Returning to the facts: Response to the refusal of tsunami traces in the ancient harbour of Lechaion (Gulf of Corinth, Greece) by ‘non-catastrophists’ – Reaffirmed evidence of harbour destruction by historical earthquakes and tsunamis in AD 69–79 and the 6th cent. AD and a preceding pre-historical event in the early 8th cent. BC

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With 4 figures and 1 table

Abstract: The ancient harbour of Lechaion supposedly was one of the most important harbours of the ancient world. Representing the western harbour of Corinth at the eastern end of the Gulf of Corinth, it was of major importance for commercial trade and military purposes. This paper is a response to the article by Kolaiti et al. (2017) who reject recent findings by Hadler et al. (2011, 2013) and Koster et al. (2013). The latter presented evidence of multiple tsunami impact on the harbour. Kolaiti et al. (2017) reassessed and interpreted historical, archaeological and climatological data concluding that there is no evidence that tsunami waves inundated the Lechaion site and that the overall tsunami potential in the eastern Gulf of Corinth is comparatively low. Instead, environmental changes in and around the ancient harbour are supposed to have been controlled by climatological factors, such as wind, swell and sea currents as well as human interventions. In this paper, we re-evaluate and synthesize geomorphological, stratigraphical and geochronological data published by Stiros et al. (1996), Morhange et al. (2012) and Hadler et al. (2013) and consider seismo-historical information collected by Mourtzas et al. (2014) and palaeoseismological data by Minos-Minopoulos et al. (2015). Based on geoscientific facts, the main statements of Kolaiti et al. (2017) are evaluated. From an epistemological point of view, the rationale brought forward by Kolaiti et al. (2017) that tsunami impact is not acceptable as long as historical evidence is missing, is untenable. Tsunami traces in geological archives dated by means of absolute dating techniques must not be rejected because they are not included in existing catalogues summarizing historical data. Earthquake and tsunami catalogues are known to be incomplete (Hadler et al. 2012, Papadopoulos 2015: 150). Based on original grain size data, we show that the sediment core from the central harbour basin drilled by Morhange et al. (2012) includes two tsunami candidate layers so far unrecognized. Moreover, the re-interpretation of vibracore data from Hadler et al. (2013) by Kolaiti et al. (2017) in terms of man-made intervention instead of tsunami-related impact is not consistent with available macro- and microfossil signatures. In order to achieve a consistent set of comparable radiocarbon data, we calculated the best-fit approximation of the local marine reservoir effect (MRE) for the Lechaion area as $\Delta R = 133 \pm 75$ for marine samples and used this new ΔR to re-calibrate all available radiocarbon ages published by Stiros et al. (1996), Morhange et al. (2012), Campos et al. (2013a, 2013b) and Hadler et al. (2013). Bringing together ancient harbour chrono-stratigraphies and the seismo-tectonic history of Lechaion and its environs, the timing of tsunami event I identified by Hadler et al. (2013) can be refined to the 770s cal BC, i.e. the early 8th cent. BC. This age is well consistent with the age of a homogenite-turbidite sequence described by Campos et al. (2013a, 2013b) from c. 42 km distant from Lechaion at 867 m water depth indicating an earthquake-triggered tsunami/seiche effect. The age of tsunami event II detected

at Lechaion by Hadler et al. (2013) can now be specified more precisely, namely to c. 44 cal BC–73 cal AD. This age is in close agreement with the age of an older tsunami candidate layer discovered in the core from Morhange et al. (2012) dated to the time before 88–215 cal AD (*terminus ante quem*). These results cover the time period for which historical sources report on a strong earthquake that caused widespread damage to Corinth's infrastructure in AD 74, AD 77 or between AD 69–79 (Mourtzas et al. 2014). We therefore suggest that the Lechaion vibracore transect and core 1 drilled by Morhange et al. (2012) give joint evidence of this major earthquake and associated tsunami impact between AD 69–79. Moreover, the uplift of the ancient harbour at Lechaion most probably occurred co-seismically in connection with the same earthquake and not hundreds of years earlier as thought before. This historical earthquake seems to have also caused severe surface deformation structures at Lechaion. Concerning geoarchaeological aspects, this paper upholds the idea that the early Christian basilica at Lechaion was originally standing on even ground and not partly entrenched into thick local sands and gravels, as suggested by Kolaiti et al. (2017). Palaeoseismological studies by Minos-Minopoulos et al. (2015) underline the initial assessment by Hadler et al. (2013) that the AD 551/552 earthquake and associated earthquake-triggered effects severely damaged the basilica (although historical accounts do not exist) and initiated ongoing disintegration of the remaining ruins. Co-seismic uplift at the Perachora Peninsula as indicated by geomorphological evidence is dated to the same period (Pirazzoli et al. 1994). This abrupt crust-uplift is a plausible trigger for the strong earthquake and local tsunami that hit both Lechaion and the diolkos area in the 6th cent. AD. This contribution also deals with an ideology-driven non-catastrophist trend that comes alight in the paper of Kolaiti et al. (2017). This trend is directed against a so-called neo-catastrophist paradigm and seeks to talk down the impact of seismo-tectonic events in the Mediterranean. We use this case study to show that the solid interpretation of geoscientific facts allows a much more differentiated picture of the reality as the simplistic one painted by Kolaiti et al. (2017). Based on our results, it is recommended not to underestimate the local to regional earthquake and tsunami hazard for the eastern Gulf of Corinth region, even if major impacts have a recurrence interval of several hundreds of years.

Keywords: Palaeotsunami; ancient harbor; beachrock; Gulf of Corinth; Lechaion

1 Introduction and state of the art of research on the harbour of Lechaion

The ancient harbour of Lechaion supposedly was one of the most important harbours of the ancient world. Representing the western harbour of Corinth at the eastern end of the Gulf of Corinth, namely in the Gulf of Lechaion (Fig. 1), it was of major importance for trade and military purposes. At Kenchreai lying at the shore of the Saronic Gulf, another, eastern harbour opened up the Aegean routes to the Corinthians.

This paper is a response to the article by Kolaiti et al. (2017) who reject geoscientific evidence of multiple tsunami impact to Corinth's ancient harbour at Lechaion presented by Hadler et al. (2011, 2013) and Koster et al. (2013).

Until recently, the palaeogeographical evolution of the ancient harbour at Lechaion was completely unknown. Morhange et al. (2012) were the first to present sedimentary data based on a core drilled in the central ancient harbour basin. Core analysis comprised grain sizes of sediment samples, a qualitative evaluation of the macrofossil content and radiocarbon dating. Although the site is known to have experienced considerable crust uplift in historical times (Stiros et al. 1996), Morhange et al. (2012) attest minor importance to tectonics as forcing factor of harbour development. Moreover, easterly long-shore currents, due to the geometry of the harbour,

“cannot significantly contribute to the silting of the harbor” (Morhange et al. 2012: 280–281). These authors rather explain the siltation of the harbour basin with local erosion effects at dredge mounds and occasional sediment input from the slopes of the nearby Akrokorinthos hills related to flash flood events.

Based on geophysical prospection using electrical resistivity tomography (ERT) and ground penetrating radar (GPR, Koster et al. 2013), Hadler et al. (2011, 2013) drilled three vibracores in the southwestern part of the harbour along a N-S transect, c. 250 m long. The data set collected from the sediment cores comprised geochemical parameters, semi-quantitative microfossil data, results of grain size analyses and radiocarbon dating; also geomorphological beachrock studies in the immediate environs of the harbour were carried out. These authors found a sublittoral shallow marine pre-harbour environment with an ascending sea floor towards the S. Younger lagoon-type, silt-dominated harbour deposits attest to a strongly protected harbour environment in ancient times. Further interpretation of the available data allowed to identify and differentiate between three major tsunami impacts that hit the site. Events I and II were interpreted based on sedimentary, geochemical and microfossil data, event III based on sedimentary data from cores and outcrops as well as on beachrock features. Age estimates for these events were given based on radiocarbon dating, namely the 8th–6th cent. BC (I), 1st–2nd cent. AD (II) and 6th cent. AD (III). Event I took place before the foundation of the harbour, whereas events II and III hit the harbour

Fig. 1. (a) Topographical overview of Corinth's ancient harbour at Lechaion located at the southern shore of the eastern Gulf of Corinth. Dots mark vibracoring sites of Morhange et al. (2012, core 1) and Hadler et al. (2013, LEC 1 to 3). Asterisks mark locations of uplifted relative sea level markers described by Stiros et al. (1996) and Morhange et al. (2012). (b) Overview of the Gulf of Lechaion showing the location of the study site. Asterisk marks uplifted notches at the Heraion temple described by Pirazzoli et al. (1994). (c) Overview of the Gulf of Corinth; the Gulf of Lechaion is situated at its southeastern most end. Asterisk marks the location of deep sea core MD01-2477 retrieved from 867 m water depth some 30 km to the NW of the Lechaion Gulf by Campos et al. (2013a, 2013b).

when it was in use. According to Hadler et al. (2013), the harbour basin was considerably filled with tsunami sediments during the youngest event in the 6th cent. AD; the present serpentine-type shape of the harbour and the dredge mounds were suggested to have been formed by the re-excitation of parts of the silted harbour during younger, most probably medieval times. Based on geo-archaeological and geomorphological findings, Hadler et al. (2013) concluded that the early-Christian basilica at Lechaion was largely destroyed by the same 6th cent. AD strong earthquake and the associated tsunami event.

Mourtzas et al. (2014) conducted a detailed archaeological and geomorphological survey at Lechaion in

order to reconstruct local sea level changes. They conducted geodetic measurements (i) of pavements of submerged quays and a submerged notch found on the blocks of the west and north sides of the quay of the east mole, (ii) of an uplifted notch level on the blocks of the south inland section of the east and the west moles of the outer harbour and (iii) at quasi-highest elevations of beachrock outcrops overlying harbour structures. Using these data, they reconstructed relative sea level (RSL) stands, namely at -0.9 m above sea level (m a.s.l.) when the harbour was in use (see (i)), at 0.7 m a.s.l. during a phase of notch formation (see (ii)) and at 1.1 m a.s.l. when beachrock was supposedly formed

(see iii). Mourtzas et al. (2014) suggest two successive co-seismic subsidence events ((i) and (ii), total subsidence by 2 m) and a subsequent tectonic uplift event ((iii), 1.1 m) ending up with the sea at present 0 m a.s.l. Apart from rough archaeological age estimates, independent age control of the reconstructed seismic events was not presented by these authors.

As a direct reaction to the interpretation of geoscientific data collected by Hadler et al. (2013), published in the *Zeitschrift für Geomorphologie*, Kolaiti et al. (2017) – in a paper published in *Marine Geology* – generally deny that the ancient harbour of Lechaion was hit by tsunami events. They bring forward mainly historical and archaeological as well as subordinate climatological and sedimentological arguments including sedimentary and mineralogical data based on two thin sections. These authors conclude that environmental changes recorded in the ancient harbour basin are mainly due to human impact and gradual coastal processes.

Based on the evaluation of catalogue entries of historical tsunamis, they state that the eastern part of the Gulf of Corinth is much less affected by tsunamis than the central and western parts. They did not find any entries for the time periods for which Hadler et al. (2013) reconstructed tsunami landfalls at Lechaion. Recent catalogues comprise only two events for the wider study area, namely for the 2nd of June in 1898 and the 24th of February 1981.

With regard to earthquakes, Kolaiti et al. (2017) summarize that for the period between the 8th–6th cent. BC for which Hadler et al. (2013) reconstructed a major tsunami event I no historical tsunami records are available and no earthquakes were reported. For the period of event II presented by Hadler et al. (2013), namely the 1st–2nd cent. AD, earthquake evidence is considered questionable by these authors; they state that the “Corinth area was supposedly damaged by a doubtful strong earthquake” dated to some point of time between AD 69 and AD 79 (Kolaiti et al. 2017: 108–109). In contrast, for the 6th cent. AD, Kolaiti et al. (2017) found several earthquake episodes, namely a major earthquake that likely occurred in AD 524 or AD 525, another possible earthquake in AD 543 as well as the “lethal earthquakes” of AD 551/552 that hit the Corinth region. For none of them, however, according to Kolaiti et al. (2017), the generation of tsunami waves are attested to by historical data.

Beyond these main arguments against tsunami-related influence on the Lechaion harbour site based on historical data, Kolaiti et al. (2017) undertook subordinate on-site investigations of beachrock units and conducted a geological survey. Two beachrock samples were studied micromorphologically and were interpreted by

the authors to represent *in situ* beachrock formation ranging from the intertidal to the supratidal zone.

