Marine Geology 271 (2010) 156–164

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

Geological and geomorphological evidence of recent coastal uplift along a major Hellenic normal fault system (the Kamena Vourla fault zone, NW Evoikos Gulf, Greece)

Andrew B. Cundy [a,*], K. Gaki-Papanastassiou [b], D. Papanastassiou [c], H. Maroukian [b], M.R. Frogley [d], T. Cane [d]

[a] School of Environment and Technology, University of Brighton, Brighton, BN2 4GJ, UK
[b] Department of Geography-Climatology, University of Athens, Gr 15784 Athens, Greece
[c] Institute of Geodynamics, National Observatory of Athens, Gr 11810 Athens, Greece
[d] Department of Geography, University of Sussex, Brighton, BN1 9QJ, UK

ARTICLE INFO

Article history:
Received 30 March 2009
Received in revised form 21 January 2010
Accepted 5 February 2010
Available online 12 February 2010

Communicated by G.J. de Lange

Keywords:
coastal uplift
central Greece
earthquakes
coastal stratigraphy
normal faulting
sea level

ABSTRACT

The active normal faulting region of central Greece has been the focus of intense study, due to its relatively high rates of tectonic deformation, and the frequent occurrence of damaging, moderate magnitude earthquakes. The structure of central Greece is dominated by a series of roughly WNW–ESE-trending extensional faults which have created a series of half-grabens, the most prominent of which are the Gulf of Corinth and the Evoikos Gulf. Of these two structures, the Evoikos Gulf, and particularly its northern part, remains poorly understood in terms of its geodynamic structure and tectonic significance. Here, we use exposed coastal sediment sequences and coastal geomorphological indicators to examine the pattern of historical sea-level change in the northern Evoikos Gulf, specifically in the hangingwall of the prominent Kamena Vourla fault system, to better constrain recent coastal elevational changes and tectonic activity in this area. In particular, we describe and analyse a series of exposed coastal sections which contain recent (<3000 year BP) marginal marine sedimentary units, apparently uplifted to elevations of >1 m above contemporary high water level. These deposits occur in the hangingwall of the prominent Arkitsa (normal) fault strand, and indicate a local uplift rate possibly exceeding 1 mm/year, significantly greater than long-term regional uplift rates. The pattern of uplift of these coastal sections is most consistent with recent coseismic uplift on an offshore, shore-parallel, fault strand north of Arkitsa.

1. Introduction

The active normal faulting region of central Greece has been the focus of intense study, due to its relatively high rates of tectonic deformation and the frequent occurrence of damaging, moderate magnitude ($M_s \approx 6$–7), earthquakes. The structure of central Greece is dominated by a series of roughly WNW–ESE-trending extensional faults (accommodating extension of 15–20 mm/year) which have created a series of half-, asymmetric, grabens (Billiris et al., 1991; Eliet and Gawthorpe, 1995). The most prominent of these extensional structures are the Gulf of Corinth and the Evoikos Gulf, both of which are WNW–ESE-trending graben systems about 100 km long, and bordered by discontinuous normal faults (Roberts and Jackson, 1991; Stefatos et al., 2002; Moretti et al., 2003; Sakellariou et al., 2007). Of these two structures, the Evoikos Gulf, and particularly its northern part, is relatively poorly understood in terms of its geodynamic structure and tectonic significance (e.g. Makris et al., 2001). The northern Evoikos Gulf (Fig. 1) is a zone of accommodation between the two stress fields of the North Aegean Trough (the extension of the North Anatolian fault system) and the Gulf of Corinth (see regional summary in Papanikolaou and Royden, 2007). The interaction between these stress fields is not well-constrained (Hollenstein et al., 2008, based on recent GPS measurements, confirm the presence of a relatively low magnitude extensional stress field in the northern Evoikos Gulf), but generally the development of large faults is prohibited, and consequently the magnitudes of earthquakes in the north Evoikos Gulf and its immediate vicinity are of limited to moderate values. Indeed, recent research indicates that seismic stress in this area may not necessarily be released with strong earthquakes, but instead with intense microearthquake activity, usually in seismic swarms (Papanastassiou et al., 2001; Papoulia et al., 2006). Despite this, the area is characterised by a series of very prominent tectonic landforms, notably the large (ca. 1000 m elevation) footwall ridge of the Kamena Vourla fault system (Fig. 1).

The Kamena Vourla fault system is a northward-dipping, active normal fault zone ca. 50 km long, trending E–W along the southern shoreline of the north Evoikos Gulf (Fig. 1). The fault zone consists of three major left-stepping fault segments: the Kamena Vourla, the Agios Konstantinos, and the Arkitsa segments (Roberts and Jackson,

* Corresponding author. Tel.: +44 1273 642270; fax: +44 1273 642285.
E-mail address: A.Cundy@bton.ac.uk (A.B. Cundy).

0025-3227/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.margeo.2010.02.009

