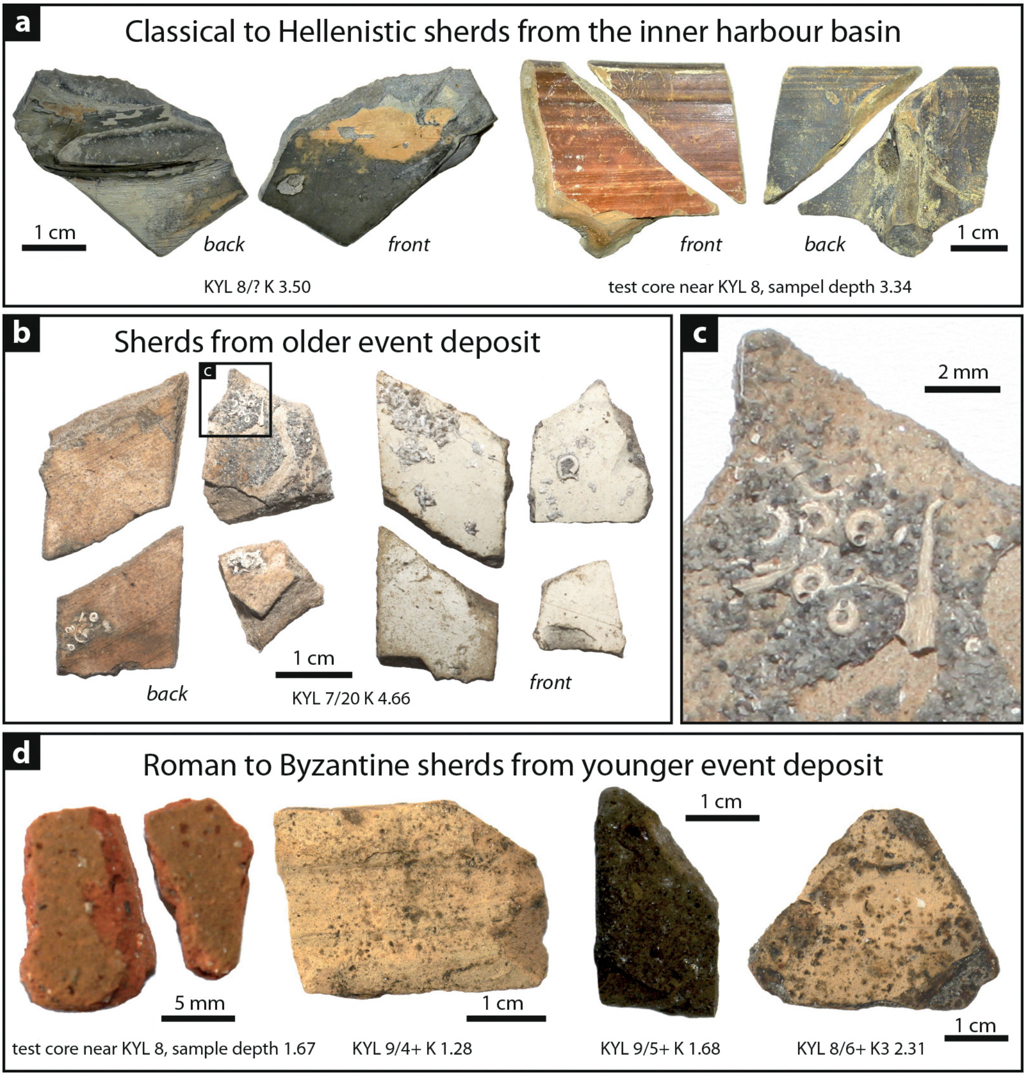

Fig. 10. Ceramic fragments encountered at the Kyllini harbour site. Classical to Hellenistic sherds provide evidence of a 5th cent. BC foundation of the harbour (a). Sherds incorporated to the older event deposit (b, c). Roman to Byzantine sherds from the 4th –6th cent. AD provide a terminus post quem for the younger tsunami generation.

towards the west on higher ground up to 1 m a.s.l., showing a thickness between 0.1 m and 1.5 m (Fig. 11a). At different outcrops, the sedimentary characteristics prove the high-energy character of the layer.

