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## **Transition from collision to subduction in Western Greece: the Katouna–Stamna active fault system and regional kinematics**

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1       **Transition from collision to subduction in Western Greece: The**  
2       **Katouna-Stamna active fault system and regional kinematics**

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27

28 **Abstract**

29 Transition from subduction to collision occurs in Western Greece and is accommodated along  
30 the downgoing plate by the Kefalonia right-lateral fault that transfers the Hellenic subduction  
31 front to the Apulian collision front. Here we present an active tectonic study of Aitolio-  
32 Akarnania (Western Greece) that highlights how such a transition is accommodated in the  
33 overriding plate. An accurate active fault traces mapping is performed on the basis of new  
34 multi-scale geomorphic and tectonic observations that provide evidence for active normal and  
35 left-lateral faulting along the Katouna-Stamna Fault (KSF), a 65-km-long NNW-striking fault  
36 system connecting the Amvrakikos Gulf to the Patras Gulf. We further show that the  
37 Cenozoic Hellenides thrusts located west of the KSF are no longer active, either in field  
38 observation or GPS data, leading us to propose that the KSF forms the northeastern boundary  
39 of a rigid Ionian Islands-Akarnania Block (IAB). Cosmic Ray Exposure measurements of  
40  $^{10}\text{Be}$  and  $^{36}\text{Cl}$  were performed on a Quaternary alluvial fan offset along the KSF (~50m left-  
41 lateral offset). A maximum abandonment age of ~12-14 ka for the alluvial fan surface can be  
42 determined, giving an estimated KSF minimum geological left-lateral slip-rate of ~4 mm.yr<sup>-1</sup>,  
43 in agreement with high GPS slip-rates (~10 mm.yr<sup>-1</sup>). Despite this high slip-rate, the KSF is  
44 characterized by subdued morphological evidence of tectonic activity, a gypsum-breccia  
45 bedrock and a low level of seismicity, suggesting a dominantly creeping behavior for this  
46 fault. Finally, we discuss how the IAB appears to have been progressively individualized  
47 during the Pleistocene (younger than ~1.5 Ma).

48

49

50

51

## 52 **Keywords**

53 Active faults, Collision/Subduction, continental neotectonics, GPS, Western Greece,  
54 Mediterranean

## 55 **1. Introduction**

56 The lateral transition from oceanic subduction to continental collision induces deformation in  
57 the overriding plate. Western Greece offers the opportunity to investigate the tectonic  
58 implications of such a transition. The old Mesozoic Ionian oceanic lithosphere (Catalano et al.  
59 2001; Speranza et al. 2012) subducts below the Peloponnesus while to the north, the nearby  
60 thick Apulian carbonate platform, on the same Ionian-Apulian micro-plate (D'Agostino et al.  
61 2008; Perouse et al. 2012), abuts against the NW Greece-Albania foreland fold and thrust belt  
62 (Fig. 1). The highly seismic right-lateral Kefalonia transform fault (Figs. 1, 2), connecting the  
63 collision and subduction fronts, has been extensively studied (e.g., Louvari et al. 1999; Pearce  
64 et al. 2012). Farther east inland, NNW-striking Hellenide units and Neogene fold and thrust  
65 system (Clews 1989; Underhill 1989) are overprinted by active E-W striking rifting systems  
66 (Gulf of Amvrakikos, Trichonis Lake, Gulf of Corinth and Gulf of Patras, Fig. 3). This  
67 distributed extension within the upper plate is possibly related to the Hellenic slab retreat  
68 (Jolivet et al. 2010; Perouse et al. 2012; Durand et al. 2014). Among the presently active  
69 rifting systems, the Corinth Rift is the one which timing evolution is the best constrained. The  
70 earliest stage of extension, distributed over a broad rift system, would have started in Pliocene  
71 (oldest syn-rift volcanic deposits are 3.6 to 4 Ma old, Collier and Dart 1991). The deepening  
72 of the rift and the deposition of giant fan deltas, which marks the inception of major tectonic  
73 activity in the Corinth rift is dated to ~1.7 Ma, according to the oldest syn-rift deposits age

74 (Rohais et al. 2007a; Rohais et al. 2007b). Then, fault activity progressively migrated  
75 northward from 1.5 to 0.7 ka, leading to the most recent rifting phase of the Gulf of Corinth  
76 (0.7 Ma to present day) where extension is localized on the northward dipping normal faults  
77 of the present-day southern Gulf of Corinth (e.g., Jolivet et al. 2010; Ford et al. 2013).

78 Previous tectonic studies of the Aitolio-Akarnania region (Western Greece) propose an active  
79 fault network consisting of a set of Quaternary E-W striking grabens (Amvrakikos Gulf,  
80 Trichonis Lake and Patras Gulf, Fig. 3) connected by a NW-striking left-lateral fault zone  
81 (Melis and Burton 1988; Clews 1989; Sorel 1989; Underhill 1989). Active left-lateral  
82 transtension along this fault system, referred as the Amvrakia or Katouna fault, has been  
83 proposed thanks to local tomography (Haslinger et al. 1999), GPS data (Le Pichon et al. 1995;  
84 Cocard et al. 1999; Hollenstein et al. 2008; Vassilakis et al. 2011; Chousianitis et al. 2015)  
85 and estimated as  $\sim 11 \text{ mm.yr}^{-1}$  (GPS slip-rate, Vassilakis et al. 2011). However, no clear  
86 geological or morphological evidence for active left-lateral faulting has yet been provided:  
87 studies were mainly focused on Cenozoic tectonics of the  $\sim N$  striking Hellenides fold and  
88 thrust system in Akarnania (Clews 1989; Underhill 1989), and geological evidence for left-  
89 lateral displacement was only observed within Mesozoic limestones (Vassilakis et al. 2006;  
90 Vassilakis et al. 2011). The existence of a block in Akarnania bounded to the west by the  
91 Kefalonia fault, to the north by the Amvrakikos graben and to the east by a NW-striking left-  
92 lateral system joining southward to the Patras-Corinth rift has been suggested (Le Pichon et  
93 al. 1995; Cocard et al. 1999; Hollenstein et al. 2008; Konstantinou et al. 2009). In the most  
94 detailed model, Vassilakis et al. (2011) proposed that the extension at the western end of the  
95 Corinth rift is transferred to the Amvrakikos graben through the Trichonis Lake graben and a  
96 left-lateral fault in the Amphiloikia valley, defining the northeastern boundary of an  
97 “Akarnania fragment”. Post-Pliocene out-of-sequence reactivation of the N-striking Neogene

98 Hellenides thrusts in Akarnania (Clews 1989) as well as present-day normal faulting  
99 (Vassilakis et al. 2006) point to possible active internal deformation within this block.  
100 The aims of our study are to accurately define the NNW striking fault system of Aitolo-  
101 Akarnania, here informally termed the Katouna-Stamna Fault (KSF), and determine whether  
102 internal deformation occurs within the Akarnania block, along the N-striking Akarnania  
103 thrusts. Based on the analysis of satellite images, Digital Elevation Model and field studies,  
104 we performed a critical reappraisal of published data, conducted an accurate mapping of  
105 active fault traces in the region, and collected multi-scale geomorphologic observations that  
106 provide evidence for active normal and strike-slip faulting, especially left-lateral displacement  
107 along the KSF. We further estimated a minimum geological slip rate for the KSF measuring  
108  $^{10}\text{Be}$  and  $^{36}\text{Cl}$  cosmogenic radionuclides produced *in-situ*. Our new results on the active  
109 tectonics of Akarnania are discussed in the light of existing and new GPS data.

## 110 **2. Morphotectonic study of Aitolo-Akarnania**

111 Figure 3 is a map summarizing active and inactive major structures of Western Greece from  
112 our reappraisal of the tectonics of the Akarnania region. In our study, we consider faults to be  
113 “active” if they control the landscape morphology at first order (offset streams, structural  
114 landscape, upward convex shaped profile, etc.) and/or if they offset Quaternary deposit. By  
115 opposition, faults are considered to be “inactive” when the landscape morphology results  
116 mainly from erosional processes. Our contributions to the figure 3 map concern the Katouna-  
117 Stamna Fault (KSF, Fig. 4), its northward termination onto the Loutraki fault and a  
118 reappraisal of the N-striking Akarnania thrusts, located west of the KSF (Fig. 3, 4).