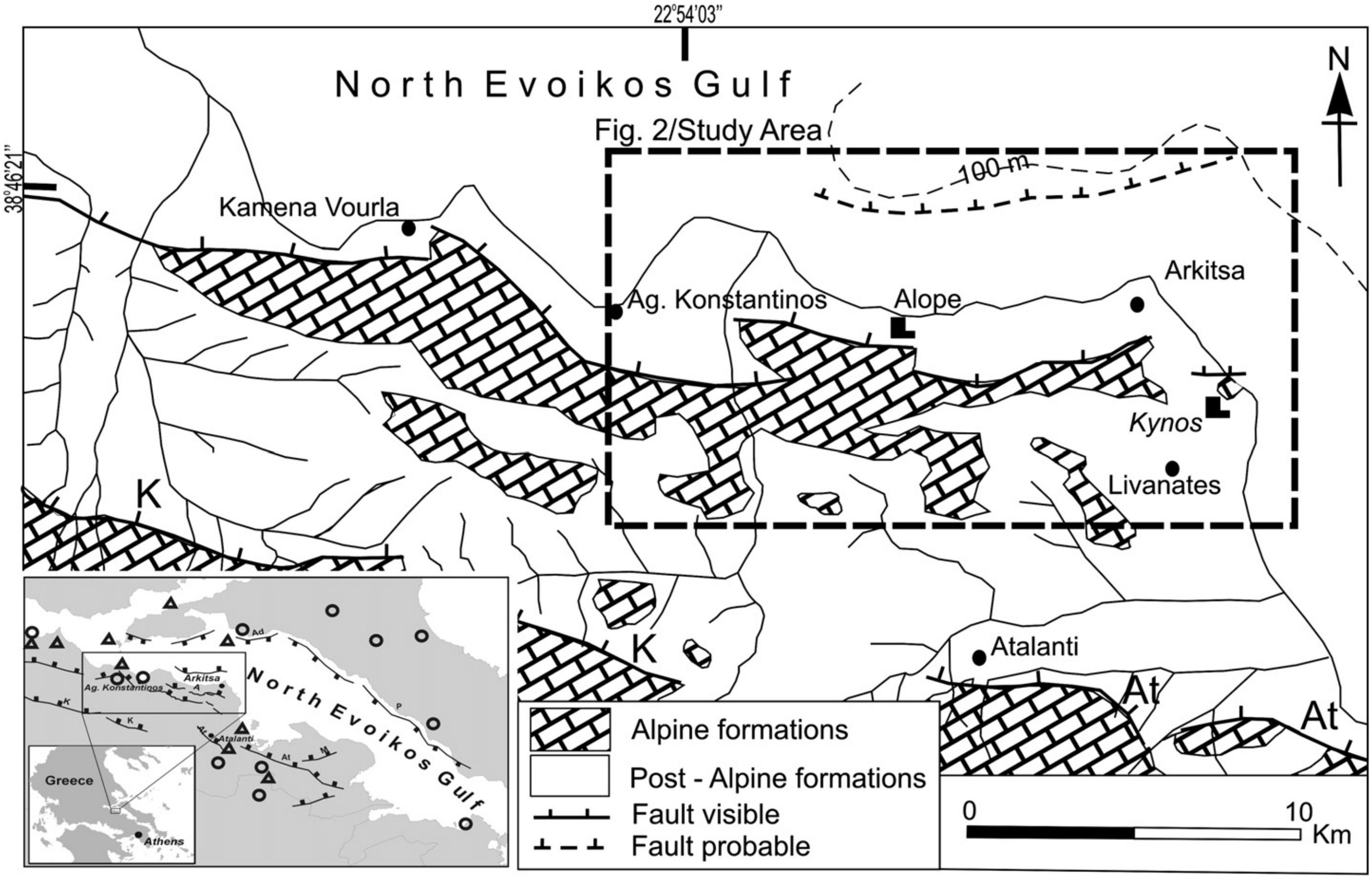

Fig. 1. Geological setting and tectonic structure of the Agios Konstantinos–Livanates coastal zone, north Evoikos Gulf, central Greece. Geological formations are drawn according to the geological maps of IGME. Inset map shows regional tectonic structure: K = Kalidromon fault; A = Arkitsa fault; At = Atalanti fault; M = Malesina fault; and Ad and P = Aedipsos–Politika fault system. Visible and probable faults are shown (Goldsworthy and Jackson, 2001; Sakellariou et al., 2007). Open triangles and circles in inset map show historical (up to AD 1900) and instrumental (after AD 1900) earthquakes respectively, of magnitude greater than or equal to 4.5.

1991; Ganas, 1997; Kranis, 1999). The fault zone displays very fresh tectonic landforms, but is not known to have hosted any major historical earthquakes (Roberts and Jackson, 1991), unlike the adjacent Atalanti (Locris) fault system, which ruptured in an M_s 6.8 event in 1894 and (according to some authors) in 426 BC, although the evidence for the latter is disputed (see Cundy et al., 2000; Pantosti et al., 2001). The evolution of the Kamena Vourla fault zone is poorly constrained, although Goldsworthy and Jackson (2001) argue that it is probably a relatively young system, initiated <1 Ma ago at the expense of the inland Kalidromon fault (Fig. 1). Jackson and McKenzie (1999) identify up to 50 increments of coseismic slip on the Arkitsa fault strand, implying that the Arkitsa segment is the active fault trace in the eastern part of the Kamena Vourla fault zone (Dewez, 2003). Dewez (2003) however identifies a series of uplifted and back-tilted terraces in the hangingwall and footwall of the Arkitsa fault, and argues that the present day dip pattern of these terraces is best explained by dislocation by the Arkitsa fault, followed by activation of, and rotational faulting on, a proposed secondary fault strand at Livanates running along the base of the prominent NNW–SSE trending Livanates escarpment (Fig. 2). Generally however the geodynamics, and notably the seismic hazard, of the tectonic structures in this part of the northern Evoikos Gulf remain poorly defined, as do those of the smaller secondary faults which have formed in the transfer zone between the Arkitsa fault strand and the historically active Atalanti fault zone to the southeast. Here, we focus on this Arkitsa segment, where we examine exposed coastal sediment sequences and coastal geomorphological indicators to assess the magnitude and timing of historical coastal elevational changes in the southeastern part of the Kamena Vourla fault system, and present the first detailed sedimentological evidence for late Holocene (possibly coseismic) coastal uplift in the northern Evoikos Gulf.

2. Methods

2.1. Geomorphology

In tectonically active areas, drainage systems are often influenced by the type, geometry, and recent activity of local faults, causing the development of a range of characteristic tectonic geomorphic features/indicators, including uplifted marine terraces, uplifted beachrocks, intense downcutting, knickpoints, alluvial cones and fans (Schumm, 1986; Leeder et al., 1991; Eliet and Gawthorpe, 1995; Burbank and Anderson, 2001; Gaki-Papanastassiou et al., 2007; Maroukian et al., 2008). In order to examine the influence of tectonism and to draw conclusions about the Quaternary landscape evolution of the Arkitsa area, detailed geomorphological mapping at a scale of 1:5000 was performed focusing on these features. In addition, the coastal slope, sediment size, beachrock formations, coastal stability and longshore drift were also mapped. Data were analysed using GIS technology.

2.2. Stratigraphy

Exposed coastal sedimentary sections were cleaned and logged, and intact shell material sampled for ^{14}C dating. Bulk sediment samples were also collected for macro- and micro-fossil analysis. The elevations of the exposed units were determined using a Jena 020A theodolite unit. In the absence of a reliable elevation benchmark, unit elevation was initially determined relative to a temporary benchmark,

