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1 **Distributed normal faulting in the tip zone of the South Alkyonides Fault System,**
2 **Gulf of Corinth, constrained using ³⁶Cl exposure dating of Late-Quaternary wave-cut**
3 **platforms.**

4
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17
18 **Abstract**

19
20 The geometry, rates and kinematics of active faulting in the region close to the tip of a major
21 crustal-scale normal fault in the Gulf of Corinth, Greece, are investigated using detailed fault
22 mapping and new absolute dating. Fault offsets have been dated using a combination of
23 ²³⁴U/²³⁰Th coral dates and *in situ* ³⁶Cl cosmogenic exposure ages for sediments and wave-cut
24 platforms deformed by the faults. Our results show that deformation in the tip zone is

25 distributed across as many as eight faults arranged within ~700 m across strike, each of which
26 deforms deposits and landforms associated with the 125 ka marine terrace of Marine Isotope
27 Stage 5e. Summed throw-rates across strike achieve values as high as 0.3-1.6 mm/yr, values
28 that are comparable to those at the centre of the crustal-scale fault (2-3 mm/yr from
29 Holocene palaeoseismology and 3-4 mm/yr from GPS geodesy). The relatively high
30 deformation rate and distributed deformation in the tip zone are discussed in terms of stress
31 enhancement from rupture of neighbouring crustal-scale faults and in terms of how this
32 should be considered during fault-based seismic hazard assessment.

33

34

35 **1. Introduction**

36 Understanding the deformation that occurs at the tips of normal faults is important
37 because (a) it contributes to knowledge on fault growth and linkage (e.g. Cowie and Shipton,
38 1998; Peacock and Sanderson, 1991; McLeod et al., 2000; Peacock, 2002), (b) has the
39 potential to inform fault-based seismic hazard analysis about fault connectivity and maximum
40 rupture extent (Scholz and Gupta, 2000), and (c) influences our understanding of fluid
41 connectivity or otherwise of faulted hydrocarbon reservoirs (Yielding et al., 1996). One of the
42 key observations from studies on tip-zone deformation is that the shape of the displacement
43 gradients differs between isolated and interacting faults as a result of perturbation to the
44 surrounding stress field (Peacock and Sanderson, 1991; Willemse et al., 1996; Cartright and
45 Mansfield, 1998; Cowie and Shipton, 1998; Scholz and Lawler, 2004). In particular, steeper
46 displacement gradients occur close to fault tips where adjacent faults are in close proximity
47 (Gupta and Scholz, 2000). However, it is not known how these steep displacement gradients
48 develop through time, whether displacement is always localised on a single fault or spread

49 across several fault strands, and how tip deformation should be incorporated into studies of
50 seismic hazard. To address these questions, this paper provides measurements of
51 deformation rates across all faults within a tip zone over timescales that allow one to
52 recognise how many individual faults are active simultaneously.

53 Our interest was raised for this topic because we note that at the tips of some crustal-
54 scale faults, distributed faulting dominates as networks of splay faults that form at acute
55 angles to the main fault (McGrath and Davison, 1995; Perrin et al., 2016) (Figure 1). It is
56 unclear whether these fault patterns and the resultant deformation can be more complex
57 where the tips of two crustal-scale faults overlap along strike and interaction occurs between
58 neighbouring faults (Gupta and Scholz, 2000). Moreover, although typically fault
59 displacement decreases to minimal values toward the tip (Cowie and Roberts, 2001), a shared
60 tip zone can host high displacement gradients relative to the main fault (Peacock and
61 Sanderson, 1991; 1994; Schlische et al., 1996) and it is unclear if this is accommodated by
62 deformation spread across multiple faults or localised on a single fault.

63 A detailed analysis of the deformation within a fault tip zone has the capacity to
64 contribute to fault-based seismic hazard assessment (e.g. Pace et al., 2016). If tip zones
65 contain relatively-high displacements, distributed across multiple faults, or localised on a
66 single fault, this may influence whether ruptures can cross the tip zone onto other
67 neighbouring faults (e.g. Field et al. 2014), influencing estimates of maximum earthquake
68 magnitude (Wells and Coppersmith, 1994). However, the lack of measured displacement data
69 within tip zones means that historic fault-based seismic hazard approaches typically rely on
70 throw/slip rate data from outside the tip zone and the assumption that displacement
71 gradients decrease toward the tips according to pre-ordained fault shapes (Faure Walker et
72 al., 2018). The above assumptions produce significant uncertainty in Probabilistic Seismic

73 Hazard Assessment (PSHA) (Pace et al., 2016), and have been shown to result in large
74 differences between calculations of recurrence intervals and ground-shaking exceedance
75 probabilities for different fault geometries (Faure Walker et al., 2018). Constraining the rates
76 of deformation at multiple locations along a fault, including within the tip-zone, is therefore
77 a vital component of reducing the uncertainty in PSHA. Furthermore, this may be particularly
78 important if this analysis is carried out in an area where overlapping tip zones occur; higher
79 displacement gradients, and consequently slip/throw rates, may mean that cumulative slip
80 rates may be relatively high, even when compared to 'on fault' values.

81 One of the main challenges to gaining insights of how tip-zone deformation
82 accumulates through time, over timescales relevant to earthquake rupture, is to derive
83 knowledge of the timescales over which faulting occurs. Existing approaches use
84 measurements of vertical displacement, coupled with the ages of offset strata/landforms (e.g.
85 Sieh et al. 1989; Armijo et al. 1991; Roberts and Michetti, 2004; Galli et al., 2008; Schlagenhauf
86 et al., 2010, Mozafari et al. 2019; Robertson et al., 2019). In tip zones where distributed
87 faulting dominates and slip-rate along individual faults may be (a) relatively low, and (b)
88 difficult to detect, it may be advantageous to concentrate on techniques that average the slip
89 over relatively long time periods. Investigations using deformed Quaternary marine terraces
90 and their associated wave-cut platforms (e.g. Armijo et al., 1996; Roberts et al., 2009, Roberts
91 et al., 2013; Binnie et al., 2016; Jara-Munoz et al., 2017; Meschis et al., 2018; Robertson et al.,
92 2019) allow deformation rates to be measured over 10^{4-5} years, and therefore displacement
93 associated with the very low slip rates of individual tip-zone faults can be resolved.

94 The western tip area of the north dipping South Alkyonides Fault System (SAFS)
95 (Morewood and Roberts, 1997), located on the Perachora Peninsula (eastern Gulf of Corinth,
96 Greece) provides an opportunity to study the throw rate, 'off-fault' deformation and possible

97 interaction with neighbouring faults. A set of distributed faults at Cape Heraion, in the far
98 west of the Perachora Peninsula, represents the western tip zone of the SAFS (Morewood and
99 Roberts, 1997) (Figure 2). While this area has been studied before (Morewood and Roberts,
100 1997), this study lacked the detailed mapping of displacement gradients along individual
101 faults, and the age constraints needed to be able to fully examine the rates and spatial
102 variation of deformation. Morewood and Roberts (1997) identified faulted offsets of what
103 they claim is a single marine terrace. Others have made an alternative interpretation where
104 marine terraces at different elevations are not faulted, but instead date from different sea-
105 level highstands (Leeder et al., 2003; Leeder et al., 2005). This disagreement could not be
106 resolved, because although some age constraints were available from $^{234}\text{U}/^{230}\text{Th}$ dating of
107 corals (Vita-Finzi et al., 1993, Leeder et al., 2003; Leeder et al., 2005; Roberts et al., 2009;
108 Houghton, 2010), ages were not available for marine terrace deposits at different elevations.

109 Our breakthrough reported herein, is that our detailed mapping revealed that the
110 coral-bearing strata can be mapped along strike into wave-cut platforms, and wave-cut
111 platforms can be dated using *in situ* ^{36}Cl cosmogenic exposure studies (Robertson et al. 2019).
112 Here we test the hypothesis of Morewood and Roberts (1997) of a single, faulted
113 palaeoshoreline by (i) constraining the ages of marine terrace deposits and landforms at
114 different elevations, (ii) calculating individual and cumulative fault throw values and, (iii)
115 exploring how these vary spatially within the tip zone and how they compare to other normal
116 fault tip zones. The results of these analyses are combined with those from Coulomb stress
117 change modelling to explore the interaction of the tip of the SAFS with neighbouring faults.
118 These findings are then discussed in the context of fault-based probabilistic seismic hazard
119 assessment.

120

121 2. Background

122

123 2.1 Tectonic setting

124 The Perachora Peninsula is located within the eastern Gulf of Corinth (Figure 2), one
125 of the world's fastest extending rift systems, with extension rates between <5 mm/yr and 10-
126 15 mm/yr (Davies et al., 1997; Clarke et al., 1998; Briole et al., 2000). The presence of a
127 complex basin structure (e.g. Moretti et al., 2003; Sachpazi et al., 2003; McNeill et al., 2005;
128 Sakellariou et al., 2007; Bell et al., 2009; Nixon et al., 2016; Gawthorpe et al., 2018) is a
129 consequence of extension accommodated along sets of north and south dipping faults. From
130 the Late Quaternary to the present day, north-dipping faults located along the rift system that
131 borders the south of the gulf are predominately responsible for extension, with other faults
132 less active or ceasing activity (Sakellariou et al., 2007; Bell et al., 2009; Roberts et al., 2009;
133 Nixon et al., 2016; Fernandez-Blanco et al., 2019). The north-dipping faults have been shown
134 to have started to dominate the deformation between 340-175 ka (Roberts et al., 2009; Nixon
135 et al., 2016).

136 The Perachora Peninsula is located between the Alkyonides Gulf to the north and the
137 Lechaion Gulf to the south (Figure 2a). This area is dominated by two crustal-scale, north-
138 dipping, active fault systems, the East Xylocastro Fault System (EXFS) (so named in this study)
139 and the South Alkyonides Fault System (SAFS) (Figure 2a). The EAFS is formed by the East
140 Xylocastro, North Kiato and Perachora faults, located offshore and arranged en-echelon. The
141 linkage of these three faults is unclear (Bell et al., 2009) with some authors suggesting fault
142 connections at depth (Armijo et al., 2006; Nixon et al., 2016) and others suggesting that they
143 are isolated faults (Stefatos et al., 2002; Moretti et al., 2003; Sakellariou et al., 2007). The
144 presence of a set of coherent terraces in the footwall of the East Xylocastro, North Kiato and

145 Perachora faults (Armijo et al., 2006) combined with the formation of a single depocentre
146 bounding the north-dipping faults on the south side of the gulf (Nixon et al., 2016) has been
147 cited as evidence to support a through-going fault that is connected at depth.

148 The predominantly onshore, ~40 km long SAFS is comprised of the Pisia, Skinios, East
149 Alkyonides and Psatha faults (Figure 2, Roberts, 1996a; Morewood and Roberts, 1997; 1999;
150 2001; 2002; Leeder et al., 2005; Roberts et al., 2009). Analysis of the fault system shows that
151 slip vectors converge toward its centre (Roberts, 1996a; 1996b) where a maximum
152 cumulative throw of 2500 m is recorded (Morewood and Roberts, 2002), which decreases
153 toward both tips (Roberts, 1996a; Morewood and Roberts, 1999; Roberts et al., 2009). In the
154 western section of the SAFS, decreasing offset is reflected in deformed Late Quaternary
155 palaeoshorelines and Holocene notches in the footwall (Cooper et al., 2007; Roberts et al.,
156 2009), where uplift rates decrease from 0.52 mm/yr to 0.25 mm/yr from east to west in the
157 most western 5 km of the fault. Roberts et al. (2009) identified that the SAFS experienced an
158 increase in slip rate since ~175 ka by a factor of ~3, suggested to be linked to the cessation of
159 faulting on neighbouring across-strike faults.

160 Evidence from recent earthquakes combined with Holocene throw and slip rate data
161 provide insight into the activity of faults within the SAFS over decadal to 10^3 year timescales.
162 Specifically, analysis of post-LGM slip on the Pisia fault revealed maximum slip rates of 2.3
163 mm/yr during the Holocene (Mechernich et al., 2018). Palaeoseismic trenching along the
164 Skinios fault yielded throw rates of 1.2-2.5 mm/yr over ~1500 years (Collier et al., 1998). Two
165 >Ms 6 earthquakes on the 24th and 25th February 1981 are reported to have partially ruptured
166 faults within the SAFS (Jackson et al., 1982; Roberts, 1996a; Collier et al., 1998). Ruptures in
167 bedrock and alluvium that extend for 15-20 km (Jackson et al., 1982; Bornovas et al., 1984;
168 Roberts, 1996a) were observed following the February 1981 earthquakes, with maximum

169 coseismic throw values of 150 cm and 100 cm identified on the Pisia and Skinos faults
170 respectively (Jackson et al., 1982).

171 The February 1981 earthquake ruptures were mapped to a throw minima along the
172 south of Lake Vouliagmeni (Figure 2c) (Bornovas, 1984; Roberts, 1996a; Morewood and
173 Roberts, 1999) where the “throw and geomorphic expression across [the SAFS] tend to zero”
174 (Morewood and Roberts, 1999) and were used to conclude that the SAFS does not extend
175 beyond the western end of the lake. Consequently, this location was identified as the western
176 fault tip of the SAFS (Morewood and Roberts, 1999, Figure 4a) (‘A’ on Figure 2c). The area to
177 the west of this location, Cape Heraion, is deformed by numerous normal faults, providing an
178 excellent opportunity to explore deformation close to the tip of a normal fault.

179

180 *2.2 Cape Heraion, Perachora Peninsula*

181 The extreme west of the Perachora Peninsula, Cape Heraion, is located beyond the
182 western tip of the SAFS (as defined by Morewood and Roberts, 1999, Figure 2c). It is bounded
183 to the north by the Perachora fault segment, the most eastern fault within the EXFS, and to
184 the south by the south dipping, active Heraion fault (Taylor et al., 2011; Charalampakis et al.,
185 2014; Nixon et al., 2016) (Figure 2a). The geology of Cape Heraion is comprised of a succession
186 of deposits from the Mesozoic to the Late Quaternary with more recent Late Quaternary-
187 Holocene geomorphic features imprinted such as wave-cut platforms and Holocene sea-level
188 notches.

189 The stratigraphic succession of the Cape comprises Mesozoic basement limestones
190 unconformably overlain by Plio-Pleistocene marls and sandstones that are, in turn, overlain
191 by algal mound bioherms (also known as cyanobacterial mounds) above which a bioclastic
192 shallow-marine coral-bearing sediment occurs (Bornovas, 1984; see Portman et al., 2005 for

193 descriptions of each lithology). The bioherms are dominated by freshwater branched
194 cyanobacterium *Rivularia haematites*, suggested to have formed when the Gulf of Corinth
195 was a lake (Kershaw and Guo, 2001, 2003, 2006). Domal-topped bioherms in the hangingwall
196 and flat-topped bioherms in the footwall suggest they grew up to water level during faulting
197 with restricted vertical growth in the footwall (Kewshaw and Guo, 2006). Subsequent relative
198 sea-level rise resulted in the presence of a marine bioclastic layer above the bioherms
199 (Portman et al., 2005; Roberts et al., 2009) and caves containing marine biota within the
200 bioherms (Kershaw and Guo, 2006). Taken together, the above evidence is suggestive that
201 faults were active during initial freshwater conditions, that were subsequently changed to
202 marine by a relative sea-level rise. However, these lines of evidence are debated by other
203 authors (Leeder et al., 2005; Portman et al., 2005; Andrews et al., 2007), who favour that the
204 bioherms grew in a marine environment.