Moreover, stratigraphical results presented by Hadler et al. (2013) underwent a re-interpretation by Kolaiti et al. (2017) associated with what was already published by Morhange et al. (2012, C. Morhange being one of the co-authors of the Kolaiti et al. (2017) study).

In contrast to Morhange et al. (2012: 280–281) who already stated that littoral processes did not significantly contribute to the siltation of the harbour, Kolaiti et al. (2017) bring forward weather data for a 6-year period (2008–2014) together with results of numerical hydrodynamic simulations (Repousis et al. 2015) to explain why coarse littoral sediments have been transported to the harbour basin by coastal currents. They suppose that wave-induced N-S directed currents have favoured high sediment transport into the inner harbour basin via the entrance and finally choked the entrance “in a period during which there is no evidence for fore-harbour infrastructure”, that means for the time before the 1st cent. BC when a fore-harbour was constructed by the Romans.

Finally, based on the evaluation of excavation reports and own archaeological surveys, Kolaiti et al. (2017) reject that the basilica at Lechaion was destroyed by tsunami and/or earthquake impact and link serious damage with “the invasion and devastation caused by the Arabs and Slavs” around AD 580. Still, the basilica remained in use at least until the middle of the 7th cent. AD.

Although the interpretation by Kolaiti et al. (2017) is mainly founded on historical and archaeological arguments, these authors finally presume to “confirm that the tsunami potential in the east Corinth Gulf is relatively low” (Kolaiti et al. 2017: 105). From our point of view this approach is selective and problematic because it underestimates the earthquake and tsunami hazard potential of the study region. We therefore see the necessity to come back to the geoscientific facts that face the historical and archaeological interpretations presented by Kolaiti et al. (2017).

The main objectives of this paper are thus (i) to respond to arguments brought forward against the interpretation of geoscientific data as related to tsunami inundation, (ii) to synthesize and interpret available stratigraphies from the Lechaion harbour from different authors, (iii) to address the problem with the local marine reservoir effect as a key for the combination of available radiocarbon data, (iv) to summarize geomorphological data on tectonically induced sea level changes using radiocarbon age control, (v) to discuss the role of beachrock in local stratigraphies and as sea level indicator, and (vi) to clarify open questions in relation with the fate of the early Christian basilica at Lechaion.

2 The dilemma with historical data on earthquake and tsunami events, especially with catalogue entries

A main argument against tsunamis having affected the ancient harbour of Lechaion is that, for the radiocarbon age intervals presented by Hadler et al. (2013), corresponding entries do neither exist in historical tsunami nor earthquake catalogues. Using historical records, these catalogues have been extended to the past far beyond the time since when instrumental records are available. For the Mediterranean, they cover the time from the middle of the 1st millennium BC to the present, in some cases even older events are recorded (Guidoboni et al. 1994, Papazachos & Papazachou 1997, Soloviev et al. 2000, Guidoboni & Comastri 2005, Ambraseys 2009). Such catalogues are a precious and helpful tool to evaluate the frequency and geographical distribution of earthquakes and tsunamis and to keep alive the collective memory of sometimes catastrophic events. However, each entry reflects a different grade of reliability that mostly depends on the intention of the historical source. Especially in earlier times, notes on natural events such as earthquakes and tsunamis were not always taken in order to objectively inform the public but to transport political, military-strategical, religious or personal intentions of the writer or the authority behind him. In some cases, for example, natural disasters were not reported at all, on a deliberate basis, in order to keep socio-political conditions stable and try and keep enemies uninformed on potential weaknesses and vulnerabilities. These phenomena are well known and have been intensely described within the frame of applied source criticism in historical sciences (e.g. Sonnabend 1999, Freifrau von Boeselager 2005, Guidoboni & Ebel 2009). Historical catalogues on earthquakes and tsunamis mostly take into account such uncertainties by discriminating between different grades of reliability. However, the socio-political background of historical information or potential disinformation should always be taken into consideration when working with historical inventories.

Moreover, from an epistemological point of view, historical catalogues – especially those starting from antiquity – always present a selection of an unknown entity of events. One has to consider several possibilities if and how a natural event is transferred to the historical record. First, one must not expect that every single event is actually registered. Second, some events were transported orally over centuries and became lost in the collective mind of local and regional societies. Third, some events were written down, sometimes by an eyewitness

shortly after a disaster happened, sometimes by persons who were told the story or copied it from another source tens or even hundreds of years later. Certainly, only selected historical accounts, which reflect actual events, made it until our days. Some inscriptions and documents may have been destroyed or, even simpler, have not been discovered so far. Yet, many ancient inscriptions become unearthed every year and not seldom bring essentially new knowledge on past societies.

In some cases, historical information may have reached our time but is not translated and/or interpreted in the right way in every single case. Finally, one may assume that there are ancient accounts originally motivated by tsunami-related phenomenon but transferred to subsequent generations in the form of misleading, incorrect explanations or interpreted as divine punishment.

Considering all these points, we are convinced that catalogues on historical earthquakes and tsunamis do only cover a selection of those events that actually occurred. Papadopoulos (2015: 150), another co-author of the Kolaiti et al. (2017) paper, is aware of this dilemma and does admit that earthquake and tsunami catalogues are incomplete. We argue that historical evidence is not necessarily congruent with geological evidence of earthquakes and tsunamis as the archives used for reconstructing such natural phenomena are different. The quality of geological archives is dependent on many different, mostly natural factors such as their susceptibility against erosion and the preservation potential of fossil tsunami traces under varying post-sedimentary conditions. Rejecting geoscientific evidence of earthquake-related impact and/or tsunami inundation because there is no corresponding historical entry means to reject parts of the reality.

Detailed insight into the significance of entries or non-entries in earthquake and tsunami catalogues for the Ionian Sea and the Gulf of Corinth is given by Hadler et al. (2012). One major results of this study is that the quantity of historical earthquake and tsunami data has significantly increased during the 15th cent. AD when book printing techniques were invented and allowed to spread information on natural disasters over wide areas within a short period. This is another argument against over-interpreting historical data sets concerning ancient times.

Another important aspect has to be mentioned regarding the dating of tsunami sediments using the radiocarbon dating technique that is the most common in coastal research. Tsunami deposits as such are problematic because they often include older, reworked material eroded from the pre-tsunami underground during inundation. Radiocarbon ages of organic material collected from tsunami layers as such therefore only render

maximum ages (*termini ad* or *post quos* for the event). For this reason, best age approximation is achieved by dating both the underlying and the overlying sediments of a tsunami-related deposit, using the so-called sandwich-dating approach. However, underlying sediments (yielding a *terminus post quem* for the event) may have been affected by tsunami erosion prior to sediment accumulation, whereas overlying sediments (yielding a *terminus ante quem* for the event) may have been deposited temporally delayed. Radiocarbon ages for the accumulation of tsunami sediments thus represent approximate time windows, often comprising tens or hundreds of calibrated years. Moreover, uncertainties are even bigger in cases where marine biogenic carbonate was used for dating (see Section 4).

For all these reasons, ages of tsunami events reconstructed from geological archives based on the radiocarbon technique can often not be transferred one-to-one to catalogue entries of historically reported tsunami events or potentially associated earthquakes. Radiocarbon dating results mostly leave space for interpretation; interpretation should consider potential contamination effects, reworking effects, old carbon effects of samples and constraints in relation with the calibration of conventional radiocarbon ages into calibrated years.

Concerning the Lechaion harbour case study, the rationale brought forward by Kolaiti et al. (2017) that there is no evidence of tsunami impact because there is no historical evidence of tsunami inundation is, for the reasons mentioned, untenable.

Apart from this issue, Kolaiti et al. (2017) also reject tsunami evidence of the prehistorical event I dated by Hadler et al. (2013) to the 8th to 6th cent. BC. Their main argument is that no corresponding geological tsunami deposits were found at the southwestern and northern shores of the Gulf of Corinth (Kortekaas 2002, Kontopoulos & Avramidis 2003, Kortekaas et al. 2011). This argumentation is not convincing because the Gulf of Lechaion is characterized by steep slopes and large water depths in the inner part (up to 350 m) and tectonic faults on both its northern and southern flanks (Charalampakis et al. 2014). Such conditions are prone to submarine mass failures (Heezen et al. 1966, Perissoratis et al. 1984) that are well known to be able to produce tsunami waves on a merely local to subregional scale (Tselentis et al. 2006). For example, the Perachora fault on the north side of the Gulf of Lechaion is known to have experienced repeated co-seismic uplift during prehistorical and historical times (Pirazzoli et al. 1994). In this context, a considerable local tsunami risk is also suggested for the Xylocaastro coast lying to the immediate west of the Lechaion Gulf (Charalampakis et al. 2007a, 2007b, see also Stefatos et al. 2006). The two tsunamis from 1898 and 1981 in the eastern Gulf of Corinth mentioned by Kolaiti et al.

(2017) themselves (see Section 1) are good examples for such moderate tsunami waves on a local scale. We therefore summarize that missing historical records of tsunami events is no appropriate argument to reject tsunami signatures in the geological record in general.

3 Evaluating stratigraphical and grain size data from core 1 drilled by Morhange et al. (2012) in the central ancient harbour at Lechaion

The argumentation brought forward by Kolaiti et al. (2017) with regard to the palaeogeographical evolution of the ancient harbour at Lechaion is mainly based on the geoarchaeological study conducted by Morhange et al. (2012). Morhange et al. (2012) have drilled two cores in the ancient harbour basin, but only one core is presented in the corresponding paper. Core 1 was drilled a few meters to the northeast of a small artificial island called “*nisaki*” in the central harbour (Fig. 1). They differentiate between a basal “biodeposition” unit 1 (2.85–2.35 m b.s.) that contains a large amount of organic remains from *Posidonia oceanica*. The subsequent unit 2 (2.35–0.85 m b.s.) is described by a “predominantly silty texture” although the authors mention that also sandy layers occur. Macrofaunal remains found in this unit are interpreted to represent “a low-energy sublittoral environment” and the occurrence of *Parvicardium exiguum* is considered “typical of a harbour environment in a leaky lagoon context” (Morhange et al. 2012: 280). The entire unit is labelled “harbour silt”. The upper unit 3 (0.85–0 m b.s.) is attested a “particularly fine-grained texture” which is interpreted as the consequence of the site being protected from littoral dynamics. According to the authors, both sediments and macrofauna remains are indicative of a lagoonal environment enriched in organic matter. The authors further underline that “the shift in the sedimentary facies [...] from marine organic material (unit 1) to silt (unit 2)” is important for the harbour development as it points “to a progressive land locking of the inner harbour and a reduction of water depth” and precedes the tectonic uplift of the area described by Stiros et al. (1996).

Returning to the facts, grain size data presented for core 1 by Morhange et al. (2012: Fig. 4) do not support the stratigraphical classification given in the paper. Altogether, 16 samples were analyzed (counted from the base to the top), but none of them for the basal unit 1 so that no grain size information is available for this unit (Fig. 2). Its interpretation is solely based on the

Fig. 2. Original (left hand side) and revised stratigraphical logs (right hand side) of core 1 drilled by Morhange et al. (2012) in the central harbour basin. Revision of stratigraphical units is based on original grain size data and additional information on stratigraphical issues in the text by Morhange et al. (2012). In the revised version, the harbour-related unit 2 is differentiated into three sub-units 2a, 2b and 2c, showing considerable differences in grain size distribution. Sub-units with maximum 40–60% sand and gravel cannot be summarized as “harbour silt”. See text for further explanations.

occurrence of sea weed remains so that it may be speculated that this unit reflects a massive paralic peat-type enrichment of sea weed in a somewhat sheltered shallow marine environment. Based on grain size data presented, there is a strong and abrupt increase in grain size towards the lower part of unit 2 which could be associated with an erosional unconformity; but detailed information on sedimentary features are not given by the authors. However, sample no. 1 and sample no. 3 of the lower unit 2 are made out of c. 8% and 15% gravel and c. 34% and 29% sand, respectively. For sample no. 2, a sand content of almost 40% was found. For samples no. 1 to 3, the remaining little more than 50% cover silts and clays (Fig. 2). Also for the following samples no. 5 to 9, the sand content ranges between minimum 30% and maximum 60%. Only sample no. 4 and samples no. 10 and 11 show sand contents <30%. Conclusively, we point to the following issues:

- (i) The vertical grain size distribution pattern of core 1 drilled by Morhange et al. (2012) is highly heterogeneous and requires sub-classification into at least 3 sub-units (Fig. 2). Grain size data for the core section between 2.35 m and 0.85 m b.s. do actually not reflect an undifferentiated “harbour silt” unit 2.
- (ii) A lowermost sub-unit 2a (samples no. 1 to 3) is coarse-grained reflecting abrupt high-energy impact to the site. Intermediate unit 2b shows a mixed sandy-silty texture but comprises a clear silt peak at 1.70 m b.s. (sample no. 4) and at least one distinct sand layer at 1.10–1.20 m b.s. (sample no. 8). Grain sizes in upper sub-unit 2c (samples no. 9 to 11) are indeed dominated by silt.
- (iii) The grain size distribution of unit 2 does actually not reflect a “fining upward sequence” (Morhange et al. 2012: 282) but rather a basal section with abruptly increased contents of coarse mineral

grains (sand and gravel) and a directly following thin mud cap (sample no. 4).