119

## 2.1. Evidence for active vertical slip component along the northern KSF

### (Loutraki fault and Katouna valley fault)

120 One prominent geomorphic feature in Akarnania is the remnant of a large uplifted paleo-  
123 surface on Triassic breccias, tilted  $\sim 4^\circ$  southward,  $\sim 700$ -m high, south of the Amvrakikos  
124 Gulf nearby the Katouna valley (Figs. 4, 5). This paleo-surface ends abruptly northward  
125 where it is cut by the ESE-striking Loutraki fault. This fault shows the typical morphology of  
126 an active normal fault escarpment: overall upward convex-shaped profile (Wallace 1978),  
127 wineglass valleys, and triangular facets (Figs. 5, 6). The  $\sim 4^\circ$  southward tilt of the paleo-  
128 surface is highlighted by a reverse sense of drainage in the windgap shown on Fig. 5a. The  
129 overall morphology can be simply interpreted as the result of footwall uplift and southward  
130 tilt associated with the northward dipping Loutraki normal fault. Topographic profiles  
131 crossing the Loutraki fault escarpment (profiles L1, L2 and L3 in Fig. 6), show two benches  
132 that represent either several parallel migrating faults (i.e. "paleo" scarps) or interaction  
133 between footwall uplift and notching due to headward erosion from high stand sea levels. In  
134 either case, the location of the present-day active normal fault would be at the base of the  
135 escarpment (Figs. 5, 6). It would account for the topography (footwall uplift southward of the  
136 fault/ hanging wall subsidence northward of the fault) and the occurrence of incision  
137 southward of the fault, compatible with footwall uplift (Fig. 5). A more complex fault  
138 geometry occurs east of the Loutraki Fault. Here, we observed in the field (1) a normal F1  
139 fault plan between Mesozoic limestones and old alluvial fan deposits (N120° 55°N 85°E, FP  
140 on Fig. 5); (2) incision to the north of F1 within an old alluvial fan deposits. This incised  
141 alluvial fan is bounded to the north by an E-striking slope break. We interpret this slope break  
142 as resulting from an additional normal fault (F2 on L1 profile of Fig. 6), which controls the  
143 uplift of the old alluvial fan deposits and the subsidence in the Amvrakikos Gulf. Thus, to the

144 east of the Loutraki Fault, deformation could have migrated northward onto a younger fault  
145 segment F2, owing to the growing depression caused by rifting in the Amvrakikos Gulf.

146 South of the Loutraki fault, the uplifted paleo-surface is bounded to the east by pronounced  
147 N158°- to N152°-striking, E-facing linear slopes with upward convex profiles (Figs. 5a, 6),  
148 such kind of escarpments are typically associated to normal fault in the U.S Basin and Range  
149 province (Wallace 1978). These linear E-facing escarpments are carved within easy erodible  
150 gypsum along the Katouna valley. The preservation of such escarpments in gypsum  
151 demonstrates that faults have a high level of activity. In addition, the fairly planar geometry of  
152 these escarpments indicates they correspond to the exhumation of normal fault plans.

153 Moreover, the British Petroleum Co Ltd (1971) mapped an east dipping normal fault in the  
154 Katouna valley. According to our geological cross-section (Fig. 7), a fault with a vertical slip  
155 component is actually necessary in the Katouna valley to account for the anomalous contact  
156 between Triassic gypsum and Early Cretaceous limestones in the Katouna valley. Our cross-  
157 section also intersects the southern termination of a northern segment (Fig 5). Upper Pliocene-  
158 Early Pleistocene lacustrine deposits are uplifted along one of these faults (profile K2 on Fig.  
159 6, Fig. 7). The inferred total vertical throw across the fault segments reaches 750 m (~300m of  
160 footwall uplift, ~450m of hanging wall subsidence). The steep dip proposed in our cross-  
161 section follows the linear fault traces at the surface (Fig. 5). A steep east-dipping normal fault  
162 agrees with the occurrence of micro-seismicity at 20 km depth, slightly east of the Katouna  
163 valley (Hatzfeld et al. 1995). We thus interpret the Katouna valley as a structural landscape,  
164 the morphology being controlled by active steep eastward dipping normal fault segments.

165 Comparing the Katouna valley with the nearby Amphilochia valley to the east suggests this  
166 major valley is quite different (Fig. 5). Previous studies (Vassilakis et al. 2011) and geological  
167 maps (British Petroleum Co Ltd, 1971; Institute of Geology and Mineral Exploration, IGME,  
168 1987), have proposed this valley to be an active left-lateral strike-slip fault zone. First of all,



169 along the Amphilochia valley, the topography follows directly the geological folding (i.e., the  
170 valley bottom coincides with a syncline axis, Fig. 7), suggesting that a large part of this  
171 depression could be inherited from Tertiary folding. The vertical throw of the hypothetical fault  
172 is small as the same layer is cropping out on both side of the reported fault (Fig. 7), and the  
173 concave regraded slopes of the valley (profile K3, Fig. 6) do not suggest any active vertical  
174 component for the fault (Wallace 1978). This could be compatible with a pure strike-slip fault  
175 running in the middle of the valley bottom (as suggested by the geological map of the Institute  
176 of Geology and Mineral Exploration, IGME, 1987), and covered by constantly aggrading  
177 Holocene deposits. However, the lack of benches and elongated small depressions along the  
178 possible fault trace within the hard limestones on the northern Amphilochia valley do not  
179 agree with any active strike-slip fault along the Amphilochia valley. Therefore, we propose  
180 that most of the northern KSF deformation is presently accommodated along the Katouna  
181 valley.

## 182 **2.2. Evidence for active left-lateral motion along the KSF**

183 In the previous section, we show that the total escarpment height of the Loutraki normal fault  
184 is ~ 700 m (Fig. 6). As the KSF, eastern border of the uplifted paleo-surface, is linked to the  
185 Loutraki fault in its northern termination, the KSF escarpment height is directly controlled by  
186 the Loutraki escapement height in its northernmost section. However, far enough from the  
187 Loutraki fault, at the west of the Amvrakia lake, the altitude of the uplifted paleo-surface  
188 becomes stationary at about ~300-m high (Fig. 5), suggesting that this area is no longer  
189 influenced by the Loutraki footwall uplift and tilt (Figs. 5, 6). Then, in this area, the uplifted  
190 paleo-surface would be only due to the KSF footwall uplift (~300m). The conspicuous  
191 difference in footwall uplift (with 2 to 1 ratio) between the Loutraki normal fault and the  
192 Katouna valley faults indicates that either the Loutraki fault initiated earlier or the Katouna

193 valley faults are not purely normal. The second option is more likely because the KSF fault  
194 segments show a typical en-echelon pattern with left stepovers systematically associated with  
195 depressions (Katouna valley, Amvrakia lake, southern Acheloos river valley, Aitoliko lagoon,  
196 Fig. 4). Along the KSF, only one right stepover occurs, and it is associated to a range in easy-  
197 erodible Triassic breccias and gypsum, at the western border of the Ozeros lake (oz. on Fig.  
198 4). These observations are thus compatible with left-releasing stepovers and right-restraining  
199 stepover, respectively, implying a left-lateral component along the KSF fault segments. At the  
200 right-restraining stepover location (oz. on Fig. 4), we surmise a possible low dip east verging  
201 thrust to account for the range west of the Ozeros lake depression (flexural depression due to  
202 a possible east verging thrust). Accounting for this oblique-slip and aware of the difficulty to  
203 connect the same objects across this type of fault, we concentrate our observations on local  
204 drainage crossing the KSF to retrieve evidence for left-lateral offsets. As it may be expected  
205 on an oblique-slipping fault, we did not find any conspicuous dogleg offset. Nevertheless, we  
206 identified several potential offsets along the southern fault segment of the Katouna valley  
207 where 8 streams are left-laterally diverted with finite displacements ranging from 5 to 50 m  
208 (five of these stream offsets are shown on Fig. 8). One could argue that such stream  
209 diversions may result from the random meanderings of the downstream channels on top of the  
210 young alluvial fans located in the hangingwall block. However, small diverted streams are  
211 observed on the northern termination of the southern fault segment of the Katouna valley,  
212 where the fault displacement and escarpment disappear (Fig. 8a). Here the stream channels  
213 incise in similar alluvial material on both sides of the KSF. Thus, these small diverted streams  
214 are more likely to preserve true left-lateral fault displacements (Fig. 8a). Interestingly, they  
215 appear to record some ~10 m of left-lateral offset while larger streams display higher amounts  
216 of left-lateral offset, the maximum value being ~50 m (Fig. 8c). It must be stressed that, as has

217 been reported for the San Andreas Fault, many streams do not display any offset or can even  
218 show right-lateral diversions (e.g., Gaudemer et al. 1989).