205 The observed geomorphology on Cape Heraion resembles that of a 'stepped' profile
206 with horizontal surfaces (terraces) separated by steep slopes. The sub-horizontal surfaces are
207 interpreted as marine terraces because they are associated with coralliferous sediments,
208 marine shoreface deposits with Quaternary marine fossils, and wave-cut platforms that are
209 commonly bored by marine lithophagid borings (Morewood and Roberts, 1997, 1999; Leeder
210 et al., 2003; Leeder et al., 2005; Roberts et al., 2009). Quaternary marine terraces typically
211 form during glacio-eustatic sea-level highstands that occur as a response to glacial melting
212 during interglacial periods. At the up-dip terminations of the marine terraces, it is common to
213 find wave-cut notches and platforms that host features such as lithophagid borings and inter-
214 tidal millholes, indicative of formation at palaeoshorelines (Westaway 1993; Griggs et al.,
215 1994; Miller and Mason, 1994; Roberts et al., 2009; Robertson et al., 2019).

216 Although the marine terraces and intertidal palaeoshoreline indicators are widely
217 accepted, the explanation for the steep slopes separating marine terraces is debated on Cape
218 Heraion. The slopes are interpreted in two ways by different authors: (1) as palaeo- sea-cliffs,
219 cut by wave-action by three successive Quaternary glacioeustatic sea-level highstands
220 (Leeder et al., 2003; Leeder et al., 2005) (Figure 3a); (2) the locations of faults offsetting a
221 single terrace surface, where the up-dip termination of a terrace surface at a slope is the
222 hangingwall cut-off of the marine terrace along the fault (Figure 3b; Morewood and Roberts,
223 1997). In this latter interpretation, the age of the marine terrace is suggested to be ~125 ka,
224 associated with MIS 5e (Morewood and Roberts, 1997; Roberts et al., 2009) (Figure 3b), with
225 the presence of complex faulting representing a Segment Boundary Zone between the EXFS
226 and SAFS. Both of these explanations rely on age constraints that link a wave-cut platform at
227 ~29 m to MIS 5e (125 ka highstand) dated using U-series coral ages (Vita-Finzi et al., 1993,
228 Leeder et al., 2003; Leeder et al., 2005; Houghton, 2010) (Locality F, Figure 4a), but no age
229 constraints have been available for higher elevation examples, and this is needed to
230 differentiate between the competing hypotheses.

231 We undertook detailed mapping and dating in an attempt to resolve the debate of
232 successive palaeoshorelines versus faults. In particular, we tried to identify whether the
233 slopes between terrace locations were continuous along strike, consistent with the
234 suggestion that they represent a succession of palaeoshorelines, or whether the offset of the
235 slopes varied along strike and displayed tip zones and relay ramps, suggestive of faulting.
236 Later we present the results of field mapping and dating that supports the hypothesis of
237 Morewood and Roberts (1997) that the observed variation in terrace elevation is as a result
238 of faulting.

239 The significance of Holocene wave-cut notches cut into the cliffs along the most
240 western point of Cape Heraion has also been the subject of debate (Pirazzoli et al., 1994;
241 Stiros, 1995; Stiros and Pirazzoli, 1998; Kershaw and Guo, 2001; Cooper et al., 2007; Boulton
242 and Stewart, 2015; Schneiderwind et al.,2017a; Schneiderwind et al.,2017b). It is clear that
243 these notches form as a result of the chemical, biological and physical wave action eroding
244 the cliffs in the intertidal zone along palaeoshorelines (Pirazzoli, 1986). The ages of four
245 notches observed on Cape Heraion were dated to between 190-440 A.D. and 4440-4320 A.D.
246 and used to infer coseismic footwall uplift increments of 0.8 m from earthquakes with
247 recurrence intervals of ~1600 years (Pirazzoli et al., 1994). However, 0.8 m has been
248 suggested to be a relatively high value for coseismic footwall uplift (Cooper et al., 2007;
249 Boulton and Stewart, 2015; Schneiderwind et al.,2017b; Meschis et al., 2019). Whatever their
250 mode of formation, we show below that the notches are deformed by active faulting and use
251 this as part of our explanation of the geological history of Cape Heraion.

252

253 *2.3 Using marine terraces and wave-cut platforms to obtain age constraints*

254 Exploring the deformation of marine terraces and wave-cut platforms relies on
255 obtaining age controls for terraces, accurate geomorphic mapping of terrace features and
256 knowledge of the timing and relative elevations of sea-level highstands (Robertson et al.,
257 2019). Existing coral ages on Cape Heraion at localities C, F and H (Figure 4a) dated using
258 $^{234}\text{U}/^{230}\text{Th}$ dating reveal ages that agree to coral growth during MIS 5e from platforms at 7 m
259 (Roberts et al., 2009), 29 m (Collier et al., 1992; Vita-Finzi et al., 1993; Leeder et al., 2003;
260 Leeder et al., 2005; Dia et al., 2007; Houghton, 2010) and 15 m (Burnside, 2010). To augment
261 these ages, this study provides new coral ages, and *in situ* ^{36}Cl cosmogenic exposure ages for
262 wave-cut platforms, inspired by the work of Stone et al. (1996), that can be mapped along

263 strike onto coral-bearing marine terrace sediments. The ^{36}Cl cosmogenic exposure ages are
264 cross checked against new and existing coral ages.

265 Integral to studies of Quaternary marine terraces and palaeoshorelines is knowledge
266 of sea-level elevation changes linked to sea-level highstands, and the time when sea-level
267 reached its maximum elevation (e.g. Waelbroeck et al., 2002; Lambeck et al., 2002; Siddall et
268 al., 2003; Grant et al., 2014; Spratt and Lisiecki, 2016). On Cape Heraion existing coral ages
269 constrain three wave-cut platforms to MIS 5e (125 ka sea-level highstand) (Localities C,F and
270 H, Figure 4a). The timing of MIS 5e occurred between 138-116 ka (Muhs and Szabo, 1994;
271 Stirling et al., 1998; Hearty et al., 2007; O'Leary et al., 2013; Dutton et al., 2015), with the
272 majority (80%) of sea-level rise suggested to have occurred prior to 135 ka (Muhs and Szabo,
273 1994; Gallup et al., 2002). Understanding the elevations and timings of past sea levels is
274 beneficial because it provides an additional check against the ages obtained from ^{36}Cl
275 exposure dating, which should fall within known highstand time periods.

276

277 3. Methods

278

279 3.1 Field mapping

280 Detailed field mapping and sampling for $^{234}\text{U}/^{230}\text{Th}$ and *in situ* ^{36}Cl exposure dating was
281 carried out during field campaigns throughout 2015 and 2017. For the field mapping we
282 concentrated on key criteria that would differentiate between the palaeo-sea-cliff versus fault
283 interpretations for the steep slopes between terrace locations. In particular, if the steep
284 slopes are palaeo- sea-cliffs they ought to be continuous along strike (Figure 3b). In contrast,
285 if the steep slopes are fault scarps, they may display relay-zone geometries where it would be

286 possible to walk continuously on a single surface, along strike, around fault tips, up relay
287 ramps onto the higher parts of the same terrace surface (Figure 3b).

288 In order to constrain the geometries and continuity of the marine terraces (Figure 3),
289 58 spot-height elevations were measured throughout the field area using a handheld
290 barometric altimeter (3 m vertical error) that was regularly calibrated at sea level. These
291 measurements were supplemented by 40 additional elevation values obtained from spot
292 heights from a 5 m digital elevation model (DEM) (4 m vertical error) in ArcGIS. The
293 combination of spot heights, outer edges and fault trace maps has allowed us to identify
294 displacement gradients, fault tips to individual faults and relay zones separating individual
295 faults. Rupture traces from recent (possibly 1981) faulting were mapped using a barometric
296 altimeter and measured with rulers to identify the vertical offsets (throw) observed in
297 colluvium and on bedrock fault scarps and the horizontal extension observed from piercing
298 points. This was carried out as per the approach outlined in Iezzi et al. (2018).

299

300 3.2 $^{234}\text{U}/^{230}\text{Th}$ sampling approach and preparation

301 We focussed our attention on a 0.5-1 m thick coral-bearing, bioclastic layer overlying
302 the bioherms. The bioclastic deposits are comprised of coarse sand and contain corallites of
303 *Cladocora caespitosa*. Whole corallite samples were removed and prepared as per the
304 approach outlined in Roberts et al. (2009). Each corallite sample was split and the septa
305 removed and discarded as septa have been shown to experience greater post-depositional
306 alteration (Roberts et al., 2009; Houghton, 2010). Individual samples were then fragmented
307 and analysed under a binocular microscope for signs of alteration that appear as patches of
308 brown colouration and small crystal growths. The corallites were physically cleaned using a
309 scalpel to remove areas of alteration and any sediment and then placed in 10% hydrochloric

310 acid for 2-3 seconds after which they were immediately rinsed in ultrapure water. This process
311 was repeated until all signs of alteration were removed. Following this process fragments
312 from each corallite were analysed for $^{234}\text{U}/^{230}\text{Th}$ as per the method detailed in Crémière et al.
313 (2016).

314

315 *3.3 ^{36}Cl sampling approach and preparation*

316 For ^{36}Cl dating we focussed our attention on wave-cut platforms that could be mapped
317 along and across strike into the coral-bearing, bioclastic layer, suggesting they would be close
318 in age. Obtaining the absolute ages of wave-cut platforms using cosmogenic ^{36}Cl exposure
319 dating relies on (i) sampling from a surface comprised of a calcium-rich lithology that has (ii)
320 experienced minimal erosion and negligible burial, under soil for example, since exposure.
321 This is because the primary production pathway of cosmogenic ^{36}Cl occurs when ^{40}Ca
322 undergoes spallation following the collision of high-energy neutrons at the earth's surface
323 (Dunai, 2010). The spallation reaction is mostly limited to the upper 2 m of rock below
324 exposed surfaces, decreasing exponentially with depth (Licciardi et al., 2008), so high levels
325 of erosion would remove the highest concentrations producing misleadingly-young ages.
326 Other pathways of ^{36}Cl production that must be considered are from low-energy neutrons
327 (Schimmelpfennig et al., 2009) and negative muons, which are the dominant production
328 mechanism for ^{36}Cl at greater depths (Dunai, 2010). We use the approach outlined in
329 Robertson et al. (2019) to identify surfaces that have experienced minimal erosion based on
330 the presence of preserved lithophagid borings and millholes. The depth of lithophagid borings
331 upon formation is between 3-9 cm (Peharda et al., 2015) while millholes, that is, erosional
332 hollows formed by pebble agitation in the intertidal zone, are usually a few centimeters to
333 less than a few decimetres deep. Therefore, the preservation of these features allows us to

334 be confident that we can constrain erosion to less than a few millimetres or centimetres. The
335 low rates of erosion mean that the ^{36}Cl concentration depth profile, determined by the ^{36}Cl
336 production rate depth variation from spallation, will be intact and amenable to age derivation
337 using modelling.

338 We sampled from wave-cut platforms comprised of differing lithologies at a range of
339 elevations: 62 m, 60 m, 46 m, 42 m and 29 m, including one location where there is an existing
340 age control from $^{234}\text{U}/^{230}\text{Th}$ coral ages (Locality F, Figure 4a) from sediments formed quasi-
341 contemporaneously with the wave-cut platform (Vita-Finzi et al., 1993; Leeder et al., 2003;
342 Leeder et al., 2005; Houghton, 2010). All samples were removed using a mallet and chisel.
343 Shielding values were noted every 30° of azimuth (as per the method in Dunai, 2010), and
344 used in the age exposure calculations to account for the shielding of cosmogenic rays on the
345 sample site by the surrounding topography (Dunai, 2010). Following removal, samples were
346 analysed in thin section to determine their lithology, washed in distilled water in an ultrasonic
347 bath, then crushed and prepared for ^{36}Cl exposure dating using Accelerator Mass
348 Spectrometry (AMS) as per the method outlined by Schimmelpfennig et al. (2009). The data
349 obtained from AMS was input into CRONUScalc (Marrero et al., 2016), an online calculator
350 that uses measured inputs from data such as ^{36}Cl concentration, elemental composition,
351 elevation, shielding, water content and appropriate uncertainties to calculate the age of the
352 samples with uncertainty values attached.

353

354 4. Results

355

356 This section explores the results of our detailed geological mapping of Cape Heraion
357 and the absolute ages obtained from our ^{36}Cl cosmogenic exposure dating and $^{234}\text{U}/^{230}\text{Th}$

358 dating. Alongside existing published ages, these new absolute ages are used to constrain the
359 ages of surfaces at different elevations on Cape Heraion in order to show that faulting is
360 responsible for offsetting a marine terrace linked to the 125 ka highstand within MIS 5e. The
361 results of the dating are used to drive throw rate analyses in order to calculate cumulative
362 throw within the tip zone since 125 ka.

363

364 *4.1 Field mapping*

365 Detailed field mapping reveals complicated, but linked spatial relationships between
366 lithologies, the stratigraphy and geomorphic features on Cape Heraion (Figures 4, 5,
367 Supplementary data 1, which contains a description of the stratigraphy). Wave-cut platform
368 features have been cut into the stratigraphy (Figure 4a) and are widespread throughout the
369 cape at elevations from 6 m to 99 m (Figures 4, 5 and 6). These horizontal to sub-horizontal
370 surfaces exhibit millholes and lithophagid borings, which are particularly well preserved on
371 the platforms composed of bioclastic packstone (Figures 4a, 6f). Associated with the wave-
372 cut platforms, several localities display coastal notches where the wave-cut platforms
373 impinge on steep outcrops. The notches are marked with lithophagid borings, for example
374 close to location B at ~41 m, with another notch observed at ~92 m (Locality J, Figure 4a).

375 Our mapping suggests that the lithologic, the stratigraphic and geomorphic features
376 can be interpreted as due to the effect of wave-erosion, at the time of wave-cut platform
377 formation, impinging on palaeo- Cape Heraion, characterised at that time by Quaternary
378 sediments onlapping onto an upstanding inlier of Mesozoic limestone (Figure 5b). The lateral
379 stratigraphic variations were denuded by the wave erosion so that the wave cut-platform
380 formed on different stratigraphic units across the mapped area. The stratigraphy, and the
381 wave-cut platform, have been subsequently offset by faulting that, therefore, post-dates the

382 wave-cut platform, the Cladocora-bearing bioclastic sands and the Rivularia-bioherms (Figure
383 7).

384 To gain further insights into the faulting, we have studied the steep slopes that occur
385 along the faults, and in particular the breaks of slope (Figure 4a, c). The map pattern produced
386 by the breaks of slopes reveals patterns that resemble displacement variations along the
387 faults, with slip maximum close to the centres of the map traces, and the positions of relay-
388 ramps at fault tips (Figure 4c). Hence, we interpret these breaks of slope to represent
389 hangingwall and footwall cut offs. Cross-sections across the faults are shown in Figure 8. To
390 cross-check the interpretation of fault segmentation in Figure 4c, we used the elevation data
391 shown in Figure 4b to measure the vertical offsets across the faults, checking that relay-ramps
392 and fault tips identified on Figure 4c are marked by decreased vertical offsets (Figure 9). This
393 cross-check confirms that locations where the hangingwall and footwall cut-offs converge in
394 map view (e.g. the relay-ramps and faults tips in Figure 9b) have low or zero vertical offsets,
395 consistent with our fault segmentation model.