- (iv) Further to the top, sand contents are again strongly increased reflecting mixed dynamic conditions showing both a protected environment in favour of the deposition of silt and an environment under the influence of sand input from the littoral system. The latter may be explained by the position of the coring location close to the entrance channel of the harbour where there was a continuous influence of salt water inflow. Comparable grain size patterns were found in the Roman Alkinoos harbour basin on Corfu Island by Finkler et al. (2017).
- (v) Moreover, there is evidence of a distinct sand-dominated layer in the upper part of sub-unit 2b which again indicates higher-than normal energetic conditions obviously induced by inflow of marine waters.
- (vi) Closure of the harbour and final protection of the environment only took place right after this inflow event, as shown by samples no. 9 to 11 as well as by homogeneous silts and clays of unit 1.

Kolaiti et al. (2017: 116) reject interpreting layers of coarse-grained material of marine origin in the ancient harbour at Lechaion as potentially related to tsunami influence, as was done by Hadler et al. (2013), because “high-energy input was not identified by Morhange et al. (2012) although their core was drilled closer to the sea”. In contrast, based on the grain size data presented by Morhange et al. (2012) themselves, there actually is evidence of a coarse-grained layer, c. 50 cm thick (sub-unit 2a). This layer documents the abrupt onset of high-energy conditions at 2.35 m b.s. and the abrupt end of high-energy conditions shortly below 1.70 m b.s. (Fig. 2). Sub-unit 2a as such reflects temporary high-energy influence to a distinct low-energy environment (unit 1). Remains of marine macrofossils described by Morhange et al. (2012) from unit 2 as well as the proximity to the sea allow suggesting that the material comes from the seaside and not from the distant slopes of the Akrokorinthos hills. Based on this, sub-unit 2a represents a neat candidate for a sediment layer laid down in relation with a tsunami event. The mud cap covering sub-unit 2a may also be seen in conjunction with tsunami landfall as mud caps are often described forming the upper end of a tsunami sediment sequence. They are usually explained by accumulation from suspension from standing water in the tsunami aftermath (Richmond et al. 2011).

Also, the intermediate sand layer encountered at 1.10–1.20 m b.s. in the upper part of sub-unit 2b (sample no. 8) reflects a temporary increase of flow dynamics and must not be ignored when looking for further potential tsunami layers.

To sum up, stratigraphical arguments against potential tsunami influence to the Lechaion site offered by Kolaiti et al. (2017) are contradictory to stratigraphical data presented and used by these authors themselves (Morhange et al. 2012, Kolaiti et al. 2017).

4 Re-evaluating available radiocarbon data by correcting the local marine reservoir effect

The correct handling and interpretation of radiocarbon ages is crucial to achieve the best possible scenario with regard to coastal changes due to siltation or tectonic uplift events. Therefore, we decided to re-evaluate and partly re-calibrate all available radiocarbon data collected in conjunction with neotectonic and palaeogeographical studies concerning the Lechaion harbour.

Marine biogenic carbonates (bivalve shells, gastropod shells) represent a major problem for radiocarbon dating, because marine organisms at least partly take their carbon from ^{14}C carbon reservoirs. As the exchange between carbon isotopes in the atmosphere and marine systems is hindered and lags behind, and the oceans, especially deep sea zones, represent large ^{14}C reservoirs, the ^{14}C concentration in ocean surface waters and coastal water bodies differs from the ^{14}C concentration in the atmosphere and dependent terrestrial systems (resulting in the so-called marine reservoir effect, MRE). This circumstance results in the significant overestimation of ages deduced from marine samples. Many authors use a reservoir age correction value (ΔR) that is known from case studies and listed in correction databases in order to correct the MRE (e.g. Reimer and McCormac 2002; see also Marine Reservoir Correction Database, <http://calib.org/calib/calib.html>). Geoscientists often correct the MRE based on the reservoir age listed for the region that is nearest to the study site. Still, the resulting calibrated age remains problematic because the real local MRE is not known in most cases. The real local MRE is subject to changes in spatial, temporal and biological factors, even on a local to regional scale (Walker 2005). Consequently, it has to be assumed that (i) there are different MRE for different environmental settings (shallow marine, lagoonal-brackish, paralic swamps etc.), that (ii) there are MRE variations through time (i.e. throughout the Holocene) and (iii) that there are variations of the MRE depending on the sampled species. So far, this variability of the local MRE is not fully understood and actually not studied for most coastal areas worldwide. Therefore, an average reservoir correction by 405 years is usually applied based on the

global marine13 dataset (Reimer et al. 2013) in order to guarantee comparability, e.g. all over the Mediterranean. However, this approach should be refined using information on the real local MRE whenever these are available.

In their discussion on radiocarbon data collected from vibracores drilled at Lechaion, Hadler et al. (2013: 164) already stated that comparing “marine and terrestrial ages from the lower unit of vibracore LEC 2 indicates a local reservoir effect slightly higher than applied. All ages retrieved from marine material must therefore be considered as maximum ages while the actual calendar age appears to be younger.”

For this response paper, we decided to re-calibrate original radiocarbon data as well as radiocarbon data published by other groups of authors by calculating a local MRE based on the Calib 7.10 software (Stuiver et al. 2017). This is possible because samples LEC 2/15+ HR and LEC 2/15+ PR, consisting of a wood fragment and sea weed, respectively, were retrieved from almost the same depth in vibracore LEC 2, namely from 4.79 m b.s. and 4.74 m b.s., respectively. Both samples were taken from *in situ* shallow marine sands so that reworking effects can be neglected. Although both samples were taken from quasi the same depth, conventional radiocarbon ages show a difference of 490 ± 15 years (LEC 2/15+ HR: 2505 ± 15 conv. BP; LEC 2/15+ PR: 2995 ± 15 conv. BP). We assume that this difference reflects the local MRE for the Lechaion site during the late Holocene. Based on the software Calib, version 7.1.0, we calculated the local MRE choosing the age of sample LEC 2/15+ HR as independent age. Doing so, we obtained a local $\Delta R = 133 \pm 75$ as correction value. Applying the Lechaion ΔR to sample LEC 2/15+ PR results in a new calibrated age of 771–566 cal BC which is quasi-identical with the calibrated age of sample LEC 2/15+ HR that already existed (767–567 cal BC, see Table 1).

In the consequence, radiocarbon ages of marine biogenic material presented by Stiros et al. (1996), Morhange et al. (2012) and Hadler et al. (2013) were re-calibrated based on this newly found ΔR value (Table 1).

Stiros et al. (1996: 257) collected samples from the east wall at the entrance of the harbour basin, namely sample Gif-A-91LE1 from the southernmost ashlar and sample Gif-A-90SS4 from an ashlar at the middle section of the wall. The samples consisted of uplifted *Lithophaga lithophaga* and undetermined *Lamellibranch* material, respectively, taken from a zone of *Lamellibranch* borings at c. 1.1 m a.s.l. documenting a higher sea level stand during historical times. Samples were split into two sub-samples (A and B) and all four samples dated in the ^{14}C AMS laboratory at Gif-sur-Yvette in France. Although these four samples yielded considerable differences in their radiocarbon ages, Stiros et al. (1996) as well as Morhange et al. (2012) decided to accept all four

sample ages in order to achieve a total time span for the age of the corresponding uplift. Doing so, Stiros et al. (1996) resume the age interval for the uplifting event to the time between the 5th–3rd cent. BC, and Morhange et al. (2012) conclude that the uplift “occurred between 500 and 200 B.C.”. However, given the fact that living boring bivalves were killed by the uplift event and that the zone of bore holes also include holes and remains of older specimens that were already dead when uplifted, “their lifespan ranging between a few and a few tens of years” (Stiros et al. 1996: 257), one should just focus on the youngest ages obtained and omit the older ones. In the consequence, we obtained newly calibrated ages for the older sub-samples (Gif-A-90SS4-A: 222 cal BC–73 cal AD; Gif-A-91LE1-A: 329–97 cal BC) which we ignore, and newly calibrated ages for the two younger sub-samples, almost identical in (radiocarbon) age (Gif-A-90SS4-B: 37 cal BC–182 cal AD; Gif-A-91LE1-B: 79 cal BC–146 cal AD) which we consider as best possible calibrated ages for the uplift event. The resulting total age range for the timing of the uplift event (79 cal BC to 182 cal AD) is much younger than the original age range of younger sub-samples by Stiros et al. (1996; 360 to 50 cal BC) and the re-calibrated age range of younger sub-samples by Morhange et al. (2012; 296 cal BC to 54 cal AD, see Table 1).

We also re-calibrated the age of a *Balanus perforatus* encrustation indicating an emerged palaeo-sea level stand first published by Morhange et al. (2012: 279, sample Gif-A-92LE1). The material was sampled from an artificial limestone structure called “*nisaki*” in the central harbour at c. 1.2 m a.s.l. Refined MRE correction and calibration yielded an age of 124 cal BC–95 cal AD (Table 1) which is considerably younger than the age presented by Morhange et al. (2012; 330–46 cal BC).

Moreover, five radiocarbon ages of marine material published by Hadler et al. (2013) were re-corrected and re-calibrated also yielding a shift towards considerably younger ages. Resulting new calibrated ages are summarized in Table 1.

5 Facts on geomorphological indicators of sea level changes – evidence of uplift

Indicators of past sea level stands are important for the reconstruction of costal palaeogeographies and the relative sea level rise. In the study area, there is ubiquitous evidence that the relative sea level (RSL) was higher than today during a specific historical period. Remains of uplifted marine boring organisms were encountered

Table 1. Table of available radiocarbon data published for Corinth's ancient harbour at Lechaion by Stiros et al. (1996), Morhange et al. (2012) and Hadler et al. (2013), with radiocarbon ages re-evaluated and recalibrated using the Calib 7.10 software (Reimer et al. 2013) considering the newly calculated local MRE correction $\Delta R = 133 \pm 75$ for marine samples. The list is complemented by the radiocarbon age of a tsunami-related homogenite-turbidite sequence found in a deep sea core in the central Gulf of Corinth published by Campos et al. (2013a, 2013b) as well as by the radiocarbon age of the youngest reliable RSL marker found on the Perachora Peninsula opposite to Lechaion at the northern shore of the Gulf of Lechaion (Pirazzoli et al. 1994). See text for further explanations.

