

1 **The uplifted terraces of the Arkitsa region, NW Evoikos Gulf, Greece: a**
2 **result of combined tectonic and volcanic processes?**

3
4 Dimitris Papanastassiou¹, A. B. Cundy^{2*}, K. Gaki-Papanastassiou³, M. R. Frogley⁴, K.
5 Tsanakas³, H. Maroukian³

6
7
8 ¹ Institute of Geodynamics, National Observatory of Athens, Gr 11810 Athens, Greece

9 ² School of Environment and Technology, University of Brighton, Brighton, BN2 4GJ, UK

10 ³ Department of Geography-Climatology, University of Athens, Gr 15784 Athens, Greece

11 ⁴ Department of Geography, University of Sussex, Falmer, Brighton, BN1 9QJ, UK

12 * Corresponding author: School of Environment and Technology, University of Brighton, Brighton, BN2
13 4GJ, UK. Email: A.Cundy@brighton.ac.uk; Tel: +44 1273 642270; Fax: +44 1273 642285

14 **ABSTRACT**

15 The Arkitsa-Kamena Vourla area of central Greece occupies a zone of accommodation
16 between the two tectonic provinces of the North Aegean Trough (the extension of the
17 North Anatolian fault system) and the Gulf of Corinth, and is characterised by a series
18 of very prominent tectonic landforms, notably the large (*ca.* 1000 m elevation)
19 footwall ridge of the Arkitsa-Kamena Vourla fault system. Despite the highly prominent
20 nature of this footwall ridge and the presence of very fresh tectonic landforms this
21 fault system is not known to have hosted any major historical earthquakes, and the
22 tectonic and geomorphic evolution of the Arkitsa-Kamena Vourla area remains poorly
23 constrained. This paper utilises a combined geomorphological, sedimentological and
24 macro-/micro-fossil approach to evaluate the Late Quaternary evolution of the Arkitsa
25 area, in the eastern part of the fault system, focussing on prominent uplifted terraces
26 present in the hangingwall of the Arkitsa fault. Three distinct raised glacio-lacustrine
27 terraces, and previously reported uplifted marginal marine deposits, suggest sustained
28 uplift of the coastline at a rate of 1 – 1.5 mm/y over at least the last 40,000 years,
29 possibly to 75,000 BP. While movement on an offshore normal fault strand may
30 explain more recent coastal uplift, purely fault-driven longer-term uplift at this rate
31 requires anomalously high fault slip and extension rates. Consequently, the
32 development of the terraces and other geomorphic indicators of uplift may be at least
33 partly due to non-faulting processes, such as Quaternary (intrusive and/or extrusive)
34 volcanic activity associated with evolution of the nearby Lichades volcanic centre.

35
36 **Keywords:** coastal uplift; central Greece; tectonic geomorphology; palaeo-terraces;
37 normal faulting; sea-level

38

39 **Introduction.**

40 The active normal faulting region of central Greece has been the focus of intense
41 research, due to its relatively high rates of tectonic deformation and the frequent
42 occurrence of damaging moderate magnitude ($M_s \approx 6-7$) earthquakes. The structure of
43 central Greece is dominated by a series of roughly WNW-ESE-trending extensional
44 faults. These have created a series of half- (asymmetric) grabens bordered by
45 discontinuous normal faults, the most prominent of which are the Gulf of Corinth and
46 the Evoikos Gulf. Of these two structures, the Evoikos Gulf, and particularly its
47 northern part, is relatively poorly understood in terms of its geodynamic structure and
48 tectonic significance (e.g. Makris et al., 2001). The Arkitsa-Kamena Vourla area
49 occupies the southern part of the northern Evoikos Gulf (Figure 1) and is characterised
50 by a series of very prominent tectonic landforms, notably the large (*ca.* 1000 m
51 elevation) footwall ridge of the Kamena Vourla fault system. This ridge is one of the
52 major geomorphological features of the northern Evoikos Gulf, and is the surface
53 expression of three major left-stepping (normal) fault segments: the Kamena Vourla,
54 the Agios Konstantinos, and the Arkitsa faults (Roberts and Jackson, 1991; Ganas,
55 1997; Kranis, 1999) (Figure 2 and 3). While it is clear that the northern Evoikos Gulf
56 occupies a zone of accommodation between the two tectonic provinces of the North
57 Aegean Trough (the extension of the North Anatolian fault system) and the Gulf of
58 Corinth (Mitsakaki et al., 2013; see Papanikolaou and Royden, 2007 for regional
59 summary), the interaction between these provinces is not well understood. Recent
60 GPS measurements indicate that the northern Evoikos Gulf is subject to a relatively low
61 magnitude extensional strain field (Hollenstein et al., 2008) which, apparently
62 contradicting the regional geomorphic evidence, should prohibit the development of
63 large faults. Recent research indicates that seismic stress in this area may not
64 necessarily be released with strong earthquakes, but instead with intense
65 microearthquake activity, usually in swarms (Papanastassiou et al., 2001; Papoulia et
66 al., 2006). Indeed, despite the highly prominent nature of the footwall ridge and the
67 presence of very fresh tectonic landforms, the Arkitsa-Kamena Vourla fault system is
68 not known to have hosted any major historical earthquakes (Roberts and Jackson,

69 1991) and the tectonic (and geomorphic) evolution of the wider Arkitsa-Kamena
70 Vourla area remains poorly constrained.

71 Goldsworthy and Jackson (2001) argue that the Kamena Vourla fault zone is probably a
72 relatively young system, initiated < 1 Ma ago at the expense of the inland Kalidromon
73 fault (located SW of Mt. Knimis, Figure 1 - see Figure 5a of Goldsworthy and Jackson,
74 2001). Jackson and McKenzie (1999) identify up to 50 increments of coseismic slip on
75 the Arkitsa fault strand, implying that the Arkitsa segment is the active fault trace in
76 the eastern part of the Kamena Vourla fault zone (Dewez, 2003). More recently
77 however Cundy et al., (2010) have identified and described a prominent raised
78 marginal marine unit (most likely a raised beach) and possibly uplifted beachrock in
79 the coastal zone occupying the hanging wall of the Arkitsa fault, near the
80 archaeological site of Alope, which these authors argue indicates recent uplift (in a
81 series of coseismic events) along a possible active offshore fault strand over the late
82 Holocene. Indeed, offshore geological and geophysical surveys carried out in the
83 northern Evoikos Gulf under the recent AMFITRITI project of the Hellenic Centre for
84 Marine Research (HCMR) (<http://amphitriti.ath.hcmr.gr>) identify several sites of
85 submarine faulting and seafloor ruptures and the presence of an E–W trending normal
86 fault system offshore of Alope / Arkitsa (Figure 2) is inferred. The activation of this
87 inferred offshore fault offers a mechanism to generate the uplift observed by Cundy et
88 al., (2010) along the Alope coast, although seismic and sub-bottom profiling across the
89 north Evoikos Gulf have (as of yet) failed to discriminate any clear evidence for
90 movement on this offshore fault strand (Sakellariou et al., 2007).

91
92 Based on radiocarbon dating of preserved marine fauna and numismatic dating Cundy
93 et al. (2010) propose an average coastal uplift rate at Alope over the last 3000 years in
94 excess of 1 mm/y. While it was unclear to what extent this rapid uplift rate had been
95 sustained over the Late Quaternary, the same authors also note the presence of a
96 series of geomorphological features (terraces (previously noted by Mercier, Dewez and
97 others (Dewez 2003)), cones etc.) between the coast and the Arkitsa fault strand which
98 may indicate longer-term uplift. Here, we present the first detailed multi-proxy study
99 of these geomorphic indicators (via a combined geomorphological, sedimentological

100 and macro-/micro-fossil approach), focussing in particular on three prominent terraces
101 in the hangingwall of the Arkitsa fault, and evaluate the Late Quaternary evolution and
102 uplift dynamics of this important zone of tectonic strain transfer.

103

104 **Materials and Methods.**

105

106 **Geomorphological mapping.**

107 Detailed geomorphological mapping at a scale of 1:5000 was performed in a series of
108 field seasons between 2007 and 2010, focusing on the prominent terraces around
109 Arkitsa previously noted by Dewez (2003) and Cundy et al., (2010), and other potential
110 tectonic geomorphic features such as knickpoints, incised alluvial cones or fans, etc. In
111 addition, 1:5000 scale topographic maps were digitised and analysed using GIS
112 technology and terraces and other features visualised and delineated using a digital
113 elevation model (DEM).

114

115 **Stratigraphy.**

116 Exposed sedimentary sections of terrace material (particularly the “cap-rock” of the
117 terrace surfaces) were cleaned and logged, and intact shell material sampled for ¹⁴C
118 dating. The elevations of the exposed units were determined using a Jena 020A
119 theodolite unit, or from 1:5000 scale maps.

120

121 **Radiometric dating.**

122 Intact carbonate shell material was dated via accelerator mass spectrometry ¹⁴C assay
123 (at the Beta Analytic Radiocarbon Dating Laboratory, Florida, U.S.A.). Radiocarbon age
124 calibration (where possible, i.e. on lower elevation, more recent material) was
125 performed using the MARINE04 database (Hughen et al., 2004), via the programme
126 CALIB 5.0 (Stuiver and Reimer, 1993). A ΔR value of -80 ± 25 years was used,
127 corresponding to the local reservoir age correction for Mediterranean surface waters
128 (Stiros et al., 1992; Pirazzoli et al., 1999).