396 As a final check on the geometries of the faults we have compared their displacement
397 (d) to length (L) ratios to those in a global database (Schlische et al. 1996), because $d = \gamma L$,
398 where $\gamma = 0.01-0.1$ with a preferred value of 0.03. We have analysed faults where we have
399 identified both fault tips, and faults where we consider that the centre of the fault has been
400 mapped, assuming that the displacement profiles will be symmetrical. We find values of
401 γ between 0.01-0.1 (Table 1), suggesting that the vertical extents of the steep slopes
402 separating terrace locations are consistent with the interpretation that they are fault scarps.
403 The exception is fault 4, which has a d/L ratio that is comparatively higher (0.27), possibly as
404 a result of being linked at depth with faults 1 and 10 (see the individual fault throw profiles in

405 Figure 9a for faults 1, 4 and 10). Consequently, the combined d/L ratio of these three faults is
406 not representative because the fault continues offshore to the west (Figure 4a, b).

407 We describe the details of the faulting below. With the exception of three faults that
408 strike approximately N-S not considered in this study, all of the faults strike parallel-sub
409 parallel to the average 260° of the SAFS between 230° and 300° (Figures 2, 4). The faults in
410 the north of the cape are all north dipping and exhibit short fault lengths (100-400 m) and
411 offsets of 2-20 m. South of Fault 11 the presence of a north dipping fault is inferred owing to
412 the 20 m offset of bioherms observed along the scarp of fault 11 (Figure 4a, b). Faults along
413 the south of the cape are longer, and extend outside of the mapping area to the east and
414 offshore to the west (faults 1, 17 and 18) (Figures 4a-c, 7a-c). Along the south of the cape,
415 there are four south-dipping faults (1, 4, 10 and 18) (Figures 4b, 7a-c, e, f). The scarp of fault
416 18 is not accessible and the offset of this fault is a minimum value as its hangingwall is
417 offshore, however, this fault has been mapped by Morewood and Roberts (1999) farther to
418 the east for ~ 2 km. South dipping faults 1, 4 and 10 appear to be en echelon to one another
419 and exhibit limestone fault scarps that decrease in offset from west to east.

420 Strike and dip values, and, where visible, fault striations were measured along the
421 limestone fault scarps of Faults 1, 2, 10 and 17 (Figure 4d). The fault dip for these faults range
422 between $43-66^\circ$. In places faults display evidence of activity in a marine setting, faults 1 and
423 4 display post-slip marine cementation of submarine scree coating the faults (Scott, 1995).
424 Along north dipping faults 2 and 11, offset algal bioherms have horizontal lines of abundant
425 lithophagid borings at 34 m and 41 m respectively, again suggesting slip pre-dates wave-cut
426 platform formation.

427 In summary, our geomorphological observations and elevation measurements
428 suggest that a pattern of distributed faulting is visible on Cape Heraion. In the context of the

429 north-dipping SAFS and its approximate E-W strike, the faulting on Cape Heraion displays a
430 set of synthetic and antithetic faults that display a 70° variation in strike. While north-dipping
431 faults are more numerous, they appear to have smaller lengths and offsets compared to the
432 four south dipping faults.

433

434 4.2 $^{234}\text{U}/^{230}\text{Th}$ coral dating

435 The *Cladocora caespitosa* corallites sampled from Cape Heraion (S6U/Th, S7U/Th)
436 (Figure 4) were removed from within a death assemblage on the 44 m wave-cut platform
437 predominantly composed of friable sediments (Figures 6c, 7a). Results of $^{234}\text{U}/^{230}\text{Th}$ dating on
438 S6U/Th and S7U/Th reveal growth ages of 137 ka and 136 ka respectively (Figure 8a, Table 2).
439 The age presented for S6U/Th is comprised of the average of three analyses from the same
440 corallite, a fourth age was also obtained from this corallite, but we have excluded it as the
441 age of 173.7 ky suggests that it is an outlier and not representative of the age of the corallite
442 (Table 2). The average age of sample S7U/Th is obtained from six analyses from the same
443 corallite (Table 2). The $^{234}\text{U}/^{230}\text{Th}$ coral ages support growth during MIS 5e and are similar to
444 existing coral growth ages from Cape Heraion (Figure 8a; Vita-Finzi et al., 1993; Leeder et al.,
445 2005; Roberts et al., 2009; Burnside, 2010; Houghton, 2010). Note that all samples have
446 relatively high values of $\delta^{234}\text{U}$ of 191-214 (a common way to represent the initial activity ratios
447 of $^{234}\text{U}/^{238}\text{U}$) compared to modern seawater in the Gulf of Corinth (value of 151; Roberts et
448 al., 2009). It is expected that the samples should have $\delta^{234}\text{U}$ values similar to modern sea-
449 water. However, previous studies of coral ages in the Gulf of Corinth, which successfully
450 produced ages of independently-known glacio-eustatic sea-level highstands, have tended to
451 show elevated values (e.g. Collier et al., 1992; Vita-Finzi et al., 1993; McNeill and Collier, 1994;
452 Dia et al., 1997; Leeder et al., 2005; Roberts et al., 2009; Burnside, 2010; Houghton, 2010;

453 Turner et al., 2010), probably due to the fact that it is a restricted basin with freshwater input.
454 The analyses herein also suggest an age similar to a well-known glacio-eustatic sea-level
455 highstand at ~125 ka. Thus, like previous studies, we use the implied age in our later analysis,
456 despite the relatively high initial activity ratio for our samples.

457

458 *4.3 ³⁶Cl exposure dating of wave-cut platforms*

459 Cosmogenic ³⁶Cl exposure dating is employed to calculate the time period that
460 sampled surfaces have been subaerially exposed and thus accumulating significantly higher
461 values of ³⁶Cl compared to pre-exposure. Five samples were removed from limestone,
462 bioclastic packstone and algal bioherm wave-cut platforms at different elevations on Cape
463 Heraion (Figures 4a, 6). Our field observations are used to inform the erosion rate used as an
464 input parameter into CRONUScalc, which is used to calculate the exposure age of the samples
465 (see Supplementary data 2 for CRONUScalc input data). The preservation of lithophagid
466 borings and millholes on bioclastic packstone and limestone surfaces (samples 1 and 3)
467 (Figure 6b, f) indicate total erosion values of less than 0.2-0.3 m, whilst samples from the tops
468 of bioherms (samples 2, 4 and 5) are expected to have experienced total erosional values
469 similar with the removed depth of bioclastic packstone/grainstone eroded from the surface
470 of ~0.6 m. These limestone/packstone and bioherm values equate to erosion rates of 0.1 and
471 ~6.0 mm/ky respectively. We note that the 0.1 mm/yr value is the same as that used on
472 limestone wave-cut platforms dated using ³⁶Cl exposure dating in south Crete (Robertson et
473 al., 2019).

474 Assuming the erosion rates stated above are correct, the ³⁶Cl exposure ages of five
475 samples (Figure 8a, Table 3) are: S1 (limestone, sampled at 60 m) 122 ± 29 ka; S2 (bioherm,
476 sampled at 62m) 108 ± 36 ka; S3 (bioclastic packstone, sampled at 42 m) 109 ± 24 ka; S4

477 (bioherm, sampled at 46 m) 120 ± 40 ka; S5 (bioherm, sampled at 29 m) 112 ± 35 ka. These
478 results agree with the new and existing U-series ages presented above, suggesting late
479 Quaternary ages close to the age of the 125 ka highstand. The error bars on the ages appear
480 relatively-large, but are comprised of internal (analytical) and external (total) uncertainties
481 that are associated with measured input parameters into CRONUScalc (e.g. H₂O content,
482 elevation, shielding, erosion rates and the production rate; Marrero et al., 2016). Where
483 samples are removed from the same geographical location using the same method, the error
484 values of the input parameters used to calculate the external uncertainty will be very similar
485 (i.e. shielding) or even the same (i.e. production rate, elevation values). Consequently,
486 Marrero et al. (2016) suggests that the external uncertainty value linked to the exposure age
487 may be overestimated when comparing results from the same geographical area, sampled
488 using the same method (see Dunai, 2010). This possible overestimate of uncertainties should
489 be borne in mind when considering the relatively-large error bars associated with the
490 exposure ages, but we have chosen to report the external uncertainties herein.

491 While the erosion rates used to calculate exposure ages are based upon field
492 observations, we recognise that they form an uncertainty in the ages obtained. Therefore, we
493 examine the sensitivity of the exposure age results to uncertainties in the estimated erosion
494 rates. For samples 1 and 3, we tested erosion rates from 0.1-1 mm/ky and for samples 2, 4
495 and 5 we tested erosion rates from 5.5-6.5 mm/ky (± 0.5 mm/ky of our estimated erosion
496 rates). The results of these analysis (Supplementary data 3) reveal that the exposure ages may
497 all be allocated to the 125 ka highstand even if our chosen erosion rate is adjusted within the
498 range of ± 0.5 mm/ky. Values for erosion rate larger than this would not be consistent with
499 our field observations of features such as preserved millholes and lithophagid borings. We
500 therefore suggest maximum and minimum values for rates of erosion for samples 1 and 3 of

501 0.1-1 mm/ky and for samples 2, 4 and 5 of 5.5-6.5 mm/ky. These results support our
502 contention that our erosion rate estimates (samples 1, 3: 0.1 mm/ky and samples 2, 4 and 5:
503 6 mm/ky) are acceptable.

504 We suggest that all our exposure ages for the wave-cut platform are associated with
505 MIS 5e, and we discuss this below. Our exposure age results link S1 and S4 and their
506 associated wave-cut platforms to MIS 5e, but the wave-cut platforms that S2, S3 and S5 were
507 removed from, might, at first sight, be linked to either MIS 5c (100 ka highstand) or MIS 5e
508 (125 ka highstand) (Figure 8a). However, using the exposure ages obtained from S1 (60 m)
509 and S4 (46 m), new $^{234}\text{U}/^{230}\text{Th}$ ages from S6 and S7 (44 m) and existing U-series dating of corals
510 on platforms at 7 m (Roberts et al., 2009), 15 m (Burnside, 2010) and 29 m (Vita-Finzi et al.,
511 1993; Leeder et al., 2003; Leeder et al., 2005; Houghton, 2010) alongside sea-level curve data
512 we suggest that it is more likely that S2 (62 m), S3 (42 m) and S5 (29 m) are associated with
513 MIS 5e (Figure 8c). Our reasoning is that it is difficult to reconcile that platforms at 60 m, 46
514 m, 44 m, 29 m, 15 m and 7 m were formed by the MIS 5e 125 ka highstand, yet platforms at
515 similar elevations (62 m, 46 m and 29 m) were formed by the MIS 5c 100 ka highstand. This is
516 especially unlikely, given that the maximum sea level during the 100 ka highstand in MIS 5c
517 was -25 m relative to today, and this is 30 m lower than the 5 m relative sea level during the
518 125 ka highstand of MIS 5e (Siddall et al., 2003) (Figure 8a).

519 The results of our dating, combined with existing age controls and detailed geological
520 mapping strongly supports that the observed wave-cut platforms on Cape Heraion were all
521 formed during the 125 ka highstand of MIS 5e and have been subsequently faulted since this
522 time (Figure 8c).

523

524 *4.4 Holocene displacements*

525 Offset Holocene notches and surface faulting that may be associated with the 1981
526 earthquake suggest occurrence of Holocene faulting on Cape Heraion (Figure 7). An offset
527 notch exists along the base of a cliff at the south west of the cape of as a result of slip on Fault
528 1 (Figures 4b, 7b). The highest notch is offset by 1.08 m between the footwall and the
529 hangingwall, but it does not appear that a lower notch is also offset (Figure 7b). Our
530 explanation for this is that faulting occurred on Fault 1 following the formation of the upper
531 notch between 4440-4320 B.C. (Pirazzoli et al., 1994) prior to the formation of the lowest
532 notch (at ~1.4 m) between 440-190 A.D.; this may be interpreted as evidence of Holocene
533 faulting on this part of the cape.

534 Evidence of recent surface faulting may also be present on the north of the cape as a
535 several metre-deep fracture offsetting the bioherms. The fracture (Locality I Figure 4a, and
536 Figure 7d) has a strike of 245° , a horizontal offset of 43 cm, and a direction of opening of 332° ,
537 as measured by matching piercing points on both hangingwall and footwall. On Fault 17
538 between localities J and K (Figure 4a), the occurrence of surface faulting is suggested by a
539 fresh, lichen-free stripe at the base of a carbonate fault plane. These possible surface
540 ruptures, if extrapolated along-strike, cover a distance of ~300 m along the faults. Between
541 localities J and K we observed seven locations that display fresh lichen-free stripes on bedrock
542 fault planes (Figure 7e and f). Bedrock offsets (measured as vertical throw) appear as a light
543 grey stripe at the base of a free face, preserving what appears to be the relative coseismic
544 movement of the colluvium along the fault rupture, ranging from 3-12 cm of throw. In places,
545 the surface rupture has also stepped forward into the hangingwall, located a few centimetres
546 to decimetres away from the carbonate fault plane, to offset the hangingwall colluvial
547 deposits (Figure 7e); vertical offset in the colluvium ranges between 7-28 cm, measured at
548 eight locations between localities J and K (Figure 4a).

549 As the 1981 earthquakes are the most recent to result in surface ruptures on the Pisia
550 fault (Jackson et al. 1982; Taymaz et al., 1991; Hubert et al., 1996; Roberts, 1996a), and
551 ruptures were reported as close by as along the shore of Lake Vouliagmeni (Bornavas et al.
552 1984; Figure 2c), we suggest that it is plausible that the ruptures on Cape Heraion, may have
553 also occurred coseismically during the 24th and/or 25th February 1981 earthquakes.

554

555 *4.6 Throw rates and uplift rates*

556 The absolute ages of wave-cut platforms gained in this paper constrain their formation
557 to the 125 ka highstand within MIS 5e. This means that we can quantify the throw-rate and
558 uplift-rates since 125 ka (Figure 9) to the present day. To constrain the fault geometries, we
559 used elevation data for the footwall and hangingwall cut-offs along the strike of fault traces
560 from the geological and geomorphological map (Figure 4) to construct throw profiles across
561 each fault. Plots of the individual throws for all faults show that faults have maximum offset
562 values of <40 m with two faults exceeding this value (17 and 18) (Figure 9a). When all of the
563 fault throw values and rates are summed across strike they show a pattern of decreasing
564 displacement from east to west (Figure 9c). We emphasise that the data in the grey area on
565 Figure 9c should be interpreted with more caution due to the lack of absolute age control
566 obtained for the wave-cut platform located in the footwall of fault 17 (Figures 4a, 9a), but
567 here we infer that if the notch and small wave-cut platform at ~92-99 m (Locality J, Figure 4a)
568 cut into the footwall of Fault 17 represents the 125 ka palaeoshoreline (Figure 8c, profile 3),
569 we can constrain the throw rate, and we include this in our summed values.

570 When fault throw and throw rates are plotted separately for the north- and south-
571 dipping faults they mirror the pattern of summed values decreasing from east to west (Figure
572 9c). It is interesting to note that four south-dipping faults accommodate more throw

573 compared to 14 north-dipping faults with the exception between 1900-1800 m to the west of
574 the 'on fault' throw minima (Figure 9c). We postulate that this may be a reflection of the
575 broader faulting pattern within the Gulf of Corinth where the polarity of faulting switched
576 from south-dipping faults to north-dipping faults during the late Quaternary (Roberts et al.,
577 2009; Nixon et al., 2016). Specifically, Roberts et al. (2009) suggested that the north-dipping
578 SAFS experienced an increase in slip at ~175 ka. The short fault lengths and small
579 displacements of the north dipping faults on Cape Heraion may indicate that they may be less
580 mature compared to their south-dipping counterparts. As the summed throw values do not
581 decrease to zero in the mapped area, we suggest that the point of zero vertical offset may lie
582 offshore to the west of Cape Heraion, unless the faulting is actually hard-linked to offshore
583 EXFS.