Sample Name	Lab. No.	Depth (m b.s.)	Depth (m b.s.l.)	Sample Description	$\delta^{13}\text{C}$ (ppm)	^{14}C Age (BP)	1 σ max; min (cal BC/AD)	2 σ max; min (cal BC/AD)	Original publication
LEC 1/7 PR2	UCI 73821	1.58	1.21	unident. plant remain	-26.4 ± 0.1	-220 ± 15^a	–	–	Hadler et al. (2013)
LEC 1/7 PR2 (test)	UCI 73836	1.58	1.21	seed picked out of unident. plant remain	not available	1575 ± 15	428; 535 AD	426–537 AD	Hadler et al. (2013)
LEC 1/8 PR	UCI 73822	1.61	1.24	unident. plant remain	-29.5 ± 0.1	170 ± 15	1670; 1943 AD	1667; 1950 AD	Hadler et al. (2013)
LEC 1/11+ HR	UCI 73823	2.63	2.26	wood fragment	-28.5 ± 0.1	2025 ± 15	44 BC; 1 BC	83 BC–23 AD	Hadler et al. (2013)
LEC 2/6 M	UCI 73816	1.30	1.34	<i>Cerastoderma gl.</i> , artic. spec.	-1.1 ± 0.1	2285 ± 15	113–305 AD*	33–401 AD	Hadler et al. (2013)
LEC 2/6+ HR	UCI 73824	1.54	1.58	wood fragment	-25.8 ± 0.1	1865 ± 15	87; 209 AD	84–214 AD	Hadler et al. (2013)
LEC 2/7+ PR	UCI 73825	1.82	1.86	sea weed	-15.2 ± 0.1^b	2455 ± 20	91–104 BC*	188 BC–207 AD	Hadler et al. (2013)
LEC 2/9+ PR	UCI 73826	2.50	2.54	unident. plant remain	-27.8 ± 0.1	2565 ± 15	793–778 BC	797–770 BC	Hadler et al. (2013)
LEC 2/15+ HR	UCI 73827	4.79	4.83	wood fragment	-25.7 ± 0.1	2505 ± 15	767; 567 BC	772–547 BC	Hadler et al. (2013)
LEC 2/15+ PR	UCI 73828	4.74	4.78	sea weed	-17.6 ± 0.1^b	2995 ± 15	771–566 BC*	815–423 BC	Hadler et al. (2013)
LEC 3/3+ PR	UCI 73829	1.25	0.69	unident. plant remain	not available	255 ± 15	1645–1657 AD	1641; 1793 AD	Hadler et al. (2013)
LEC 3/3+ M	UCI 73817	1.28	0.72	<i>Cerastoderma gl.</i> , artic. spec.	-1.1 ± 0.1	2495 ± 15	137 BC–58 AD*	254 BC–154 AD	Hadler et al. (2013)
LEC 3/3+ HR	UCI 73830	1.53	0.97	wood fragment	-25.1 ± 0.1	1950 ± 20	26; 73 AD	3; 120 AD	Hadler et al. (2013)
LEC 3/7+ PR	UCI 73831	2.48	1.92	unident. plant remain, probably sea weed	-17.1 ± 0.1	5450 ± 20	3806–3634 BC*	3933–3596 BC	Hadler et al. (2013)
Gif-A-90SS4-A	Gif-A-90SS4-A	–	-1.1	<i>Lamellibranch</i>	–	2530 ± 90	222 BC–73 AD*	369 BC–189 AD	Stiros et al. (1996)
Gif-A-90SS4-B	Gif-A-90SS4-B	–	-1.1	<i>Lamellibranch</i>	–	2400 ± 45	37 BC–182 AD*	159 BC–286 AD	Stiros et al. (1996)
Gif-A-91LE1-A	Gif-A-91LE1-A	–	-1.1	<i>Lithophaga</i>	–	2620 ± 50	329–97 BC*	390 BC–36 AD	Stiros et al. (1996)
Gif-A-91LE1-B	Gif-A-91LE1-B	–	-1.1	<i>Lithophaga</i>	–	2430 ± 50	79 BC–146 AD*	190 BC–261 AD	Stiros et al. (1996)
Gif-A-92LE1	Gif-A-92LE1	–	-1.2	barnacles	–	2470 ± 45	124 BC–95 AD*	235 BC–227 AD	Morhange et al. (2012)
Lyon-2378 OxA	Lyon-2378 OxA	0.80	0.80	charcoal	–	1070 ± 35	903; 1017 AD	894; 1022 AD	Morhange et al. (2012)
Lyon-2379 OxA	Lyon-2379 OxA	1.80	1.80	wood	–	1860 ± 40	88; 215 AD	65; 243 AD	Morhange et al. (2012)

Sample Name	Lab. No.	Depth (m b.s.)	Depth (m b.s.l.)	Sample Description	$\delta^{13}\text{C}$ (ppm)	^{14}C Age (BP)	1 σ max; min (cal BC/AD)	2 σ max; min (cal BC/AD)	Original publication
Lyon-2312 OxA	Lyon-2312 OxA	2.40	2.40	charcoal	–	2440 $\pm$ 30	731; 429 BC	751; 408 BC	Morhange et al. (2012)
92PE1	Gif-92PE1	–	-1.10	<i>Chtalamus</i>	–	1990 $\pm$ 100	416–668 AD*	248–783 AD	Pirazzoli et al. (1994)
MD01-2447	–	2.63	869.63	plant debris and wood fragments	–	3190 $\pm$ 40	971–791 BC*	1114–731 BC	Campos et al. (2013a, 2013b)

Note: b.s. – below ground surface; b.s.l. – below sea level; Lab. No. – laboratory number: Hadler et al. (2013): UCI – Radiocarbon Laboratory, University of California, Irvine, U.S.A.; Stiros et al. (1996): Gif-A – Radiocarbon Laboratory, Gif-sur-Yvette, France; Morhange et al. (2012): Lyon – University of Lyon, France, and/or OxA – Oxford Radiocarbon Accelerator Unit, Oxford University, Great Britain; Pirazzoli et al. (1994): Gif – Radiocarbon Laboratory, Gif-sur-Yvette, France; Campos et al. (2013a, 2013b): Saclay CEA Laboratory, Paris-Saclay, France; 1 σ max; min (cal BP, cal BC/AD) – calibrated ages, 1 σ range; “;” – there are several possible age intervals due to multiple intersections with the calibration curve; * – marine reservoir correction with local $\Delta R = 133 \pm 75$ newly calculated for the Lechaion site; a – contaminated sample, i.e. contains bomb ^{14}C ; b – $\delta^{13}\text{C}$ value indicates aquatic plant material and a potential reservoir effect; unident. plant remain – unidentified plant remain; artic. spec. – articulated specimen; *Cerastoderma gl.* – *Cerastoderma glaucum*. Calibration based on Calib 7.10 software (Stuiver et al. 2017).

along the eastern segment of the harbour entrance wall (Stiros et al. 1996) and a zone of emerged littoral bio-encrustations was described by Morhange et al. (2012) from the ‘nisaki’ temple island in the central harbour area (see above). RSL indicators are well preserved indicating that the uplift occurred rapidly and guaranteed protection of the fossil RSL markers from weathering and reworking in the littoral and wave zones. As far as concerns elevation data, the “nisaki” bio-crust is described laying at 1.2 m a.s.l. (Morhange et al. 2012: Table 1). Regarding the remains of boring bivalves along the harbour wall, Stiros et al. (1996: 257) document sampling from 1.1 m a.s.l., whereas Morhange et al. (2012), recalibrating these data, present a different sampling elevation of 0.7 m a.s.l. but without offering any explanation. From our point of view, there is no reason to mistrust the original elevation data published by Stiros et al. (1996). Consequently, both sites along the harbour entrance and in the central harbour basin do reflect roughly the same period of RSL high stand (difference in elevation: 0.1 m). This is also corroborated by the fact that newly corrected and recalibrated ages from these two sites show largely overlapping age intervals (Section 4). These data show that the ancient harbour at Lechaion was characterized by a RSL high stand of c. 1.1–1.2 m a.s.l. until some point of time between 79 cal BC and 182 cal AD near the harbour entrance wall and until some point of time between 124 cal BC and 95 cal AD at the “nisaki” site.

Further geomorphological RSL indicators observed by Mourtzas et al. (2014) such as indicators of the

functional sea level for the time when the fore-harbour was used as well as uplifted marine notches on the breakwaters of the fore-harbour constructions measured at an elevation of –0.9 m a.s.l. and 0.7 m a.s.l., respectively, are problematic to interpret with regard to the local RSL evolution because absolute age control is missing. However, we assume that uplifted notches at 0.7 m a.s.l. might be contemporaneous with the uplifted markers from near the harbour entrance and “nisaki” site although there is a slight discrepancy in elevation. This assumption seems corroborated by the fact that the notches were formed in blocks from the outer harbour, the construction of which is associated with the growth of Corinth during the Julio-Claudian period (second half of the 1st cent. BC to AD 68, see Kolaiti et al. 2017: 116).

Mourtzas et al. (2014) also used beachrock as RSL indicator. In our opinion, beachrock – especially in the area of the Lechaion Gulf with its considerable seismotectonic activity – must not automatically be used as RSL indicators as long as the possibility that it has (partly) been formed in conjunction with temporary and exceptional sea level high stands during tsunami landfall cannot explicitly be excluded (see Vött et al. 2010, Hadler et al. 2015). Therefore, we do not take into account RSL data based on the Lechaion beachrock as proposed by Mourtzas et al. (2014). Kolaiti et al. (2017: 111) state that the Lechaion beachrock does “not show evidence of beachrock-type tsunamite as suggested by Vött et al. (2010)” but in fact they did not discuss any geomorphological, sedimentological and stratigraphical

characteristics of local beachrocks and associated sediments as described by Hadler et al. (2013). This is, however, necessary to understand the formation processes of beachrock at Lechaion and to assess its potential contribution to the reconstruction of RSL changes.

6 Microfossil evidence from ancient harbour deposits

Microfossil investigations are essential to understand changes in sedimentary environments and coastal palaeogeographies. Together with grain size data and further geochemical and mineralogical parameters, they are used as a set of palaeoenvironmental proxies. Hadler et al. (2013) based their interpretation of the vibracore transect along the ancient harbour of Lechaion to a considerable extent on the results of microfaunal studies. Palaeotsunami impacts leave a specific signal in the microfaunal record introducing allochthonous species from littoral, sublittoral and open marine environments into near-coast geological archives such as backbeach swamps or ancient harbours (see for instance, Reinhardt et al. 1994, Pilarczyk et al. 2014). Hadler et al. (2013) also refer to similar approaches successfully conducted in the Gulf of Corinth to detect palaeotsunami influences (e.g. Kortekaas et al. 2011). Under certain circumstances, therefore, microfossils provide sound evidence of palaeotsunami impact. In their efforts to reject the scenario of multiple tsunami landfall at Lechaion, Kolaiti et al. (2017), however, completely ignore the microfaunal data presented. At this central aspect, their study thus lacks geoscientific requirements.

So far, the semi-quantitative analyses by Hadler et al. (2013) represent an exclusive palaeoenvironmental data set for the Lechaion site. Hadler et al. (2013) discriminated between six foraminifera units encountered in sediments retrieved from core LEC 2 (Fig. 3). Unit 1 (9.00–7.21 m b.s.) is interpreted as a fully marine foraminifera assemblage containing some signals of deeper shelf regions while foraminifera in unit 2 (7.21–4.74 m b.s.) are characteristic for a near-coast shallow marine environment with decreased water depths. In contrast, subsequent unit 3 (4.74–2.56 m b.s.) shows a mixture of species from different marine environments including indicators for open marine, cold to temperate conditions as well as abundant broken foraminifera tests. These features document that a major high-energy tsunami impact hit the existing shallow-marine environment. Subsequent unit 4 (2.56–1.83 m b.s.) mirrors completely different conditions with an abrupt decrease of abundance and diversity including species typical of more sheltered, lagoon-type environments. Hadler et al. (2013) interpret unit 4 as related to the time when the site was used

as harbour. Subsequent unit 5 (1.83–1.50 m b.s.) again reveals the occurrence of foreshore shallow marine and locally atypical species. Although the allochthonous foraminifera signal is clearly weaker than the one observed for unit 3, the mixture of foraminifera species together with the abrupt increase in grain size and abundant shell debris are interpreted as imprint of another tsunami landfall. Unit 5 is followed by a layer (unit 6, 1.50–0.95 m b.s.) with a foraminifera record similar to the one found for lagoonal unit 4, indicating another harbour phase at Lechaion. The sediment from 0.95 m b.s. towards the top is almost void of microfossils representing a stage of reduced saltwater influence and final siltation of the harbour basin (unit 7, Fig. 3).

Kolaiti et al. (2017: 114) re-interpret vibracore data presented by Hadler et al. (2013: Fig. 3, Section 4). They suggest that deposits assigned by Hadler et al. (2013) to the first high-energy tsunami-event I were actually accumulated after an entrance channel (or several channels) to the harbour was opened by the Kypselids. During the Kypselids period (7th–6th cent. BC) Corinth experienced a strong economic boom so that a harbour had to be built at the southern shores of the Gulf at Lechaion (Mourtzas et al. 2014: 155, Kolaiti et al. 2017: 112). These authors argue that the opening channel(s) flooded the inner harbour basins with sea water and “marine sandy sediments entered, aided by the landward NW to NE dominant winds and waves”.