129

130 **Microfossil analysis.**

131 Approximately 250 g of material from each terrace was processed for microfossil
132 analysis using a variation of the Glauber's Salt method (Franke, 1922; Wicher, 1942).
133 Indurated sediment samples were soaked in a hot, super-saturated solution of
134 hydrated sodium sulphate and slowly allowed to cool before being frozen overnight.
135 The samples were subsequently defrosted in a microwave oven and the soak-freeze-
136 thaw cycle repeated until the sediments had been sufficiently disaggregated; they
137 were then wet-sieved at $>63\ \mu\text{m}$ to remove any finer material. The residue was dried
138 overnight in an oven at 105°C before being examined under a reflected-light binocular
139 microscope (up to 80 x magnification). Specimens were individually hand-picked from
140 small ($\sim 5\ \text{g}$) residue sub-samples and mounted on cavity slides. Identification of the
141 ostracod fauna was made with reference to Meisch (2000).

142

143 **Results.**

144

145 **Geomorphology: Fluvial systems.**

146 There are four important drainage systems (torrents) in the study area (Figure 3). The
147 longitudinal profiles of the four torrents differ significantly as their evolution depends
148 heavily on the fault tectonism of the area (Figure 4). The Alope and Kounoupitsa
149 torrents are located west of Arkitsa and cross the Arkitsa fault, resulting in convex
150 stream profiles. The Alope torrent flows in a SSW-NNE direction and the Kounoupitsa
151 torrent initially has a W-E direction and then deflects towards the North. Both of these
152 torrents perpendicularly cross the Arkitsa fault zone and exhibit prominent
153 knickpoints. The Alope and Kounoupitsa torrents have both heavily incised into Plio-
154 Pleistocene deposits but the Kounoupitsa torrent exhibits an asymmetric transverse
155 valley cross section with steep cliffs on the south side (Figure 4, inset) due to the tilting
156 of the Arkitsa fault footwall and differential erosion. The Kounoupitsa torrent is further
157 characterized by two distinct cones, the older one being of (presumed) Late
158 Pleistocene age located just north of the Arkitsa fault scarp and the second most
159 recent one of Holocene age located near the shore further north. The older cone is
160 deeply incised up to 26 m at the apex of the fan. The reactivation of the Arkitsa fault
161 seems to be almost continuous until the present day (in accordance with Jackson and

162 MacKenzie 1999) because the almost 100 m high nickpoint of the Kounoupitsa torrent
163 has not moved upstream from the fault scarp. The other two torrents, the Kynos and
164 Livanates torrents (located south of Arkitsa and flowing to the east), are located wholly
165 on the footwall of the Arkitsa fault, and do not exhibit prominent knickpoints. These
166 two torrents have formed normal alluvial cones which are currently eroding. The Kynos
167 and Livanates torrents depict normal concave longitudinal profiles having evolved
168 mostly on easily-erodible Neogene formations (marls, sandstones and conglomerates).

169

170 **Geomorphology: Palaeosurfaces and terraces.**

171 In the footwall of the Arkitsa fault four (presumed) Pleistocene-age palaeosurfaces can
172 be identified (Figure 3) which have evolved on Neogene formations composed of
173 conglomerates, sandstones and marls. The oldest of these extends from 400-480 m
174 amsl (above mean sea level), the second 300-390 m, the third 200-280 m, and the
175 most recent one from 140-170 m. The general dip of these palaeosurfaces is towards
176 the south indicating the continuous activity of the Arkitsa fault system.

177 The geomorphology in the hangingwall of the Arkitsa fault is dominated by a series of
178 deeply-incised colluvial fans and a number of distinct terraces, at elevations of 2-20 m
179 (terrace A), 25-55 m (terrace B) and 50-80 m (terrace C) amsl (Plate 1, Figures 3 and 5).
180 The formation and evolution of the older terrace (C) is contemporaneous with the
181 Kounoupitsa older cone. The higher terraces in the extreme south of this area, around
182 a proposed secondary fault strand at Livanates, are described by Dewez (2003), with
183 the 25-55 m terrace (terrace B) and 50-80 m terrace (terrace C) (Figure 3 and 5)
184 described in the present study correlating with Dewez's T1 and T2 terraces
185 respectively. The terraces are cut into Plio-Pleistocene marls, which are unconformably
186 overlain (most clearly in terraces B and C) by well-cemented arenaceous sediments,
187 forming a prominent "cap-rock". Detailed descriptions of this cap-rock are given
188 below. The two higher and older terraces are deeply dissected down to 27 m by recent
189 fluvial activity. In addition, north of the Arkitsa fault scarp (at 38° 43.680' N; 22°59.340'
190 E) a series of small talus cones have formed during late Pleistocene-Holocene times,
191 which are also deeply incised (Figure 3).

192

193 **Terrace stratigraphy: Terrace A**

194 This terrace has developed east of the village of Arkitsa and extends for more than 3
195 km in a NW-SE direction. The terrace has a clear dip to the NE of ~2 %. Its inner edge is
196 found at an elevation of about 20 m. A prominent exposure of terrace A was located at
197 38° 45.128' N; 23° 01.753' E, at +6 m elevation. While the section was partly-obscured
198 and overgrown, the exposure consisted of 90 cm of highly fossiliferous coarse
199 sandstone unconformably overlying 17 cm of Plio-Pleistocene white silty-clay. The
200 silty-clay unit (in the lower part of the exposure) was relatively unconsolidated, and
201 contained no apparent bedding. The arenaceous cap-rock in the upper part of the
202 exposure consisted of a coarse, well-rounded and sorted sand with grit and occasional
203 small (<1 cm) sub-rounded limestone pebbles. Macrofossil remains were common and
204 included both intact and disaggregated bivalve and gastropod shell material, with
205 identifiable fragments (*ca.* 5mm in size) consisting entirely of juvenile *Mytilus* sp.
206 (possibly *Mytilus galloprovincialis*). Shell remains were distributed highly
207 heterogeneously; in some parts they were almost absent, whereas in other areas they
208 comprised 30–50 % of the cap-rock. Occasional disarticulated juvenile ostracod
209 remains of *Cyprideis torosa* were present, as well as rare single valves of juvenile
210 *Candona* sp.

211

212 **Terrace stratigraphy: Terrace B**

213 This terrace is the most prominent in the area, and extends for 7.5 km in an E-W
214 direction. Its elevation increases towards the east, so the inner edge rises from a
215 height of 25 m in the west to 55m in the east. The terrace is tilted towards the south
216 with a dip of 1 %. A clear roadside exposure of terrace B was found at 38° 44.517' N;
217 23° 01.823' E, at +30 m elevation. The exposure consisted of a 1 m-thick unit of well-
218 cemented sandstone, unconformably overlying a lower unit (1.6 m thick) of thinly-
219 bedded marly silts and sands. Bed thickness in this thinly-bedded lower (Plio-
220 Pleistocene) unit was 1 – 5 cm, dipping at 16° WNW. The upper sandstone (cap-rock)
221 unit consisted of a well-cemented medium sand and silt, with sub-rounded to rounded
222 grits and pebbles of limestone and chert composition. Pebbles ranged between 1 and 3
223 cm in diameter. Small (< 1 cm) isolated gastropod fragments (apparently *Viviparus* sp.)

224 were locally present. A more complete and extensive sequence of the well-cemented
225 arenaceous cap-rock was found in a roadside cut and adjacent private land at 38°
226 44.589' N; 23° 02.002' E, showing 1.8 m of exposure, consisting of 0.55 m of well-
227 cemented sandstone (stratigraphy as detailed above) overlying 1.25 m of bedded
228 *Viviparus* sp.-rich well-cemented medium to coarse sand, with sub-angular to sub-
229 rounded chert (and occasional limestone) pebbles, up to 3 cm diameter. Intact
230 *Viviparus* sp. shells occurred throughout this unit, locally concentrated into coquina-
231 type beds. Juvenile valves of the ostracods *Cyprideis torosa* and *Candona* spp. were
232 common throughout, valves of *Ilyocypris* sp. and *Tyrrhenocythere* sp. (also juvenile)
233 were also present but were considerably rarer.