584 Another way to consider the results is to explore how throw across active faults has
585 produced spatial variation in uplift relative to present-day sea-level. In other words, the
586 absolute ages of wave-cut platforms, and knowledge of their elevations, allows calculation of
587 spatial variation in uplift rates since 125 ka. Uplift rates since 125 ka from the highest and
588 lowest dated wave-cut platforms are calculated as 0.46 mm/yr (S2, 62 m) and 0.02 mm/yr
589 (Sample P1CWall, 7 m, Roberts et al., 2009) respectively (Figure 4a). If our assertion that the
590 observed notch at 92 m (Locality J, Figure 4a) marks the palaeoshoreline of the 125 ka is
591 correct then a maximum uplift rate of 0.7 mm/yr on Cape Heraion is derived using the 92 m
592 elevation (N.B. these calculations take into account that the sea-level elevation of the MIS 5e
593 highstand was +5 m relative to today's sea-level). The extreme variability in uplift rate over
594 distances of tens of metres or less precludes simple interpretations of regional tectonic signals
595 in our opinion, as the local uplift is clearly dominated by local faulting (c.f. Leeder et al. 2005).

596 While the ages obtained in this study and the existing coral U-series link the formation
597 of the wave-cut platforms to the MIS 5e highstand, field observations suggest that some faults
598 were already active prior to MIS 5e. Evidence for this is in the form of (a) marine cementation
599 within submarine screes coating the fault planes on Faults 1 and 4, (b) stratigraphic variations
600 across faults in and below the bioherms, and (c) flat-topped bioherms in the footwall versus
601 domed-topped bioherms in the hangingwall that are suggested to have grown up toward
602 water surface levels during formation (Figure 5) (also observed by Kershaw and Guo, 2006).
603 This evidence suggests that faulting on Cape Heraion was active prior to the beginning of the
604 MIS 5e (~138 ka) and continued throughout the marine stage and beyond. It is possible that
605 along the faults with smaller offsets (such as those in the north) any coseismic offset prior to
606 125 ka may have either been consequently covered by syn-wave-cut platform sediments or
607 eroded prior to or during the formation of the 125 ka platform; this is particularly plausible
608 given that between the start of MIS 5e at ~138 ka and the highstand at 125 ka any fault offset
609 on the peninsula over this time would have been subject to the erosive forces of rising sea
610 level. Furthermore, coseismic offsets on the faults on the peninsula are expected to be
611 relatively small (a few cm) and therefore easier to erode or obscure with sediment.

612

613 5. Discussion

614 Detailed fault mapping and absolute dating on Cape Heraion reveals that the western
615 tip zone of the SAFS accommodates deformation via distributed faulting along synthetic and
616 antithetic faults. Importantly, our findings provide evidence of faulting during the Late
617 Quaternary, specifically over decadal, 10^3 and 10^5 year timescales that is ongoing into the
618 Holocene and perhaps even as recently as 1981. Offset marine terraces and their wave-cut
619 platforms throughout the entire mapped area can be linked to the 125 ka highstand within

620 MIS 5e. The findings presented in this study, therefore, provide evidence of significant late-
621 Quaternary faulting on Cape Heraion. This outcome is in direct contrast to the findings of
622 Leeder et al. (2003) and Leeder et al. (2005) who refute the notion of displacement of
623 Holocene and late Quaternary shoreline deposits within the study area, and conclude that the
624 Perachora Peninsula is uplifting at a constant, low, uniform rate of 0.2-0.3 mm/yr possibly
625 linked to angle of dip of the subducting African plate beneath the eastern Gulf of Corinth
626 (Leeder et al., 2005) and representing a 'background' uplift rate for the region.

627 Our fault throw analyses show that summed throw rates in the tip area appear to be
628 relatively high, up to ~1.6 mm/yr (Figure 9), compared to throw and slip rates near the centre
629 of the Pisia and Skinos faults of up to 2.3 mm/yr (Mechernich et al., 2018) and 0.7-2.5 mm/yr
630 (Collier et al., 1998) over the Holocene and 1.2-2.3 mm/yr over the longer term (Collier et al.,
631 1998). From the findings presented here, we conclude that detailed across strike mapping
632 within the tip zone of a fault is imperative in order to constrain accurate rates of long-term
633 faulting that could otherwise be underestimated. We show that the tips of faults should be
634 considered as zones of deformation, rather than localised surface features where a fault stops
635 as they contain multiple active faults.

636

637 *5.1 High throw rates on Cape Heraion*

638 Our findings lead us to question why the throw values obtained in the western tip
639 zone over 125 ka are anomalously high compared to those observed along the localised fault
640 (Figure 10a). Studies of tip displacement gradients commonly suggest high gradients occur
641 where the tips of two faults overlap, as a consequence of the interaction between the stress
642 fields of the faults (e.g. Peacock and Sanderson, 1991; Huggins et al., 1995; Willemse et al.,
643 1996; Cartwright and Mansfield, 1998; Cowie and Shipton, 1998; Gupta and Scholz, 2000;

644 Ferrill and Morris, 2001; Scholz and Lawler, 2004; Fossen and Rotevatn, 2016). Analysis of an
645 isolated fault tip by Cowie and Shipton (1998) revealed an average tip displacement gradient
646 of 0.018, whereas Cartwright and Mansfield (1998) obtained gradients between 0.0164 to
647 0.25, in their study of 20 normal faults comprised of a mixture of isolated and interacting
648 faults. In comparison, the tip displacement gradient for the investigated western tip zone of
649 the SAFS is 0.233 (Figure 10b), at the upper range of those observed above.

650 An explanation of the relatively high summed throw rates on Cape Heraion may be
651 due to fault interaction between the stress fields of the EXFS and the SAFS located along strike
652 to one another and whose eastern and western fault tips overlap (Figure 2a). While this
653 suggestion has been proposed by Morewood and Roberts, (1997), it has not been
654 quantitatively investigated. One way of exploring fault interaction between overlapping faults
655 relies on modelling the calculated Coulomb stress transfer from rupturing a source fault onto
656 a receiver fault. Studies of Coulomb stress transfer (King et al., 1994; Toda et al., 2005) show
657 that following an earthquake, changes in the stress around the slipping patch on the source
658 fault occur that may influence seismicity on neighbouring receiver faults, with positive
659 Coulomb stress transfer bringing a receiver fault closer to failure and negative Coulomb stress
660 transfer resulting in stress shadows. The presence of a stress shadow on the tip zone of a
661 receiver fault may result in deceleration of the propagation of the tip of the receiver fault,
662 which consequently results in displacement accumulating near its interacting tips, causing
663 steeper displacement gradients (Gupta and Scholz, 2000, Figure 14). The deceleration occurs
664 because the fault at the interacting tip must overcome the rupture resistance and stress drop
665 imposed by the adjacent fault (Walsh and Watterson, 1991; Scholz and Lawler, 2004).

666 We explore whether the location of the eastern EXFS tip zone (Figure 2a) could perturb
667 the stress field of the western tip zone of the SAFS by modelling the Coulomb stress changes

668 following an earthquake on the EXFS (source fault) onto the SAFS (receiver fault) using
669 Coulomb 3.3.01 software. We use the approach and updated code of Mildon et al. (2016)
670 within Coulomb 3.3.01 that allows strike-variable faults to be used, as Coulomb stress transfer
671 is particularly sensitive to changes in the strike of receiver faults (Mildon et al., 2016). An
672 accurate fault trace drawn using Google Earth™ and geometries (dip, strike, rake) of the
673 source (EXFS) and receiver (SAFS) faults (Table 4) were input into the code from Mildon et al.
674 (2016). The source fault was then ruptured to produce a ‘standard’ earthquake, determined
675 using fault-scaling relationships to calculate the maximum magnitude from the length of the
676 fault rupture (Wells and Coppersmith, 1994). Three source fault rupture scenarios are
677 modelled: (1) the rupture of the SAFS with the exception of the western 2.5 km of the SAFS;
678 (2) the rupture of the entire EXFS; (3) a partial rupture of the EXFS, which involves only the
679 most eastern segment (the Perachora fault) (Figure 2a). Scenario (1) was modelled in order
680 to establish the Coulomb stress transfer imparted from a partial rupture of a fault onto its
681 own tip area (e.g. Roberts 1996). Note that within the Coulomb stress transfer scenarios, the
682 western tip area of the SAFS is defined as the western 2.5 km section of the SAFS, from Point
683 A (Figure 2a) to the west tip of Cape Heraion.

684 The results of Coulomb stress transfer modelling show stress enhancement on the
685 shallow portions of faults in the region of Cape Heraion, or stress enhancement to greater
686 depths, depending on the exact source to receiver geometry. Rupturing the entire SAFS with
687 the exception of the western 2.5 km section (Scenario 1), results in a significant positive
688 Coulomb stress change of 2 bars onto the entire fault plane of the SAFS western 2.5 km
689 section (Figure 11b). Rupturing the entire EXFS (Scenario (2)) results in the upper and lower 2
690 km of the SAFS western 2.5 km section experiencing positive stress transfer of 2 bars, while
691 the majority of the western 2.5 km section of the fault plane displays negative stress transfer

692 of up to -2 bars (Figure 11c). Similarly, in scenario (3), rupturing only the Perachora fault
693 segment of the EXFS also results in negative stress transfer of -2 bars over almost all of the
694 western 2.5 km section of the fault with the exception of the upper 1 km, which experiences
695 positive stress transfer values of 1-2 bars (Figure 11d). Overall, the high values of
696 displacement observed on Cape Heraion over 125 ka may be explained by fault interaction
697 between the overlapping tips of the EXFS and the SAFS.

698

699 *5.2 Impacts on seismic hazard*

700 Our findings have implications for fault-based probabilistic seismic hazard assessment
701 (PSHA). We show here that the tip zone of a crustal-scale normal fault can accommodate
702 significant displacement 'off the localised fault', possibly linked to interaction with a
703 neighbouring fault. If these patterns of deformation are assumed to be typical for other
704 normal crustal-scale faults within fault systems that overlap along strike, such as those in the
705 Central and Southern Italian Apennines (Roberts and Michetti, 2004; Papanikolaou et al.,
706 2005; Papanikolaou and Roberts, 2007; Iezzi et al., 2019) and Basin and Range Province,
707 Western USA (e.g. Machette et al., 1991; Anders and Schlische, 1994; Schlische and Anders,
708 1996, *and references therein*) then our findings may help shed light on how to incorporate
709 slip/throw values into regional datasets, and whether displacements can jump from one
710 major fault to another.

711 It is known that measurements of slip rate are key inputs into PSHA calculations to
712 gain recurrence intervals and probability of shaking events (e.g. Boncio et al., 2004; Pace et
713 al., 2010; 2016; Valentini et al., 2017). However, due to a sparsity of data, it is common to
714 extrapolate slip rate data from measurements collected on a single location along a fault. This
715 is predominantly done by assuming that displacement decreases towards fault tips (Faure

716 walker et al., 2018). The present study shows that this approach can be problematic, because
717 the interaction between overlapping and interacting fault tips of neighbouring faults might
718 result in anomalously-high displacement in the tip zone, so that throw and slip rates do not
719 simply decrease along strike. Thus, calculation of recurrence rates and the probabilities of
720 given shaking intensities may be in error in such situations.

721 If our suggestion that high values of displacement in the overlapping tip zones
722 between the EXFS and the SAFS are as a result of fault interaction is correct, then the
723 possibility that earthquake ruptures may jump between the EXFS and SAFS should also be
724 explored. Fault interaction has the capacity to affect rupture sequences whereby seismic
725 events may 'jump' across interacting faults, causing multi-fault earthquakes (e.g. Gupta and
726 Scholz, 2000; Iezzi et al., 2019). For instance, from analysis of the source parameters of the
727 1981 earthquake sequence, Abercrombie et al. (1995) suggested that the 1981 earthquake
728 sequence might represent a multi-fault rupture between the SAFS and EXFS (or a segment of
729 the EXFS), during which the rupture might have originated offshore and propagated eastward
730 onshore. However, this analysis was carried out without consideration of the distributed
731 faulting reported herein. It is beyond the scope of this paper to confirm or deny whether the
732 presence of distributed faulting may make jumps between co-located faults more or less
733 likely. However, this topic is important because the recent UCERF 3 model (Field et al., 2017)
734 recognises the potential of ruptures to jump between faults that are co-located along strike
735 separated by small distances (5 km), a value similar to those identified by empirical studies of
736 normal faulting earthquakes between 5-7 km (e.g. DePolo et al., 1991; Wesnousky, 2008). The
737 maximum step between the SAFS and EXFS is ~4 km (Figure 2), within the values reported
738 above. Moreover, the observation that anomalously high displacement has accumulated in
739 the Cape Heraion tip zone may be evidence that earthquake ruptures do cross the tip zones,

740 but their presence is only detected if detailed mapping is conducted, and excellent age
741 constraints are available to gain rates of deformation.

742 We contrast the wealth of observations we provide in the Cape Heraion tip zone with
743 the more typical situation away from sea-level, where transverse bedrock ridges tend to
744 occupy tip zones, and these ridges are made of uniform pre-rift lithologies. In these locations,
745 sparse Quaternary or Holocene sediments may make it difficult to study and gain evidence
746 for active faulting and rates of deformation (e.g. Roberts and Koukouvelas, 1996, elsewhere in
747 central Greece; Roberts and Michetti, 2004, Italian Apennines; Zhang et al., 1991; Crone and
748 Haller, 1991; Wu and Bruhn, 1994 western USA, for examples of such transverse bedrock
749 ridges). It may be that smaller distributed displacements remain undiscovered in tip zones
750 between major active faults, and this warrants more investigation, because their study may
751 be one of the few ways to observe whether ruptures cross tip zones to produce hazardous,
752 multi-fault earthquakes.

753

754 **6. Conclusions**

755

756 1. Cape Heraion, in the western tip zone of the South Alkyonides Fault System, deforms via a
757 set of distributed faults that are synthetic and antithetic to the 'main fault' and have been
758 active over decadal, 10^3 yr and 10^5 yr timescales. New age constraints using ^{36}Cl cosmogenic
759 exposure dating and $^{234}\text{U}/^{230}\text{Th}$ age dating of corals reinforce that the marine terraces and
760 associated wave-cut platforms on Cape Heraion are linked to the 125 ka highstand within MIS
761 5e rather than a set of terraces from three successive MIS phases.

762 2. On Cape Heraion, summed throw values (211 – 35 m), throw rates (1.68 – 0.25 mm/yr) and
763 uplift rates (maximum 0.7 mm/yr) appear to exceed those reported on the main fault. These

764 deformation rates are reflected in an anomalously high displacement gradient of 0.233.
765 Coulomb stress change modelling suggests that this is a consequence of the fault interaction
766 between the overlapping tips of the EXFS and the SAFS.

767 3. Our findings have implications for probabilistic seismic hazard calculations as they show
768 that the tip zones of crustal-scale faults may host high deformation rates caused by
769 distributed faulting and as such should be mapped in detail across strike. This is particularly
770 important for fault systems worldwide where crustal-scale faults may overlap and where the
771 slip rates are typically propagated along strike from one or two measurements assuming a
772 fault that linearly decreases to zero at the tips.