There are two arguments that speak against this re-interpretation: First, the sand layers in question were encountered distant to the ancient harbour entrance channel, remains of which are still present in the northeast of the harbour area and where supposedly also the Kypselid harbour entrance was located. Vibracoring site LEC 2 is situated c. 750 m distant from the harbour entrance (as the crow flies, in ENE-WSW direction), vibracoring site LEC 1 another 150 m (NE-SW direction) and vibracoring site another 200 m (NW-SE direction) in the central and rear basins of the harbour in its present shape (Fig. 1). Given that the entrance channel opens to the ENE towards the dead end of the Gulf of Lechaion where a best possible protection from prevailing northern and western winds is given, the input of marine sands by usual outer-harbour littoral drift processes and storm winds is impossible from a geomorphological and sedimentological point of view; rear and central harbour zones are supposedly built in such a way (like any other sea harbour) that flow velocity tends to be nil. The given re-interpretation by Kolaiti et al. (2017) thus denies central operational characteristics of the Lechaion harbour.

Second, Kolaiti et al. (2017) ignore that the foraminifera signature of the marine sands identified as event deposits by Hadler et al. (2013) is characterized by a strong mixture of species originating from different sedimentary environments also including open marine

Fig. 3. Results of foraminifera analyses of selected sediment samples retrieved from vibracore LEC 2 compared to stratigraphical data. Core LEC 2 was drilled in the westernmost part of the inner harbour basin c. 750 m distant from the harbour entrance. Adapted from Hadler et al. (2013: Figs. 3 and 6). See text for further explanations.

cold-water species (Fig. 3). Neither the mixed signal nor the presence of cold-water species can logically be explained by the artificial opening of a harbour channel and related sediment inflow. The latter is restricted to the immediate proximity of the entrance channel where some minor flow velocity may still be present and is composed of relocated local shallow marine sands from the immediate outer harbour environment. Such conditions were, for example, reported from the Roman Alkinoos harbour on Corfu Island by Finkler et al. (2017).

Apart from these two arguments, the re-interpretation, re-evaluation and re-calibration of available radiocarbon data (see Section 7) will bring forward a third argument, namely that event I deposits can be more precisely dated to the beginning 8th cent. BC and thus to the time before the Kypselids are supposed to have built the harbour.

Kolaiti et al. (2017: 116) further doubt that sand layers found intersecting silt-dominated harbour sediments

at sites LEC 1 and LEC 2 and overlying older marine deposits at site LEC 3 are associated with a second high-energy tsunami event II described by Hadler et al. (2013). They speculate that “marine shell debris and gravels with large limestone fragments and marine macrofossils [...] were [...] deposited after the reopening of the entrance channel, the sea inflow with marine debris transportation to the inner basins, and the intensive human activity during this period”. Apart from the fact, that also the microfossil signature of the sand layers in question reveals a clear allochthonous signal that speaks for tsunami-related influence, we have already explained above why the speculation of these authors is untenable considering basal geomorphological and sedimentological aspects of Mediterranean harbours. Finally, they argue that the “high-energy input was not identified by Morhange et al. (2012) although their core was drilled closer to the sea.” However, original grain

size data of core 1 drilled by Morhange et al. (2012) indeed bear a high-energy signature which was overlooked by both Morhange et al. (2012) and Kolaiti et al. (2017; see Section 3, Fig. 2). Moreover, we will show in a later stage of our argumentation that high-energy imprint, now revealed, is stratigraphically and chronologically consistent with data presented by Hadler et al. (2013).

We conclude that the LEC 2 microfossil record presented by Hadler et al. (2013, see Fig. 3) unambiguously supports the interpretation of events I and II as tsunami events. Kolaiti et al. (2017) did not provide any argument against these findings.

7 Bringing together ancient harbour chrono-stratigraphies and the seismo-tectonic history of Lechaion and its environs

In the next step, we bring together improved geochrono-stratigraphies resulting from the re-evaluation of radiocarbon ages, improved MRE correction and subsequent re-calibration of radiocarbon data from different sources (Fig. 4).

First of all, we are able to narrow the time window obtained for tsunami event I as presented by Hadler et al. (2013: 167). Sandwich dating of tsunami event layer I is achieved by considering the *termini post quos* 767–567 cal BC (LEC 2/15+ HR) and 771–566 cal BC (LEC 2/15+ PR) as well as the *terminus ad quem* for the event (sample LEC 2/9+ PR), namely 793–778 cal BC (Fig. 4). Considering that both samples are not retrieved from the high-energy layer itself, which means that potential reworking effects can be excluded, both *termini post quos* and *terminus ante quem* are regarded reliable. This results in the timing of event I in the 770s cal BC, i.e. the early 8th cent. BC. This narrowed time window gives further evidence of the event character of the corresponding layer.

Despite clear geological evidence, Kolaiti et al. (2017) argue that there is no historical record of such an early event and thus regard it as improbable. However, the non-appearance of events in earthquake and tsunami catalogues (Hadler et al. 2012) is neither a sufficient nor a logical argument against palaeoseismological evidence recorded in geological archives (Section 2).

Tsunami signatures in the Gulf of Corinth may be of local to regional extent, for example because they are related to earthquake-induced submarine mass failures. But they may also affect larger areas because large

tsunamis in the gulf may be reflected several times and induce secondary underwater landslides. Campos et al. (2013a, 2013b) investigated homogenite and turbidite units (HmTu) that are interpreted as related to earthquake triggering and tsunami/seiche effects in a sediment core recovered from the central Gulf of Corinth at 867 m water depth. The coring location is only 30 km distant from the opening to the Lechaion Gulf in the SE (Fig. 1). Kastens and Cita (1981, see also Cita et al. 1996, Cita 2008) were the first to describe such tsunami-induced fine-grained “homogenites” encountered in deep-sea basins. The latter come to existence out of a suspension of fine particles persisting for several weeks after an event in the form of homogeneous layers. According to Campos et al. (2013a, 2013b), HmTu associations show a sharp contact at the base, a subsequent lower term Tu out of sand and silt, followed by a mixed term with to-and-fro currents evidences and an upper term Hm. HmTu associations may follow one another or cover hemipelagic “normal” deep-sea deposits.

The youngest HmTu sequence described by Campos et al. (2013a, 2013b) was radiocarbon dated to 3064–2734 cal BP based on organic material and calibrated using the marine dataset and an average $\Delta R = 89 \pm 58$ deduced from MRE ages reported from Nafplio (Gulf of Argolis) and Piraeus (Saronic Gulf). Considering the real local MRE calculated for the Gulf of Lechaion (Section 4) which is much closer to the coring site than the Argolid and Saronic gulfs using a $\Delta R = 133 \pm 75$ yields a re-calibrated age of 971–791 cal BC (Table 1). As the dated material was retrieved from the HmTu unit itself, the obtained age represents a *terminus ad* or *post quem* for the responsible tsunami event. We conclude that this age estimate is well consistent with the *terminus ad quos* obtained from vibracore LEC 2 dating to the 770s cal BC.

This consistency in age may be accidental but it may also reflect a larger tsunami impact that is recorded both in the deep-sea archive offshore Ligia and in the near-shore record at Lechaion where later the ancient harbour of Corinth was established. It is conceivable that a tsunami developed in the central part of the Gulf of Corinth and by wave progradation and multiple wave reflection intruded the dead-end Gulf of Lechaion. In our eyes, the consistency in radiocarbon ages and sedimentary evidence at both sites are strong arguments for a tsunami landfall by event I in this area during the early 8th cent. BC as reported by Hadler et al. (2013).

Due to the re-correction and re-calibration of radiocarbon ages, the age interval given by Hadler et al. (2013) for tsunami event II can now be better defined (Fig. 4). Following the sandwich dating approach along the Lechaion vibracore transect, the following *terminus post quem* for the tsunami event is now available: 44–1 cal BC (LEC 1/11+ HR). Moreover, sample LEC

Fig. 4. Cross section through Corinth's ancient harbour at Lechaion based on available stratigraphical data, namely core 1 drilled by Morhange et al. (2012) and vibracores LEC 1 to 3 drilled by Hadler et al. (2013). Reliable geomorphological RSL marker published by Stiros et al. (1996) and Morhange et al. (2012) are also depicted. All radiocarbon ages are re-calibrated using the Calib 7.10 software (Stuiver et al. 2017) and the newly calculated MRE correction $\Delta R = 133 \pm 75$ for marine samples. See text for further explanations.

2/7+ PR from the base of the event layer provided 91 cal BC–104 cal AD as *terminus ad post quem*. In addition, the following, partly new *termini ante quos* were found: 87–209 cal AD (LEC 2/6+ HR), 113–305 cal AD (LEC 2/6 M), 26–73 cal AD (LEC 3/3+ HR). The age given by sample LEC 3/3+ M (137 cal BC–58 cal AD) is not considered reliable due to age inversion compared to the younger, underlying sample LEC 3/3+ HR. The resulting sandwiched time window for event II as such (*terminus ad quem*) left between the stratigraphically closest age intervals is, therefore, best approximated by maximum c. 44 cal BC–73 cal AD. We further assume that

the *terminus ante quem* 428–535 cal AD (LEC 1/7 PR2) indicates dredging activities during the 5th/6th cent. AD.

Reconsidering the coring results from Morhange et al. (2012) based on the refined stratigraphy shows that the coarse-grained tsunami candidate layer (unit 2a, Fig. 2) can be dated by the *terminus ante quem* (post tsunami mud) 88–215 cal AD (recalibrated sample Lyon-2379 OxA). This age is in good agreement with the time window obtained for event II based on the re-evaluated ages of Hadler et al. (2013), namely 44 cal BC–73 cal AD. We therefore conclude that tsunami event II occurred between 44 cal BC–73 cal AD.

Again, we refer to Kolaiti et al. (2017) who summarized earthquake catalogue entries; although there is an earthquake candidate contemporaneous to the timing of tsunami event II (Hadler et al. 2013: 1st/2nd cent. AD; now confined to 44 cal BC–73 cal AD, see above), these authors consider this candidate “doubtful”, as a “strong earthquake, with chronological estimates varying from 69 CE to 79 CE”. In contrast to Kolaiti et al. (2017), Mourtzas et al. (2014: 157) write about the same earthquake (note that E. Kolaiti and N.D. Mourtzas are (co-) authors of both papers): “The most important earthquake is the one that occurred on 20 June AD 77 (Papazachos & Papazachou 1997; Spyropoulos 1997), or according to others in AD 74 (Papadopoulos 2000; Valkaniotis et al. 2008), which caused extensive damage to the public buildings of ancient Corinth. Roman historians Quintus Curtius (AD 41–79) and Gaius Suetonius (AD 69–122), and the Byzantine chronicler Ioannis Malalas (AD 491–578) interpreted it as an “Act of God” that hit Roman Corinth. They referred also to the extensive reconstruction project of the public buildings, funded by the Roman Emperor Vespasian, which commenced after the earthquake (Georgiadis 1904; Stillwell 2052; Williams & Zervos 2087). The severe earthquake caused the submersion by 0.70 m of the NW coast of the Saronic Gulf, as well as the port facilities of the Roman harbour of Kenchreai (Scranton et al. 2078). The epicenter of the earthquake was located between Acrocorinth and Hexamilia, and its magnitude has been estimated to be $M = 6.3$ (Papazachos & Papazachou 2097; Valkaniotis et al. 2008).”

From this detailed report on earthquake-related damages based on accounts by historians, we conclude that the ‘doubtfulness’ of the earthquake (Kolaiti et al. 2017) for the Corinth area is rebutted.

As a matter of fact, the chronological consistency between the timing of tsunami event II (Hadler et al. 2013: 1st/2nd cent. AD; this paper: *terminus ad quem*: 44 cal BC–73 cal AD, *terminus ante quem*: 88–215 cal AD) and the timing of the contested earthquake (AD 74 or AD 77 or between AD 69–79) seems to be more than accidental. We suggest that the Lechaion vibracore transect and core 1 drilled by Morhange et al. (2012) give evidence of tsunami impact actually related to this earthquake.

One might question why ancient writers did not report on the tsunami event. We hypothesize that the damage caused by the earthquake was considerably larger than the damage caused by the tsunami. Tsunami event II seems to have been less severe than event I considering the thickness of tsunami layers and the microfossil signal. Moreover, it may be speculated that already in ancient times, tsunamis were regarded as being part of the earthquake phenomenon and were not in every single case mentioned separately. However, the facts presented here

give strong reason to reject the non-catastrophists’ scenarios of negligible seismo-tectonic factors (Morhange et al. 2012) and gradual processes dominating the siltation of the harbour (Kolaiti et al. 2017).