i. Well rounded gravel components, mixed with abundant angular ceramic fragments, numerous marine macrofossils and many bone fragments are incorporated into a silty to sandy matrix (Fig. 11b). In places, the deposit contains large ashlars possibly originating

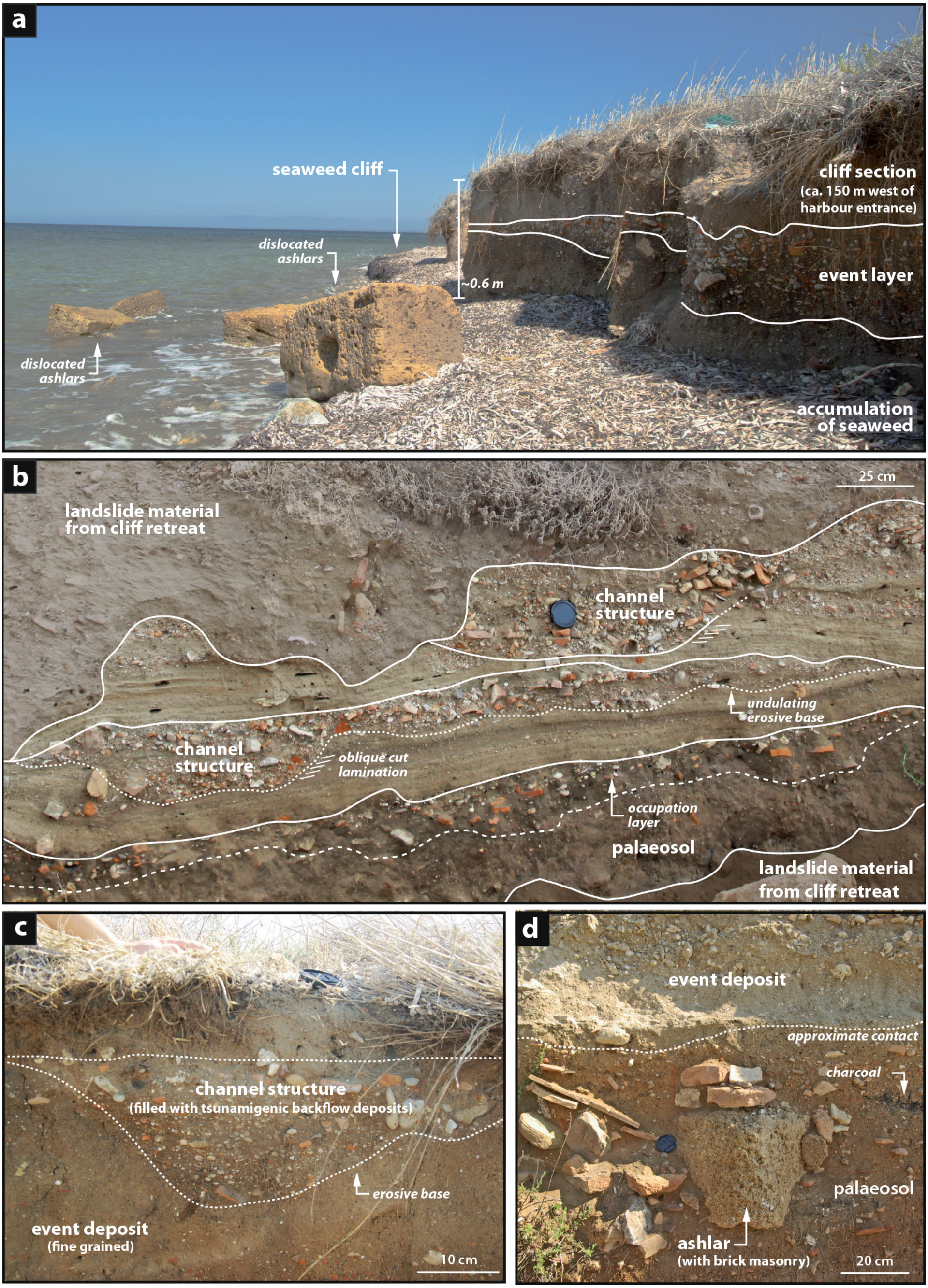

Fig. 11. Cliff section with geoarchaeological destruction layer to the west of the harbour entrance (a). In the westernmost part of the harbour, the layer overlies a palaeosol and occupation layer (b) with foundation remains (d). Sedimentary characteristics comprise lamination and fining upward-sequences (b). Seaward orientated channel structures are incised in the destruction layer. The channel fill comprises a mixture of terrestrial and marine deposits, including gravel, ceramic fragments and marine molluscs (b, c).