773

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783

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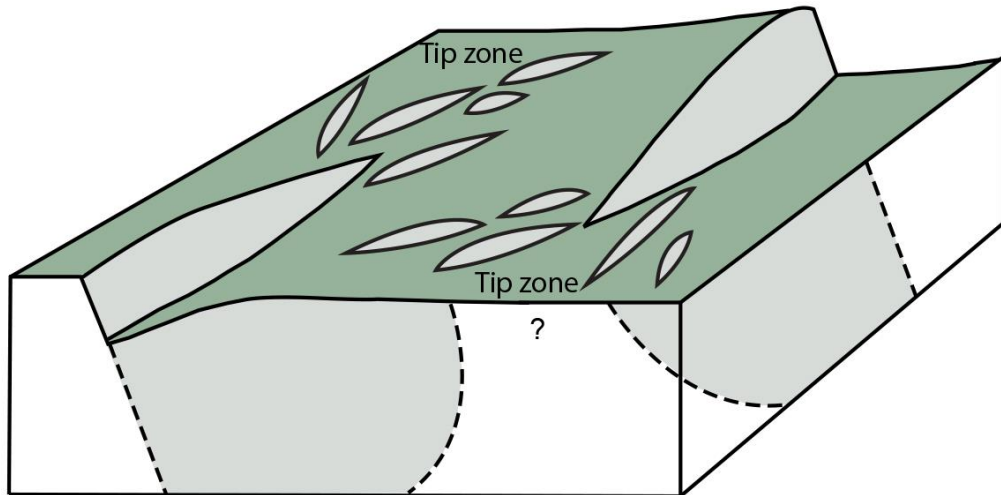
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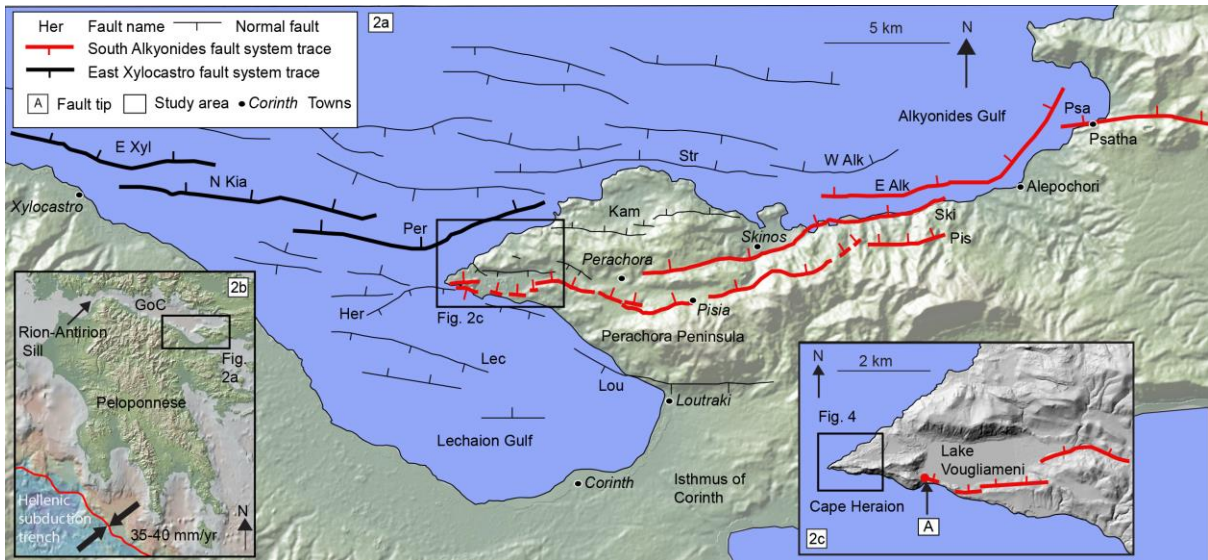
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- 1163 Figures



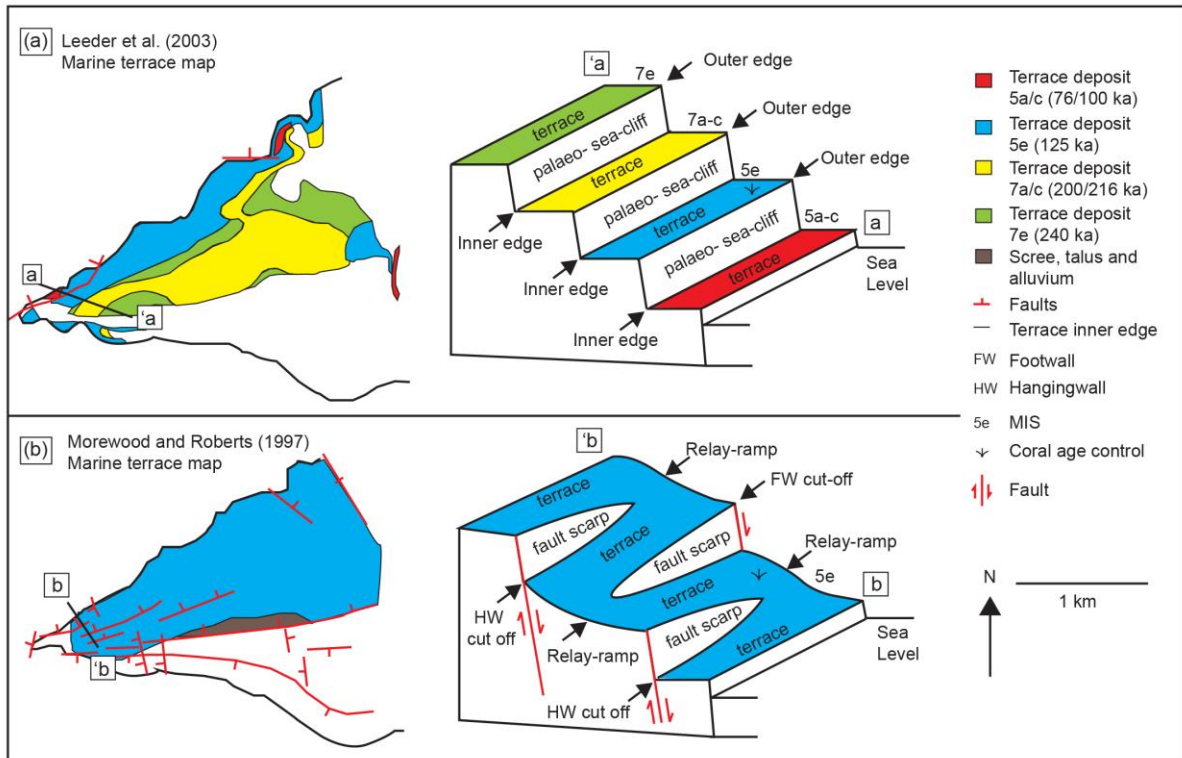
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1165 Figure 1: Schematic diagram of a possible tip zone deformation where the tips of two along-
 1166 strike faults overlap.



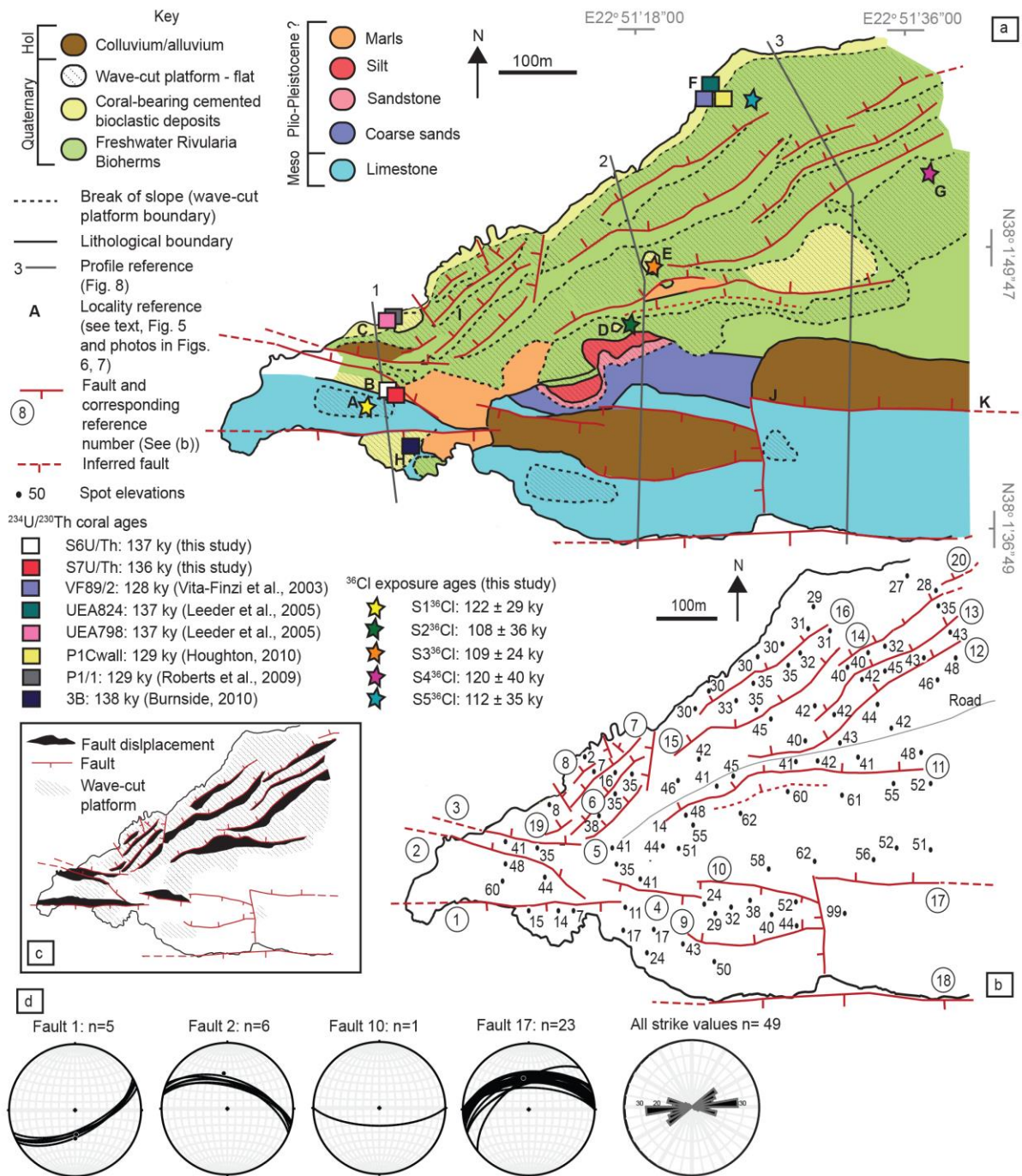
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1168 Figure 2: (a) Map of the eastern Gulf of Corinth and the Perachora Peninsula, surface trace
 1169 of the South Alkyonides Fault system (SAFS) (red) (Morewood and Roberts, 2002), East
 1170 Xylocastro Fault System (EXFS) trace (Bold) as per Nixon et al., 2016, all other faults as per
 1171 Nixon et al., 2016. (b) Location of the Gulf of Corinth and Hellenic subduction trench taken
 1172 from Kreemer and Chamot-Rooke (2004), GPS data from Nocquet (2012). (c) 5 m Digital
 1173 Elevation Model showing the western surface trace of the SAFS as per Morewood and
 1174 Roberts (2002) and Cape Heraion. 'A' marks the location of the 'on-fault' tip of the SAFS
 1175 (Morewood and Roberts, 1999).



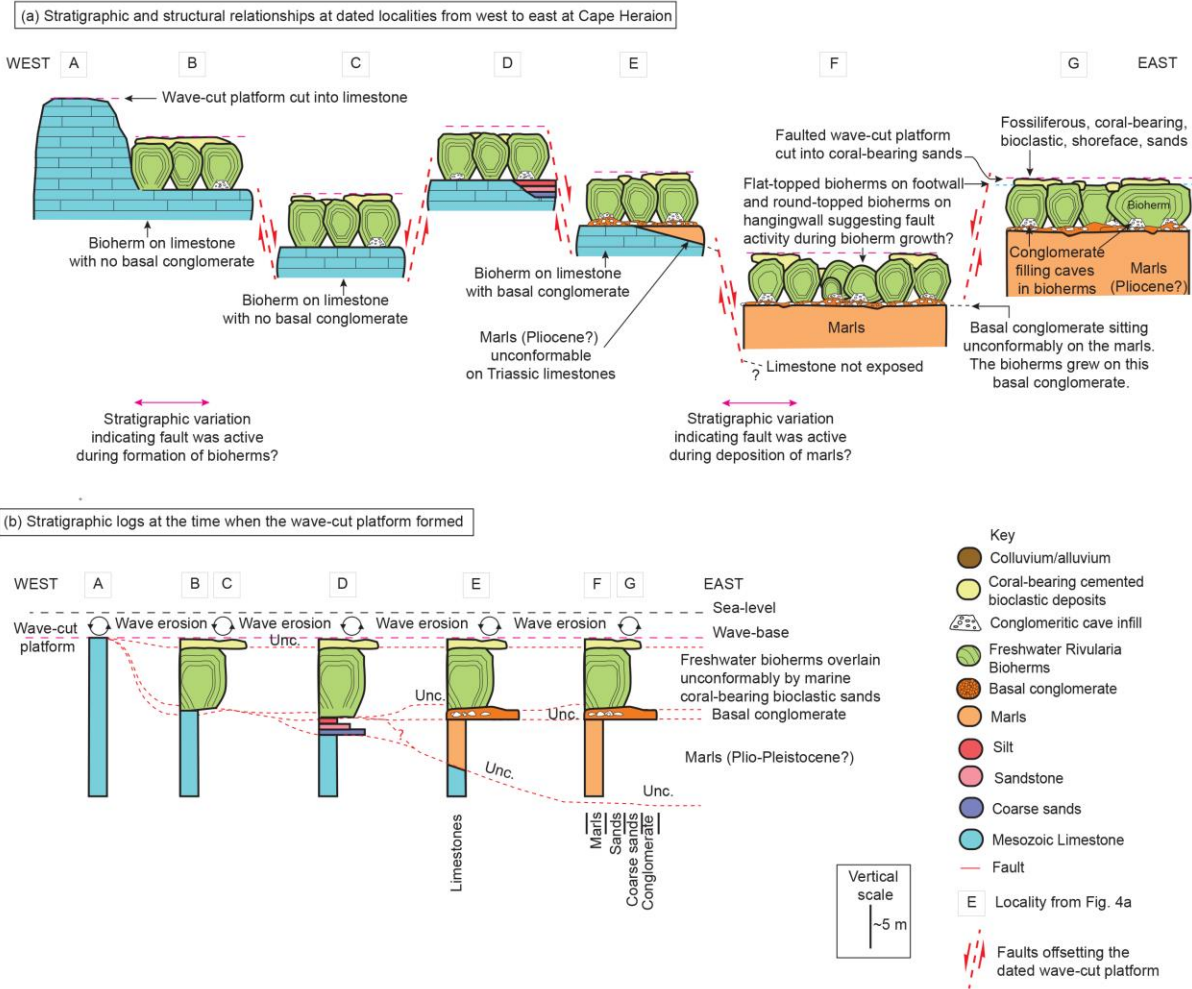
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1177 Figure 3: Comparison of two explanations for the observed geomorphology on Cape
 1178 Heraion. (a) Geological map redrawn from Leeder et al. (2003) and interpreted schematic 3D
 1179 diagram, Leeder et al. (2003) suggest a sequence of palaeoshorelines from MIS 5a/c (76.5
 1180 ka/100 ka) to 7e (240 ka). (b) Geological map redrawn from Morewood and Roberts (1997)
 1181 and interpreted schematic 3D diagram, Morewood and Roberts (1997) suggest Cape
 1182 Heraion is linked to the MIS 5e 125 ka highstand and has been latterly faulted.