Coming back to radiocarbon dated geomorphological RSL indicators, boring bivalves at the eastern harbour wall and barnacles encrusting the “nisaki” actually died off by tectonic uplift between 79 cal BC and 182 cal AD and between 124 cal BC and 95 cal AD, respectively (Table 1, Fig. 4). Considering these data, it seems highly probable that the uplift of the ancient harbour at Lechaion occurred co-seismically in conjunction with the above mentioned earthquake that was radiocarbon dated to the time between 44 cal BC–73 cal AD, and that is most probably consistent with the destructive historical earthquake at AD 74 or AD 77 or between AD 69–79. This scenario seems all the more realistic as this earthquake is reported to have caused co-seismic crust movements, in this case submergence, at Kenchreai (Scranton et al. 1978).

8 The beachrock paradox – beachrock overlying the Lechaion harbour entrance quay and the beachrock stratigraphy at the ancient diolkos

Hadler et al. (2013) also investigated beachrock outcrops and discussed the formation of beachrock sediments considering their geomorphological and sedimentological background. Both for a consolidated beachrock unit right in front of the ancient harbour and associated channel fill deposits in front of an industrial area to the west of Lechaion harbour – partly consolidated in the form of beachrock, partly unconsolidated – Hadler et al. (2013: 161ff., Fig. 9, Section 8) present stratigraphical evidence and describe conspicuous sedimentary features. The latter comprise, for example, multiple fining upward sequences out of sand and gravel, convolute bedding structures, injection features and intact ashlar incorporated in a matrix of sand and gravel all of which are untypical of usual littoral processes. Based on the analysis of numerous thin sections of beachrock samples Vött et al. (2010, 2011) made similar observations along beachrock-type outcrops on Greek coasts – namely fining upward sequences, load casts, convolute bedding, thinning inland, rip up clasts of underlying bedrock, basal erosional unconformities – that reflect high-energy conditions. Such characteristics are also known from

recent as well as historical tsunami deposits (Dawson & Shi 2000, Dominey-Howes et al. 2006, Morton et al. 2007, Donato et al. 2008, see Röbbke & Vött 2017 and references therein).

Similar findings have also been described from different coasts of the world. High-energy sedimentary characteristics of beachrock deposits along selected beaches of Hong Kong, for example, were found associated with deposits of exceptional storm events (Wang 1998). Moreover, recent geoscientific studies in the French West Indies revealed that local beachrocks show the textural and taphonomic imprint of high-energy wave events (Caron 2011). Finally, from a near-coast site in southeast Tunisia, Frébourg et al. (2010) report on a beachrock-type sequence encountered in the midst of a Holocene eolianite which was also formed associated with a catastrophic event. These studies underline that beachrock may have been formed under other than normal sea level conditions and that, therefore, its use as RSL indicator is problematic.

Vött et al. (2010) emphasize that beachrock outcrops may represent lithified sections of tsunami-related high-energy deposits with the lithification taking place by post-sedimentary decalcification of overlying allochthonous marine deposits, rich in carbonate, and percolation of carbonate-saturated waters. These observations led to the recommendation not to use beachrock outcrops as RSL indicators unless it is clear that beachrock formation took place independently from high-energy impact and allochthonous marine sediments (Vött et al. 2010: 42).

Consequently, Hadler et al. (2013) argued that the beachrock at Lechaion can be interpreted as beachrock-type tsunamite. High-energy channel fill structures, untypical of all-day littoral processes, were both observed along the beach, associated with the outcropping beachrock, and in the central harbour area by means of geophysical investigations using ground penetrating radar (Koster et al. 2013).

Kolaiti et al. (2017) do not comment on any of the geomorphological and sedimentological arguments presented by Hadler et al. (2013); they rather suggest that the beachrock, because its “structure is generally non-chaotic, there is a significant majority of well-rounded clasts and almost complete absence of mollusc fragments”, provides no evidence of tsunami events as forming mechanism. However, none of these arguments are solid: tsunami deposits may, of course, appear well layered, i.e. laminated (e.g. Fujiwara et al. 2000), and they are mostly made of sediments from local sedimentary archives (e.g. Sato et al. 1995, Röbbke & Vött 2017), including pre-tsunami gravel beaches at Lechaion. Besides, marine macrofossils are ubiquitous in the beachrock at Lechaion and their presence should not be doubted based on thin

section photographs covering a total surface of c. 60 mm² each (Kolaiti et al. 2017: Fig. 7).

Based on the analysis of two thin section samples from local beachrock material, Kolaiti et al. (2017) aimed to “define the cementation models of beachrock” (Kolaiti et al. 2017: 110). They adopt the results of specific mineralogical studies on the contribution of micro-organisms to cementation processes by Neumeier (1998, 1999) and conclude that “the cementation patterns suggest a beachrock formation ranging from the upper intertidal to slightly supratidal zone” (Kolaiti et al. 2017: 111). Although this conclusion is not new and not contradictory to what was found by Vött et al. (2010) regarding the cementation process, they reason that their observations “did not show evidence of beachrock-type tsunamite as suggested by Vött et al. (2010)” (Kolaiti et al. 2017: 111).

The cementation process during beachrock formation is far from being a uniform and well-understood process because a number of different, partly competing theories exist (Turner 2005). First, beachrock cementation was found associated with the precipitation of high-magnesium calcite (HMC) and aragonite from marine water in the intertidal zone, either resulting from high temperatures, supersaturation of carbonates or evaporation (e.g. Ginsburg 1953, Alexanderson 1972). Second, beachrock formation is reported in the context of the precipitation of HMC or aragonite following the de-gassing of CO₂ from pore water of beach sediments in the intertidal zone (e.g. Hanor 1978). Third, the precipitation of low-magnesium calcite (LMC) due to the mixing of meteoric or groundwater with marine waters in the supratidal zone may form beachrock (e.g. Russel 1962, Schmalz 1971, Richter et al. 1990, Schillings 1994). Finally, cementation may result as a by-product of microbial activity causing the precipitation of micritic calcium carbonate (e.g. Krumbein 1979, Neumeier 1999).

Thus, the question of how the cement within the Lechaion beachrock actually formed is highly complex and certainly needs further research to be fully resolved. From a geomorphological point of view, however, the clarification of specific cementation processes that took place between the intertidal and supratidal zones is of secondary importance in an effort to better understand the depositional processes of the beachrock material and related coastal changes. In this regard, none of the arguments brought forward by Hadler et al. (2013) regarding the geomorphological, sedimentological and stratigraphical context of beachrock formation at Lechaion has lost its significance and validity.

As for the observations on beachrock outcrops near the diolkos at the Posidonia entrance of the Canal of Corinth, Kolaiti et al. (2017: 112) did not carefully take

into account the observations of Hadler et al. (2013). Hadler et al. (2013: 173) state that at the western entrance to the Corinth Canal beachrock outcrops occur at the immediate coastline along both sides of the canal. A “beachrock complex extends at minimum 300 m inland (Fig. 10b) and covers the paving stones of the ancient ship slipway, called diolkos (Fig. 10d). Another older beachrock complex lies several decimetres below the diolkos pavement and can be traced up to 200 m inland.”, Kolaiti et al. (2017: 112), however, incorrectly claim that “Hadler et al. (2013) were probably misled by the mistaken interpretations of Mourtzas and Marinos (1994) and Pirazzoli (2010), and considered that there was only a single beachrock generation.”

Based on a detailed analysis of the younger beachrock generation, Hadler et al. (2013: 173, Fig. 10, Section 10.6) conclude that the diolkos beachrock resembles the Lechaion beachrock regarding stratigraphical, sedimentary and chronological aspects. Considering the huge landward extent of the younger beachrock – reaching by far beyond the landward extent of the beach zone – they consequently suggest that also the diolkos itself was hit by tsunami impact and that “the age of the beachrock [i.e. the tsunami landfall] is about 2000 years or younger”. It is further hypothesized that this beachrock unit corresponds to event II or III recorded in the Lechaion harbour archives; at the same time, the older beachrock unit – underlying the diolkos – is a candidate tsunami sand layer that was accumulated in relation with tsunami event I that hit the Lechaion area before the harbour was built (see Section 7). However, lithification of the tsunami sands must have started right after sediment deposition.

9 Palaeoseismological evidence from geoscientific studies

Within the framework of a thorough geoscientific study focusing on the systematic detection of liquefaction phenomena and the reconstruction of corresponding palaeoseismological events, Minos-Minopoulos et al. (2013, 2015) retrieved sediment cores down to 4 m b.s. from inside the basilica located between the inner harbour basin and the present beach (Fig. 1). They compared the stratigraphies obtained with stratigraphical observations made within the course of archaeological trenching published in several excavation reports. Moreover, they conducted a geophysical survey using electromagnetic, ground penetrating radar and electrical resistivity tomography measurements combined with mapping and cataloguing distinct ground deformation structures where

the basilica floor is well preserved (Apostolopoulos et al. 2015).

These authors conclude that the Lechaion harbour area was repeatedly affected by earthquake-induced ground liquefaction. They found evidence of “[at] least two and three ground liquefaction events” (Minos-Minopoulos et al. 2015: 88) for which they present potential ages. Candidate periods or candidate ages of associated seismic events were searched for mainly on the base of historical information on local and regional earthquakes, but also the results of geoarchaeological studies were taken into account. Based on their results and deduced from surface deformation structures on the basilica’s floor as well as from potential restoration works in a subsequent architectural phase, Minos-Minopoulos et al. (2015: 88) suggest “severe but repairable damage [...] by the A.D. 524 event, followed by [...] the A.D. 551 earthquake, that caused severe and irreparable damages to the temple”.

Moreover, Minos-Minopoulos et al. (2015) identified (a) seismic event(s) that potentially caused severe damage to the harbour infrastructure pre-dating the basilica’s construction. On the strict base of historical accounts only, this earthquake “can be no other but the earthquake in A.D. 77 ($M_L = 6.3$), an event with macroseismic MMI of IX, located at 4 km distance from the ancient harbour [...]. [...] the event caused extensive damage to the ancient city of Corinth and aid was provided by the Roman Emperor Vespasian (Papazachos & Papazachou 1989)” (Minos-Minopoulos et al. 2015: 88).

There are several points that are interesting to discuss compared to the non-catastrophic interpretation by Kolaiti et al. (2017):

Kolaiti et al. (2017) obviously handle their arguments in a selective way. In the discussion section of their paper, they directly accept that liquefaction occurred “commensurate with the 551/552 CE earthquakes and the destruction of the temple” (Kolaiti et al. 2017: 117) as documented by the liquefaction phenomena described by Minos-Minopoulos et al. (2015). On the contrary, the interpretation of earthquake-related tsunami impact suggested by Hadler et al. (2013) also for the 6th cent. AD was rejected by the same authors because of the lack of historical data (Kolaiti et al. 2017: 109).

In the preceding historical section of their paper, Kolaiti et al. (2017), however, still doubt that the AD 551/552 earthquakes “caused severe damage in Corinth” at all because this “was neither reported by Procopius [a Roman writer] nor supported by other evidence” (Kolaiti et al. 2017: 109). They also claim that the assumption that “the destruction [...] of the Basilica was caused by the 551/552 CE earthquake is groundless, since according to Pallas’ excavation reports there is no archaeological

evidence that the earthquake struck Corinth” (Kolaiti et al. 2017: 117).

It is interesting to note that the immediate surroundings of Corinth have indeed been strongly affected by the AD 551/552 event, as written in a paper by E. Kolaiti and N.D. Mourtzas, themselves: “The strong earthquakes of AD 365–400, 551, 1756, 1858 and 1928 caused serious damage in the area [of Corinth’s eastern harbour at Kenchreai] and their macroseismic effects are associated” with the Oneia Fault zone which runs in E-W direction only 5 km south of Corinth (Kolaiti & Mourtzas 2016: 401).

It is obvious that Kolaiti et al. (2017), in their prejudice against tsunami-related impact to the Lechaion site, apply inconsistent, say double standards with regard to the acceptance and chronological interpretation of reliable palaeoseismological data. Yet, there actually is consistent geoscientific evidence for earthquake-related damage to the early Christian basilica and its surroundings that occurred during the 6th cent. AD (Hadler et al. 2013, Minos-Minopoulos et al. 2015) even though the exact timing of the destruction remains problematic (see Section 10).

Moreover, Kolaiti et al. (2017) do not lose a word on the earthquake candidate preferred by Minos-Minopoulos et al. (2015) associated with the pre-basilica liquefaction event that affected the ancient harbour, namely the AD 77 earthquake. This dating of the liquefaction phenomenon – based on historical information (Minos-Minopoulos et al. 2015: 88) – is consistent with the age determined for tsunami event II and the concurrent coseismic uplift of the area based on field evidence and re-evaluated and re-calibrated radiocarbon ages (Section 8).