219 We also found some evidence of active strike-slip motion in the Stamna area, to the south of  
220 the Katouna valley (Sta on Fig. 4a). Here, a N162°-striking linear depression extends ~5.5  
221 km from the southwesternmost tip of the Trichonis depression to the Stamna village (Fig. 9).  
222 This linear depression is carved within Plio-Pleistocene deposits, close to the limit with  
223 Triassic breccias (Fig.4b), forming a 300-400 m wide, ~10m deep, flat bottomed, perched  
224 valley, with similar heights of both western and eastern valley divides (Fig. 9). This perched  
225 valley is drained by small streams only, and thus appears oversized (Fig. 10). This peculiar  
226 feature is interpreted as due to the differential erosion of the sheared zone along an active  
227 N162°-striking strike-slip fault. This would account for the dominant linear drainage network  
228 (Fig. 10) and the small streams flowing nearly orthogonally toward the perched valley,  
229 whereas the major natural draining outlet of the area is the Aitoliko lagoon (Figs. 9, 10). This  
230 suggests these small streams result from headward erosion associated with the tectonically  
231 controlled perched valley. Interestingly, a small fault plane (N162° 65°W 13°S, Fig. 11)  
232 within Plio-Pleistocene deposits has been observed along the perched valley. The absence of  
233 morphological evidence for active vertical component (i.e., no fault escarpment and same  
234 height for perched valley divides), as well as the sub-horizontal slickensides of the fault plane  
235 (Fig. 11) suggest a nearly pure strike-slip faulting along the Stamna segment. Unfortunately,  
236 drainage network does not allow characterizing the sense of slip along the Stamna segment  
237 (i.e., no clear left-lateral offset stream, Fig. 10). We can only propose a left-lateral slip for the  
238 Stamna segment based on the overall KSF segments geometry (i.e., left-releasing stepovers  
239 north and south of the Stamna segment, Fig. 9). Moreover, the left-lateral slip indicated by the  
240 slickensides on the observed fault plane also agrees with left lateral motion (Fig. 11).

241 Overall, the KSF thus depicts a 65-km-long NNW-striking active fault system extending from  
242 the Patras Gulf to the Amvrakikos Gulf (Figs. 3, 4). KSF segments are typically ~10 km-long.  
243 Motion along the KSF evolves from left-lateral transtension on faults segments striking  
244 N158°-N152° (Katouna area) to nearly pure left-lateral strike-slip on segments striking N162°  
245 (Stamna area).

### 246 **2.3. Internal deformation within Akarnania? Investigating the N-striking** 247 **Akarnania thrusts**

248 External Hellenides orogen in Akarnania led to the formation of both W- and E-verging, N-  
249 striking thrusts during the Neogene (Clews 1989; Underhill 1989)). These N-striking thrusts  
250 are located to the west of the present KSF and separate Mesozoic limestones in the  
251 hangingwalls from Tertiary molasses and flysch basins in the footwalls (Paleros, Mytikas, and  
252 Astakos thrusts, Fig. 4). Post-Pliocene out-of-sequence reactivation of these thrusts have been  
253 proposed (Clews 1989), as well as present-day normal faulting along the Astakos thrust  
254 (Vassilakis et al. 2006). However, we report below some geologic, tectonic, and geomorphic  
255 observations suggesting these Cenozoic thrusts are no longer active.

256 The contact between Ionian Mesozoic limestones thrusting eastward over Oligocene flysch  
257 deposits is exposed to the south of the Astakos fault (Fig. 12a). Nevertheless, this E-verging  
258 thrust is seen sealed by strongly calcite-cemented breccias (SBr. on Fig. 12a). These breccias  
259 consist of cryoclastic angular elements with no clay matrix, which result from limestone  
260 bedrock degradation during a cold climate. Such kind of strongly calcite-cemented breccias  
261 are attributed to the Middle Pleistocene (~600 ka, Sorel 1976). The fault sealing indicates that  
262 no tectonic activity has occurred along the Astakos thrust for the last ~600 ka. Farther north,  
263 along this Astakos thrust, destroyed houses of the Paleo Karaiskakis village stand on the  
264 Oligocene flysch deposits. At this place, a roughly N-striking, curved scarp points to the limit

265 between the Ionian limestones and their screens, overlying the flysch deposits and hiding the  
266 Astakos thrust contact (Fig. 12b). We interpret this curved scarp trace as a landslide head scar,  
267 caused by gravitational processes that occurred within the flysch deposits and destroyed the  
268 Paleo Karaiskakis village. The N-striking normal fault reported close to Astakos village  
269 (Vassilakis et al. 2011) should correspond to similar gravitational processes. Therefore, in the  
270 Astakos area, there is no evidence for tectonic activity either on the Astakos thrust or on N-  
271 striking normal faults.

272 Strongly cemented slope breccias are also observed sealing the W-verging Paleros thrust front  
273 (Fig. 12c). At some places, a discontinuous linear cliff highlights the contact between the  
274 Ionian Mesozoic limestones, covered by strongly cemented breccias, and the more erodible  
275 Miocene molasses deposits. This linear feature could be interpreted as an active normal fault  
276 scarp. However, the along-strike strong variation of cliff height (red arrows on Fig.12c)  
277 results more likely from differential erosion between Miocene sandy molasses and the  
278 limestone rocks (Ionian Mesozoic and Quaternary slope breccias). This observation also  
279 agrees with a lack of tectonic activity along the Paleros thrust. Similar conclusions can be  
280 derived from observations along the Mytikas E-verging thrust.

281 All our geomorphic/tectonic observations in central Akarnania are summarized in a  
282 conceptual sketch (Fig. 13). They show the N-striking Akarnania thrusts presently inactive,  
283 and some apparently normal fault scarp resulting from gravitational processes and/or gully  
284 differential erosion. As there is no evidence for significant active deformation in Akarnania  
285 west of the KSF, we consider Akarnania as a rigid block.

286 **3. Cosmic Ray Exposure (CRE) dating of an offset alluvial fan**  
287 **along the KSF and minimum geological slip-rate**

288 Along the Katouna valley, the normal component of slip of the KSF cannot be constrained  
289 because the hangingwall displays recent alluvial or colluvial deposits that are not present in  
290 the footwall block. In contrast, the horizontal component of slip may be estimated thanks to  
291 diverted streams that appear to record the left-lateral component of the KSF (See previous  
292 section). The smaller streams show two convincing offsets of ~10 m (Fig. 8a). We are not  
293 aware of any data that could provide an estimate of the age of these streams. They could  
294 correspond to the mid-Holocene incision (5-7 ka), which is subsequent to the sapropel  
295 sedimentation in the Mediterranean domain (Gasse et al. 2015). Such an assumption would  
296 lead to a maximum slip rate of ~2 mm/a. However, these smaller incisions might also  
297 correspond to younger climatic episodes, or even to historical ones. Hence, they cannot be  
298 used to derive accurate slip rates. Thus, we focused on the largest stream offsets as they may  
299 provide, due to their deeper incisions within the proximal part of the younger alluvial fans,  
300 more favorable conditions for radiometric dating.

301 **3.1. Description and location of the sampling site**

302 The site selected to perform Cosmic Ray Exposure (CRE) dating is the largest left-laterally  
303 offset stream where the upslope part of a displaced alluvial fan forms a shutter ridge facing a  
304 ravine incised into the footwall escarpment of the southern Katouna fault (Fig. 14). To the  
305 east of the fault, the downstream prolongation of this ravine forms a ~6 m-incised gully in the  
306 alluvial fan (Fig. 14c). The gully is left-laterally offset by  $54 \pm 4$  m (Fig. 14b). As alluvial fan  
307 aggradation and abandonment predate gully incision, the age of the alluvial fan abandonment  
308 provides the upper bound age for the gully incision. Dating this abandonment using *in situ*-

309 produced cosmogenic nuclides should provide an estimate of the minimum geological  
310 horizontal slip-rate of the Katouna fault. The CRE dating method is widely used to constrain  
311 cosmic ray exposure duration of geomorphic features. Applied to an alluvial fan, the CRE age  
312 reflects the abandonment age of the alluvial surface after its aggradation and before its  
313 subsequent incision.