234

235 **Terrace stratigraphy: Terrace C**

236 This terrace extends for 5 km in an E-W direction. Its elevation increases towards the
237 east, so the inner edge from a height of 50 m in the west reaches 80 m in the east. The
238 terrace is tilted towards the south having a dip of 1.5 %. A prominent exposure in a
239 road cut (adjacent to the main access road to Arkitsa port) at 38° 44.622' N; 23°
240 01.567' E, +50 m elevation, showed *ca.* 0.5–0.7 m of well-cemented, gastropod-rich,
241 sandstone unconformably overlying yellow-white marls. The stratigraphy of the lower
242 (Plio-Pleistocene) marls is described in detail in Dewez (2003). The upper sandstone
243 (cap-rock) unit was rich in intact and fragmented *Viviparus* sp. (Dewez's "*Viviparus*
244 *cayrock*") and other gastropods (including rare *Valvata piscinalis*), sometimes forming
245 coquina-type lenses, in a medium to coarse sand matrix. Ostracod remains were rare,
246 however, and limited to occasional juvenile, disarticulated valves of *Cyprideis torosa*
247 and *Candona* spp.. The sand contained sub-rounded to rounded limestone and chert
248 grit clasts, and rounded to sub-rounded limestone, chert and (sporadic) mafic pebbles,
249 of 4–5 cm diameter. The structure of the cap-rock layer here was relatively complex, as
250 the *ca.* 100 m of horizontal exposure indicated the presence of two unconformable
251 cap-rock layers (Plate 2), an upper (horizontally-bedded) unit above a lower (slightly
252 older) cap-rock unit with bedding dipping at 5° E. At a small quarry N of this road cut
253 (38° 44.642' N; 23° 01.528' E), where the cap-rock has been removed for use locally as
254 a building stone, intact *Viviparus* sp. fragments were less frequent, although the
255 section contained a series of highly abraded broken shell or coquina layers.

256

257 **Radiocarbon dating**

258 Two valves of *Mytilus galloprovincialis* collected from terrace A (at +6 m) gave
259 conventional radiocarbon ages of 36200 ± 340 BP and 40530 ± 500 BP (Table 1). An
260 intact *Viviparus* sp. specimen from terrace B (at +30 m) gave a further conventional
261 radiocarbon age of >43500 BP (Table 1).

262

263 **Discussion**

264 The main factor controlling the late Quaternary deposits of the Northern Evoikos Gulf
265 coast and sea floor was global sea level change caused by the numerous glacial-
266 interglacial cycles of the Pleistocene. Exchange of water masses with the Aegean Sea is
267 restricted via (a) the narrow and shallow Oreos-Trikeri straits, which have a maximum
268 depth of approximately 45 m and a mean width of 4 km, and (b) the artificially
269 maintained Euripus Channel (length 60 m, width 40 m, depth 8.5 m) in the southeast
270 of the region (Figure 1). The maximum pre-Holocene sill depth in the Oreos-Trikeri
271 straits is currently approximately 45 m below sea-level (bsl), although Van Andel and
272 Perissoratis (2006) argue for a late glacial sill depth at about 55 m bsl based on high-
273 resolution seismic profiling data. The Northern Evoikos Gulf was isolated from the
274 Aegean Sea at *ca.* 50,000 yrs BP (Figure 6) and became a lake during Oxygen Isotope
275 Stage (OIS) 3 and 2. The lake began to fill with seawater as soon as sea level reached
276 the critical sill depth at the Oreos-Trikeri straits at about 10,500 ^{14}C BP (Lambeck,
277 1996).

278

279 Of the terraces described here, only the lowest (terrace A) is datable via ^{14}C (Table 1);
280 the higher terrace B gives a date which exceeds the dating range of ^{14}C ($> 43,500$ BP).
281 While further dating using U-series methods may better constrain the ages of the
282 upper terraces B and C, given the thin, delicate nature of the preserved *Viviparus*
283 fossils, and the high likelihood that these gastropods may act as open systems in terms
284 of U-exchange, such dating is unlikely to definitively ascribe an accurate age to the
285 upper cap rocks. The ^{14}C dates from terrace A (*ca.* 36,000 – 41,000 BP) specify its
286 formation at a period of low regional and global sea-level, on the margins of the

287 Evoikos glacial lake. While water levels in the glacial lake clearly fluctuated due to
288 climatic variations, the dates for terrace A correlate with OIS-3, a period with warmer
289 and wetter intervals, which Van Andel and Perissoratis (2006) tentatively correlate
290 with a cluster of erosional submarine terraces incised in the Evoikos Gulf floor between
291 50 and 70 m bsl. The sedimentology of the terrace A cap-rock (i.e. coarse, well-
292 rounded and sorted sand with grit and occasional small [<1 cm] sub-rounded
293 limestone pebbles) indicates deposition in the higher-energy lake shallow margins,
294 although the dominant faunal remains, those of juvenile *Mytilus* sp. (possibly *Mytilus*
295 *galloprovincialis*), indicate deposition in at least a brackish environment (e.g.
296 Ceccherelli and Rossi 1984). The age of this terrace correlates with a period of relative
297 high stand, when sea-levels were close to the sill depth (Shackleton 1987, Labeyrie et
298 al 1987 and discussion in Van Andel and Perissoratis 2006), which may explain the
299 dominance of *Mytilus* sp.. This interpretation is further supported by the microfossil
300 assemblage. *Cyprideis torosa* are euryhaline ostracods, tolerating a broad range of
301 salinities from almost freshwater to hypersaline (but they are never fully marine)
302 (Meisch, 2000). They tend to occupy estuaries, lagoons, brackish-water bays and
303 shallow near-shore littoral environments that have sandy/muddy substrates with some
304 algal/organic cover. Their valves are moderately robust and so they can tolerate
305 moving water and moderate energy conditions, further evidenced here by a lack of
306 larger instars. On the other hand, candoniid ostracods are not usually associated either
307 with elevated salinities or high-energy environments (Meisch, 2000), suggesting that
308 the rare *Candona* sp. valves here may have been washed in from the local catchments.

309
310 Regardless of the precise (palaeo) lake level, the current elevation of terrace A
311 compared to the estimated late glacial Oreos-Trikeri sill depth of 55 m bsl indicates
312 considerable uplift over the last *ca.* 40,000 years. Based on the age of the *Mytilus* sp.
313 at +6 m and a sill depth of 55 m bsl, a minimum average uplift rate of 1.5 mm/y can be
314 derived (i.e. 61 m in 40,000 years, which is a minimum estimate due to uncertainties in
315 palaeo-lake level). Considering the higher terraces, while the ages of terraces B and C
316 are not well-constrained ($> 43,500$ BP), their sedimentological characteristics
317 (arenaceous to conglomeratic) and fossil content indicates their formation in a

318 freshwater lake margin. *Viviparus* sp. prefer shallow freshwater or (occasionally)
319 oligosaline habitats with muddy substrates such as might be found on the margins of
320 slow-moving lowland rivers and the littoral areas of large lakes (e.g. Glöer, 2002).
321 Coupled with the presence of freshwater (*Candona* spp., *Ilyocypris* sp.) and oligosaline
322 (*Cyprideis torosa*, *Tyrrhenocythere* sp.) ostracods (e.g. Meisch, 2000; Griffiths, 2002;
323 Alvarez-Zarikian, 2008), the faunal evidence points to a shallow, freshwater or very
324 slightly brackish lake / lagoonal margin. Based on the discussion above, it is likely that
325 these terraces were formed in earlier phases of OIS 3 and OIS 4 during relative high
326 stand periods, and then uplifted to their present elevations. Indeed, Van Andel and
327 Perissoratis (2006) note a series of submerged erosional terraces in the northern
328 Evoikos Gulf clustered around discrete depth intervals, and probably correlating with
329 lake level fluctuations over OIS 2-4. Sea-level curves (Figure 6) suggest that terrace B
330 may have been formed around 55,000–60,000 yrs BP and terrace C prior to about
331 70,000 yrs BP. Further support for this inference comes from the terrestrial pollen
332 record, including evidence from the well-dated lacustrine sequences from Ioannina in
333 the north-west of Greece (Tzedakis et al., 2002) and Kopais on the Boetian plain,
334 located less than 40 km south of Arkitsa (Tzedakis, 1999). Palynological data from both
335 of these sites indicate the presence of intermediate forest (including a temperate tree
336 component) for part of the Middle Pleniglacial between ca. 50,000 and 59,000 yrs BP
337 (encompassing the proposed formation of terrace B), and fully-forested interstadial
338 conditions between ca. 68,000 and 83,000 yrs BP (encompassing the proposed
339 formation of terrace C). During these relatively wet and warm periods, sea-level was at
340 a depth of ca. 60 m below present sea level or higher, below but not far from the
341 proposed sill depth of 55 m. If correct these estimates would suggest that terrace B
342 was uplifted by ca. 85 m (i.e. 60 m + 25 m [lowest position of the inner terrace edge]),
343 and terrace C by ca. 110 m (i.e. 60 m + 50m [lowest position of the inner terrace edge]),
344 having uplift rates of about 1.4 mm/y (85 m/60,000 yrs for terrace B and 110 m/75,000
345 yrs for terrace C).