from the old harbour installations. Since there is no river or creek discharging in the study area, a fluvial deposition of the well rounded gravel must be excluded, while the high content of marine macrofossils documents a sea-born origin of the deposit. The massive occurrence of sherds and bones, however, indicates a major terrestrial component. Since the deposit obviously derives from diametrically opposed sedimentary environments, the site must have been affected by high-energy transenvironmental geomorphodynamics.

ii. The overall multimodal grain size distribution of the event deposit implies the simultaneous transport and deposition of coarse- and fine-grained components for instance by sheet floods or mud flows, generally characterized by a water-saturated matrix. Angular-shaped ceramic fragments and numerous well-preserved marine macrofossils additionally point to a short transport distance and rapid deposition, as long-term littoral processes would have rounded sherds and destroyed or abraded macrofossils.

iii. In places, channel-like structures can be seen incised at right angles to the cliff, thus being orientated in seaward direction (Fig. 11c). The channel-infill out of larger ceramic fragments as well as gravel components is horizontally adjusted resulting from a high level of water saturation during transportation and strong flow dynamics.

iv. Multiple sandy sequences sharply overlie a palaeosol and occupation layer. The sediments show a laminated structure with fining upward cycles from sand to clay and include abundant shell debris and intraclasts. Within the sandy layer, channel structures with undulating bases are incised and filled with gravel, ceramic sherds, marine molluscs and bones (Fig. 11b). The top of the lower channel is covered by sand documenting repeated and cyclic widespread sedimentation (laminated sand layer) and linear erosion (channel structure). In the vicinity, the layer covers the remains of a wall foundation (Fig. 11d).

Along the Kyllini harbour site, strong winter storms lead to constant erosion of the coastal cliff. Consequently, all-day coastal dynamics cause considerable reworking of the event deposits incorporated in the cliff. As a result, coarse components like gravel or stones (up to 0.3 m in diameter) and also large ceramic fragments accumulate along the beach. In some places, however, these deposits including ceramic fragments and abundant gravel are cemented by a carbonate matrix and exposed in the form of widespread beachrock-type conglomeratic slabs (Fig. 12a). Where cliff retreat continues, beachrock slabs break down and are embedded in the present-day littoral deposits (Fig. 12b–c).

5 *Discussion*

5.1 *Sedimentary, geochemical and microfaunal evidence of tsunami impact*

For the Kyllini harbour site, detailed geo-scientific studies based on multi-proxy analyses document repeated high-energy impacts that seem to have influenced the history of the harbour. The following geomorphological and geoarchaeological traces as well as detailed geo-scientific multi-proxy evidence reflect repeated tsunami events.

i. Pre-existing low-energy environments were repeatedly interrupted by the input of coarse-grained allochthonous deposits that exceed the prevailing energetic potential and document high-energy impact. Basal erosional unconformities and rip-up clasts of eroded underlying