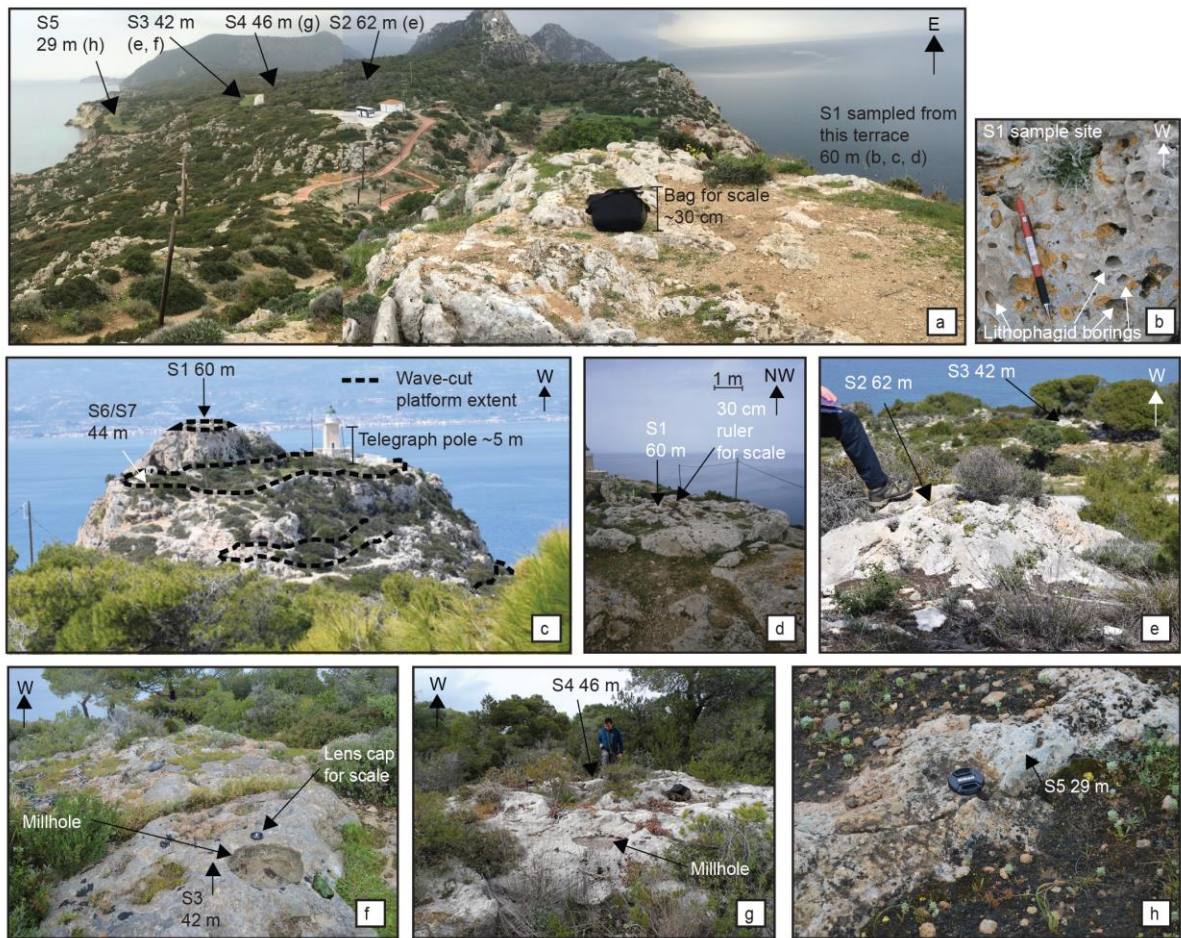
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1184 Figure 4: (a) Geological and geomorphological map of Cape Heraion, age controls from this
 1185 study and other coral studies (Vita-Finzi et al., 2003; Leeder et al., 2005; Roberts et al., 2009;
 1186 Burnside, 2010; Houghton, 2010). (b) Fault map of Cape Heraion and spot height elevations
 1187 used to plot the fault displacement in (c). (d) Stereonet plots for faults 1, 2, 10 and 17, rose
 1188 diagram representing all measured strike values.



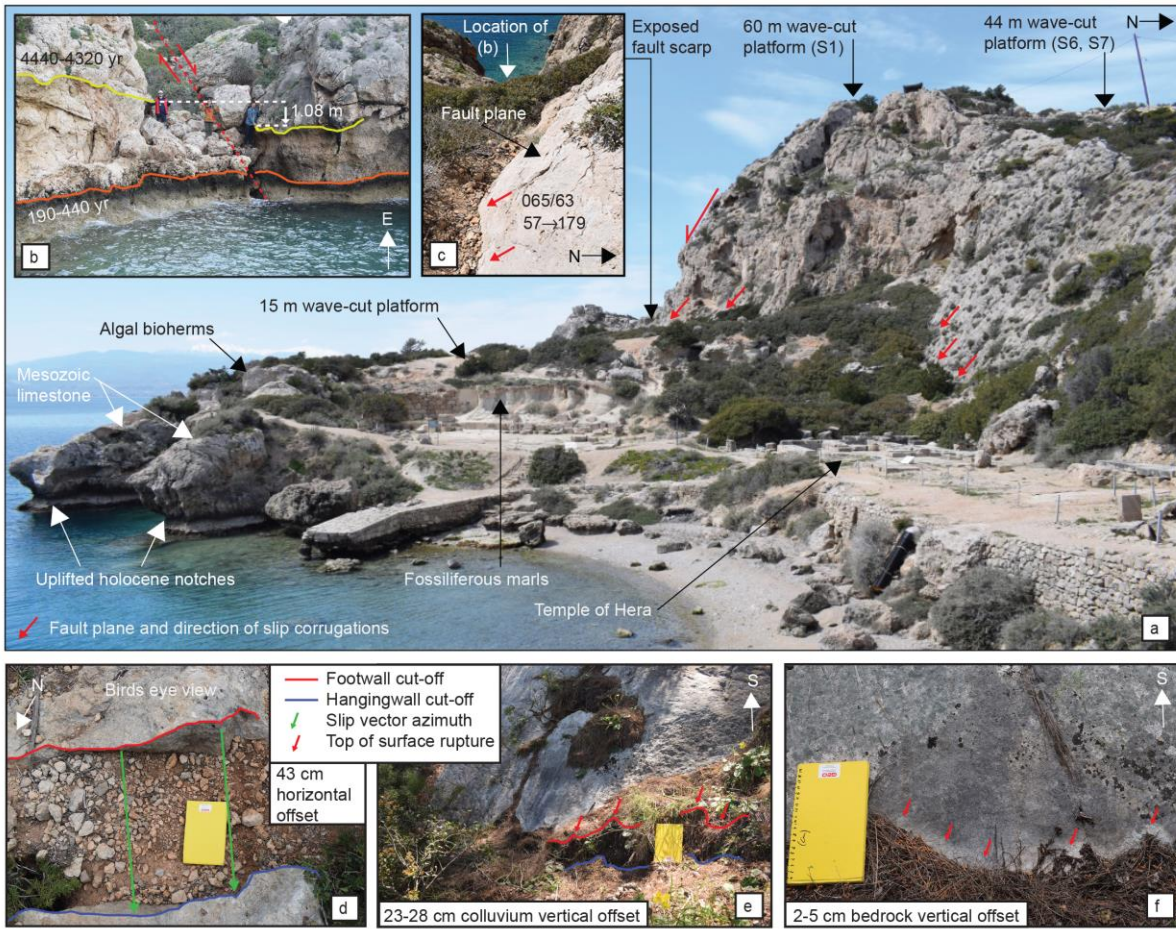
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1190 Figure 5: (a) Stratigraphic and structural relationships and (b) stratigraphic logs for dated
 1191 localities from West to East, see Figure 4 for localities



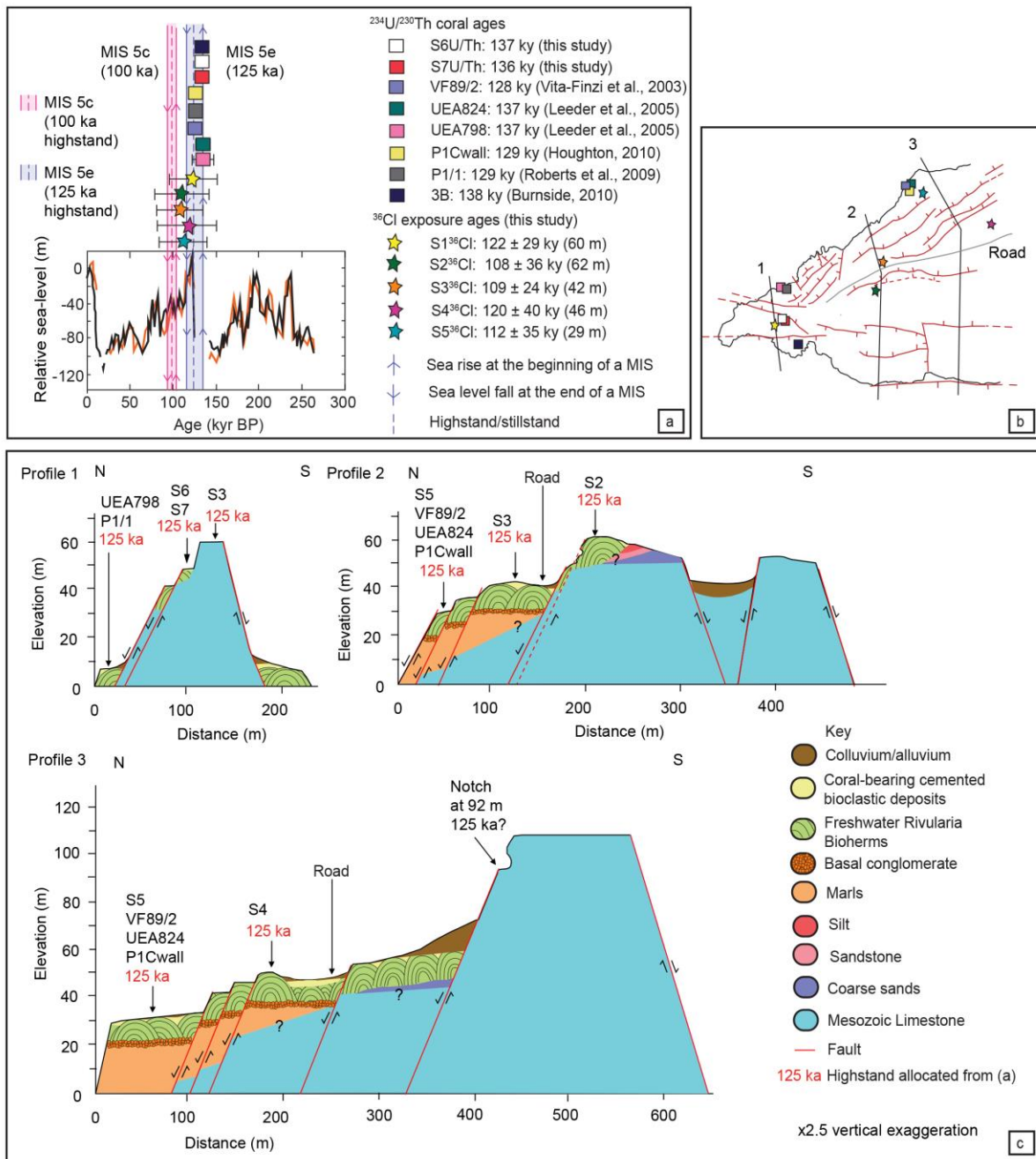
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1193 Figure 6: (a) overview of ^{36}Cl sample locations. (b-h) Photographs of ^{36}Cl and $^{234}\text{U}/^{230}\text{Th}$
 1194 sample locations. See Figure 4a for locations of samples.



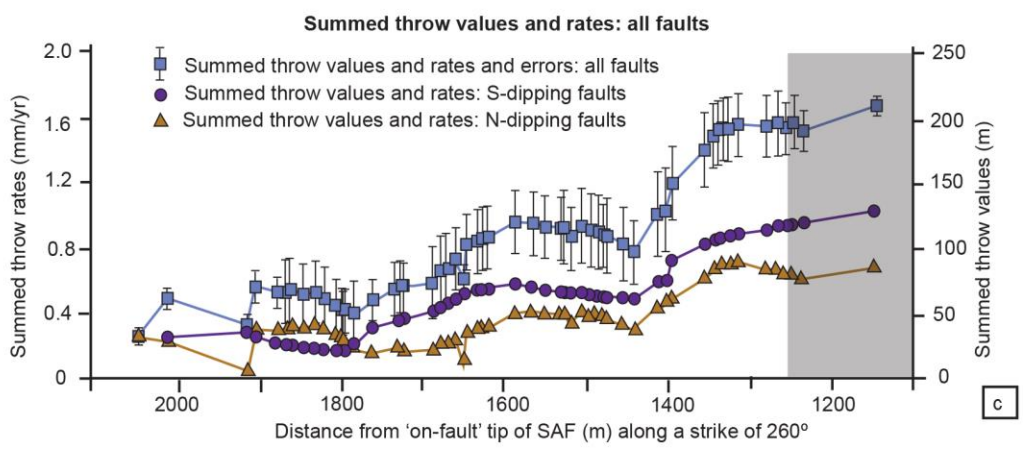
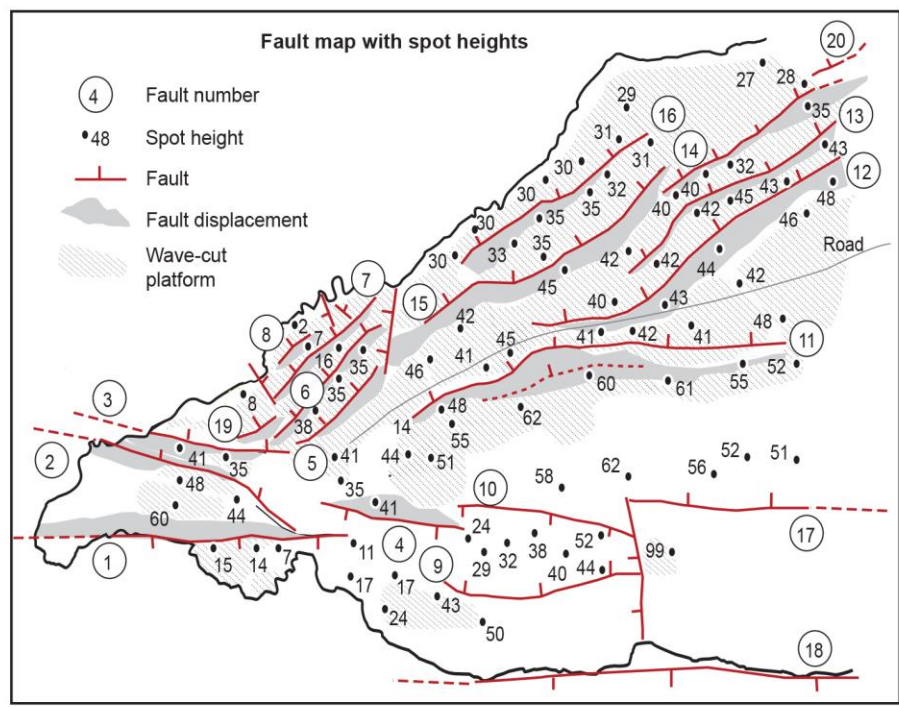
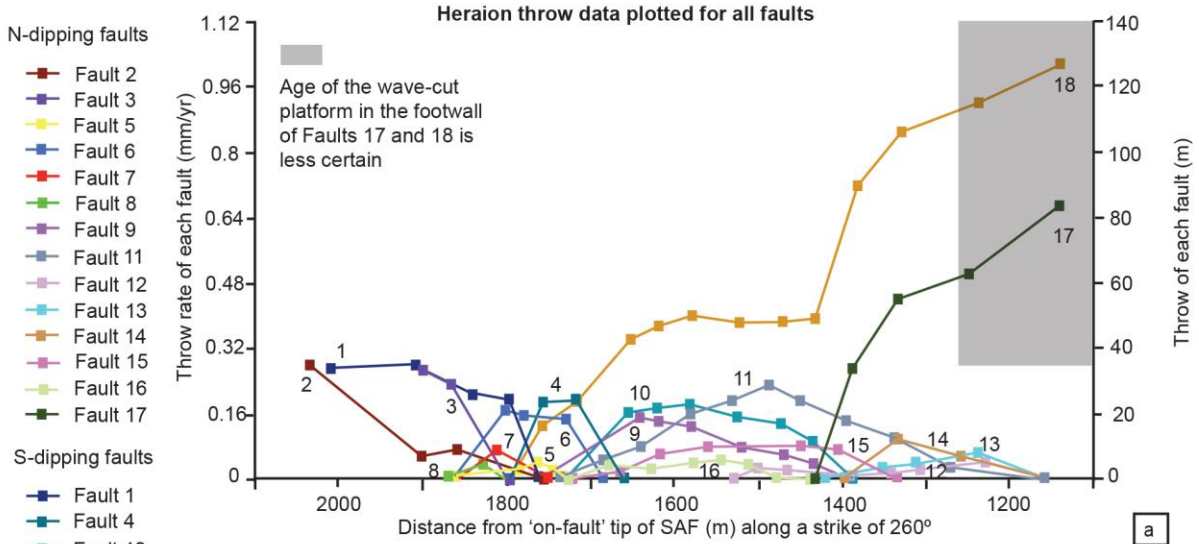
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1196 Figure 7: (a) View of Fault 1 offsetting a wave-cut platform at 60 m and 15 m. (b) Annotated
 1197 photograph of offset wave-cut notches on Fault 1. (c) Fault plane and annotated direction of
 1198 fault slip for Fault 1. (d) North-south horizontal offset of 43 cm on a bioherm on the north
 1199 side of Cape Heraion at Locality I, Figure 4. Offset colluvium (e) and bedrock (f) along fault
 1200 17 between localities J and K, Figure 4, UTM location: 663350/4210630.