346 Terrace data therefore suggest uplift at average rates of 1–1.5 mm/y beyond the
347 Holocene in the late Pleistocene, to at least 40,000 yrs BP. This estimated uplift rate is
348 significantly higher than the long-term (footwall) uplift rate of 0.2 mm/y calculated by

349 Goldsworthy and Jackson (2001) for the eastern end of the Arkitsa fault segment (also
350 reported by Walker et al., (2010)), and while it agrees well with Late Holocene uplift
351 rates of 1–1.4 mm/y proposed by Cundy et al., (2010) based on nearby slightly uplifted
352 marginal marine units around Alope, it poses significant problems in terms of fault
353 dynamics and extension rates in the area. While rupture of the offshore fault inferred
354 by Sakellariou et al., (2007) and Cundy et al., (2010) provides a mechanism for recent
355 coseismic coastal uplift in the Alope area, sustained coastal uplift on this fault of 1 –
356 1.5mm/y requires anomalously high slip and extension rates. Specifically, if a footwall-
357 hangingwall partition of 1:2 is adopted (following McNeill et al.'s (2005) range of 1:1.2
358 to 1:2.2 derived from active faults in the Gulf of Corinth rift, which have similar dip to
359 those in the Arkitsa area), then the resultant slip rate on this offshore fault would be
360 *ca.* 4 – 6 mm/y, with an extension rate of 3 – 4.5 mm/y. This slip rate is much higher
361 than recent estimates using continuous GPS stations in central Greece (Chousianitis et
362 al., 2013), which (a) indicate that most of the extensional strain across the northern
363 Evoikos Gulf is accommodated by the Arkitsa fault, and (b) suggest at most a 1.2 -
364 1.5mm/y slip rate on other active faults in this area. The high uplift rate estimates are
365 similarly problematic given that renewed activity on the onshore Arkitsa fault will
366 down-throw the terraces, and require even higher slip rates on offshore fault systems.
367 In this respect, of note is the apparent presence in terrace C of two unconformable
368 cap-rock layers (Plate 2) with differing bedding dip angles. The contrast in dip angle is
369 laterally extensive and, although the section is partly obscured by vegetation, the
370 unconformable relationship between the two units is clear (Plate 2). This indicates
371 formation of the cap-rock here in at least two phases, interrupted by an episode of
372 slight tilting and erosion, possibly related to local coseismic movement from the
373 activity of the Arkitsa fault. In other words, after the formation of the lower cap-rock,
374 it is possible that the Arkitsa fault reactivated and caused the tilting of this formation
375 towards the fault. The proximity of this site (some tens of metres) to the scarp of the
376 Arkitsa fault and its position on the fault's hanging wall supports this hypothesis.
377 Subsequently, the newer cap-rock was formed in discordance with the former one.
378 This event should have happened during the formation of terrace C, i.e. possibly
379 around 70,000–75,000 yrs BP. The existence of a fresh strip of fault scarp at the base
380 of the Arkitsa fault, attributed to Holocene activity (Jackson and MacKenzie 1999), and

381 the geomorphology of the fluvial systems which cross the fault, indicates that the
382 Arkitsa fault remains active.

383 Given the excessively high, long-term offshore fault slip rates required to generate
384 purely extensional fault-driven uplift of the terraces to their present elevation, some
385 other explanation must therefore be found for their presence at up to 80m above
386 current sea-level. Possible causes are non-extensional local uplift, or formation of the
387 terraces at elevations above the contemporary shoreline due to local damming of the
388 Evoikos glacial lake. Two volcanic centres are present (the Lichades and Chronia
389 volcanic centres) to the northwest and northeast of the Arkitsa area which were
390 activated during the Pliocene and Quaternary (Pe-Piper and Piper 1989, 2002;
391 Lambrakis and Kalergis, 2005, although the Chronia volcanic centre is of questionable,
392 possibly older, age, [Karasththis et al., 2011]), and a magma chamber at 8km depth has
393 been detected north of Arkitsa (Karasththis et al., 2011) which is argued to be the
394 source of the widespread hydrothermal activity observed in the northern part of the
395 Evoikos Gulf. Basaltic sill intrusion could potentially generate local uplift, and extrusion
396 of lava cause local shoreline changes, particularly near to the Oreos-Trikeri straits, and
397 “barriering” or damming of lakes at higher elevations. The exact causal mechanism of
398 terrace development and uplift remains enigmatic, and further detailed studies of
399 these volcanic centres and their influence on palaeo-shoreline geomorphology and
400 local uplift (coupled with offshore geophysical work in the NW Evoikos Gulf to better
401 constrain offshore fault slip and activity and the relationship between onshore and
402 offshore (submerged) terraces) are needed to better constrain the Late Quaternary
403 uplift pattern in this area, and determine the relative roles of extensional faulting and
404 other regional processes (e.g. volcanic centre activity) in driving palaeoterrace
405 formation and uplift.

406

407 **Conclusions**

408 A combined geomorphological, sedimentological and macro-/micro-fossil approach
409 has been used to evaluate the Late Quaternary tectonic evolution and uplift of the
410 Arkitsa area, in the eastern part of the Arkitsa-Kamena Vourla fault system, focusing on
411 prominent terraces present in the hangingwall of the Arkitsa fault. Three distinct raised

412 glacio-lacustrine terraces, and previously reported uplifted marginal marine deposits,
413 indicate sustained uplift of the coastline at a rate of 1 – 1.5 mm/y over at least the last
414 40,000 years, possibly to 75,000 BP. While movement on an offshore normal fault
415 strand may partly explain this (and more recent) coastal uplift, purely fault-driven
416 uplift requires anomalously high fault slip and extension rates over the Late
417 Quaternary. Consequently, the development of the terraces and other geomorphic
418 indicators of uplift may be at least partly due to non-extensional faulting mechanisms,
419 such as Quaternary (intrusive and/or extrusive) volcanic activity associated with
420 evolution of nearby volcanic centres. Further detailed studies of these volcanic centres
421 and their influence on palaeo-shoreline geomorphology and local uplift, coupled with
422 offshore geophysical work in the NW Evoikos Gulf to better constrain offshore fault
423 slip and activity, are needed to determine the relative roles of extensional faulting and
424 other processes in driving palaeo-terrace formation and uplift around Arkitsa.

425

426 **Acknowledgements.**

427 Tim Cane (University of Sussex) is thanked for laboratory assistance. We are also
428 indebted to Professor James Jackson and a further (anonymous) reviewer who
429 provided in-depth comments which significantly improved the overall quality of this
430 paper.

431

432 **References cited.**

433

434 Alvarez-Zarikian, C.A., Soter, S., Katsonopoulou, D., 2008. Recurrent submergence and
435 uplift in the area of Ancient Helike, Gulf of Corinth, Greece: microfaunal and
436 archaeological evidence. *Journal of Coastal Research*, 24 (1A), 110-125.

437 Armijo, R., Lyon-Caen, H., Papanastassiou, D., 1992. East-west extension and Holocene
438 normal fault scarps in the Hellenic arc. *Geology*, 20, 491-494.

439 Ceccherelli, V. U., Rossi R., 1984. Settlement, growth and production of the mussel
440 *Mytilus galloprovincialis*. *Marine Ecology Progress Series*, 16, 173-184.

441 Chousianitis, K., Ganas, A., Gianniou, M., 2013. Kinematic interpretation of present-day
442 crustal deformation in central Greece from continuous GPS measurements.
443 *Journal of Geodynamics*, 71, 1– 13. doi:10.1016/j.jog.2013.06.004

444 Cundy A.B., Gaki-Papanastassiou K., Papanastassiou D., Maroukian H., Frogley M.R.,
445 Cane T., 2010. Geological and geomorphological evidence of recent coastal uplift
446 along a major Hellenic normal fault system (the Kamena Vourla fault zone, NW
447 Evoikos Gulf, Greece). *Marine Geology*, 271, 156-164.

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

451 Franke, A., 1922. Die Präparation von Foraminiferen und anderen mikroskopischen
452 Tierresten, p. 509-533. In Keilhack, K. (ed.), *Lehrbuch der praktischen Geologie,*
453 *Mineralogie, und Palaeontologie* (fourth edition). Enke-Verlag, Stuttgart.

454 Ganas, A., 1997. Fault segmentation and seismic hazard assessment in the Gulf of Evia
455 rift, Central Greece. Unpublished PhD Thesis, University of Reading, Reading, U.K.
456 368 pp.

457 Glöer, P., 2002. Süßwassermollusken Nord und Mitteleuropas. Bestimmungsschlüssel,
458 Lebensweise, Verbreitung. ConchBooks, Hackenheim., 327 pp.

459 Goldsworthy, M., Jackson, J., 2001. Migration of activity within normal fault systems:
460 examples from the Quaternary of mainland Greece. *Journal Structural Geology*,
461 23, 489-506.

462 Griffiths, S.J., Griffiths, H.I., Altinsacli, S., Tzedakis, P.C., 2002. Interpreting the
463 Tyrrhenocythere (Ostracoda) signal from Palaeolake Kopais, central Greece.
464 *Boreas*, 31, 250-259.

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

468 Hughen, K.A., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell,
469 P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks,
470 R.G., Friedrich, M., Guilderson, T.P., Kromer, B., McCormac, F.G., Manning, S.W.,
471 Bronk Ramsey, C., Reimer, P.J., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver,
472 M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004.
473 Marine04 Marine radiocarbon age calibration, 26 - 0 ka BP, *Radiocarbon*, 46,
474 1059-1086.