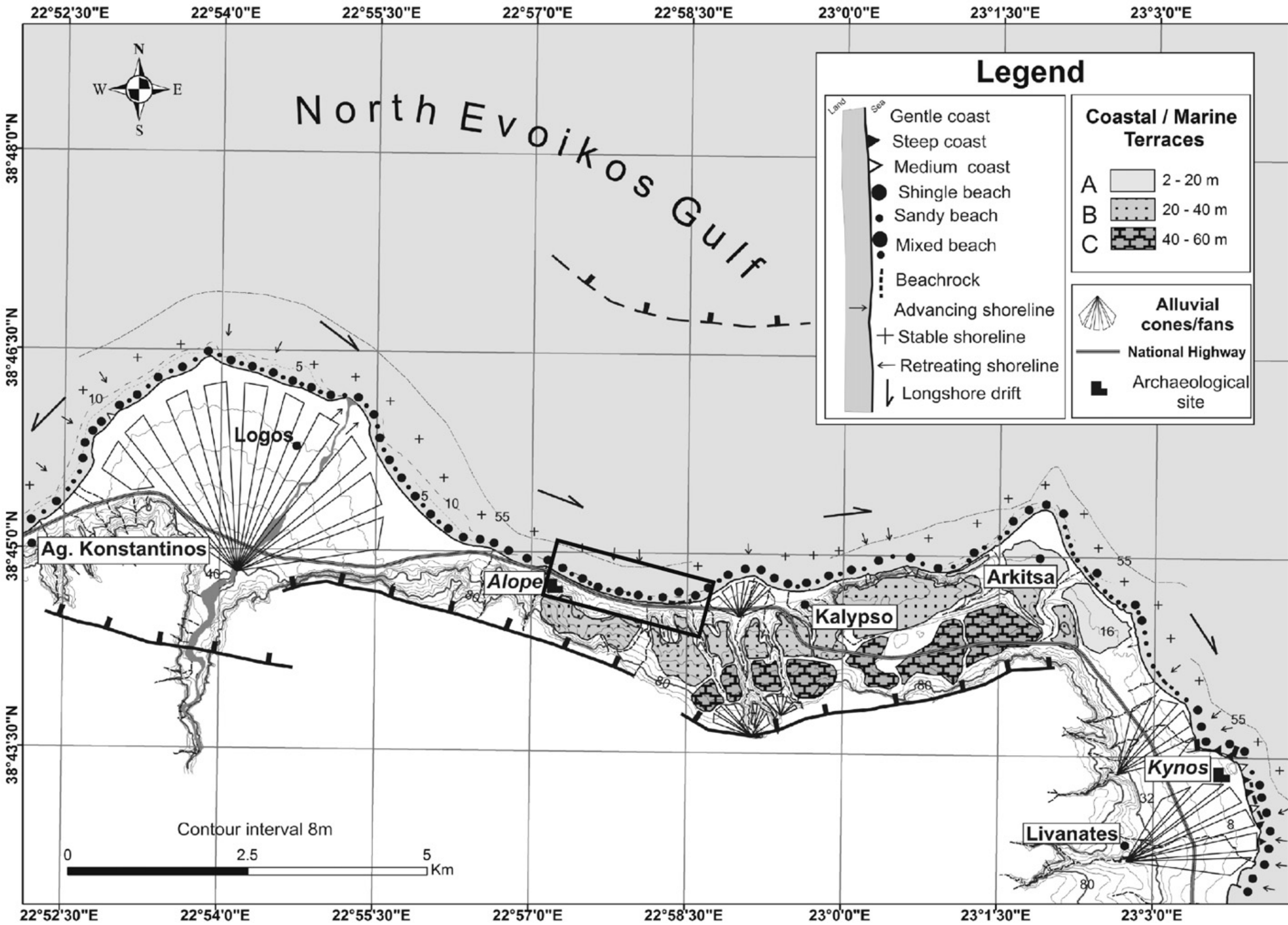

Fig. 2. Geomorphological map of coastal zone, Agios Konstantinos to Livanates. Faults are marked as in Fig. 1. Open black box marks the extent of exposure of the pebble conglomerate units Alope A and B (see text for details).

and then surveyed to contemporary sea level. All elevations are therefore reported relative to highest tidal level on 18th September 2006 (referred to subsequently here as HWL). The mean spring tidal range in the area is 60–70 cm (Cundy et al., 2000).

2.3. Radiometric dating

Intact carbonate shell material was screened using a Leo S420 scanning electron microscope (SEM) (to assess the extent of sample recrystallisation) and then dated via accelerator mass spectrometry ^{14}C assay (at the Beta Analytic Radiocarbon Dating Laboratory, Florida, U.S.A.). Radiocarbon age calibration was performed using the MARINE04 database (Hughen et al., 2004), via the programme CALIB 5.0 (Stuiver and Reimer, 1993). A ΔR value of -80 ± 25 years was used, corresponding to the local reservoir age correction for Mediterranean surface waters (Stiros et al., 1992; Pirazzoli et al., 1999).

2.4. Micro-fossil analysis

Sediment samples for faunal analysis were first disaggregated in water; small amounts of 5% H_2O_2 were added as necessary to aid the break-down process. Samples were then wet-sieved and the >63 µm grain-size fraction dried and retained for analysis (e.g. Griffiths and Holmes, 2000; Gehrels, 2002). Specimens were individually hand-picked under a reflected-light microscope (up to 80× magnification) and mounted on cavity slides. Foraminifera specimens were further analysed using a Leo S420 scanning electron microscope.

3. Results

3.1. Coastal geomorphology

The coastal geomorphology in the hangingwall of the Arkitsa fault strand is dominated by a series of deeply-incised colluvial fans and a number of distinct terraces, at elevations of +2–20 m (terrace A), +20–40 m (terrace B) and +40–60 m (terrace C) above mean sea level (Fig. 2). The terraces are apparently marine/lacustrine in origin, and are cut into Plio-Pleistocene marls, which are unconformably overlain by consolidated coastal sediments (Dewez, 2003). The terraces in the extreme southeast of this area, around the proposed Livanates secondary fault strand, are described in detail by Dewez (2003), with the 20–40 m terrace and 40–60 m terrace (Fig. 2) identified in the present study correlating with Dewez's T1 and T2 terraces respectively. The terraces are heavily incised by recent fluvial activity. In addition, north of the Arkitsa fault scarp (at 38° 43.680′N; 22°59.340′E) a series of small talus cones have formed during late Pleistocene–Holocene times, which are also deeply incised (Fig. 2).

The coastal zone itself is dominantly erosional (probably due to sediment starvation), with active sediment deposition confined to moderate to large fan deltas, most prominently (locally) the Loggos fan delta, and alluvial cones such as the Kalypso cone (Fig. 2 — immediately west of Kalypso village). On the northwestern edge of the Kalypso cone (38°44.683′N; 22°58.549′E), beachrock is exposed in the current intertidal and supratidal beach face. Two distinct beachrock units can be identified at Kalypso: a coarse pebble and boulder conglomerate unit at up to +0.5 m above HWL, and a finer (grit and small pebble) conglomerate in the current intertidal zone. While there is some variability in clast composition and size across the exposed section, the upper unit consists dominantly of a coarse sand/grit-supported pebble and boulder conglomerate, with sub-rounded to rounded limestone, dolomite, chert and metabasic clasts ranging between <1 cm and 40 cm diameter (modal size is 8–15 cm clast diameter). Occasional marine gastropod shells are present which have been eroded by marine action but have not undergone any detectable recrystallisation (based on SEM scanning of the shell walls). The upper surface of this beachrock unit is eroded and often irregular, but ranges in elevation between +0.3 and +0.5 m above HWL. The lower beachrock unit consists of a coarse sand supported grit and small pebble conglomerate, with rounded to sub-angular and oblate clasts of similar composition to the upper beachrock unit. Clast sizes range from <1 cm to 4 cm diameter, with occasional larger pebbles (up to 10 cm diameter). Shell material is infrequent in this unit, although isolated bivalve-rich sections are present. The bivalves present are highly weathered or present as shell fragments, and are of indeterminate species composition. No archaeological remains (e.g. ceramic fragments) were observed in either beachrock unit. Further reworked massive beachrock blocks (up to 2 m × 3 m, and 30–50 cm in thickness) are stacked at the rear of the beach (at elevations of +1.2–1.5 m above HWL) at approximately 5 m distance from the present high water level. This reworking may be a result of storm waves or other sudden marine flooding events such as tsunami, or disturbance by recent anthropogenic activity.