1201

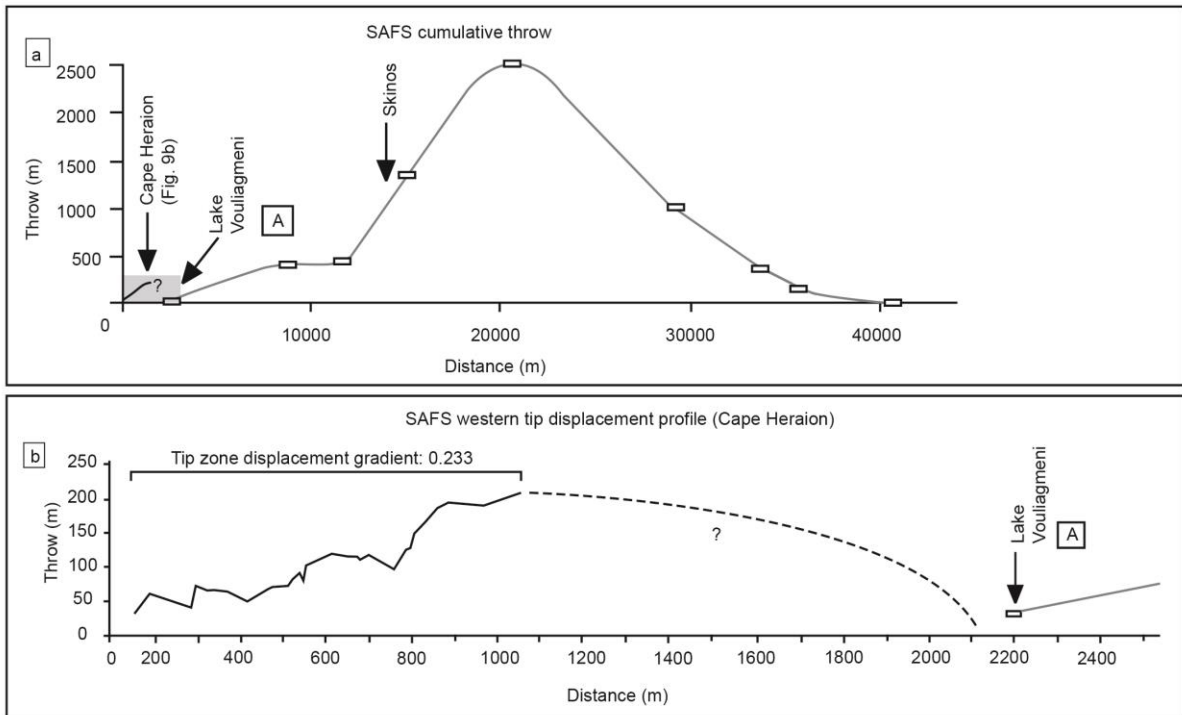
1202 Figure 8: (a) ³⁶Cl exposure ages and ²³⁴U/²³⁰Th coral ages (where error bars are not visible,
 1203 the value of error is smaller than the plot marker). Ages are plotted against the sea level
 1204 curve from Siddall et al., 2003, orange and black lines represent different cores used to
 1205 construct the sea-level curve. (b) Fault map and the location of profile lines from Figures 4a,
 1206 b that are shown as schematic cross sections in (c).



1207

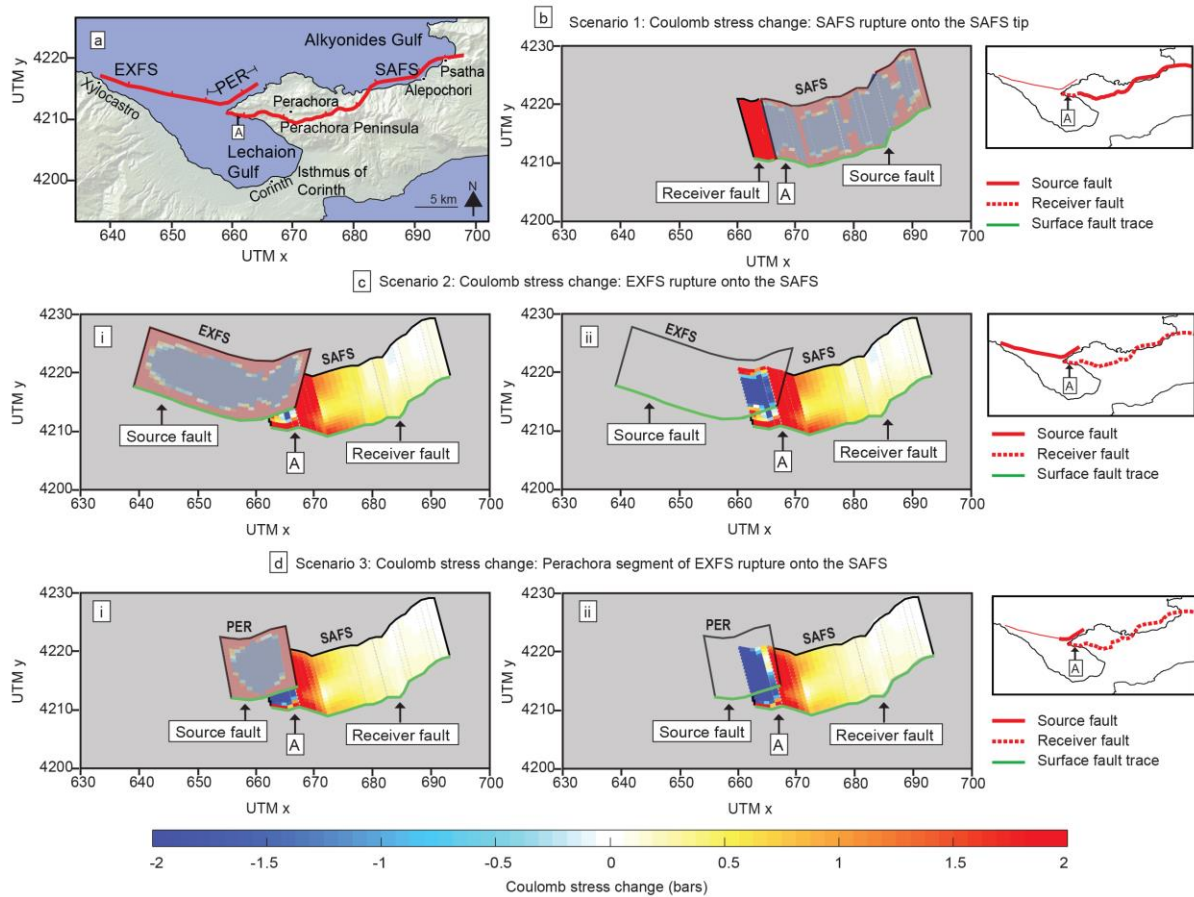
1208 Figure 9: (a) Throw profiles for individual faults constructed using elevation data (shown in
 1209 (b)). Throw values for Fault 19 is not plotted owing to a lack of elevation data. (c) Summed

1210 throw values and rates for all faults with uncertainties, summed throw values for north- and
1211 south-dipping faults. For (a) and (c) throw for each fault is plotted against the distance from
1212 the 'on-fault' tip (A) shown in Figure 2c from Morewood and Roberts (1999).



1213

1214 Figure 10: (a) Summed throw of Cape Heraion faults plotted alongside cumulative throw of
1215 the SAFS (modified from Morewood and Roberts (1999)). (b) Tip zone throw and
1216 displacement gradient from Cape Heraion. See Figure 2c for the location of A ('on-fault' tip
1217 of the SAFS).



1218

1219 Figure 11: (a) Map of eastern Gulf of Corinth showing the fault traces modelled in Coulomb
 1220 stress change (b-d) for the South Alkyonides Fault System (SAFS) and East Xylocastro Fault
 1221 System (EXFS) (adapted from Figure 2a). See table 4 for inputs into Coulomb modelling. (b)
 1222 Coulomb stress change from rupturing the source fault (entire SAFS with the exception of
 1223 the western 5 km) onto the receiver fault (western 5 km section of the SAFS). (c) Coulomb
 1224 stress change from rupturing the source fault (entire EXFS) onto the receiver fault (SAFS), (i)
 1225 shows the source fault rupture, (ii) shows the source fault outline only. (d) Coulomb stress
 1226 change from rupturing the source fault (Perachora segment of the EXFS) onto the receiver
 1227 fault (SAFS), (i) shows the source fault rupture, (ii) shows the source fault outline only.

Fault number	d/L ratio
4	0.27
5	0.04
6	0.10
7	0.06
8	0.08
9	0.05
10	0.08
11	0.04
12	0.01
13	0.02
14	0.06
15	0.03
16	0.03

1228

1229 Table 1: displacement length (d/L) ratios for mapped faults on Cape Heraion, with the
1230 exception of Fault 19 due to a lack of elevation data and Faults 1, 2, 3, 17, 18, 20 as both tips
1231 could not be mapped.

Sample name	Lab ID	UTM		Sampling elevation (m)	Age (ky)	±2s (abs) (ky)	U (ppm)	²³² Th (ppb)	⁽²³⁰ Th/ ²³² Th)	⁽²³² Th/ ²³⁸ U)	±2s (%)	⁽²³⁰ Th/ ²³⁸ U)	±2s (%)	⁽²³⁴ U/ ²³⁸ U)	±2s (%)	δ234U	±2s (%)
		Easting	Northing														
S6U/Th (1)	138-34	662540	4210594	44	133.5	0.7	2.42	0.005	1210.7	0.00068	0.04	0.81787	0.25	1.1354	0.14	197	±2
S6U/Th (2)	141-29	662540	4210594	44	135.4	1.2	2.44	0.006	1073.3	0.00076	0.12	0.82081	0.35	1.1315	0.28	193	±4
S6U/Th (3)	141-30	662540	4210594	44	142.7	1.3	2.57	0.006	1074.0	0.00079	0.10	0.85306	0.34	1.1429	0.25	214	±4
S6U/Th (4)	145-12	662540	4210594	44	173.7	2.0	2.13	0.009	674.9	0.00136	0.17	0.92101	0.34	1.1287	0.29	210	±5
S7U/Th (1)	138-35	662540	4210594	44	140.8	0.8	2.26	0.008	736.1	0.00114	0.04	0.83619	0.22	1.1298	0.13	193	±2
S7U/Th (2)	145-13	662540	4210594	44	139.1	0.9	2.28	0.012	467.2	0.00179	0.08	0.83630	0.25	1.1359	0.18	201	±3
S7U/Th (3)	145-14	662540	4210594	44	135.2	1.0	2.24	0.009	599.5	0.00137	0.10	0.81931	0.29	1.1301	0.21	191	±3
S7U/Th (4)	145-15	662540	4210594	44	134.5	1.0	2.34	0.014	426.6	0.00192	0.11	0.81943	0.29	1.1328	0.22	194	±3
S7U/Th (5)	145-16	662540	4210594	44	134.7	0.9	2.13	0.008	658.4	0.00125	0.09	0.82413	0.26	1.1380	0.19	202	±3
S7U/Th (6)	145-17	662540	4210594	44	132.3	0.9	2.39	0.016	364.2	0.00223	0.08	0.81141	0.29	1.1315	0.21	191	±3

1232

1233 Table 2: ²³⁴U/²³⁰Th coral age dating analytical results for samples S6U/Th and S7U/Th (see Figure 4a for sample location). Activity ratios
1234 calculated using the ²³⁴U and ²³⁰Th decay constants of Cheng et al. 2013. Activity ratios corrected for ²³⁰Th, ²³⁴U and ²³⁸U contribution
1235 from the synthetic ²³⁶U-²²⁹Th tracer, instrument baselines, mass bias, hydride formation and tailing. ²³⁰Th blanks amounting to 0.15 ± 0.03
1236 fg were subtracted from each sample. ²³⁸U blanks were on the order of 10 pg, and were negligible relative to sample size. Age and δ²³⁴U
1237 data were corrected for the presence of initial ²³⁰Th assuming an initial isotope composition of (²³²Th/²³⁸U) = 1.2 ± 0.6, (²³⁰Th/²³⁸U) = 1 ±
1238 0.5 and (²³⁴U/²³⁸U) = 1 ± 0.5 (all uncertainties quoted at the 2σ level).