- 475 Jackson, J., Mackenzie, D., 1999. A hectare of fresh striations on the Arkitsa Fault,
476 central Greece. *Journal Structural Geology*, 21, 1-6.
- 477 Karastathis, V.K., Papoulia, J., Di Fiore, B., Makris, J., Tsambas, A., Stampolidis A.,
478 Papadopoulos, G.A., 2011. Deep structure investigations of the geothermal field
479 of the North Euboean Gulf, Greece, using 3-D local earthquake tomography and
480 Curie Point Depth analysis. *Journal of Volcanology and Geothermal Research*,
481 206, 106–120. doi:10.1016/j.jvolgeores.2011.06.008.
- 482 Kranis, H.D., 1999. Fault zone neotectonic activity in Lokris. Unpublished PhD Thesis.
483 Dept. of Geology, Athens University, Greece.
- 484 Labeyrie, L.D., Duplessy, J.C., Blanc, P.L., 1987. Variations in the mode of formation and
485 temperature of oceanic deep waters over the past 125,000 years. *Nature* 327,
486 477–482.
- 487 Lambeck, K., 1996. Sea-level change and shore-line evolution: a general framework of
488 modelling and its application to Aegean Greece since Palaeolithic time. *Antiquity*
489 70, 588–611.
- 490 Makris, J., Papoulia, J., Papanikolaou, D., Stavrakakis, G. 2001. Thinned continental
491 crust below northern Evoikos Gulf, central Greece, detected from deep seismic
492 soundings. *Tectonophysics*, 341, 225-236.
- 493 McNeill, L.C., Cotterill, C.J., Henstock, T.J., Bull, J.M., Stefatos, A., Collier, R.,
494 Papatheoderou, G., Ferentinos G., Hicks, S.E., 2005. Active faulting within the
495 offshore western Gulf of Corinth, Greece: Implications for models of continental
496 rift deformation. *Geology*, 33/4, 241–244. doi: 10.1130/G21127.1
- 497 Meisch, C., 2000. Freshwater Ostracoda of Western and Central Europe. In:
498 Schwoerbel, J., Zwick, P. (eds.), *Süßwasserfauna von Mitteleuropa* 8/3.
499 Spektrum Akademischer Verlag, Heidelberg, 522pp.
- 500 Mitsakaki, C., Sakellariou, M.G., Tsinas, D., 2013. A study of the crust stress field for the
501 Aegean region (Greece). *Tectonophysics*, 597–598, 50–72.
502 doi:10.1016/j.tecto.2012.10.003.
- 503 Papanastassiou, D., Stavrakakis, G., Makaris, D., 2001. Recent micro-earthquake
504 activity at northern Evoikos gulf, central Greece. *Bulletin of the Geological*
505 *Society of Greece*, XXXIV, 1567-1572.
- 506 Papanikolaou, D.J., Royden, L.H., 2007. Disruption of the Hellenic arc: late Miocene
507 extensional detachment faults and steep Pliocene-Quaternary normal faults - or
508 what happened at Corinth? *Tectonics*, 26, TC5003 doi:10.1029/2006TC002007.

- 509 Papoulia, J., Makris, J., Drakopoulou, V., 2006. Local seismic array observations at
510 north Evoikos, central Greece, delineate crustal deformation between the North
511 Aegean Trough and Corinthiakos Rift. *Tectonophysics*, 423, 97-106.
- 512 Pe-Piper, G., Piper, J.W., 1989. Spatial and temporal variation in Late Cenozoic back-arc
513 volcanic rocks, Aegean Sea Region. *Tectonophysics*, 169, 113–134.
- 514 Pe-Piper, G., Piper, D.J.W., 2002. The igneous rocks of Greece, the anatomy of an
515 orogen. *Beitrage regionalen geologie der erde*. Gebruder borntraeger. 573 pp.
- 516 Pirazzoli, P.A., Stiros, S.C., Arnold, M., Laborel, J., Laborel-Deguen, F., 1999. Late
517 Holocene coseismic vertical displacements and tsunami deposits near Kynos,
518 Gulf of Euboea, central Greece. *Physics and Chemistry of the Earth (A)*, 24, 361-
519 367.
- 520 Roberts, S., Jackson, J., 1991. Active normal faulting in central Greece: an overview, in:
521 Roberts, A.M., Yielding, G., Freeman, B. (Eds), *The Geometry of Normal Faults*,
522 Geological Society Special Publications 56, Geological Society, London, pp. 125 -
523 142.
- 524 Sakellariou, D., Rousakis, G., Kaberi, H., Kapsimalis, V., Georgiou, P., Kanellopoulos, Th.,
525 Lykousis, V., 2007. Tectono-sedimentary structure and Late Quaternary evolution
526 of the North Evia Gulf basin, central Greece: preliminary results. *Bulletin of the*
527 *Geological Society of Greece*, XXXX, 451–462.
- 528 Shackleton, N.J., 1987. Oxygen isotopes, ice volume and sea level. *Quaternary Science*
529 *Reviews*, 6, 183–190.
- 530 Stiros, S.C., Arnold, M., Pirazzoli, P.A., Laborel, J., Laborel, F., Papageorgiou, S., 1992.
531 Historical coseismic uplift on Euboea Island, Greece. *Earth and Planetary Science*
532 *Letters*, 108, 109-117.
- 533 Stuiver, M., Reimer, P.J., 1993. Extended 14C database and revised CALIB radiocarbon
534 calibration program. *Radiocarbon*, 35, 215-230
- 535 Tzedakis, P.C., 1999. The last climatic cycle at Kopais, central Greece. *Journal of the*
536 *Geological Society of London*, 156, 425-434.
- 537 Tzedakis, P.C., Lawson, I.T., Frogley, M.R., Hewitt, G.M., Preece, R.C., 2002. Buffered
538 tree population changes in a Quaternary refugium: evolutionary implications.
539 *Science* 297, 2044-2047.
- 540 van Andel, T.H., Perissoratis, C., 2006. Late Quaternary depositional history of the
541 North Evoikos Gulf, Aegean Sea, Greece. *Marine Geology*, 232, 157-172.

- 542 Walker, R.T., Claisse, S., Telfer, M., Nissen, E., England, P., Bryant, C., Bailey, R., 2010.
543 Preliminary estimate of Holocene slip rate on active normal faults bounding the
544 southern coast of the Gulf of Evia, central Greece. *Geosphere*, 6/5; 583–593; doi:
545 10.1130/GES00542.1
- 546 Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K.,
547 Balbon, E., Labracherie, M., 2002. Sea-level and deep water temperature
548 changes derived from benthic foraminifera isotopic records. *Quaternary Science*
549 *Reviews*, 21, 295–305
- 550 Wicher, C.A., 1942. *Praktikum der angewandten Mikropaläontologie*. Gebrüder
551 Borntraeger, Berlin-Zehlendorf, 143 pp.
- 552
- 553

554

555 **Figures and Tables:**

556

557 Table 1: Radiocarbon and numismatic dates from the Arkitsa terraces and uplifted
558 marginal marine units exposed around Alope.

559

560 Figure 1. Location of the Northern Evoikos gulf in central Greece. Relief shading shows
561 the general bathymetry of the Gulf and the topography of the coast and inland
562 areas. The location of the Oreos-Trikeri straits in the north and Euripus channel
563 in the south, and location and names of major fault systems (K.V.: Kamena
564 Vourla, A.G.: Agios Konstantinos, Ar: Arkitsa, At.: Atalanti, T: Tragana, M:
565 Malesina, Efv.: Evia fault zone) are also marked. Stars indicate the Lichades (L)
566 and Chronia (C) volcanic centers. Projection/datum used: Hellenic Geodetic
567 Reference System 1987 - non-geocentric datum.

568 Figure 2. Geological setting and tectonic structure of the Arkitsa-Kamena Vourla area,
569 north Evoikos Gulf, central Greece. After Institute of Geology and Mineral
570 Exploration (IGME) sheets (1:50,000 scale): Elateia (1967), Pelasgia (1957),
571 Livanatai (1965) and Istiaia (1984).

572 Figure 3. Geomorphological map of study area: Kynos-Arkitsa-Alope coastal zone.
573 Topographic data taken from 1:5000 scale topographic maps (Hellenic Military
574 Geographical Service, 1979). Line CS₁ shows location of cross-section for Figure 4
575 inset.

576 Figure 4. The longitudinal profiles of the Alope, Kounoupitsa, Kynos and Livanates
577 torrents. Inset gives the N-S cross section of the Kounoupitsa torrent, marked as
578 line CS₁ in Figure 3.

579 Figure 5: Digital elevation model (20m x 20m) of the Arkitsa area, highlighting terrace A
580 (green), B (orange) and C (blue). Vertical exaggeration is x5. Google Earth
581 imagery reference: Google earth V 7.1.2.2041. (10/7/2013). Arkitsa, Greece.
582 38°44.041' N; 22°59.735' E; Eye alt. 1500m. Digital Globe 2014.
583 <http://www.earth.google.com> [January 15, 2014].

584 Figure 6. Global eustatic sea-level curves for the last *ca.* 80 kyr after Shackleton (1987)
585 and Waelbroeck et al., (2002), illustrating major global sea-level trends during
586 the Late Quaternary. OIS 3 and OIS 4 are labeled, and the estimated depth of the
587 Oreos-Trikeri sill during late glacial periods is also marked (after Van Andel and
588 Perissoratis 2006).

589

590 Plate 1: Panoramic view of the 3 prominent terraces in the area of Arkitsa (view east,
591 from 38°44.50' N; 23°00.50' E). From left to right: terrace A (2-20 m), terrace B
592 (25-55 m), terrace C (50-80 m).