We therefore conclude that it is more than likely that the earthquake that occurred in AD 77 or between AD 69–79 not only severely damaged Corinth’s infrastructure but was also associated with a tsunami event that hit the harbour area around Lechaion and, at the same time, caused strong ground deformation structures.

10 The early Christian basilica at Lechaion

Concerning the destruction of the early Christian basilica, Kolaiti et al. (2017: 117) base their evaluation on excavation reports by Pallas (last 1967). The excavators found the ground surface facing the immediate northern wall of the basilica on a higher level than the internal floors and Kolaiti et al. (2017) interpret this to represent the original situation. They argue that the conspicuous mixture of coarse sand and marine gravel facing the

northeastern wall of the building is the “same material [...] that] appears below the foundation of the south building VI, which is earlier than the Basilica”. In contrast, this material was interpreted by Hadler et al. (2013) as post-construction high-energy deposit.

Returning to the facts, one has to discuss several points. First, Kolaiti et al. (2017) do not give any further stratigraphical and/or chronological proofs that the material described from below the basilica is identical with the material facing the northeastern basilica wall aside from a simple visual assessment by the excavator. Second, the reference site for the basilica’s substruction is the south building VI and not the northeastern part of the basilica and no information is given on the question if these different parts of the building can be reliably dated to the same time. Third, the authors do not consider archaeological and architectural aspects brought forward by Hadler et al. (2013: 157) documenting that the northeastern part of the basilica seems to have been built on even ground and that a thick layer of sand and gravel was accumulated after its construction. These arguments are (i) plaster decoration along the outer walls that prove that the brickwork was originally exposed to sight, attesting a lower original ground surface, (ii) an *in situ* threshold encountered in the eastern part of the basilica (Hadler et al. 2013: Fig. 7h) documenting the foundation level to be the original ground surface during the construction period, and (iii) a former door lintel re-used as threshold at some point in time after the destruction of the building close to the northeastern corner (Hadler et al. 2013: Fig. 7i). These archaeological findings speak for an early phase of repair after the basilica was severely damaged. Within the course of these repair measures, the walking level was elevated from the original ground surface by 1.5 to 2 m to its present day level.

Hadler et al. (2013) studied thick outcrops of coarse-grained (sand and gravel) high-energy deposits found close to the basilica and to the west of the building. There, these deposits are associated with partly loose, partly consolidated channel fill sediments and characterized by distinct features of high-energy, pulse-type inundation from the sea side (remains of marine macrofossils mixed with terrestrial deposits, bones, and ceramic fragments; several fining upward sequences; basal erosional unconformity; high-energy channel formation). This stratigraphical unit close to present ground surface can be followed from the beach to an area south of the inner harbour basin by means of electrical resistivity as well as ground penetrating radar measurements. To the immediate south of the inner harbour the corresponding thick, coarse-grained layer was found related to a strong erosional unconformity at its base (Koster et al. 2013). The facts that the basilica is coated by material from this unit at least at its northeastern side,

and this sheet extends to the south of the inner harbour let Hadler et al. (2013) conclude that a tsunami hit both the basilica and the harbour, the latter being partly dredged and re-used during later times.

The overall dating of this event by Hadler et al. (2013) to the 6th cent. AD is consistent with the dating of major earthquake-related damages to the basilica as recently presented by Minos-Minopoulos et al. (2015). In contrast to Lechaion tsunami event II for which we were able to identify co-seismic uplift of c. 1.1 m contemporaneous to the triggering earthquake (Section 7), no signs of crust uplift are reported from the Lechaion area for the time of tsunami event III. However, Pirazzoli et al. (1994) found evidence of a young, strong co-seismic uplift event that hit the Perachora Peninsula. Near the Heraion temple, he encountered a barnacle crust out of *Chtalamus* sp. at 1.1 m a.s.l. (Pirazzoli et al. 1994: Table 1, sample 92PE1, with typing error: 1.4 m instead of 1.1 m a.s.l.) forming a distinct RSL marker. Applying the newly calculated local MRE correction $\Delta R = 133 \pm 75$ to the dating results yields a re-calibrated age of 416–668 cal AD. We conclude that the Perachora Peninsula was subject to a major earthquake at that time that caused co-seismic uplift of 1.1 m. It may further be hypothesized that this seismic event is associated with the liquefaction event and the tsunami event identified at Lechaion by Minos-Minopoulos et al. (2015) for AD 551/552 and by Hadler et al. (2013) for the 6th cent. AD, respectively, meaning that co-seismic uplift, liquefaction event and tsunami impact were associated with one and the same earthquake.

On a speculative base, this Perachora earthquake and uplift in late antiquity – bound to the Perachora fault which is known to represent a major tsunamigenic zone (Tselentis et al. 2006) – may have actually been the cause for the local tsunami wave that hit both Lechaion and the diolkos area, where Hadler et al. (2013) also report on a young beachrock-type tsunamite overlying the archaeological remains of the diolkos (see also Stewart 2017). This speculation is plausible bearing in mind that tsunami-generating earthquakes often go hand in hand with local crust-uplift along the shores, as shown for the 2004 Boxing Day tsunami in southeast Asia (Meltzner et al. 2006).

Regarding the exact timing of this major local event, the most destructive earthquake candidate for the period in question is the series of earthquakes in AD 551/552 that caused, according to Procopius' *History of the Wars*, “great damage and human victims [...] in countless towns and eight cities”, for example Chaeronea, Coronea (both in Boetia), Naupactos, Patras and in the Gulf of Lepanto (in the Gulf of Corinth). However, “Corinth was not collected among the cities reported by Procopius” (Koukouvelas et al. 2017: 260). There are two possible ways of interpretation; first, Corinth was not hit by the earthquake so that, consequently, no damage related

to earthquake influence is reported; second, this is an example of an incomplete historical record and Corinth was also hit by the earthquake but did not become part of the mentioned report due to a variety of possible political, strategic, religious etc. reasons. The fact the AD 551/552 earthquake destroyed sites both in the western part of the Gulf of Corinth (Naupactos) and in Boetia to the immediate west of the former Kopais lake (Coronea, Chaeronea) may indicate that also the Gulf of Lechaion was affected by this event. Note that Coronea and Chaeronea are located only c. 47 km and 61 km to the north of Lechaion, respectively, whereas Naupactos lies some 102 km to the northwest of Lechaion.

For the Corinth area, historical information documents intense seismic activity for the first part of the 6th cent. AD, “very likely for AD 524 or AD 525” when according to Procopius' *Anecdota* “Corinth was overthrown by earthquakes” (Koukouvelas et al. 2017: 260); moreover, earthquakes likely occurred in AD 543, AD 580 and AD 599 (Koukouvelas et al. 2017: 260f.). Considering the fact that Minos-Minopoulos et al. (2015) differentiated between two different liquefaction events that affected the basilica, and that they relate the first event to the AD 524/525 earthquake, it appears plausible to suggest that the second liquefaction event – together with tsunami inundation of the Lechaion harbour and co-seismic uplift of the Perachora Peninsula – was related to the strong earthquake series in AD 551/552 although no direct historical details regarding the city of Corinth are delivered to posterity.

Summarizing the building history of the Lechaion basilica as given from the side of archaeology, Kolaiti et al. (2017) state that its construction began not earlier than in the AD 450s and that it was incomplete and “potentially roofless (Pallas 2067)” (Kolaiti et al. 2017: 117) until c. AD 530. As a major argument against the tsunami-related destruction of the basilica as suggested by Hadler et al. (2013), these authors bring forward that a coin from the time between AD 641–668 was found in the earlier fill of the basilica documenting that “the Basilica remained in use until at least the middle of the 7th century” (Kolaiti et al. 2017: 117).

Returning to the facts, this finding only documents that an early fill of the inner basilica with sediments can be age-estimated by a *terminus ad* or *post quem* of AD 641–668 but it does not give any information on how, by whom, why and under which circumstances the corresponding coin became part of the fill. In no case, a single finding of a coin allows the conclusion that the building as a whole remained “in use”. The same is the case for another coin from the 11th/12th cent. AD found as part of a later infill sequence described from adjacent to the bema. Residents searching for usable building material may have simply lost the coins in question.

All the arguments brought forward by Kolaiti et al. (2017) do not contradict the interpretation given by Hadler et al. (2013) that the basilica was severely hit and damaged by an earthquake-related tsunami land-fall, traces of which were also described by Koster et al. (2013) on the base of geophysical investigations. Both Hadler et al. (2013) and Minos-Minopoulos et al. (2015) suggest irreparable damages to the temple triggered by the seismic shock in AD 551/552. One may legitimately hypothesize that this includes at least the partial collapse of the building as done by Hadler et al. (2013: 157f.). Minos-Minopoulos et al. (2015: 88) report on “a packed layer of variable thickness throughout the temple floor composed of fragments of ceramic [roof] tiles and mortar located between the floor surface and the limited structural elements of the Basilica preserved (Pallas 2056, 1960, 1957)”. This assessment, however, does not exclude that parts of the building could still be used, for example also as religious place. Please note that Hadler et al. (2013) themselves report on repair measures after the event (see above). This assessment does also not exclude that building material was removed from the place to be re-used in other buildings or that simply looting took place. In each case, the building was certainly still present as a ruin, strongly damaged and partly collapsed, and it goes without saying that it was affected by further gradual destruction in the course of the following centuries.

11 Some comments on non-catastrophist ideologies in coastal research

Another point has to be discussed on the occasion of the ancient Lechaion harbour case study, namely the obvious *a priori* bias against the effects of seismo-tectonic events on coastal environments and man-made infrastructure and against the effects of seismically triggered high-energy wave events, called tsunamis, which comes to light in the paper of Kolaiti et al. (2017).

For example, these authors summarize their studies already in the ‘Materials and methods’ section of their paper saying that “[R]apid changes in the Lechaion coastal geomorphology have been *controlled* by meteorological factors, such as wind, swell and sea currents as well as by human intervention” (Kolaiti et al. 2017: 108), i.e. before having presented their data and interpreted the results obtained. They even go a step further towards a severely restricted approach by saying, in the subsequent sentence, “[i]n this regard, we collected and analyzed wind data and performed field surveys to better understand mainly the erosional processes, affecting

coastal geomorphology. In addition, human intervention in Lechaion was examined on the basis of archaeological findings and historical documentary sources”. In this part of the paper, not a single word is said on destructive effects of earthquakes that had obviously controlled major changes in the natural and human environments – earthquakes that are known, for example, to have crucially damaged Corinth’s infrastructure between AD 69 and AD 79 (Papazachos & Papazachou 1997, Mourtzas et al. 2014: 156f.; see Section 7).

Geoscientific evidence presented by Hadler et al. (2013 – e.g. microfauna), Koster et al. (2013 – e.g. geophysical evidence of high-energy channels), Minos-Minopoulos et al. (2013, 2015 – e.g. liquefaction events) and Apostolopoulos et al. (2015 – e.g. geophysical evidence of surface deformation structures) who point out that changes induced by seismic events have played a major role are not considered in the quintessence conclusions of Kolaiti et al. (2017). Another prominent example is given by liquefaction and seismic destruction evidence associated with the earthquake at AD 551/552 that caused “irreparable damages” to Corinth’s basilica, be it mentioned or not by historical accounts (Minos-Minopoulos et al. 2015: 88).

In chapter 5 of their paper, Kolaiti et al. (2017) repeat their overall evaluation that “[t]he south coast of Lechaion Gulf is naturally dynamic. Wind, swell and currents, are natural forces that, in combination with human interventions over time, *define* the coastal morphology resulting in rapid changes in the coastal area.” Again, they exclude any seismo-tectonic triggers in their assessment of those factors that “control” (see above) or “define” coastal changes. Still, it is doubtful how processes with different scales of duration can be brought together so that “natural forces” and “human intervention *over time*” are able to produce “*rapid changes*”.