314 The sampling site is a natural outcrop carved within the offset alluvial fan material, where the  
315 external part of an active meander forms an active cliff (Fig. 15, sampling site location  
316 referred as P on Fig. 14b). Remnants of historical-time flood deposits within the bottom of the  
317 gully incision indicate that the outcrop is frequently rejuvenated and has consequently not  
318 been long exposed. As the top of the alluvial fan is covered by ~1.20 m-thick sand bearing,  
319 historical colluvium, we sampled ~5.30 m-high depth profiles without collecting any surface  
320 sample (Fig. 15). The alluvial material crops out on a 4.10-m section and consists of proximal  
321 debris flow with sub-angular to sub-rounded elements (gravels and cobbles), comprising  
322 reworked Mesozoic limestones and flints from the Ionian unit series. Due to the nature of these  
323 elements, we sampled along two depth profiles: one including only cherts and the other only  
324 carbonates to perform concentration measurements of *in situ*-produced  $^{10}\text{Be}$  and  $^{36}\text{Cl}$   
325 cosmogenic nuclides, respectively. Sample preparations were performed at CEREGE (Aix-en-  
326 Provence) and AMS measurements at the French national AMS facility ASTER (CEREGE,  
327 Aix-en-Provence) (detailed procedures are given in Supplementary Material).

### 328 **3.2. CRE dating results and minimum geological slip-rate**

329 Cosmogenic nuclide concentrations measured as a function of depth are controlled by three  
330 parameters: (1) the exposure duration to cosmic rays at the sampling depth; (2) the denudation  
331 rate affecting the sampled surface and, (3) the inherited cosmogenic nuclide concentration  
332 accumulated during a pre-exposure history and/or the transport from the source region

333 (inheritance). In case of homogeneous inheritance, the *in-situ* produced cosmogenic nuclide  
334 concentrations decrease exponentially with depth and tend to an asymptotic value of zero (no  
335 inheritance) or non-zero, corresponding to the amount of the measured concentration that is  
336 inherited (Siame et al. 2004; Braucher et al. 2009). In this case, the three unknown parameters  
337 can be determined from the modeling of measured depth-profile concentrations.

338 The presented results do not show such a distribution (Fig. 16). Measured  $^{10}\text{Be}$  and  $^{36}\text{Cl}$   
339 concentrations are both scattered and do not exhibit any exponential decrease with depth,  
340 indicating most likely that the samples were deposited in the alluvial fan with a highly  
341 variable inherited component. In addition,  $^{36}\text{Cl}$  surface *in situ*-production rate is significantly  
342 higher than  $^{10}\text{Be}$  surface *in situ*-production rate (Nishiizumi et al. 2007; Schimmelpfennig et  
343 al. 2009). Therefore, measured  $^{36}\text{Cl}$  concentrations significantly lower than  $^{10}\text{Be}$   
344 concentrations along the profile may indicate that chert samples were exposed to cosmic ray  
345 prior to their deposition in the alluvial fan for a much longer time-period than carbonate  
346 samples, leading to a more concentrated  $^{10}\text{Be}$  inherited component in cherts than the  $^{36}\text{Cl}$   
347 inherited component in carbonates. On the other hand, measured *in situ*-produced  $^{10}\text{Be}$   
348 concentrations largely exceed the maximum allowed  $^{10}\text{Be}$  concentration that corresponds to  
349 infinite exposure duration on a non-eroding surface (Suppl. Material, Table S1). This then  
350 suggests a possible adsorption of  $^{10}\text{Be}$  at the surface within amorphous silica as recently  
351 evidenced (Zerathe et al. 2013). For all these reasons, measured  $^{10}\text{Be}$  concentrations in cherts  
352 are not suitable for dating the alluvial fan abandonment age.

353 Nevertheless, the  $^{10}\text{Be}$  concentrations accumulated during an assumed infinite pre-exposure  
354 duration correspond to the steady-state  $^{10}\text{Be}$  concentrations that only depend on the  
355 denudation rate. They give therefore the opportunity to calculate maximum denudation rates  
356 ( $\epsilon_{\text{max}}$ ) (Suppl. Material, Table S2). As source regions for cherts should be the Ionian zone  
357 (Suppl. Material, Fig. S1), a possible explanation to account for such high inheritance would



358 be that these cherts have been spread as residual elements onto the Katouna paleo-surface that  
359 eroded most of the Ionian thrust sheet, up to the Triassic breccias. This paleo-surface is  
360 presently eroded by the upstream catchments of the alluvial fan (Fig. 14a) allowing cherts to  
361 be transported and aggraded downstream in the alluvial fan. The maximum denudation rates  
362 ( $\epsilon_{\max}$ ) determined on cherts would thus correspond to the denudation of the Katouna paleo-  
363 surface. Most of these calculated  $\epsilon_{\max}$  are lower than 5 m/Ma (Suppl. Material, Table S2),  
364 suggesting a relatively low denudation rates for the region.

365 The carbonate  $^{36}\text{Cl}$  concentrations, ranging from  $1.10^5$  at/gr. to  $2.5.10^5$  at/gr. (Fig. 16) are less  
366 scattered than those of  $^{10}\text{Be}$ . Carbonate elements, sampled in the same alluvial fan as the  
367 cherts, thus carry a less complicated pre-exposure history. Hence, it allows modeling the *in-*  
368 *situ* produced  $^{36}\text{Cl}$  concentrations, and then to estimate an abandonment age for the alluvial  
369 fan. As the upper 1.20 m of the depth profile consists of historical colluviums, we consider  
370 that the initial fan surface is located at 1.20 m depth below the surface. Consequently, the  
371 CRE age modeling of the alluvial deposits was performed on the carbonate samples below  
372 1.20 m depth (Fig. 17b). The scattering of the measured  $^{36}\text{Cl}$  concentrations and the  
373 occurrence of high  $^{36}\text{Cl}$  concentrations in the deepest part of the profile suggest variable  
374 inherited  $^{36}\text{Cl}$  concentration in the carbonate samples, that do not permit to run a simple CRE  
375 age modeling assuming an homogeneous inheritance. In case of variable inheritance, a  
376 rejuvenation depth profile analysis (Le Dortz et al. 2012) allows providing a maximum  
377 abandonment age for the fan surface. Assuming a negligible denudation rate as estimated  
378 from the  $^{10}\text{Be}$  concentrations (Suppl. Material, Table S2), this rejuvenation analysis provides  
379 a maximum exposure duration (i.e., abandonment age) for the alluvial fan surface of  $\sim 10$  ka  
380 (Fig. 17b, Table 2). Then, the sensitivity of this abandonment age has been tested for different  
381 denudation rates of 5, 20, and 30 m/Ma (Table 3), yielding to maximum exposure durations  
382 ranging between 10.2 and 11.7 ka. Therefore, a maximum abandonment age for the alluvial

383 fan surface of 10-12 ka is retained. Considering an age of ~2 ka for the 1.20m thick historical  
384 colluviums and a maximum abandonment age for the alluvial fan surface of 10-12 ka, this  
385 leads to a maximum alluvial fan aggradation duration of 12-14 ka, i.e., approximately coeval  
386 with the transition between the Marine Isotopic Stages 2 and 1. This suggests that the fan  
387 aggraded at most, after the Last Glacial Maximum, close to the beginning of Holocene.  
388 Finally, as alluvial fan aggradation and abandonment predate the inception of gully incision, it  
389 can thus only be concluded that incision started at most 12-14 ka ago. Because only a  
390 maximum age for the fan incision can be determined, only the minimum slip-rate of the KSF  
391 can be estimated, using the minimum value of the left-lateral offset. The stream incision offset  
392 of at least 50 m (Fig. 14b) that started at most 12-14 ka ago yields an estimated Holocene  
393 minimum left-lateral slip rate bracketed between 3.6 and 4.2 mm.yr<sup>-1</sup> (~4 mm.yr<sup>-1</sup>).