593 Plate 2: Panorama of terrace C exposure (view towards east, from 38° 44.622' N; 23°
594 01.567' E), showing two unconformable layers of cap-rock. Note contrast in dip
595 angle (see text for further discussion). Figure for scale is 1.8m in height.

596

597

Sample ¹	Species / type	Sample elevation (above HWL)	Conventional ¹⁴ C age (a BP, ± 1 σ)	Lab. number	¹³ C/ ¹² C (‰)	Calibrated age (a BP) ²	Source
Shell	<i>Viviparus</i> sp.	30m	>43500 BP	Beta-285990	-7.0	-	This study
Shell	<i>Mytilus</i> sp. (prob. <i>M.galloprovincialis</i>)	6m	40530 ± 500 BP	Beta-258442	+0.6	-	This study
Shell	<i>Mytilus</i> sp. (prob. <i>M.galloprovincialis</i>)	6m	36200 ± 340 BP	Beta-285989	-0.5	-	This study
Shell	<i>Cerithium</i> sp.	1.1 – 1.6 m	2900 ± 40 BP	Beta-218939	+0.8	916 – 724 BC	Cundy et al. (2010)
Shell	<i>Cerithium</i> sp.	1.1 – 1.6 m	2980 ± 40 BP	Beta-218940	+0.7	1001 – 783 BC	Cundy et al. (2010)
Shell	<i>Spondylus</i> sp.	0.9 – 1.5 m	3430 ± 40 BP	Beta-236948	+1.6	1581 – 1332 BC	Cundy et al. (2010)
Coin	Base metal Roman <i>nummus</i>	1.1 – 1.6 m	–	–	–	AD 378 – 383 ³	Cundy et al. (2010)
Shell	Gastropod (sp. indet.)	0.30 m	1820 ± 40 BP	Beta-236949	-0.1	AD 394 - 623	Cundy et al. (2010)

¹ Shell samples pretreated by etching with HCl.

² 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.

³ Age based on identification of coin as *Reparatio Reipub* type. Richard Abdy, Curator, Roman Coins, British Museum, pers. comm. See Cundy et al. (2010) for discussion.