Another example concerns the question where the material accumulated in the silted Lechaion harbour basin comes from, especially the coarse spectrum found in the form of gravel and sand. Morhange et al. (2012) favours input of sediments by erosion from the dredge mounds that were heaped up in the harbour area as well as from the lower slopes of the Akrokorinthos hill within the course of flash flood events. But both the macrofossil and microfossil signatures of corresponding sediments reported by Morhange et al. (2012: 280) themselves and by Hadler et al. (2013: Fig. 6) give clear evidence of a marine origin of the deposits (Fig. 3) and torrential rivers are presently absent. Moreover, dredged materials always reflect the sediments recorded in the harbour basin and do not represent an independent sediment source. However, in their concluding statement with regard to the siltation history of the harbour, all the arguments brought forward by Kolaiti et al. (2017: 118) – namely the opening of

harbour channel(s), seawater flooding, entering of marine sands, prevailing winds and waves, findings of dredge mound material and influences by flash flood events from uphill – intendedly suppress any alternative and/or additional explanatory approach of harbour siltation and harbour development, based on geoscientific data, that are brought forward by other scientists.

The paper by Kolaiti et al. (2017) is a good example representative of an ideological trend of ‘non-catastrophism’ that seeks to talk down or even ignore rapid coastal changes in the Mediterranean associated with seismo-tectonic events. Initiated by devastating earthquake and tsunami events that caused hundreds of thousands of casualties and that shocked our societies, e.g. the 2004 Boxing Day tsunami in southeast Asia, the 2011 tsunami in Japan, the 2016 earthquakes in Italy, studies on seismo-tectonic events and seismically triggered effects have strongly increased in palaeoenvironmental and geoarchaeological research. Much more light is now shed on low frequency-high magnitude events such as earthquakes and tsunamis with their abrupt and massive effects on coastal societies and landscapes. Traditional explanatory approaches that are based on classical factors such as sea level fluctuations, long-term climatic effects, variable sedimentation rates and changing erosional effects in the hinterland due to changing human impact now have to be complemented by seismo-tectonically triggered factors that are able to cause immediate and abrupt large-scale interferences of ecological and societal systems. This may be hard to accept from the side of researchers ideologically struggling against what they call “neo-catastrophism” (Marriner et al. 2010, 2017, Morhange et al. 2014), but geoscientific evidence and facts will finally prevail.

12 Conclusions

This paper is a response to the article by Kolaiti et al. (2017) who – in their attempt to draw a picture of the palaeoenvironmental evolution of Corinth’s ancient harbour at Lechaion – reject recent findings published by Hadler et al. (2011, 2013) and Koster et al. (2013). The latter collected stratigraphical, geophysical, geochronological, micropalaeontological and geochemical data on the base of which multiple tsunami impact to the harbour was reconstructed. Kolaiti et al. (2017) re-assessed and interpreted historical, archaeological and climatological data, undertook geomorphological surveys and studied beachrock outcrops at Lechaion based on two thin section samples. Moreover, they evaluated and re-interpreted palaeoenvironmental studies published by other authors coming to the conclusion that there is no evidence that tsunami waves inundated the Lechaion harbour and

that the overall tsunami potential in the eastern Gulf of Corinth is comparatively low. Instead, environmental changes in and around the ancient harbour are supposed to have been controlled by climate-related factors, such as wind, swell and sea currents and human intervention.

Although the paper by Kolaiti et al. (2017) is a direct reacting to the findings of Hadler et al. (2013), only selected parts of the original data set are considered. Major arguments of the pro-tsunami study were not taken into account, for example detailed results of geophysical surveys, beachrock studies and microfossil analyses.

In this paper, our main approach was to establish an interpretation and reconstruction of the palaeoenvironmental evolution of the Lechaion site based on geoscientific facts published by different groups of authors. We re-evaluated and synthesized geomorphological, stratigraphical and/or geochronological data published by Stiros et al. (1996), Morhange et al. (2012) and Hadler et al. (2013) as well as considered seismo-historical information collected by Mourtzas et al. (2014) and palaeoseismological data by Minos-Minopoulos et al. (2015). The main conclusions can be summarized as follows.

- (1) Based on epistemological principles, catalogues on historical earthquakes and tsunamis do only cover a selection of those events that actually occurred and have to be regarded as incomplete. Tsunami events traced in geological archives and dated by means of absolute dating techniques must not be rejected because they are not included in existing catalogues summarizing historical data. Concerning the Lechaion harbour case study, the rationale brought forward by Kolaiti et al. (2017) that there is no evidence of tsunami impact because there is no historical evidence of tsunami inundation is untenable.
- (2) Stratigraphical and grain size data from core 1 drilled by Morhange et al. (2012) in the central ancient harbour were re-evaluated according to published original data. In contrast to the interpretation by Morhange et al. (2012) and Kolaiti et al. (2017), who identified a thick “harbour silt” unit, there is grain size evidence of at least two coarse-grained high-energy sediment layers. These layers, one to several decimeters thick, consist of up to c. 50–60% gravel and/or sand and obviously reflect temporary high-energy influence to a low-energy shallow marine or harbour-type environment.
- (3) Based on the radiocarbon dataset provided by Hadler et al. (2013), we calculated the best-fit approximation of the local marine reservoir effect (MRE) for the Lechaion site as $\Delta R = 133 \pm 75$ for marine samples. We used this new ΔR to re-calibrate all available radiocarbon ages published by Stiros et al. (1996), Morhange et al. (2012), Campos

- et al. (2013a, 2013b) and Hadler et al. (2013) aiming at a consistent set of comparable radiocarbon data. Moreover, we re-evaluated dating results by Stiros et al. (1996) considering the geomorphological constellation and the life span of boring organisms used as relative sea level indicators.
- (4) The ancient harbour at Lechaion experienced a RSL high stand of c. 1.1–1.2 m a.s.l. until some point of time between 79 cal BC and 182 cal AD near the harbour entrance wall (original data by Stiros et al. 1996) and until some point of time between 124 cal BC–95 cal AD at the “nisaki” site (original data by Morhange et al. 2012), based on the newly calculated Lechaion ΔR with regard to reliable geomorphological RSL indicators and co-seismic uplift. These ages are several hundred years younger than previously thought (c. 340 BC: Stiros et al. 1996, Morhange et al. 2012; between 600–50 BC: Kolaiti et al. 2017) and document sea level conditions during Roman times.
 - (5) The re-interpretation of vibracore data from Hadler et al. (2013) by Kolaiti et al. (2017) in terms of man-made intervention instead of tsunami-related impact is not supported by macro- and microfossil signatures of sediment cores described by Morhange et al. (2012) and Hadler et al. (2013). Based on microfaunal data, the interpretations given by Hadler et al. (2013) are consistent with micropalaeontological approaches applied in modern palaeotsunami research. The microfossil record of vibracore LEC 2 unambiguously supports the interpretation of two tsunami events.
 - (6) The timing of tsunami event I reconstructed by Hadler et al. (2013) can be refined to the 770s cal BC, i.e. the early 8th cent. BC. This *terminus ad quem* is consistent with the age of a homogenite-turbidite sequence recovered from 867 m water depth c. 42 km distant from Lechaion and related to earthquake triggering and tsunami/seiche effects (971–791 cal BC, 1 σ , *terminus ad* or *post quem*; Campos et al. 2013a, 2013b). We conclude that the central and eastern parts of the Gulf of Corinth experienced a strong earthquake and associated tsunami landfall in the early 8th cent. BC which corresponds to what Hadler et al. (2013) described as event I.
 - (7) Following the re-correction and re-calibration of radiocarbon ages, the age interval given by Hadler et al. (2013) for tsunami event II can be specified more precisely. The sandwiched time window is now best approximated by c. 44 cal BC–73 cal AD. This is consistent with the age of the corresponding tsunami candidate layer in the core from Morhange et al. (2012) dated by the *terminus ante quem* 88–215 cal AD. We conclude that tsunami event II occurred between 44 cal BC–73 cal AD.
 - (8) There is a strong chronological consistency between the timing of tsunami event II (44 cal BC–73 cal AD) and the timing of a major earthquake in AD 74 or AD 77 or between AD 69–79 (Papazachos & Papazachou 1997). Historical accounts report on extensive damage to the ancient city of Corinth by this earthquake (Mourtzas et al. 2014, Minos-Minopoulos et al. 2015). We therefore suggest that the Lechaion vibracore transect by Hadler et al. (2013) and core 1 drilled by Morhange et al. (2012) give joint geological evidence of this very strong earthquake and associated tsunami impact between AD 69–79.
 - (9) Boring bivalves at the eastern harbour wall and barnacles encrusting the “nisaki” actually died off by tectonic uplift between 79 cal BC–182 cal AD and between 124 cal BC–95 cal AD, respectively. We conclude that the uplift of the ancient harbour at Lechaion most probably occurred co-seismically in conjunction with the above mentioned earthquake between AD 69–79.
 - (10) Beachrock is a problematic as RSL indicator whenever it reveals traces of high-energy sediment transport and associated depositional features (Vött et al. 2010). Such characteristics were observed by Hadler et al. (2013) at Lechaion and interpreted as tsunami-related. Although Kolaiti et al. (2017) do not comment on geomorphological and sedimentological issues, they suggest in situ lithification of beach deposits. None of the arguments brought forward by Hadler et al. (2013) regarding the geomorphological, sedimentological and stratigraphical context of tsunami-related beachrock formation at Lechaion has lost its significance and validity.
 - (11) Concerning the beachrock outcrops at the diolkos near Posidonia at the canal of Corinth, Hadler et al. (2013) – other than claimed by Kolaiti et al. (2017) – already differentiated between two beachrock generations. Considering geomorphological and sedimentary characteristics of high-energy impact as well as the huge landward extent of the beachrocks of several hundreds of meters we still suggest that also the diolkos was repeatedly hit by tsunami impact. Kolaiti et al. (2017) present no arguments that speak against this interpretation. The younger beachrock likely corresponds to event II or III at Lechaion. The older beachrock – underlying the diolkos – is a candidate tsunami layer most probably accumulated in relation with tsunami event I that hit the Lechaion area in pre-harbour times in the early 8th cent. BC.

- (12) Palaeoseismological studies on surface deformation structures suggest a strong liquefaction event which, most probably, occurred in AD 77 or between AD 69–79 (Minos-Minopoulos et al. 2015, see Mourtzas et al. 2014); this is in very good accordance with the timing of the major earthquake and tsunami event reconstructed for the same time in this paper. We conclude that it is more than likely that the earthquake in AD 77 (AD 69–79) not only severely damaged Corinth's infrastructure but was associated with a tsunami event that hit the harbour area around Lechaion and, at the same time, caused strong ground deformation structures.
- (13) Another period with liquefaction events is dated to the 6th cent. BC, most probably associated with the AD 524 and the AD 551/552 earthquakes (Minos-Minopoulos et al. 2015). Together with findings of tsunami sediments dated to the same period already presented by Hadler et al. (2013), these results underline that the AD 551/552 earthquake seems to have had severe impact on Lechaion although historical accounts do not exist for this site. Geomorphological evidence of a strong co-seismic crust uplift event at the southern flank of the Perachora Peninsula right opposite to Lechaion is provided by Pirazzoli et al. (1994) for the same period. We therefore speculate that this local earthquake may be the responsible trigger for the destruction of infrastructure and the strong tsunami that hit both Lechaion and the diolkos area in the 6th cent. AD.
- (14) As for the early Christian basilica at Lechaion, stratigraphical, architectural and archaeological findings already reported by Hadler et al. (2013) underline that the temple was originally standing on even ground and not partly entrenched into thick local sands and gravels, as suggested by Kolaiti et al. (2017). Studies on earthquake-related surface deformation structures (Minos-Minopoulos et al. 2015) underline that the AD 551/552 earthquake severely damaged the basilica and initiated ongoing disintegration of the remaining ruins. Post-earthquake repair measures indicate that parts of the building were re-used and the site was continuously visited as evidenced by coin findings embedded in debris layers.
- (15) The paper by Kolaiti et al. (2017) is a representative example for an ideological trend within coastal geoscience against a so-called neo-catastrophist paradigm. This trend seeks to talk down or even ignores evidence of rapid coastal changes associated with seismo-tectonic events in the Mediterranean in favour of climate-related factors and human intervention (Marriner et al. 2010, 2017, Morhange et al. 2014). As far as concerns the Lechaion case study, geoscientific facts and their solid interpretation, however, allow a much more differentiated picture of the reality as the simplistic non-catastrophist one painted by Kolaiti et al. (2017).
- (16) Based on geoscientific evidence of repeated surface deformation and tsunami inundation events at Lechaion, both triggered by earthquakes, it is strongly recommended not to underestimate the local to regional earthquake and tsunami hazard (Kolaiti et al. 2017, see also Papadopoulos 2015: 149) even if major impacts have a recurrence interval of several hundreds of years. The shores of the Gulf of Lechaion are densely populated and attract thousands of tourists every year resulting in a very high vulnerability against earthquake and tsunami events.

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