3.2. Coastal stratigraphy

At Alope (also referred to as Alopi in some texts, Fig. 2), adjacent to the Athens–Thessaloniki national road, coastal erosion has exposed a series of quasi-horizontal conglomeratic sedimentary units (Plate 1), described below, which have been partly incised and eroded by younger (abandoned) fluvio-torrential channels. The channels of these former torrents are clearly recognisable in the exposed coastal sections. The fill deposits in the channels consist of a poorly-sorted, unstratified pebble–boulder conglomerate in a sand and grit matrix. The channel-fill unit is matrix-supported, and boulders and pebbles angular to sub-rounded, and are dominantly carbonate (limestone and dolomite) and mafic (derived from local ophiolite sequences) in composition. Boulders of up to 1 m diameter are present, many of which have eroded out of the cliff, and are present in the contemporary beach face.

Plate 1. Exposed coastal section at Alope. The pebble conglomeratic units Alope A and B are clearly exposed in the photograph (in the lower 2/3 and the upper 1/3 of the visible exposure respectively, although the contact between the two units is not readily visible at this scale), Alope C is obscured by overhanging vegetation. Note the near-horizontal bedding of Alope A and B.

The main exposure at Alope described here occurs between 38°44.950′N, 22°57.235′E and 38°44.935′N, 22°57.275′E. Three main units are present (Fig. 3), recorded here as Alope A–C. The lowest exposed unit, Alope A, which extends below the present day beach face, consists of a (limestone and mafic/metabasic) pebble and cobble conglomerate. The matrix fines upwards from coarse sand at the base of the unit to fine sand at the top, although there is little evidence for any significant graded bedding in the pebble clasts. Clasts are generally oblate and sub-rounded, and show some evidence for imbrication into the cliff face (i.e. southwestwards). Frequent ceramics are present (although these are not archaeologically diagnostic), as was a highly corroded (base metal) coin. Marine gastropod (*Cerithium* sp.) shells are common in this unit. The unit is cemented into beachrock near to the base of the exposed section. This cemented base is present along the entire exposure, and forms a laterally continuous unit. Alope A is overlain by a pebble conglomerate (unit Alope B), consisting of oblate limestone, chert and mafic clasts in a silt and sand matrix. Oblate clasts show patchy imbrication into the cliff face. Ceramics are again present, with fragments of shell material (including *Cerithium* sp.). In the upper part of this unit, clasts are very densely packed, and are dominantly of limestone (>90% of the pebble clasts) composition. Alope B is overlain (unconformably) by the uppermost unit, Alope C, a massive silt and fine sand unit with angular to sub-angular (mainly limestone) pebbles, which grades into the contemporary soil. There was no evidence in unit Alope C for pebble imbrication, and shell material and ceramic fragments were apparently absent.

The pebble conglomerate of units Alope A and B is periodically exposed for a further ca. 1 km east along this section of the coast (Fig. 3), although the exposures are frequently poor and partly eroded, due to construction activity and deliberate waste dumping along the coast. Consequently, it is difficult to distinguish Alope A and B in these sections. No significant dip is observed in units Alope A and B over the length of the exposed sections (a very slight dip cannot be excluded due to the erosional surfaces observed between units). There is, however, some degree of lateral variability in the pebble conglomerate. Clast composition is similar throughout, but there is some variation in clast sphericity and size (clasts range in size from small pebbles (<5 cm diameter) to large cobbles of up to 25 cm diameter), and matrix composition (which ranges from fine sand to coarse sand/grit), across the length of the exposure.

3.3. Micro-fossil and macro-fossil evidence

Intact, reworked carbonate macro-fossils were common in unit Alope A, the low-diversity assemblage including several species of *Cerithium*, a robust gastropod common in Mediterranean shallow, nearshore environments, lagoons and estuaries (e.g. Batjakas and Economakis, 2002; De Smit and Bába, 2002). Non-articulated marine bivalve fragments were also present in this unit, including examples of *Spondylus* sp. Shell fragments were also present in unit Alope B, including fragments of *Cerithium* sp. and occasional shells of terrestrially-derived molluscan fauna. Micro-fossil remains were almost entirely absent throughout these sequences, except in unit Alope A. Occasional remains of marginal marine foraminifera (including examples of *Elphidium* and *Ammonia*) were present in section 06/4 (Fig. 3), though these showed clear evidence of dissolution processes (Fig. 4a). It would seem plausible that the general paucity of calcareous micro-fossils in these sequences (where they might otherwise be expected to occur) is due to post-depositional dissolution effects.

3.4. Radiocarbon and artefact dating

Two intact, reworked specimens of *Cerithium* sp. sampled from unit Alope A gave concordant (i.e. overlapping at the 2σ confidence interval) conventional radiocarbon ages of 2900 ± 40 BP and 2980 ± 40 BP (calibrated ages 1001–724 BC) (Table 1). A further *Spondylus* sp. (intact valve, but non-articulated) specimen sampled from unit Alope A (exposure 06/5, Fig. 3) gave a slightly older radiocarbon age of 3430 ± 40 BP (calibrated ages 1581–1332 BC) (Table 1). The highly corroded coin retrieved from unit Alope A (Fig. 4b) is a base metal *nummus* of Roman age. While the mint and emperor are illegible due to the highly degraded nature of the coin, its size and surface