#### 394 **4. Active kinematics of Western Greece from GPS data**

395 We used the GPS data compilation of Perouse et al. (2012) and added new data. Original GPS  
396 vectors (Hollenstein et al. 2008; Floyd et al. 2010; GPSscope permanent GPS network) and  
397 new data (Briole 2013) have been rotated into a self-consistent Eurasian reference frame.  
398 GPS velocities in Akarnania can be minimized by a single rigid rotation defining an  
399 Akarnania fixed reference frame (Fig. 18). The absence of a gradient in the fault parallel  
400 component of velocity vectors across the KSF attests to localized deformation implying either  
401 low elastic coupling (i.e., superficial elastic locking depth) or/and creeping behavior.  
402 However, residuals exist in the Ionian Islands. These trend parallel to the Kefalonia fault, and  
403 are NE directed (Fig. 18). To account for this measured GPS velocity field, we interpret the  
404 Ionian Islands and Akarnania as moving as a single rigid block: the IAB (Ionian Islands-

405 Akarnania Block). Then, the NE directed residuals in the Ionian Islands would result from  
406 interseismic elastic loading along the dextral Kefalonia fault.

407 The northern and northeastern boundaries of the IAB would be the Amvrakikos Gulf and the  
408 Katouna valley fault (northern KSF), respectively (Fig. 19). According to GPS vectors on Fig.  
409 18, these structures accommodate IAB/continental Greece relative motion as  $\sim 10 \text{ mm.yr}^{-1}$  of  
410 N-S extension across the Amvrakikos Gulf and approximately the same amount of left-lateral  
411 motion along the Katouna fault, a result in agreement with the Vassilakis et al. (2011)  
412 estimation. The actual motion along the Katouna fault (northern KSF) is transtensional:  $\sim 11$   
413  $\text{mm.yr}^{-1}$  of fault-parallel left-lateral motion and  $\sim 3 \text{ mm.yr}^{-1}$  of fault perpendicular extension  
414 (Fig. 19). The western boundary of the IAB, that accommodates the relative motion between  
415 IAB and the Apulian platform, is the dextral Kefalonia fault. Determining the Kefalonia Fault  
416 slip-rate is not straightforward as no GPS vectors are available west of the fault, which is an  
417 offshore domain (Fig. 18). However, the triple junction occurrence between the Apulian  
418 platform, the Continental Greece and the IAB (Fig. 19) enables a slip-rate assessment for the  
419 Kefalonia fault: as the Apulian platform converges toward continental Greece at  $\sim 5 \text{ mm.yr}^{-1}$   
420 (e.g., Perouse et al. 2012), and considering  $\sim 10 \text{ mm.yr}^{-1}$  of N-S extension between IAB and  
421 continental Greece, it would imply a Kefalonia fault slip-rate of  $\sim 15 \text{ mm.yr}^{-1}$  (Fig. 19).  
422 Precision of this estimation, which gives an order of magnitude for the Kefalonia fault slip-  
423 rate, has to be improved in the future accounting elastic coupling processes.

424 Finally, the Southern Trichonis region belongs neither to continental Greece, nor to the IAB  
425 in contrast to what has previously been proposed (Vassilakis et al. 2011). Indeed, this region  
426 moves at  $\sim 6 \text{ mm.yr}^{-1}$  toward the NW relative to the IAB (Fig. 18). This motion is  
427 accommodated by  $\sim 6 \text{ mm.yr}^{-1}$  of pure left-lateral strike-slip along the Stamna fault (southern  
428 KSF), and  $\sim 4 \text{ mm.yr}^{-1}$  of N-S extension across the Trichonis graben (Figs. 18, 19). The  
429 Trichonis graben is located at the junction between the northern KSF (Katouna area) and the

430 southern KSF (Stamna area). The  $\sim 4 \text{ mm.yr}^{-1}$  of N-S extension across the Trichonis graben  
431 would thus account for the left-lateral slip-rate difference between the Katouna segment ( $\sim 11$   
432  $\text{mm.yr}^{-1}$  of left-lateral motion) and the Stamna segment ( $\sim 6 \text{ mm.yr}^{-1}$ ). Motions in southern  
433 Trichonis increase eastward, reaching values close to those of continental Greece, resulting in  
434 insignificant relative motion between the eastern tip of the southern Trichonis and the western  
435 Gulf of Corinth (Fig. 18).

## 436 **5. Discussion**

### 437 **5.1. A creeping behavior for the KSF ?**

438 High slip-rate on the KSF ( $> 4 \text{ mm.yr}^{-1}$  according to geological data, possibly up to  $11 \text{ mm.yr}^{-1}$   
439  $^1$  according to GPS) contrasts with the subdued morphological evidence for tectonic activity  
440 (this study) and the relatively low level of historical (Papazachos and Papazachou 1997) and  
441 instrumental seismicity (Fig. 2). Indeed, if mesoscale deformation is well expressed along the  
442 KSF (fault valley, rectilinear convex-shaped upward escarpments, en-échelon fault pattern),  
443 the small scale deformation is nearly missing. The fault shows no clear "earthquake-related"  
444 scarps, and scarce well developed dogleg stream offsets. This could suggest that the short-  
445 term tectonic landscape is not preserved due to the high level of anthropogenic activity along  
446 the KSF. Nevertheless, a stick-slip behavior on a fast slipping KSF should preserve at least  
447 some earthquake-related landforms even with high anthropogenic activity. An entirely locked,  
448  $11 \text{ mm.yr}^{-1}$ -slipping fault (see previous section) would produce a  $\sim M_w 7$  earthquake in  
449 average at least each 500 years with a 1-2 m-high scarp, resulting from the expected  $3 \text{ mm.yr}^{-1}$   
450  $^1$  of extension across the northern KSF. Such a scenario is very unlikely, because such a scarp  
451 would not be entirely erased everywhere in some hundreds of years and further, there should  
452 be some evidence of large earthquakes in the historical seismicity records. Even assuming that

453 a high percentage of the GPS-derived deformation is transitory and that the average KSF slip  
454 rate is closer to the geological minimum estimate, it would not change significantly these  
455 conclusions. Consequently, a high percentage of the fault displacement should be  
456 accommodated by creep slip. This creep should increase significantly the average return  
457 period between two subsequent seismic events as well as lower their magnitudes. Less  
458 frequent earthquakes with smaller surface displacements may explain why the small-scale  
459 seismic landform is not preserved. Creeping, which may be favored by the gypsum-breccias  
460 of the KSF bedrock, is further suggested by the absence of gradient in the fault parallel  
461 component of velocity GPS vectors across the KSF (Fig. 18). It also agrees with the large  
462 deficit of seismic moment rate compared to geodetic moment rate in Akarnania (Chousianitis  
463 et al. 2015).

## 464 **5.2. Ionian Islands-Akarnania Block (IAB) geometry and kinematics**

465 East of the Kefalonia fault that connects the Apulian collision front to the Hellenic subduction  
466 front, we show that deformation in the overriding plate domain is localized along the KSF and  
467 the Amvrakikos gulf as no significant deformation occurs along the Neogene N-striking  
468 thrusts of Akarnania, located west of the KSF. It delineates a Ionian-Akarnania block (IAB,  
469 Fig. 19).

470 The NNW- striking KSF, northeast boundary of the IAB, terminates northward onto the ESE-  
471 striking Loutraki fault. Regionally, the Loutraki fault could belong to an ESE-striking  
472 Amvrakikos Gulf half-graben system, with a northward dipping master fault (Fig. 3). Indeed,  
473 E-W active fault segments have been imaged at the western termination of the Gulf (sparker  
474 seismic-reflection profiles, Anastasakis et al. 2007). The submerged morphology, the  
475 southward flexure and the absence of clear E-W active normal fault trace on the northern side  
476 of the Amvrakikos Gulf suggest a half-graben geometry. However, the eastern submerged

477 part of the Gulf has not been imaged yet, so we cannot clearly constrain what is controlling  
478 the subsidence east the Loutraki fault. The ESE-striking Amvrakikos Gulf half-graben system  
479 we propose would represent the northern boundary of the IAB. The western and southwestern  
480 boundaries of the IAB would be the Kefalonia fault and the Hellenic subduction front  
481 respectively (Fig. 19). Finally, the IAB southeastern boundary might be located in the NW  
482 Peloponnesus, along the right-lateral Achaia-Elia fault (Fig. 19) associated to the 2008  $M_w$  6.4  
483 Movri earthquake (Serpetsidaki et al. 2014). This Achaia-Elia fault zone should accommodate  
484 the relative motion between the IAB and the Peloponnesus. The trenchward motions of these  
485 two blocks are  $\sim 10$  mm/yr for the IAB (constrained by the KSF rate) and some  $\sim 15$  mm/yr for  
486 the Peloponnesus (constrained by the opening rate of the Corinth Rift), respectively.  
487 Consequently the right-lateral rate of the Achaia-Elia fault zone should be  $\sim 5$  mm/yr. In our  
488 model, the Gulf of Patras graben system should correspond to a triple junction between the  
489 western tip of the Corinth Rift, the KSF and the Achaia-Elia Fault zone (Fig. 19). In more  
490 details, the triple junction zone between Peloponnesus, Continental Greece and our  
491 determined IAB could actually be a diffuse zone spread over the Nafpaktos basin (basin  
492 linking the western tip of the Corinth rift to the Patras gulf), as proposed by Beckers et al.  
493 (2015), based on a submarine active faults study of the region. Thus, kinematics of the IAB  
494 fault boundaries indicates a trenchward motion, compatible with the regional Hellenic slab  
495 retreat.