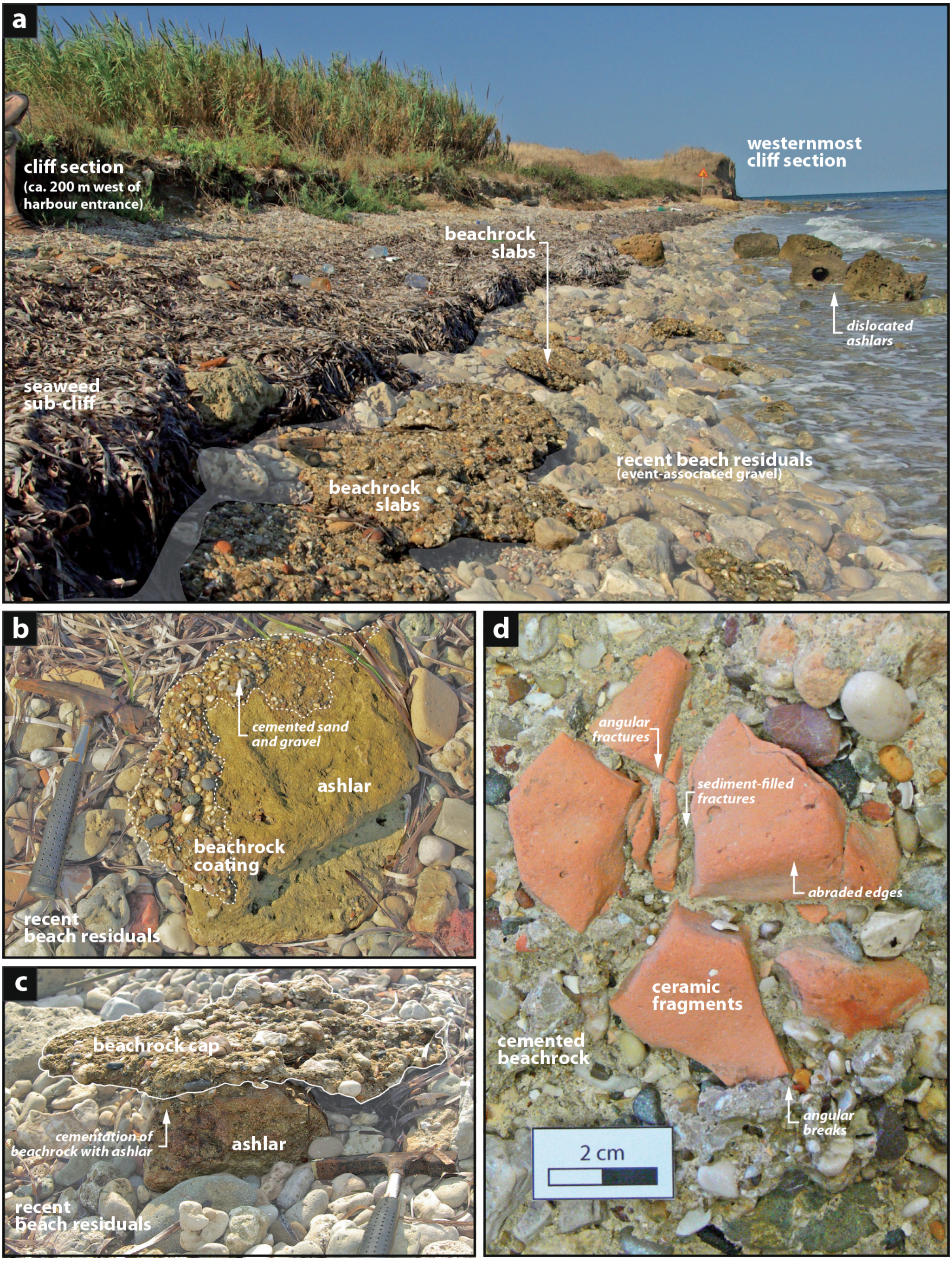

Fig. 12. Beachrock deposits at the Kyllini harbour site. Where the geoarchaeological destruction layer has been calcified posterior to deposition, calcarenitic beachrock-type slabs are exposed along the beach due to constant coastal erosion (a). Large ashlars that are incorporated into the beachrock slabs indicate high-energy deposition (b,c). Angular ceramic fragments with sediment-filled cracks in between document that destruction and deposition of the sherd were coincident (d).

deposits indicate that the event was of abrupt temporary and high-energy character. Several fining upward sequences from sand to silt with mud caps, partially being eroded, document repeated inflow, subsequent stagnation and backflow of water masses. The different sedimentary structures observed for tsunami-associated deposits in the study area have also been found for recent tsunami sediments (e.g. Gelfenbaum & Jaffe 2003, Bahlburg & Weiss 2007, Chague-Goff et al. 2011).

ii. Depending on the local topography, recent tsunami deposits are often deposited with a far landward extent and associated sediments frequently overly the pre-tsunami surface with an erosional basal contact (e.g. Goto et al. 2011, Mori et al. 2011). Comparable sharp contacts at the base of event layers were found at the Kyllini harbour site where – on top of an erosive contact – quiescent harbour deposits are covered by a massive allochthonous sand layer.