1239

Sample name	Lithology and geomorphology	Latitude	Longitude	Elevation	Lithology	Erosion rate (mm/ky)	Total erosion (cm)	Cl (ppm)	±	³⁶ Cl (atoms/g)	±	CaO (wt%)	±	Age (kyr)	Internal uncertainty (kyr)	External uncertainty (kyr)
1	Limestone: flat WCP with lithophagid borings. Sample removed from the the area displaying lithophagid borings (Fig. 6b)	38.0288	22.85106	60	Limestone	0.1	1.2	17.0503	0.2856	2327699	63421	57.41	1.38	122	3.7	29
2	Bioherm top, bioclastic sands infill spaces between adjacent bioherms. Sample removed from the top iof the bioherm (Fig. 6e)	38.0292	22.85297	62	Bioherm	6	64.8	22.5328	0.4739	1195064	34923	43.85	1.53	108	8.4	36
3	Bioclastic packstone, excellent millholes preserved. Ssample removed from immediately adjacent to the millhole (Fig. 6f)	38.0304	22.85522	42	Packstone	0.1	1.1	38.7794	0.8003	1887336	54970	49.02	1.52	109	3.5	24
4	Bioherm top, millholes, abundant lithophagid borings preserved on the adjacent backwall (Fig. 6g)	38.032	22.8596	46	Bioherm	6	72.0	33.3263	0.6646	1616569	47009	53.80	1.47	120	8.8	40
5	Bioherm top, visible above surrounding alluvium (Fig. 6h)	38.0305	22.85516	29	Bioherm	6	67.2	60.5561	1.6227	1684932	46140	54.01	1.44	112	9.3	35

1240

1241

1242 Table 3: ³⁶Cl exposure dating analytical results and sample descriptions (see Figure 4a for the sample location). ³⁶Cl concentrations are based
 1243 on 1.2×10^{-12} ³⁶Cl/Cl ratio for Z93-0005 (PRIME Lab, Purdue). This standard agrees with standards prepared by K. Nishiizumi, which were used as
 1244 secondary standards. Cl concentrations were determined by AMS isotope dilution (Stuart and Dunai, 2009). ³⁶Cl/Cl processed blank ratios
 1245 ranged between 2.4 and 6.03% of the samples ³⁶Cl/Cl ratios.

Fault name	Fault information (fault trace, kinematics)	Length (km)	Depth of seismogenic zone (km)	Dip °	Facing direction °	Rake °	Sub-surface maximum slip value (m)	Max. Mw	Figure
East Xylocastro Fault System (EAFS)	Whole fault length is used combining fault traces of the East Xylocastro Fault, North Kiato Fault and Perachora Fault as per Nixon et al., 2016.	29	15	55	010	-90	1.6	6.53	11b
Perachora Fault (EXFS)	Fault trace from Nixon et al., 2016	11	15	55	350	-90	1.4	6.21	11c
South Alkyonnides Fault System (SAFS)	Whole fault length is used as per Roberts et al., 2009 (rupturing the Pisia, East Alkyonides and Psatha faults), with the exception of western 5 km tip zone. Dip data averaged from Jackson et al., 1982 (45°) and Mechernich et al., 2016 (60°)	38.7	15	55	345	-90	2.4	6.74	11a

1246

1247 Table 4: Inputs for Coulomb stress change modelling. Slip at the surface is set at 0.1 (10%) of the slip value at depth. This value is based upon
 1248 the relationship between surface slip (Vittori et al., 2011) and maximum slip values at depth (Wilkinson et al., 2015) for the Mw 6.3 2009
 1249 L'Aquila Earthquake, Italy

1250 Supplementary 1:

1251 Description of the observed stratigraphy on Cape Heraion to accompany Figures 4a and 5)

1252

1253 At the base of the stratigraphic column is Mesozoic limestone (Figures 4a, 5, Locality A).

1254 Unconformably above the limestone is a sedimentary succession, only observed in the centre

1255 of the cape, that fines up from coarse sands to silts (Locality D, Figure 4a and Figure 5). Plio-

1256 Pleistocene marls are inferred to occur stratigraphically above the sands and silts although

1257 the contact between them has not been observed, and they may be lateral equivalents. The

1258 marls form large cliff outcrops along the north of the cape (e.g. Locality F in Figures 4 and 5)

1259 and are overlain by a coarse boulder conglomerate that displays an erosive base cut into the

1260 underlying marls (Locality F). Algal carbonate bioherms formed of *Rivularia haematities* have

1261 grown on the basal conglomerate (Localities E, F and G, Figure 5) and directly on the basement

1262 limestone (Localities B, C and D, Figure 5). In turn, the bioherms are overlain by fossiliferous,

1263 coral-bearing, marine bioclastic sands preserved as a continuous 0.6-1.0 m thick layer

1264 (Localities B, C, E, F and H, Figures 4a, 5) or as patches infilling cavities between or within the

1265 bioherms (Locality C and D Figure 4a, 5). These bioclastic deposits have rich fossil assemblages

1266 with colonies of the branching coral *Cladocora caespitosa* in life position, frameworks of

1267 serpulid worm tubes, and bivalves, pecten, turritella, bryozoa, and elsewhere broken

1268 fragments of *Cladocora caespitosa* within the sediment that form death assemblages. In

1269 places, the inside of the bioherms has been eroded and small caves have formed, which have

1270 been bored by lithophagids (Figure 5). The caves contain marine deposits such as *Cladocora*

1271 *caespitosa* (e.g. Locality C), suggesting the cave-filling deposits are the age-equivalents of the

1272 coral-bearing bioclastic sands that lie on top of the bioherms.

1273 Supplementary 2

1: Sample Name	2: Scaling (Select One)	3: Latitude decimal degrees	4: Longitude decimal degrees	5: Elevation meters	6: Pressure hPa	7: Atmospheric Pressure or Elevation	8: Sample Thickness cm	9: Bulk Density g/cm 3	10: Shielding Factor unitless	11: Erosion Rate mm/kyr	12: Conc. 36Cl Atoms of 36 Cl/g of sample	13: Attenuation length g/cm 2	14: Depth to Top of Sample g/cm 2	15: Year Collected Year A.D.	16: Water Content in Pores volume fraction	17: Mineral Separation (Select One)	18: Bulk Rock SiO2 oxide weight %	19: Bulk Rock TiO2 oxide weight %	20: Bulk Rock Al2O3 oxide weight %
1	DE	38.02877	22.851055	60		Elevation	3.7	2.649	0.9999	0.1	2327699	160	0	2000	0.01	No	0	0	0
2	DE	38.02919	22.852974	62		Elevation	4	2.565	0.9999	6	1195064	160	0	2000	0.01	No	0	0	0
3	DE	38.03036	22.855224	42		Elevation	3.4	2.565	0.9981	0.1	1887336	160	0	2000	0.01	No	0	0	0
4	DE	38.03203	22.859599	46		Elevation	4.5	2.233	0.9999	6	1616569	160	0	2000	0.01	No	0	0	0
5	DE	38.03046	22.855155	29		Elevation	4.1	2.565	0.9995	6	1684932	160	0	2000	0.01	No	0	0	0

1274

21: Bulk Rock Fe2O3 oxide weight %	22: Bulk Rock MnO oxide weight %	23: Bulk Rock MgO oxide weight %	24: Bulk Rock CaO oxide weight %	25: Bulk Rock Na2O oxide weight %	26: Bulk Rock K2O oxide weight %	27: Bulk Rock P2O5 oxide weight %	28: Analytical Water weight %	29: Bulk Rock CO2 oxide weight %	30: Bulk Rock Cl ppm	31: Bulk Rock B ppm	32: Bulk Rock Sm ppm	33: Bulk Rock Gd ppm	34: Bulk Rock U ppm	35: Bulk Rock Th ppm	36: Bulk Rock Cr ppm	37: Bulk Rock Li ppm	38: Target K2O weight %	39: Target CaO weight %	40: Target TiO2 weight %
0.05148	0	0.00	57.38099	0	0.00000	0	1.00000	42.56753	17.05027	0	0	0	0	0	0	0	0.00000	57.41238	0.00000
0.02843	0	0.00	43.82164	0	0.00000	0	1.00000	56.14993	22.5328	0	0	0	0	0	0	0	0.00000	43.84561	0.00000
0.061312	0	0.00	48.98905	0	0.00000	0	1.00000	50.94964	38.77938	0	0	0	0	0	0	0	0.00000	49.01585	0.00000
0.02793	0	0.00	53.77027	0	0.00000	0	1.00000	46.20180	33.32635	0	0	0	0	0	0	0	0.00000	53.79968	0.00000
0.120106	0	0.00	53.98398	0	0.00000	0	1.00000	45.89592	60.55609	0	0	0	0	0	0	0	0.00000	54.01351	0.00000

1275

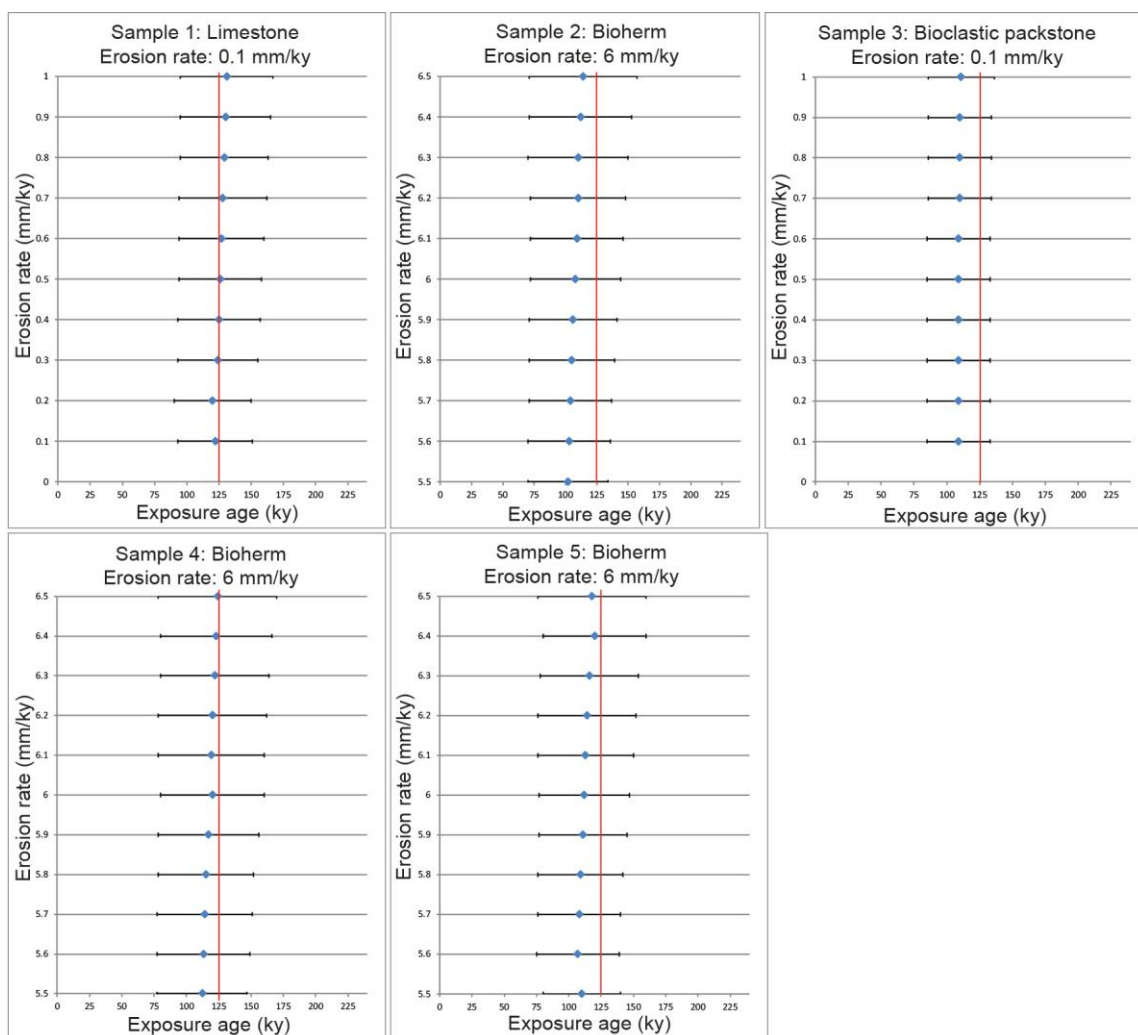
41: Target Fe2O3 weight %	42: Target Cl ppm	43: Latitude Uncertainty decimal degrees	44: Longitude Uncertainty decimal degrees	45: Elevation Uncertainty meters	46: Pressure Uncertainty hPa	47: Sample Thickness Uncertainty cm	48: Bulk Density Uncertainty g/cm 3	49: Shielding Factor Uncertainty unitless	50: Erosion-Rate Uncertainty mm/kyr	51: Conc. 36 Cl Uncertainty Atoms of 36 Cl/g of sample	52: Attenuation Length Uncertainty g/cm 2	53: Depth to Top of Sample Uncertainty g/cm 2	54: Year Collected Uncertainty Year A.D.	55: Water Content in Pores Uncertainty Volume %	56: Bulk Rock SiO 2 Uncertainty oxide weight %	57: Bulk Rock TiO 2 Uncertainty oxide weight %	58: Bulk Rock Al 2 O 3 Uncertainty oxide weight %	59: Bulk Rock Fe 2 O 3 Uncertainty oxide weight %	60: Bulk Rock MnO Uncertainty oxide weight %
0.05148	17.05	0	0	10		0.5	0.2	0	0	63421	10	0	10	0.01	0	0.0000	0	0.46670195	0
0.02843	22.53	0	0	10		0.5	0.2	0	0	34923	10	0	10	0.01	0	0.0000	0	0.51572725	0
0.061312	38.78	0	0	10		0.5	0.2	0	0	54970	10	0	10	0.01	0	0.0000	0	0.51356044	0
0.02793	33.33	0	0	10		0.5	0.2	0	0	47009	10	0	10	0.01	0	0.0000	0	0.49714071	0
0.120106	60.56	0	0	10		0.5	0.2	0	0	46140	10	0	10	0.01	0	0.0000	0	0.48551267	0

1276

1277

61: Bulk Rock MgO Uncertainty oxide weight %	62: Bulk Rock CaO Uncertainty oxide weight %	63: Bulk Rock Na 2 O Uncertainty oxide weight %	64: Bulk Rock K 2 O Uncertainty oxide weight %	65: Bulk Rock P 2 O 5 Uncertainty oxide weight %	66: Analytical Water Uncertainty weight %	67: Bulk Rock CO 2 Uncertainty oxide weight %	68: Bulk Rock Cl Uncertainty ppm	69: Bulk Rock B Uncertainty ppm	70: Bulk Rock Sm Uncertainty ppm	71: Bulk Rock Gd Uncertainty ppm	72: Bulk Rock U Uncertainty ppm	73: Bulk Rock Th Uncertainty ppm	74: Bulk Rock Cr Uncertainty ppm	75: Bulk Rock Li Uncertainty ppm	76: Target K2O Uncertainty weight %	77: Target CaO Uncertainty weight %	78: Target TiO2 Uncertainty weight %	79: Target Fe2O3 Uncertainty weight %	80: Target Cl Uncertainty ppm	81: Covariance unitless
0	1.3804232	0	0.0000	0	1.00000	1.3804232	0.28561763	0	0	0	0	0	0	0	0.00000	1.3804232	0.00000	0.46670195	0.28561763	0
0	1.5254315	0	0.0000	0	1.00000	1.5254315	0.47391526	0	0	0	0	0	0	0	0.00000	1.5254315	0.00000	0.51572725	0.47391526	0
0	1.51902247	0	0.0000	0	1.00000	1.51902247	0.80026479	0	0	0	0	0	0	0	0.00000	1.51902247	0.00000	0.51356044	0.80026479	0
0	1.47045576	0	0.0000	0	1.00000	1.47045576	0.66456149	0	0	0	0	0	0	0	0.00000	1.47045576	0.00000	0.49714071	0.66456149	0
0	1.43606203	0	0.0000	0	1.00000	1.43606203	1.62273089	0	0	0	0	0	0	0	0.00000	1.43606203	0.00000	0.48551267	1.62273089	0

1278 Supplement 2: Input data for CRONUScalc to determine ages of ³⁶Cl exposure samples



1280

1281 Supplement 3: Sensitivity tests for the erosion rates of 0.1-1.0 mm/ky for samples 1 and 3, and of
 1282 5.5-6.5 mm/yr for samples 2, 4 and 5.

1283