496 At first order, the IAB geometry we propose in this paper shares several similarities with the  
497 Akarnania “fragment” proposed by Vassilakis et al. (2011). However, our study delineates the  
498 NNW-striking Stamna fault segment as the south-eastern prolongation of the Katouna fault,  
499 indicating the southern KSF fault system connects directly with the Patras Gulf, contrasting  
500 with a Amphilochia valley-Trichonis graben-Gulf of Corinth faults network (Vassilakis et al.  
501 2011). Consequently, in our model, the opening of the Trichonis graben, located at the

502 junction between the Katouna and the Stamna faults, accommodates the left-lateral slip-rate  
503 difference between the northern and southern KSF (Fig. 18, 19). Finally, despite a high  
504 seismic activity along a NW trend connecting the western tip of the Corinth rift to the  
505 Trichonis graben (Fig. 2, Evangelidis et al. 2008; Kiratzi et al. 2008), active faulting is not  
506 observed either in the morphology or from GPS data (Fig. 18). It suggests that this area,  
507 seismically "crackling", could represent an incipient fault zone, not yet established (Fig. 19).

### 508 **5.3. Timing individualization of the Ionian Islands-Akarnania Block (IAB)**

509 Such a high slip rate on short surface fault segments suggests that the KSF (northeastern  
510 boundary of the IAB, Fig. 19) is not yet a mature system. The direction of the KSF, collinear  
511 with the NNW-striking Ionian thrust formed during Hellenides orogen (Figs. 3, 4), suggests  
512 structural inheritance. However, in the Katouna area, our results show that the KSF is a steep  
513 fault, crosscutting the Ionian thrust sheet at depth (Fig. 7). The KSF could thus be a  
514 neoformed fault, but whose direction has been controlled by the Hellenides orogen fabric.

515 As the KSF is directly connected to the Loutraki fault, initiation of the Loutraki  
516 fault/Amvrakikos half-graben and the KSF should be synchronous. According to the  
517 sedimentological record of Amvrakikos Gulf series, regional subsidence in the Amvrakikos  
518 Gulf would have initiated at least since MIS 8 (245-300 ka, Anastasakis et al. 2007). In  
519 addition, due to the triple junction between Continental Greece, the Apulian-Ionian micro-  
520 plate and the IAB (Fig. 19), extension initiation across the Amvrakikos Gulf may be  
521 contemporary or younger than dextral initiation along the Kefalonia fault. Dextral shear along  
522 the Kefalonia fault, an inherited normal fault of the Apulian platform (Sorel 1976), would  
523 have initiated ca. 1.5-1.3 Ma (Sorel 1976; Cushing 1985; Nielsen 2003). The present-day  
524 Loutraki fault has an escarpment height of ~700 m (Fig. 6). For comparison, the East Helike  
525 fault, a northward dipping active normal fault of the Corinth Rift system having a ~800 m

526 escarpment height (1600m of total vertical throw, ~800 of footwall uplift, ~800 of  
527 hangingwall subsidence), and which extension rate evolution is well constrained, would have  
528 initiated at 700-800 ka (McNeill and Collier 2004; Ford et al. 2013). However, as we have no  
529 constrain about the Loutraki fault extension rate evolution, a reasonable age initiation for the  
530 Loutraki fault/Amvrakikos Gulf system (and consequently its connected KSF) can thus be  
531 bracketed between ~1.5 Ma and 300 ka. Finally, our observations suggest that no more  
532 internal E-W compression occurs in Akarnania since ~600 ka since the N-striking Astakos  
533 thrust is sealed by Middle Pleistocene slope breccia (Figs. 12, 13). All these age constraints  
534 and faults geometries in Akarnania are compatible with a change from E-W compressional  
535 stress regime to a near N-S horizontal  $\sigma_3$  axis during the Pleistocene, leading to the  
536 progressive individualization and trenchward motion of the IAB. Hence, initiation of the IAB  
537 individualization could be coeval with the Corinth rifting phase 2 or 3 (~1.7 Ma to ~700 ka,  
538 and ~700 ka to present-day, respectively, Ford et al. 2013). The right-lateral Achaia-Elia fault,  
539 potential southeastern boundary of the IAB, is considered juvenile because no coseismic  
540 surface rupture occurred during the 2008  $M_w$  6.4 Movri earthquake (Feng et al. 2010) and no  
541 morphological evidence attests long-term fault activity (Stiros et al. 2013).

## 542 **6. Conclusion**

543 An accurate mapping of active and inactive fault traces, new multi-scale geomorphologic and  
544 tectonic observations and a geodetic study provide evidence for active normal and left-lateral  
545 faulting along the Katouna Stamna Fault (KSF), a 65-km-long NNW-striking fault system  
546 connecting the Amvrakikos Gulf to the Patras Gulf. The KSF segments are typically ~10 km-  
547 long. We further show that the N-striking Cenozoic Hellenides thrusts, located west of the  
548 KSF in Akarnania, are no longer active, by either field observation or GPS data. It results that



549 the transition from subduction to collision in Western Greece is accommodated in the  
550 overriding plate by the individualization of a Ionian Island-Akarnania block (IAB, Fig. 19).  
551 The KSF, that we interpret as a neofomed immature fault system, but which strike is likely to  
552 be inherited from the Hellenides orogen, forms presently the northeastern boundary of the  
553 IAB. The northern KSF accommodates IAB motion relative to continental Greece by active  
554 left-lateral transtension along the Katouna valley. The southern KSF accommodates relative  
555 motion between the IAB and the southern Trichonis Lake region by left-lateral slip along the  
556 Stamna fault. The KSF slip-rate is high: at least 4 mm.yr<sup>-1</sup> of geological slip-rate was  
557 determined by CRE dating on the Katouna valley segment. GPS data shows ~11 mm.yr<sup>-1</sup> and  
558 ~6 mm.yr<sup>-1</sup> of left-lateral slip-rate along the northern KSF (Katouna segments) and the  
559 southern KSF (Stamna segments), respectively. We suggest the localized strain and high slip-  
560 rate along the KSF should be dominantly released by aseismic creep, compatible with the  
561 gypsum-breccias bedrock along the fault and the low level of seismicity. We finally propose  
562 that a change from E-W compressional stress regime to a near N-S horizontal  $\sigma_3$  axis would  
563 have occurred in Akarnania during the Pleistocene, leading to the progressive  
564 individualization and trenchward motion of the IAB from Pleistocene time (younger than ~1.5  
565 Ma) to present day.

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578

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## Tables

Table 1: Measured cosmogenic  $^{36}\text{Cl}$  and natural  $^{35}\text{Cl}$  concentrations of samples collected along the depth profile at the sampling site (Figs. 13, 14).

Sample	Depth (cm)	Measured $^{36}\text{Cl}$ (at/gr.)	Error measured $^{36}\text{Cl}$ ( $\pm$ at/gr.)	Natural $^{35}\text{Cl}$ (ppm)	Geologic material
CI 01	20	114 310	4 290	25.55	Historic colluviums
CI 03	60	109 270	3 614	15.93	
CI 06	120	147 333	4 754	29.10	
CI 07	140	249 731	5 883	6.89	Alluvial fan
CI 08	160	171 920	4 357	4.06	
CI 09	180	131 278	4 247	11.12	
CI 10	200	95 645	3 297	11.01	
CI 12	240	181 391	4 702	12.83	
CI 14	275	75 182	2 964	1.23	
CI 16	330	101 152	3 130	15.82	
CI 18	400	144 827	4 134	6.04	
CI 21	530	152 744	5 144	8.77	

Table 2: Measured  $^{36}\text{Cl}$  concentrations and results of depth profile rejuvenation (Fig. 15b).