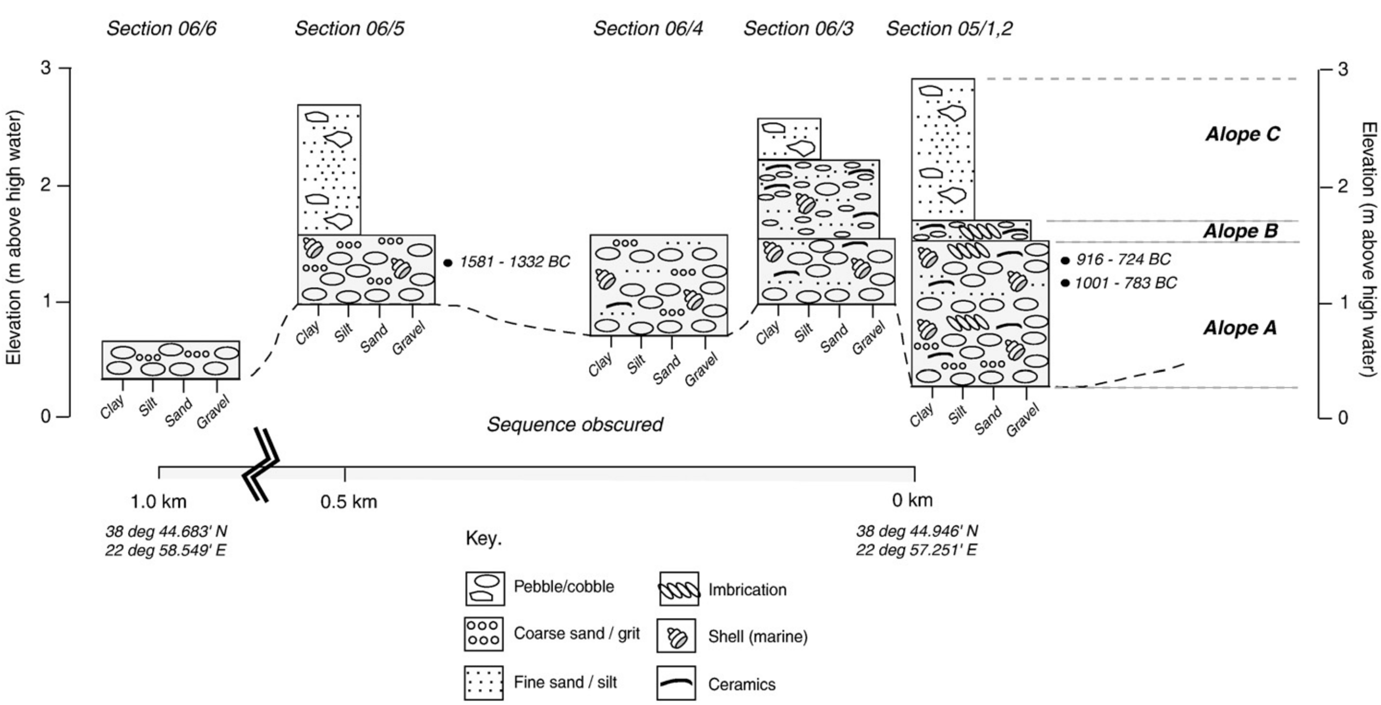

Fig. 3. Schematic log of pebble conglomerate exposure and vertical relationships, Alope coastline. Note the near-horizontal bedding in unit Alope A. The contact between Alope B and C is erosive and irregular. Sampling locations, and calibrated ages, of ^{14}C-dated shell material are marked (using filled black circles).

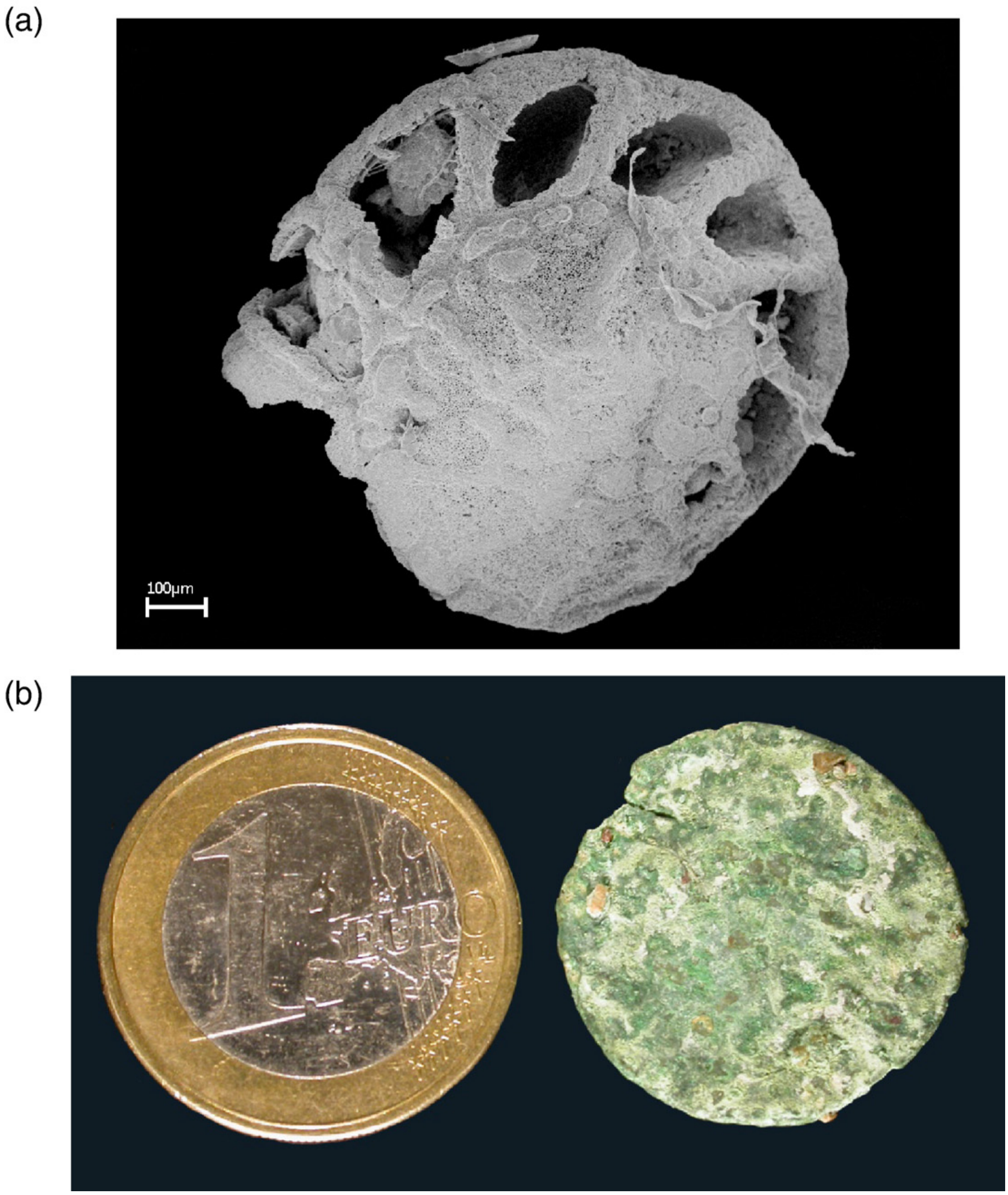

Fig. 4. (a) Scanning electron microscope image of marginal marine foraminifera (*Ammonia* sp.) from unit Alope A. Note clear dissolution of carbonate shell material. (b) Roman base metal *nummus* retrieved from unit Alope A, with 1 Euro coin (24 mm diameter, left) for scale.

morphology/patterning indicate that it is most likely of the *Reparatio Reipub* type, dating to AD 378–383 (Richard Abdy, Roman Coins Curator, British Museum, pers. comm.).

Other datable shell remains were found in the exposed beachrock sections described in Section 3.1. An almost intact marine gastropod specimen removed from the upper beachrock exposed at the Kalypso

Table 1
Radiocarbon and archaeological dates from Alope and Kalypso cone sequences, NW Evoikos Gulf, central Greece.

Sample[a]	Species/type	Unit	Sample elevation (above HWL[b]) (m)	Conventional ^{14}C age (a BP, $\pm 1\sigma$)	Lab. number	$^{13}C/^{12}C$ (‰)	Calibrated age (a BP)[c]
Shell	*Cerithium* sp.	Alope A (exposure 05/1)	1.10–1.61	2900 ± 40 BP	Beta-218939	+0.8	916–724 BC
Shell	*Cerithium* sp.	Alope A (exposure 05/1)	1.10–1.61	2980 ± 40 BP	Beta-218940	+0.7	1001–783 BC
Shell	*Spondylus* sp.	Alope A (exposure 06/5)	0.90–1.50	3430 ± 40 BP	Beta-236948	+1.6	1581–1332 BC
Coin	Base metal Roman *nummus*	Alope A (exposure 05/1)	1.10–1.61	–	–	–	AD 378–383[d]
Shell	Gastropod (sp. indet.)	Upper beachrock, Kalypso Cone	0.30	1820 ± 40 BP	Beta-236949	−0.1	AD 394–623

[a] Shell samples pretreated by etching with HCl.
[b] HWL = Highest tidal level on 18th September 2006. See text for discussion.
[c] Calibration performed using the MARINE04 database (Hughen et al. 2004), using the programme CALIB 5.0 (Stuiver and Reimer, 1993). A delta *R* value of −80 ± 25 years was used, corresponding to the local age reservoir of Mediterranean surface waters (Stiros et al. 1992, Pirazzoli et al. 1999). Values presented show a 2σ error margin.
[d] Age based on identification of coin as *Reparatio Reipub* type. Richard Abdy, Curator, Roman Coins, British Museum, pers. comm. See text for discussion.

cone (at +0.3 m above HWL) gave a conventional ^{14}C age of 1820 ± 40 BP (calibrated ages AD 394–623). This date should be regarded as providing a maximum age for this deposit, as the shell was clearly not *in-situ*.