iii. Tsunamis may cause major changes to established coastal constellations (Richmond et al. 2012). For example, tsunami waves are well capable of breaching coastal barriers and inundate lagoonal systems (e.g. Donato et al. 2008). In case of the 2011 Japan tsunami, breaching of a coastal barrier was associated with massive scouring on the landward side causing the establishment of a coastal lake (Tanaka et al. 2012). At Kyllini, the high-energy impacts are associated with sudden environmental changes, e.g. transitions from marine to lagoonal/limnic conditions or vice versa.

iv. Geochemical and microfaunal data document the input of allochthonous marine deposits into a harbour basin and/or shallow marine environment. A disturbed or atypical macro- and microfossil content or characteristic geochemical patterns as described for the Kyllini site have also been attested for recent tsunami deposits (e.g. Donato et al. 2008, Chague-Goff et al. 2011, 2012, Pilarczyk et al. 2012).

Against the background of the local geomorphological setting as well as the sedimentary, geochemical and microfaunal characteristics of the event layers originating from the seaside, the repeated high-energy impact on the harbour site of Kyllini must be of tsunamigenic origin. For the Ionian Sea and the western Peloponnese, Vött et al. (2011b, 2015) and Willershäuser et al. (2013, 2015a, b) provide similar evidence of palaeotsunami impact.

Throughout the year, prevailing winds from western and northwestern directions dominate the Ionian Sea and western Greece (Hofrichter 2002). Thus, the (north-)westward orientated Kyllini Peninsula may especially be exposed to storm activity.

However, this area is quite well protected by the Ionian Islands with their high mountain ridges reaching up to 1600 m above sea level (Mt. Ainos/Cefalonia) and forming kind of a protection shield for the inner Ionian Sea. Due to the restricted fetch (about 50 km), average wave heights along the coastline of the northwestern Peloponnese do not exceed 0.9 m during the winter month (Soukissian et al. 2008). Exceptional storm events of hurricane-like character occasionally develop in the Mediterranean (Fita et al. 2007). Known as so called Medicanes, these storms generally develop in the western Mediterranean and are accompanied by strong precipitation, heavy wind gusts and occasional flooding of low-lying coastal areas (Luque et al. 2007, Lionello et al. 2006, Tous et al. 2010). They also occur in the Ionian Sea (e.g. in 1995, Pytharoulis et al. 2000) but generally proceed in southeastern direction towards Africa and the Levante.

Additionally, it has been observed that even during strongest storms sea level maxima merely reach about +1 m (Krestenitis et al. 2011). Thus, major modifications of coastlines and lagoonal systems in the Mediterranean seem to be subject to repeated storm impact and do not occur during single events (Andrade et al. 2004). Consequently, neither winter storms nor Medicanes are suitable candidates to explain the abrupt environmental changes and sedimentary characteristics of high-energy deposits found at the Kyllini harbour site.

However, for the coastal area of the Kyllini peninsula a considerable tsunami risk arises from two different sources. Events may either develop on a supra-regional scale triggered along the Hellenic Arc, or may occur on a regional to local scale triggered by local tectonic fault systems (Papazachos & Dimitriu 1991, Maroukian et al. 2000). Offshore Kyllini, two major active normal faults paralleled the north-south trending graben of the Zakynthos Strait. As a consequence, the area shows a high seismic activity with a common occurrence of strong earthquakes, in cases associated with considerable vertical displacements (e.g. in 1953 along the eastern coastline of Zakynthos and Cefalonia, Brooks & Ferentinos 1984). For the 20th cent., Maroukian et al. (2000) list five earthquakes with magnitudes of M > 5.5. Many earthquakes caused local tsunami events as documented by historical records, e.g. in 1633 AD or 1820 AD (Maroukian et al. 2000).

For the Kyllini coastal area, submarine mass movements have to be taken into consideration as another factor that enhances the tsunami hazard. Their occurrence is frequent, triggered either by earthquakes or salt diapirism affecting the slopes of the Zakynthos graben system. Once induced, these slope failures may induce a chain reaction and cause further mass movements (Ferentinos et al. 1985).

Numerical simulation of tsunami wave propagation in the Gulf of Kyparissia by Röbke et al. (2013) shows that apart from the regional bathymetry, the local coastal constellation additionally affects tsunami wave dynamics. Although the Kyllini harbour site is situated in a leeward position for tsunami waves approaching from the south or west, strong refraction effects at the northern Kyllini peninsula are expected to redirect any approaching wave towards the southeast and cause flooding of the adjacent coastal areas (Röbke et al. 2013, 2015).