Table 1

Figure 1

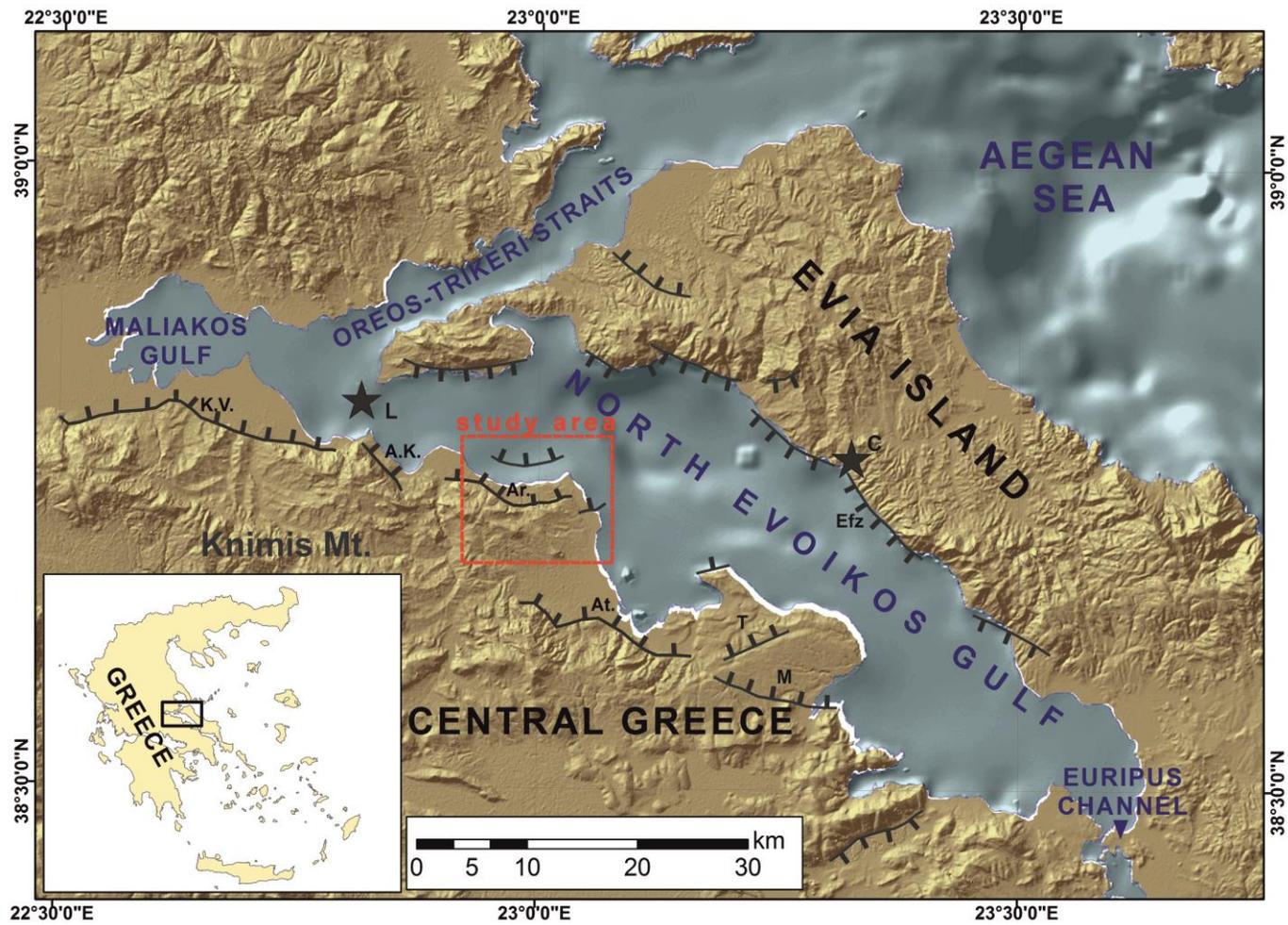


Figure 2

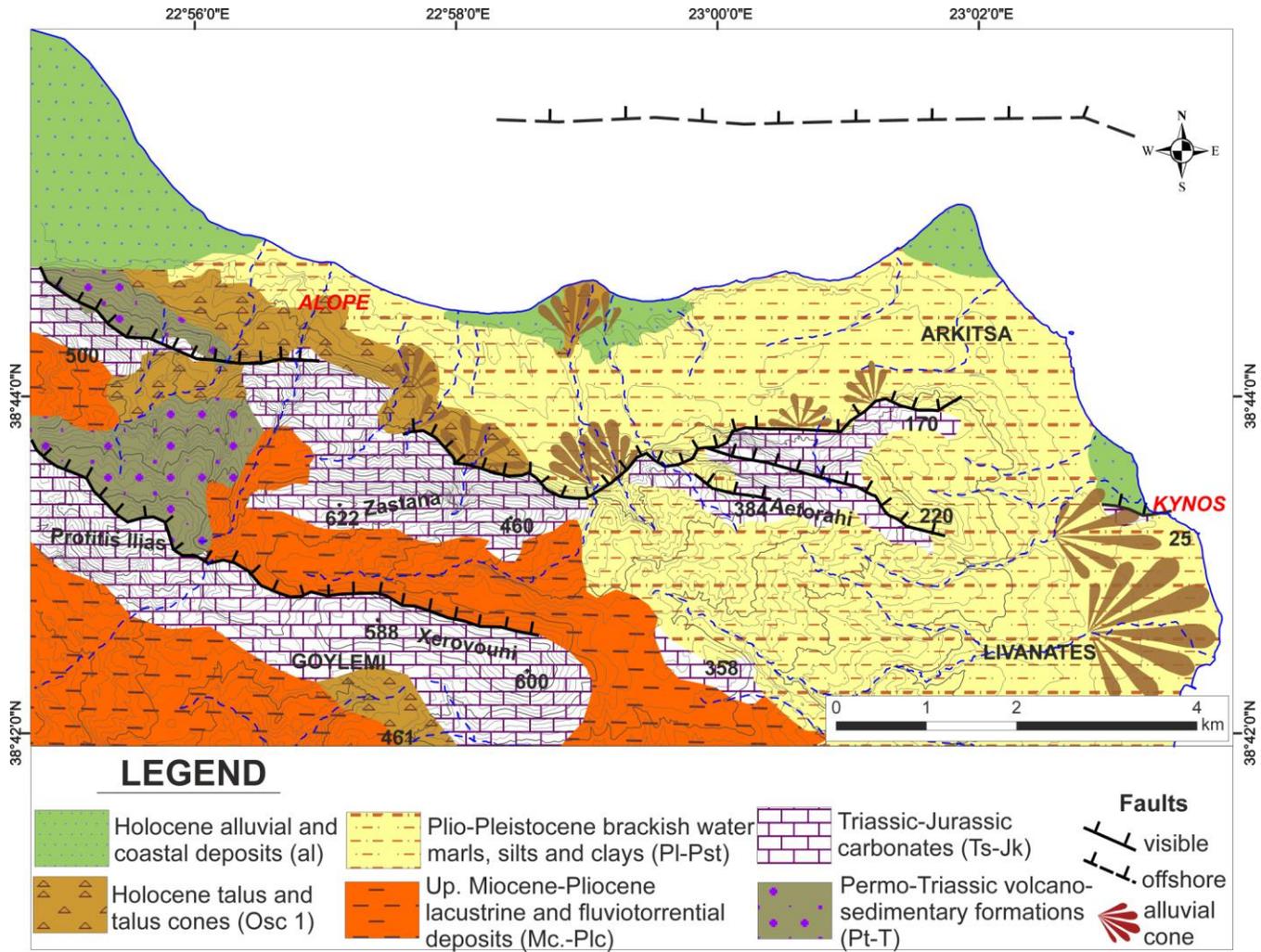


Figure 3

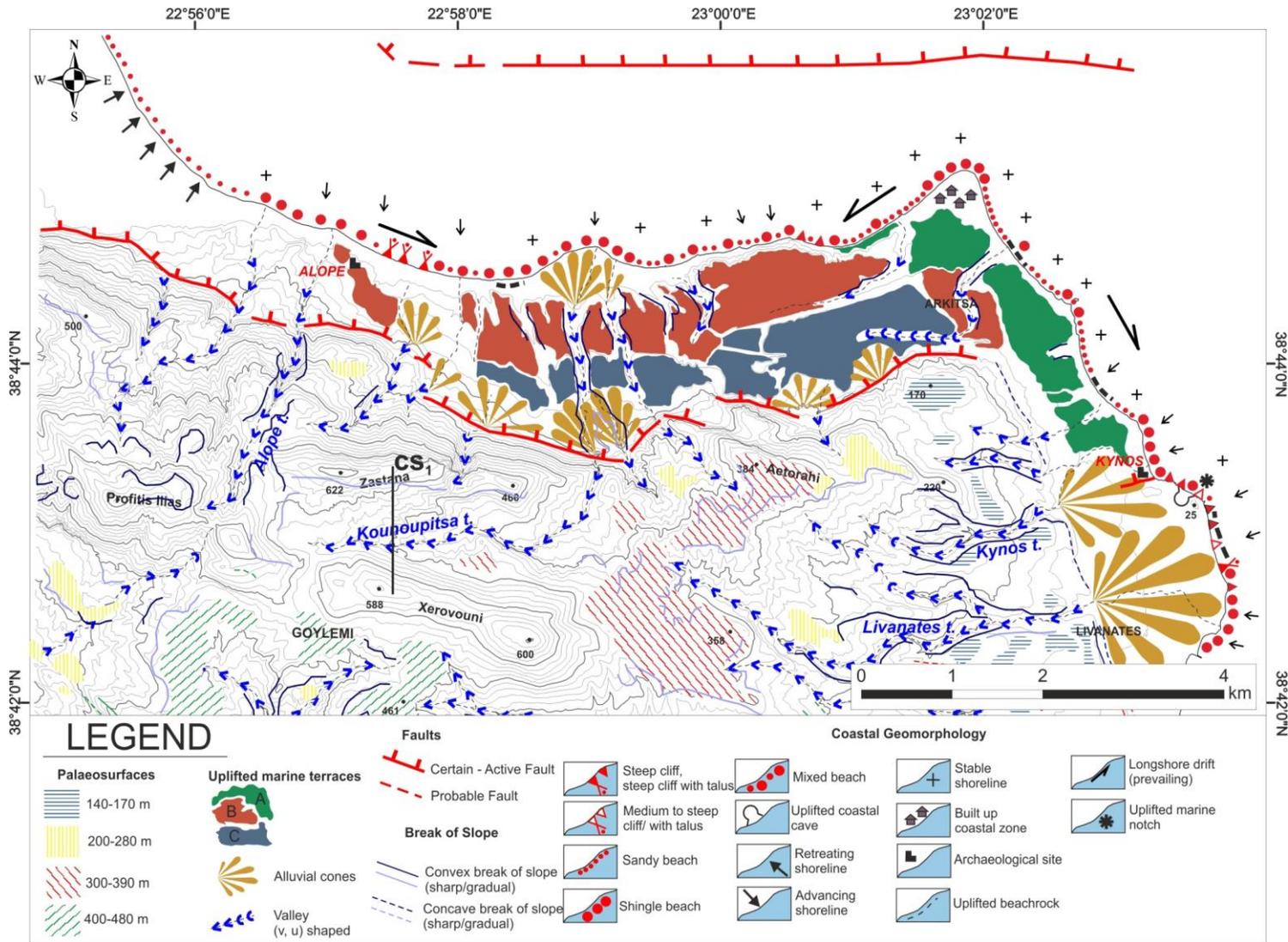


Figure 4