4. Discussion

The coastal stratigraphy at Alope contains two prominent units which show evidence of coastal or marine deposition: Alope A and Alope B. Both units contain marine (specifically shallow or nearshore marine) -derived macro-fossil material and, despite poor preservation due to dissolution effects (Section 3.3), marginal marine foraminifera. While dissolution effects (and physical abrasion in these relatively coarse-grained units) mean that the more robust shells, such as *Cerithium* sp. and *Spondylus* sp., are significantly over-represented in the preserved faunal assemblage, the assemblage is clearly indicative of deposition in a marginal marine environment. Sparse, terrestrially-derived molluscan fauna were observed in unit Alope B, which most probably represent later "contamination" (due to subsequent colonisation of the exposed strata by terrestrial species), or which may have been blown or washed in from the local terrestrial environment, the lower energy/finer grain size of this unit ensuring that they were preserved. Although archaeological material is present in both Alope A and Alope B, it is unlikely that these deposits represent cultural middens or other anthropogenic structures/constructions. Archaeological remains are common in the local area: An archaeological excavation behind the observed coastal sections (Whitley, 2002) has revealed a 4th Century BC city wall of the town of Ancient Alope, plus part of a cemetery, while the (nearby) Alope acropolis also shows evidence of Myceanaean and Roman habitation. While these sites provide a possible source of Roman-age (and earlier) artefacts and ceramics (including coinage) to the Alope sections, the lateral extent of the exposures at Alope (ca. 1 km), the relatively limited range of cultural artefacts present, and the lack of obvious constructional stones or blocks, indicate that the Alope sections are not middens or anthropogenic constructional features (e.g. an engineered coastal protection structure).

The apparently marginal marine units of Alope A and B are present at elevations >1 m above contemporary HWL, indicating either post-depositional uplift, or deposition via a high-magnitude marine flooding event (e.g. a tsunami). The apparently recent (Late Holocene) age of these units (Section 3.4 and Table 1) precludes the idea that they may have been deposited during earlier sea-level highstand events, i.e. the 125,000 year BP Tyrrhenian highstand or the proposed 6000 BP mid-Holocene highstand (e.g. Kelletat, 2005). The coasts of the Evoikos Gulf are known to be subject to inundation by periodic tsunami, and local tsunami have been described or hypothesised by a number of authors, including a supposed >6 m high tsunami at the nearby Kynos site in Late Helladic times (12th century BC, Dakoronia, 1996), although the evidence for this event is not conclusive, and its possible source is unconstrained. Tsunami have been recorded in this area associated with earthquakes in 426BC (see discussion by Papaioannou et al., 2004) and 1894 (Cundy et al., 2000). For the latter event, Sakellariou et al. (2005) identify a submarine landslide deposit NW of Arkitsa as a potential trigger for the tsunami, although the event left little discernible sedimentary signature in recent coastal deposits (Cundy et al., 2000). Comparison of various features of the proposed marginal marine unit Alope A with sedimentary and micro-fossil criteria proposed as being diagnostic of tsunami deposition (Dominey-Howes et al., 2006) indicates that Alope A lacks a range of criteria indicative of deposition by tsunami activity (e.g. distinctive layering, upwards fining of grain size, and cross bedding). In particular, the observed macro- and micro-faunal assemblage, which lacks pelagic and deeper water benthic species and is dominated by estuarine/shallow marine gastropods and bivalves (including well-preserved specimens) and marginal marine foraminifera, is not consistent with tsunami deposition. This, coupled with the relative thickness of the deposit (in excess of 1.5 m) compared to other (proposed) tsunamigenic sediments in Greece (e.g. Gaki-Papanastassiou et al., 1999, 2001; Dominey-Howes et al., 2000; Kontopoulos and Avramidis, 2003), indicates that the unit was most likely deposited in a marginal marine environment such as a beach or nearshore area, and subsequently uplifted. This uplift was followed by partial erosion/incision by younger (now abandoned) fluvio-torrential channels, and deposition of colluvial fan material (i.e. the poorly-sorted, silt and fine sand with angular/sub-angular clasts deposit of unit Alope C).

The maximum age of unit Alope A is ca. AD 378–383 (based on the age of the Roman coin recovered from this unit). Notably, this age is significantly younger than that indicated by the ^{14}C ages of shell material retrieved from the unit (Table 1). The coin sampled was clearly incorporated into the deposit (and was not apparently added recently as "contamination"), and was present alongside frequent (although non-archaeologically diagnostic) ceramic fragments. The apparently diachronous ages indicated by the archaeological and the ^{14}C evidence may be due to either (or a combination of): (a) a considerable period of reworking of the ^{14}C-dated shell material prior to incorporation into the deposit (indicated by the preferential preservation of more robust shell material), coupled with possible uncertainties in the local reservoir age correction (ΔR); or (b) archaeological disturbance and burial of the archaeological artefacts during Roman habitation of the area, although there is little clear stratigraphic evidence for this. Despite these chronological uncertainties, the presence of late Holocene marginal marine deposits at elevations >1 m above high water suggest significant recent coastal uplift. Assuming a regional sea-level rise of 0.5 mm/year (based on data in Lambeck, 1996 and Pirazzoli et al., 1999), the ^{14}C-derived shell ages and the numismatic date indicate uplift rates of 1 mm/year or more (the units provide minimum uplift estimates as a consequence of the lack of *in-situ* datable material, and possible incorporation of older shell and archaeological material; possible erosion of their upper surface(s); and the lack of fossils that can be used to determine a precise relationship with a former (palaeo)sea level).

The evidence for recent uplift at Alope is consistent with local geomorphological evidence (cf. Section 3.1), specifically the presence of heavily-incised raised coastal/marine terraces and talus cones inland (south and southwest) of the coastal sections. The beachrock deposits present in the contemporary supratidal beach face at Kalypso (described in Section 3.1) may also record uplift — the upper beachrock unit described in Section 3.1 is clearly located significantly above HWL, and includes incorporated marine gastropods, and so may have been exposed by a combination of uplift and shoreline regression. The (maximum) ^{14}C age on this upper beachrock unit is significantly younger than the ^{14}C and archaeological dates for unit Alope A, indicating relatively recent formation (and possibly uplift). It should be noted however that beachrock formation may potentially occur in the supratidal zone (e.g. Kelletat 2006), and so the use of beachrock as a precise sea-level indicator in uplifted coastal sections, particularly where its elevation is close to contemporary sea level, is potentially problematic (e.g. Kelletat, 2005, Vousdoukas et al., 2007).