5.2 *Establishing a local geochronostratigraphy of tsunami events*

Radiocarbon ages as well as age estimations obtained for diagnostic ceramic fragments from the Kyllini harbour site were used to establish a local geochronostratigraphy of tsunami events.

Tsunami generation I and the time of harbour use

For tsunami generation I, sample KYL 2/8 PR yielded 645-491 cal BC as *terminus ad* or *post quem*. Moreover, sample KYL 3/10 HR yielded 400-383 cal BC as terminus ante quem for the same impact. As the sample was retrieved from the lowermost lagoonal-type harbour deposit, this radiocarbon age also provides a *terminus ad* or *ante quem* for the foundation of the harbour site that fits well the historical reports about an active harbour from the beginning of the 5th century BC onwards. Diagnostic ceramic fragments from the lowermost harbour deposit at site KYL 8 and a test core close by were assigned to the Classical to Hellenistic period (5th to 3rd cent. BC) representing a corresponding *terminus ad* or *ante quem* for the beginning of the Kyllini harbour (Fig. 10). Tsunami generation I preceded the foundation of the harbour and, according to the presented dates, hit the coastal embayment at Kyllini between the early 7th and early 4th cent. BC. The post-tsunamigenic phase of harbour usage in Greek times was obviously most intense between the 4th and 1st cent. BC, since the majority of ceramic fragments found within the lowermost harbour deposits originate from the Hellenistic to Roman period.

Tsunami generation II

Sample KYL 7/10 PR yielded 40 cal BC-21 cal AD as *terminus post quem* for tsunami generation II. Since the degree of tsunamigenic erosion remains unknown, the date must be considered as maximum age. Diagnostic ceramic fragments incorporated in the event layer provide another *terminus ad* or *post quem* for the tsunami that is consistent with radiocarbon dating indicating an event during Roman to Byzantine times (samples KYL 5/3+K, KYL 9/4+K, KYL 8/6+K3, sample from test core). The youngest diagnostic sherd was dated to the 4th to 6th cent. AD (Fig. 10). Therefore, a 4th to 6th cent. AD age seems to be most plausible for tsunami generation II. In correlation to historical accounts on major tsunami events, tsunami generation II is probably associated with the 365 AD or 522/551 AD tsunami event that affected wide areas of the eastern Mediterranean and is also reported from coastal areas of the southern Peloponnese.

Considering the geoarchaeological findings along the recent cliff and with regard to the archaeological remains of harbour installations, it is obvious that (i) the extensive distribution of the deposit, (ii) the mixture of marine and terrestrial components, (iii) the average grain size and bad sorting, (iv) the short-distance transport and rapid deposition as well as (v) simultaneous erosive effects are related to the widespread tsunamigenic impact to the Kyllini harbour site. Concerning the associated beachrock deposits, our study provides distinct evidence that the local outcrops do not present lithified beach deposits but also exhibit features related to tsunami impact.

i. The Kyllini beachrock is in perfect stratigraphical correlation with high-energy tsunami deposits visible along the Kyllini cliff and in different vibracore stratigraphies.
ii. At present, the beachrock is in a state of subsequent destruction due to littoral wave action. No recent beachrock formation can be observed.
iii. Sherds found embedded in the beachrock provide evidence for a rapid deposition without further reworking (Fig. 12d). While loose ceramic fragments along the beach are exposed to wave action and appear well rounded, fragments in the beachrock show angular fractures and have thus not been reworked prior to or after deposition.
iv. The Kyllini beachrock even contains matching ceramic fragments in the state of breakage (Fig. 12d). As the cracks between the fragments are filled with sediment, the sherd obviously broke when being incorporated into the deposit without further reworking.