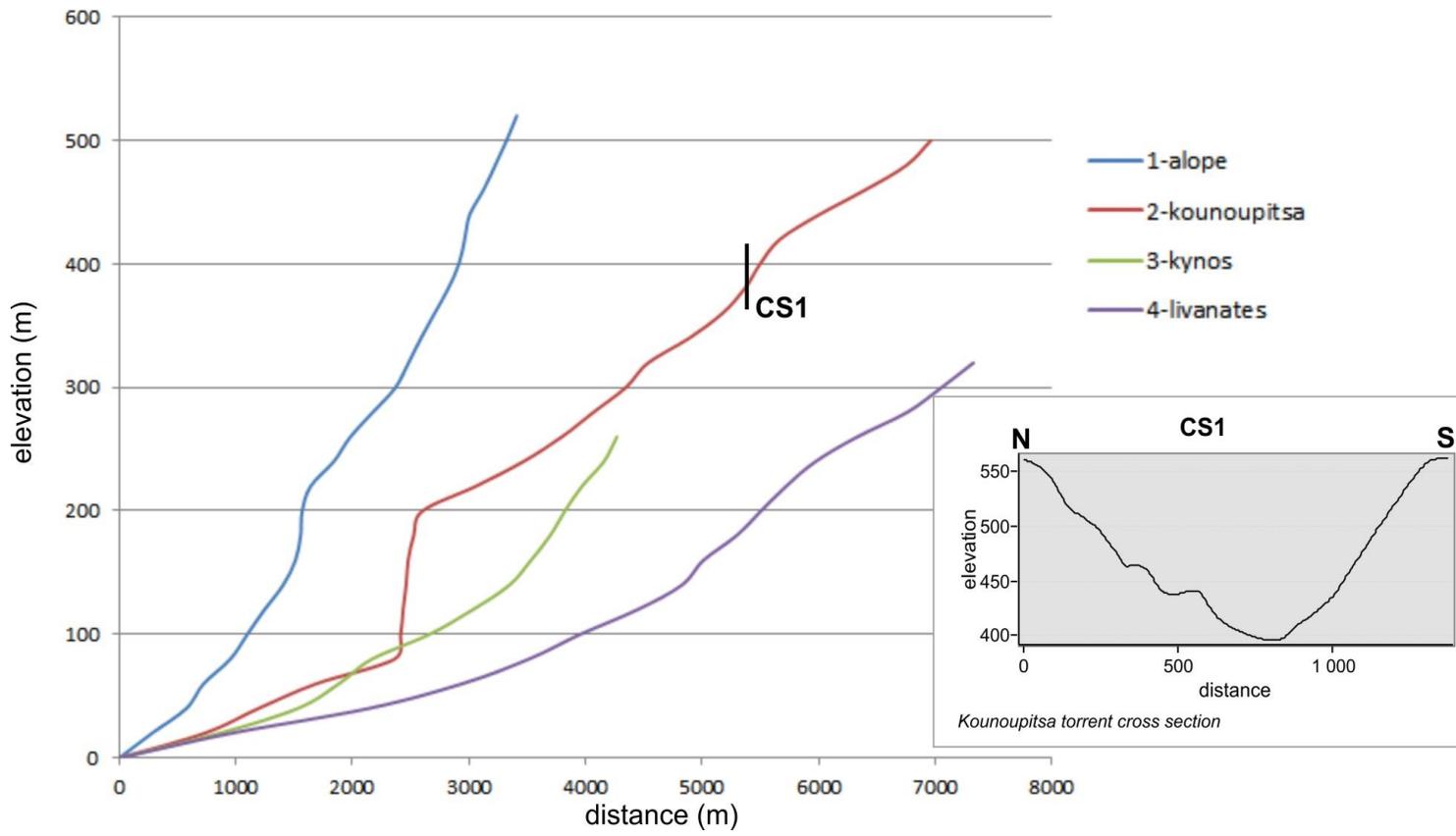


Figure 5

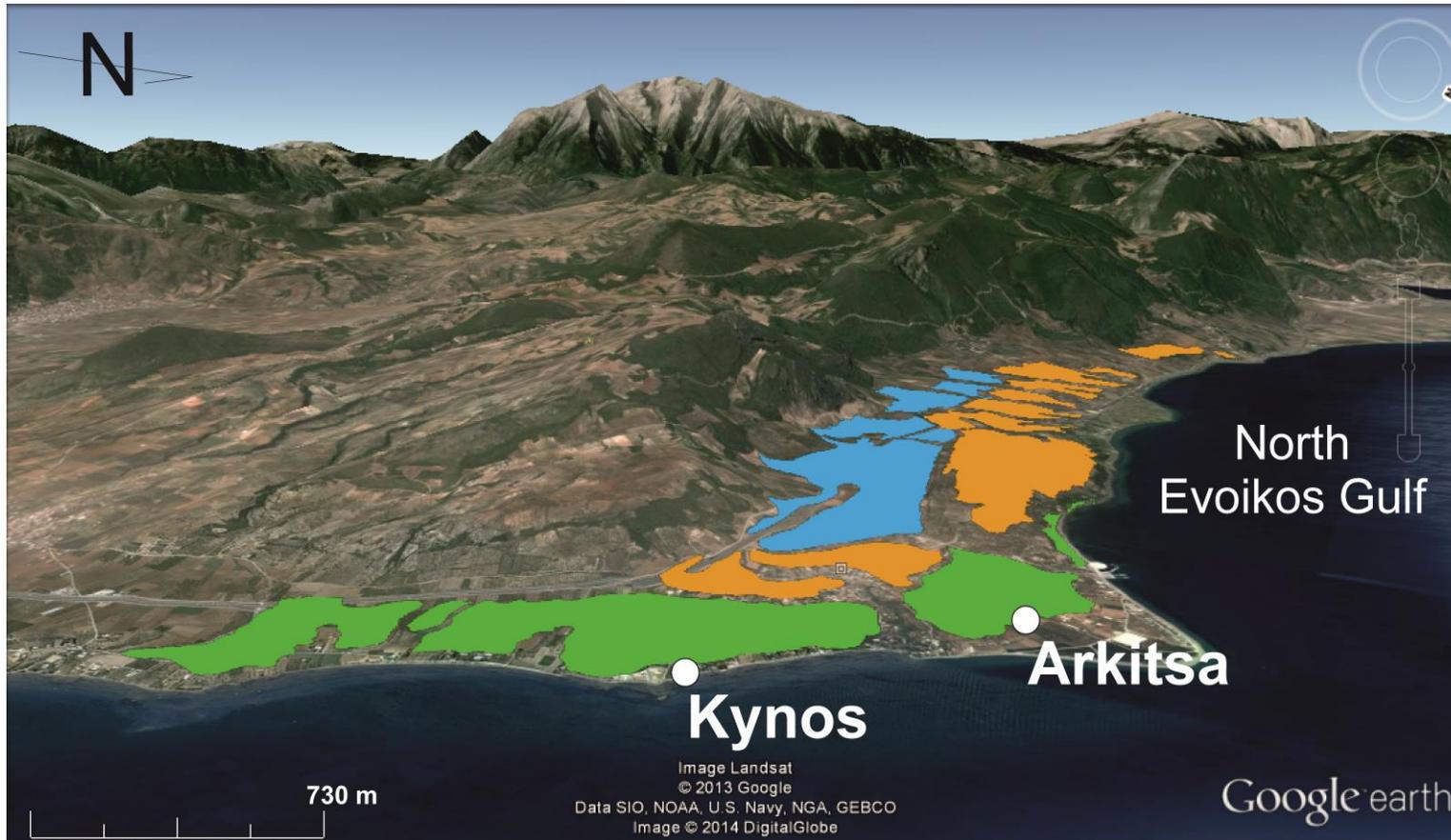


Figure 6

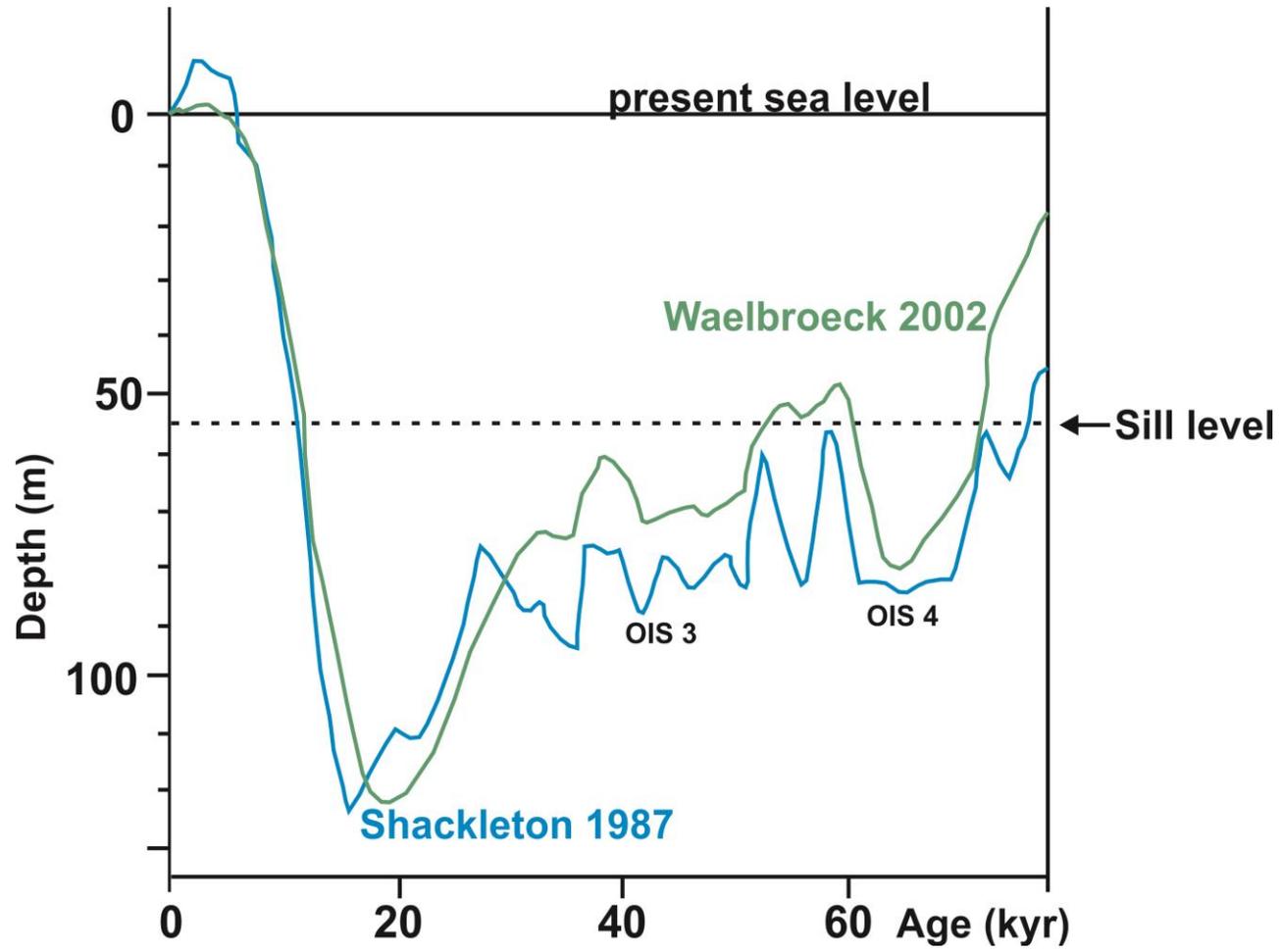


Plate 1



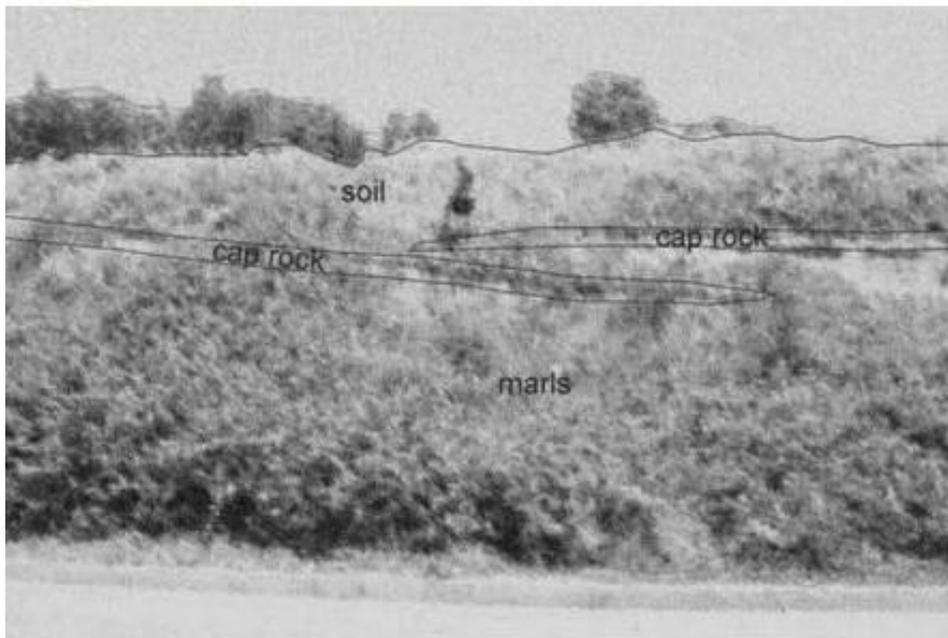


Plate 2