The apparent coastal uplift observed at Alope (i.e. in sections Alope A and B) has occurred in the hangingwall of the prominent (normal) Arkitsa fault. As noted previously, Dewez (2003) invokes rotational faulting on a proposed secondary fault strand at Livanates to explain the morphology of uplifted terraces in the hangingwall of the Arkitsa fault, but a lack of significant dip in the exposed (uplifted) coastal sections at Alope (Plate 1), and their distance from the proposed Livanates fault (which exceeds 8 km, Fig. 2), indicates that the Livanates fault strand is highly unlikely to be responsible for the observed uplift at Alope (or (possibly) at Kalypso). Instead, the observed pattern of uplift in the coastal sections described here can be much more coherently explained by either aseismic (regional) uplift, or uplift on the footwall of an offshore, shore-parallel fault strand. For the former mechanism, the estimated uplift rate of 1 mm/year or greater at Alope is significantly higher than long-term (footwall) uplift rates of 0.2 mm/year calculated for the western end of the Kamena Vourla fault zone by Goldsworthy and Jackson (2001). Given these much lower long-term uplift rates, it is highly unlikely that the rapid uplift that has apparently occurred at Alope over the Late Holocene can be explained by regional (aseismic) deformation. Instead, the uplift is most likely due to recent coseismic movement (s). Age uncertainties mean that it is not possible to reliably correlate the proposed coastal uplift at Alope with historical (documented) earthquake events, although it is notable that the postulated uplift of the deposits at Alope apparently post-dates a +1.4 m uplift argued by Pirazzoli et al. (1999) to have occurred on a local fault strand at Kynos (to the southeast of the study area, Fig. 2) between 360 BC and AD 210. Recent offshore geological and geophysical surveys in the northern Evoikos Gulf published in Sakellariou et al. (2007) have shown several sites of submarine faulting and seafloor ruptures, and these authors infer the presence of a secondary, E–W trending, normal fault system offshore of Alope (Fig. 1). Activation of this putative offshore fault provides a mechanism to generate the uplift observed along the Alope coast, although seismic and sub-bottom profiling across the north Evoikos Gulf has (as of yet) failed to discriminate any clear evidence for movement on this offshore fault strand (Sakellariou et al., 2007). The stratigraphic and geomorphological evidence presented here indicates the need for further detailed offshore geophysical and geological work in the NW Evoikos Gulf, and detailed studies (including dating) of the raised inland terraces around Arkitsa (which have been described in previous work, but which have, as of yet, poor chronological control) to better constrain Late Quaternary uplift patterns, and the activity of offshore fault strands in this region.

5. Conclusions

Late Holocene, uplifted, marginal marine deposits crop out in the coastal zone around the settlements of Alope and Kalypso, on the southern shoreline of the NW Evoikos Gulf, central Greece. Estimated Late Holocene coastal uplift rates (based on ^{14}C and archaeological dating of the uplifted deposits) greatly exceed reported long-term regional uplift rates in the area, and indicate local, recent, coseismic uplift. While correlation of uplift with documented historical earthquake events in the region is not possible due to uncertainties in the dating of these coastal sections, the pattern of uplift of these deposits is most consistent with uplift on an offshore, shore-parallel, fault strand north of Arkitsa.

Acknowledgements

Richard Abdy, Roman coins curator at the British Museum, is thanked for identification of the Roman coin found in unit Alope A. David Addison (University of Sussex) provided laboratory support for micro-fossil analysis, while Konstantinos Tsanakas, Miriam Rose and Laura Welsh are thanked for their assistance in the field. This work was partially supported by the Special Account for Research Grants (ELKE) of the University of Athens. Dimitris Sakellariou, and one anonymous reviewer, are thanked for constructive and thorough reviews of an earlier version of this manuscript.

References

Batjakas, I.E., Economakis, A.E., 2002. The Greek Seashore : A Field Guide to Coastal Invertebrates. Efstathiadis Group, Athens. 226 pp.

Billiris, H., Paradissis, D., Veis, G., England, P., Featherstone, W., Parsons, B., Cross, P., Rands, P., Rayson, M., Sellers, P., Ashkenazi, V., Davison, M., Jackson, J., Ambraseys, N., 1991. Geodetic determination of tectonic deformation in Central Greece from 1900 to 1988. Nature 350, 124–129.

Burbank, D., Anderson, R., 2001. Tectonic Geomorphology. Blackwell Publishing, Oxford. 288 pp.

Cundy, A.B., Kortekaas, S., Dewez, T., Stewart, I.S., Collins, P.E.F., Croudace, I.W., Maroukian, H., Papanastassiou, D., Gaki-Papanastassiou, K., Pavlopoulos, K., Dawson, A., 2000. Coastal wetlands as recorders of earthquake subsidence in the Aegean: a case study of the 1894 Gulf of Atalanti earthquakes, central Greece. Marine Geology 170, 3–26.

Dakoronia, P.H., 1996. Earthquakes of the Late Helladic III period (12th century BC) at Kynos (Livanates, central Greece). In: Stiros, S., Jones, R.E. (Eds.), Archaeoseismology, British School at Athens, Fitch Laboratory Occasional Paper, 7, pp. 41–50.

De Smit, M., Bába, K., 2002. New data to the marine malacofauna from Euboea Island (Greece). Malacological Newsletter 20, 83–91.

Dewez, T.J.B. 2003. Geomorphic markers and digital elevation models as tools for tectonic geomorphology in Central Greece. Unpublished PhD thesis, Brunel University, Uxbridge, U.K., 173 pp.

Dominey-Howes, D.T.M., Cundy, A.B., Croudace, I.W., 2000. High Energy Marine Flood Deposits on Astypalaea Island, Greece: Possible Evidence for the ^{AD}1956 southern Aegean Tsunami. Marine Geology 163, 303–315.

Dominey-Howes, D.T.M., Humphreys, G.S., Hesse, P.P., 2006. Tsunami and palaeotsunami depositional signatures and their potential value in understanding the late-Holocene tsunami record. Holocene 15, 1095–1107.

Eliet, P., Gawthorpe, R., 1995. Drainage development and sediment supply within rifts, examples from the Sperchios basin, central Greece. Journal of the Geological Society of London 152, 883–893.

Gaki-Papanastassiou, K., Maroukian, H., Papanastassiou, D., Palyvos, N., 1999. Geoarchaeology and morphotectonics of the area of Livanates–Kynos–Arkitsa during the Holocene. 5th Greek Geographical congress. Athens, 11–13 Nov, pp. 101–111. in Greek.

Gaki-Papanastassiou, K., Papanastassiou, D., Maroukian, H., 2007. Recent uplift rates at Perachora Peninsula, east Gulf of Corinth, Greece, based on geomorphological–archaeological evidence and radiocarbon dates. Hellenic Journal of Geosciences 42, 45–56.

Gaki-Papanastassiou, K., Maroukian, H., Papanastassiou, D., Palyvos, N., Lemeille, F., 2001. Geomorphological study in the Lokrian coast of N. Evoikos Gulf (Central Greece) and evidence of Palaeoseismic destructions. 36th CIESM Congress, Monaco, Sept 2001.