$^{36}\text{Cl}$  half-life is 301 ka (Gosse and Phillips 2001). Scaling factor for surface nucleonic and muonic production as a function of latitude and altitude are respectively 1.01 and 0.97 (Stone et al. 1996) and have been calculated using CosmoCalc (Vermeesch 2007). We input a bulk rock density of 1.8. Production  $^{36}\text{Cl}$  rates and modeling results have been obtained using Excel spreadsheet of (Schimmelpfennig et al. 2009). Spallation production rate from Ca is  $\sim 42$  atoms  $^{36}\text{Cl.g.Ca}^{-1}$  (Braucher et al. 2011; Schimmelpfennig et al. 2011). We considered no denudation.

Sample	Depth (cm)	Nmeas: Measured $^{36}\text{Cl}$ (at/gr.)	Error Nmeas ( $\pm$ at/gr.)	Nth: Theoretical $^{36}\text{Cl}$ for modeled age of 10.158 ka (at/gr.)	Error Nth (at/gr.)	Excess concentration (= Nmeas - Nth) (at/gr.)
Cl 07	20	249 731	5 883	164 721	47 657	85 009
Cl 08	40	171 920	4 357	137 440	38 296	34 480
Cl 09	60	131 278	4 247	114 464	30 875	16 814
Cl 10	80	95 645	3 297	95 645	25 004	0
Cl 12	120	181 391	4 702	68 085	16 749	113 306
Cl 14	155	75 182	2 964	51 971	12 240	23 211
Cl 16	210	101 152	3 130	36 091	8 319	65 061
Cl 18	280	144 827	4 134	25 281	6 239	119 545
Cl 21	410	152 744	5 144	16 810	4 922	135 934

Table 3: Maximum modeled ages obtained by depth profile rejuvenation considering different denudation rate values ( $\epsilon$ ).

Denudation rate $\epsilon$ (m/Ma)	Maximum modeled age (yr.)
0	10 157.9
5	10 387.2
20	11 155.4
30	11 746.3



## Figure Captions

**Fig. 1** Geodynamic setting of Western Greece. Tectonic structures and crust nature are from Chamot-Rooke et al. (2005) and Papanikolaou et al. (2006). Velocity vectors, relative to fixed Eurasia, are from the regional interpolated velocity field (Perouse et al. 2012). AP: Apulian Platform; CR: Corinth Rift; CSZ: Calabrian Subduction Zone; KF: Kefalonia Fault; NAF: North Anatolian Fault; Pel: Peloponnesus. Black structures are active, grey ones are inactive (cf. Perouse et al. 2012). The blue star is the rotation pole of the Apulian-Ionian microplate relative to Nubian plate, shown with its 95% confidence ellipse (Perouse et al. 2012).

**Fig. 2** Instrumental seismicity in the Western Greece region. Focal mechanisms of superficial events (< 30 km) from the Harvard CMT catalog (1976 to 2007) and the Regional CMT catalog (1995 to 2007) have been relocalized according to the Engdahl catalog (Engdahl et al. 1998). Compressional quadrants of focal mechanisms: blue, red and green indicate reverse, strike slip and normal faulting, respectively. Seismicity distribution of superficial events (< 30 km), with magnitude  $M_l > 3.7$ , is plotted in yellow (from NOA catalog, 1970 to 2008).

**Fig. 3** Tectonic map of Western Greece showing active (red) and inactive (black) faults.

Lou: Loutraki fault; Tri: Trichonis Lake. Fault traces from the present study: Loutraki and KSF. Fault traces from other studies: onshore Ionian islands (Cushing 1985; Nielsen 2003); offshore Amvrakikos (Anastasakis et al. 2007); Trichonis graben (Perouse 2013); Patras Gulf (Ferentinos et al. 1985); Corinth Rift (Jolivet et al. 2010); Apulian collision front, Hellenic backstop, Calabrian prism (Chamot-Rooke et al. 2005); Achaia-Elia fault (e.g., Stiros et al. 2013), N-striking Akarnania thrusts (Clews 1989, see Fig. 4 for details). Hellenides units: yellow, Pre-Apulian zone (PA zone), purple, Ionian zone, brown, Gavrovo-Tripolitza (Gvo-

Tz) and green, Pindos unit (Aubouin 1959; British Petroleum Co Ltd 1971; Karakitsios and Rigakis 2007). Neogene and Quaternary deposits in white. Inset: regions names. Aka: Akarnania; Aito: Aitolia; Pelop: Peloponnesus.

**Fig. 4** Map of the KSF system. Active (red) and inactive (black) fault traces. Lou: Loutraki Fault; Kat: Katouna Fault; Sta: Stamna Fault; Amph: Amphilochia valley; Amv: Amvrakia Lake; Oz: Ozeros Lake. The Neogene Hellenides Akarnania thrusts are shown as Pal: Paleros thrust; Myt: Mytikas thrust; Ast: Astakos thrust. (a) Topography background, SRTM (3seconds resolution); (b) Simplified geological map based on our reappraisal and geological maps (British Petroleum Co Ltd 1971; Institute of Geology and Mineral Exploration, IGME, 1987). Sealed thrusts are shown with dashed lines.

**Fig. 5** (a) Morphological map of Loutraki and Katouna Faults. Topography background with height contours, SRTM (3 seconds resolution). Main drainage network is in blue. Solid roundish-shaped black lines: wine glass valleys; dashed black line: benches on Loutraki fault escarpment. (b) Simplified geological background (same captions as Fig. 4b). The FP yellow point is a normal fault plan N120° 55'N 85°E, between Mesozoic limestones and old alluvial fan deposits (38.864572°N, 21.070004°E).

**Fig. 6** Topographic profiles across the Loutraki and Katouna Faults, with vertical exaggeration ( $\times 3$ ). Profile lines are plotted in Fig. 5. H: escarpment height; EFT: Escarpment Flat Top; blue arrows: benches. Red arrows: active faults.

**Fig. 7** Geological cross section through the Katouna and Amphilochia valley, based on the 1:50,000 Amphilochia geological map (Institute of Geology and Mineral Exploration, IGME, 1987), and interpretative Katouna fault geometry. Section line is plotted in Figs. 4, 5.

**Fig. 8** Offset streams along the southern Katouna fault. Sites locations are plotted on Fig. 5. Site (a) displays three stream offsets. The field photograph and the enlarged inset show a close-up of two small stream offsets of 5-7m and ~12 m, respectively. Site (b) displays a ~40 m offset stream. Site (c) is an offset stream with a  $54 \pm 4$ m offset. Satellite images from Google Earth.

**Fig. 9** (a) SRTM (3 seconds resolution) of Stamna area and (b) interpreted Stamna active fault segment.

**Fig. 10** Drainage network along the Stamna Fault (satellite image from Google Earth, see Fig. 9 for location). FP: Fault Plane shown in Fig. 11, close to the freeway bridge.

**Fig. 11** Fault plane measured within Plio-Pleistocene alluvial deposits (location on Fig. 10). Fault plane is  $N162^{\circ} 65^{\circ}W$ , with a  $13^{\circ} S$  dipping slickenside (underline by red line), indicating a nearly pure left-lateral slip.

**Fig. 12** Field photographs of the N-striking Neogene thrusts in central Akarnania. Location of thrusts on Fig. 4a. (a) View of the Astakos thrust sealed by strong calcite-cemented breccias (SBr). SBr consists of cryoclastic angular elements of Ionian Mesozoic limestone with no clay matrix attributed to the Middle Pleistocene (Sorel 1976); (b) Landslide head scar along the Astakos thrust. White arrows indicate this head scar. The destroyed house on the left attests

for a recent landslide movement. Inset shows the scar of the last movement. PBr: poorly consolidated slope breccias. They may correlate with either Holocene or the last climatic crisis coeval with LGM (i.e., MIS 2); (c) W-facing discontinuous cliff made of Ionian Mesozoic limestone covered by strongly cemented slope breccias (SBr) seen along the Paleros thrust. This cliff height displays an along-strike variation (red arrows) resulting from gully differential erosion between the limestone material and the Miocene molasses.

**Fig. 13** Conceptual 3D block diagram summarizing tectonic and geomorphologic field observations seen on the N-striking Akarnania thrusts (Fig. 12) and interpretations.