The stratigraphical correlation of the Kyllini beachrock links it to the nearby high-energy event deposits of tsunami event II and proves it to represent a lithified section of a complex tsunamite unit. Post-depositional cementation of the event layer visible along the cliff obviously led to beachrock formation, while present-day wave action uncovers the lithified parts and erodes the non-calcified sediments above and below. Based on detailed geo-scientific findings in other coastal areas of western Greece, beachrock-type calcarenitic deposits were identified as high-energy deposit related to tsunami impact (Vött et al. 2010, Hadler et al. 2013). Post-depositional decalcification of ex-situ marine sediments followed by subsequent recrystallization cause the cementation of parts of the tsunamigenic sediments (Vött et al. 2010). Along the coast of the Kyllini peninsula, further outcrops of beachrock-type deposit were described as cemented beach and used as indicator to reconstruct sea level changes (Maroukian et al. 2000). For the Kyllini harbour site, it must be emphasized that the beachrock is associated to tsunami-related high-energy dynamics. The beachrock must therefore not be regarded as *in situ* lithified beach; it rather testifies to short-term event-related sea level rise. Due to its event-related origin, the calcarenitic beachrock-type tsunamite must also not be used as sea level indicator (Vött et al. 2010, Hadler et al. 2013).

5.3 *Geoarchaeological implications of tsunami impact for the harbour evolution*

Recently, the severe consequences of major tsunami impact on coastal areas were strikingly demonstrated by major events (i.e. Japan 2011). Comparable effects of palaeotsunami impact must also be assumed for ancient coastal settlements and associated infrastructure, i.e. harbour facilities. Like other ancient harbour sites throughout the Mediterranean (e.g. Pheia, Vött et al. 2011b, Yenikapı, Bony et al. 2012, or Lechaion, Hadler et al. 2013), the (partial) destruction of the Greek and Roman harbour facilities at Kyllini seems to be closely related to palaeotsunami impact. A widespread tsunamigenic sand sheet was deposited between the 4^{th} to 6^{th} cent. AD and caused at least a partial burial of the harbour site. However, at that time the harbour site may have been out of use, as indicated by increasing siltation of parts of the harbour basin. Nevertheless, the harbour was partly re-used during Frankish times.

At Kyllini, a major tsunami event precedes the foundation of the harbour site (Fig. 5). As derived from the stratigraphical sequence, the high-energy impact was related to significant modifications of the palaeo-coastline. Posterior to tsunami generation I, the shallow marine environment at Kyllini changed into a coastal lake – the predecessor of the later harbour basin. The Kyllini case study thus underlines the close interdependency between settlement activities and palaeotsunami events and provides valuable results for palaeotsunami research.

Considering the available historical record, is must be noted that even for quite well documented sites like Kyllini, no historical account is known that reports on tsunamigenic impact, not to mention the destruction of the site. Whether or not an account was written, the geoscientific evidence presented within this study again emphasizes the wide gap in the historical record (Hadler et al. 2012). Clearly, further geo-scientific studies are needed to better assess the consequences of palaeotsunami events as well as the risk of future impacts. In search of a complete harbour stratigraphy to fully understand its detailed evolution, future studies will have to comprise further vibracores from the inner harbour basin within the main archaeological protection zone.

6 *Conclusions*

i. Repeated tsunami impact on the Kyllini harbour site was identified from sedimentological, geomorphological, geochemical and microfossil analyses of selected sediment samples from the Holocene stratigraphical record.

ii. Tsunami generation I hit the coast between the early 7th to late 4th cent. BC while tsunami generation II took place between the 4th and 6th cent. AD or later.

iii. In accordance to historical accounts, the Kyllini harbour started to operate in the 5th cent. BC. The harbour was thus built shortly after tsunami generation I took place and is probably associated with a tsunamigenic modification of the coastline that caused the formation of a coastal lake/lagoon. It was likely used until the end of the 1st cent. AD.

iv. Vibracoring sites KYL 2, KYL 3 and KYL 7 show that the parts of the harbour were subject to strong siltation starting in the 2nd cent. BC.

v. Posterior to the siltation, the inner harbour basin was affected by tsunami impact of event generation II. The fact that tsunami deposits are weathered documents the final transition from lagoonal to terrestrial conditions in parts of the harbour area.

vi. At vibracoring site KYL 8, no geo-scientific evidence of a harbour re-activation during Frankish time was found. Thus, our results indicate that only parts of the ancient Greek and Roman harbour were re-activated during Frankish times. Further stratigraphical data from the archaeological protection zone are however needed to draw further conclusions.

vii. In the mid- and outer harbour basin, merely thin layers of event generation II are preserved. We suppose that the event layer was either eroded by constant wave action and longshore drift or excavated by dredging activity during the Frankish period.

viii. In a synoptic view, the history of the Greek harbour of Kyllini seems to be closely related to tsunami impact.

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