Ganas, A. 1997. Fault segmentation and seismic hazard assessment in the Gulf of Evia rift, Central Greece. Unpublished PhD Thesis, University of Reading, Reading, U.K. 368 pp.

Gehrels, W.R., 2002. Intertidal foraminifera as palaeoenvironmental indicators. In: Haslett, S.K. (Ed.), Quaternary Environmental Micropalaeontology. Arnold, London, pp. 91–114.

Goldsworthy, M., Jackson, J., 2001. Migration of activity within normal fault systems: examples from the Quaternary of mainland Greece. Journal of Structural Geology 23, 489–506.

Griffiths, H.I., Holmes, J.A., 2000. Non-marine ostracods and Quaternary palaeoenvironments. : Technical Guide, 8. Quaternary Research Association, London. 188 pp.

Hollenstein, Ch., Muller, M.D., Geiger, A., Kahle, H.-G., 2008. Crustal motion and deformation of Greece from a decade of GPS measurements, 1993–2003. Tectonophysics 449, 17–40.

Hughen, K.A., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Kromer, B., McCormac, F.G., Manning, S.W., Bronk Ramsey, C., Reimer, P.J., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. Marine04 Marine radiocarbon age calibration, 26–0 ka BP. Radiocarbon 46, 1059–1086.

Institute of Geology and Mining Research (I.G.M.E) geological maps 1:50.000. Sheets Elatia, Livanates, Pelasgia (Myli).

Jackson, J., McKenzie, D., 1999. A hectare of fresh striations on the Arkitsa Fault, central Greece. Journal of Structural Geology 21, 1–6.

Kelletat, D., 2005. A Holocene sea-level curve for the Eastern Mediterranean from multiple indicators. Zeitschrift für Geomorphologie Suppl. 137, 1–9.

Kelletat, D., 2006. Beachrock as sea-level indicator? Remarks from a geomorphological point of view. Journal of Coastal Research 22, 1555–1564.

Kontopoulos, N., Avramidis, P., 2003. A late Holocene record of environmental changes from the Aliki lagoon, Egion, North Peloponnesus, Greece. Quaternary International 111, 75–90.

Kranis, H.D., 1999. Fault zone neotectonic activity in Lokris. Unpublished PhD Thesis. Dept. of Geology, Athens University, Greece.

Lambeck, K., 1996. Sea-level change and shoreline evolution in Aegean Greece since Upper Palaeolithic time. Antiquity 70, 588–611.

Leeder, M.R., Seger, M.J., Stark, C.P., 1991. Sedimentation and tectonic geomorphology adjacent to major active and inactive normal faults, southern Greece. Journal of the Geological Society of London 148, 331–343.

Makris, J., Papoulia, J., Papanikolaou, D., Stavrakakis, G., 2001. Thinned continental crust below northern Evoikos Gulf, central Greece, detected from deep seismic soundings. Tectonophysics 341, 225–236.

Maroukian, H., Gaki-Papanastassiou, K., Karymbalis, E., Vouvalidis, K., Pavlopoulos, K., Papanastassiou, D., Albanakis, K., 2008. Morphotectonic control on drainage network evolution in the Perachora Peninsula, Greece. Geomorphology 102, 81–92.

Moretti, I., Sakellariou, D., Lykousis, V., Micarelli, L., 2003. The Gulf of Corinth: an active half graben? Journal of Geodynamics 36, 323–340.

Pantosti, D., De Martini, P.M., Papanastassiou, D., Palyvos, N., Lemeille, F., Stavrakakis, G., 2001. A reappraisal of the 1894 Atalanti earthquake surface ruptures, central Greece. Bulletin of the Seismological Society of America 91, 760–780.

Papaioannou, I., Papadopoulos, G.A., Pavlides, S., 2004. The earthquake of 426BC in N. Evoikos gulf revisited: amalgamation of two different strong earthquake events? Bulletin of the Geological Society of Greece, XXXVI. Proceedings of the 10th International Congress, Thessaloniki, April 2004, pp. 1477–1481.

Papanastassiou, D., Stavrakakis, G., Makaris, D., 2001. Recent micro-earthquake activity at northern Evoikos gulf, central Greece. Bulletin of the Geological Society of Greece XXXIV, 1567–1572.

Papanikolaou, D.J., Royden, L.H., 2007. Disruption of the Hellenic arc: late Miocene extensional detachment faults and steep Pliocene-Quaternary normal faults-or what happened at Corinth? Tectonics 26, TC5003 doi:10.1029/2006TC002007.

Papoulia, J., Makris, J., Drakopoulou, V., 2006. Local seismic array observations at north Evoikos, central Greece, delineate crustal deformation between the North Aegean Trough and Corinthiakos Rift. Tectonophysics 423, 97–106.

Pirazzoli, P.A., Stiros, S.C., Arnold, M., Laborel, J., Laborel-Deguen, F., 1999. Late Holocene coseismic vertical displacements and tsunami deposits near Kynos, Gulf of Euboea, central Greece. Physics and Chemistry of the Earth (A) 24, 361–367.

Roberts, S., Jackson, J., 1991. Active normal faulting in central Greece: an overview. The Geometry of Normal Faults. : In: Roberts, A.M., Yielding, G., Freeman, B. (Eds.), Geological Society Special Publications, 56. Geological Society, London, pp. 125–142.

Sakellariou, D., Karambas, Th., Lykousis, V., Rousakis, G., Alexandri, S., Georgiou, P., Nomikou, P., Kaberi, H., Ballas, D., Papoulia, I., 2005. Tsunami hazard in the North Evia Gulf: source areas, triggering mechanism and propagation of past and future tsunamis. Proceedings of the 22nd IUGG International Tsunami Symposium, Chania, 27–29 June 2005, page 312.

Sakellariou, D., Rousakis, G., Kaberi, H., Kapsimalis, V., Georgiou, P., Kanellopoulos, Th., Lykousis, V., 2007. Tectono-sedimentary structure and Late Quaternary evolution of the North Evia Gulf basin, central Greece: preliminary results. Bulletin of the Geological Society of Greece XXXX, 451–462.

Schumm, S.A., 1986. Alluvial river response to active tectonics. Active Tectonics. National Academic Press, Washington D.C, pp. 80–94.

Stefatos, A., Papatheodorou, G., Ferentinos, G., Leeder, M., Collier, R., 2002. Seismic reflection imaging of active offshore faults in the Gulf of Corinth: their seismotectonic significance. Basin Research 14, 487–502.

Stiros, S.C., Arnold, M., Pirazzoli, P.A., Laborel, J., Laborel, F., Papageorgiou, S., 1992. Historical coseismic uplift on Euboea Island, Greece. Earth and Planetary Science Letters 108, 109–117.

Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C database and revised CALIB radiocarbon calibration program. Radiocarbon 35, 215–230.

Vousdoukas, M.I., Velegrakis, A.F., Plomaritis, T.A., 2007. Beachrock occurrence, characteristics, formation mechanisms and impacts. Earth Science Reviews 85, 23–46.

Whitley, J., 2002. The archaeology in Greece 2002–2003, archeological reports. The Society for the Promotion of Hellenic Studies, pp. 1–88.