**Fig. 14** Selected left-lateral offset stream to perform CRE dating and location of the sampling site. (a) Local geological map (close-up of Fig. 5) showing the catchment area of the selected offset stream. (b) Satellite image of the offset stream as on Fig. 8c. Measured offset stream is  $54 \pm 4\text{m}$  (50m minimum considering near-field piercing points, see Suppl. Material Fig. S2). P: sampling site location of depth profiles for CRE dating (Fig. 15). (c) Field photograph (looking SW) of the analyzed offset stream. The green almond shaped patch facing the upstream gorge corresponds to a shutter ridge. Purple wooded area in the background corresponds to the Triassic breccias bedrock of the KSF escarpment; in the foreground, green color corresponds to alluvial fan material and slope screes aggraded on the hangingwall block.

**Fig. 15** Sampling site of depth profiles used for CRE dating (located as P on Fig. 14b). Geographic coordinates: 38.79077°N, 21.13115°E. Profile altitude: 95m. No significant shielding affects the fan surface (maximal values ~10 %). (1) Historic colluviums with heterometric clasts and anthropic elements (tiles, bricks, pottery sherds); (2) Alluvial fan material with heterometric carbonates and cherts clasts within a sandy matrix; PS: pebbly

layer; MS: muddy layer with sparse and small angular clasts within a silty-clayed matrix; (3) Alluvial fan material with fairly homometric carbonates and cherts clasts within a sandy matrix.

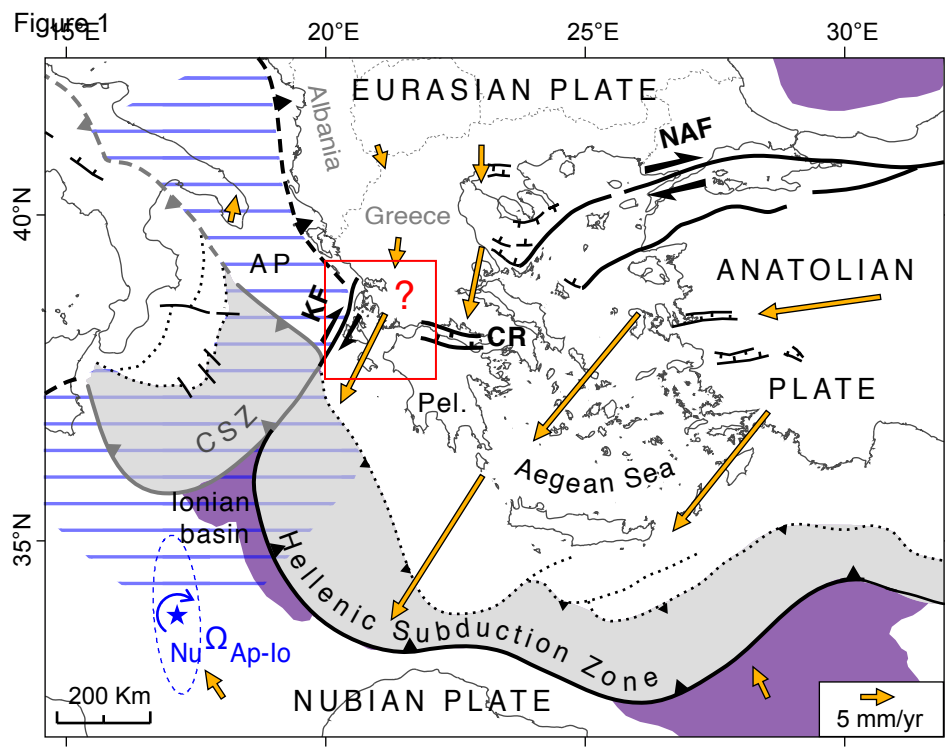
**Fig. 16** Measured  $^{36}\text{Cl}$  and  $^{10}\text{Be}$  concentrations as a function of depth (values in Table 1 and Suppl. Material, Table S1).  $^{36}\text{Cl}$  and  $^{10}\text{Be}$  have been measured in carbonates and cherts, respectively. This plot emphasizes two distinct origins and pre-exposure histories for carbonates and cherts.

**Fig. 17** (a) Measured  $^{36}\text{Cl}$  concentrations in carbonate clasts as a function of depth; (b) Rejuvenation depth profile procedure model of  $^{36}\text{Cl}$  concentrations (See text for more details). We only consider samples from the alluvial fan material (historic colluviums are not considered, so that the 1.20 m depth corresponds to the initial fan surface).  $t$ , maximum *in-situ* exposure duration;  $\varepsilon$ , denudation rate. The best fit is obtained for zero denudation and Cl 10 sample with a measured  $^{36}\text{Cl}$  concentration carrying zero inheritance (Table 2). For all the other samples, the differences between the measured and the modeled concentrations result from pre-exposure processes.

**Fig. 18** GPS velocity field relative to fixed Akarnania. GPS sites minimized to define this reference frame are shown with green squares. Green diamond site, not used to define the reference frame, shows nonetheless a residual close to zero (See text for discussion). GPS vectors are shown with their 95% confidence ellipses. Velocity vectors are taken from Hollenstein et al. (2008), Floyd et al. (2010), Briole (2013) and GPSscope data, available at <http://crlab.eu>

**Fig. 19** Simplified tectonic map of Western Greece. IAB: Ionian Islands-Akarnania Block. Arrows and numbers show relative motions and fault slip-rate values in mm/yr. *Italic numbers* refer to GPS slip-rate determined in previous studies (Briole et al. 2000; Perouse et al. 2012). Regular numbers indicate GPS slip-rate assessed in this study. The minimum geological slip-rate determined from CRE dating for the Katouna fault is reported as (geol). Dotted areas are diffused deformation zones. Green asterisk and dashed line point to possible incipient fault (See Discussion for details).

Figure 1



Continental crust	Accretionary prism	Subduction front
Oceanic crust	Normal fault	Collision front
Apulian-Ionian microplate	Strike-slip fault	Backstop front

Figure 2

[Click here to download Figure Fig.2\\_2.pdf](#)

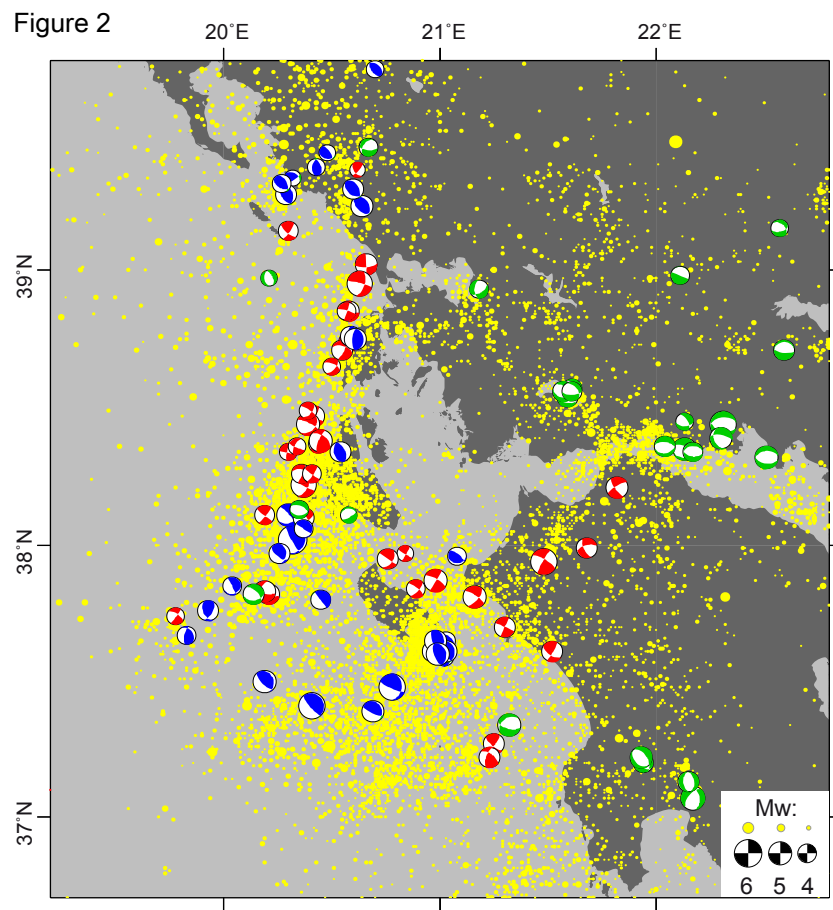




Figure 3

20°E

21°E

22°E

[Click here to download Figure Fig.3\\_revised2.pdf](#)

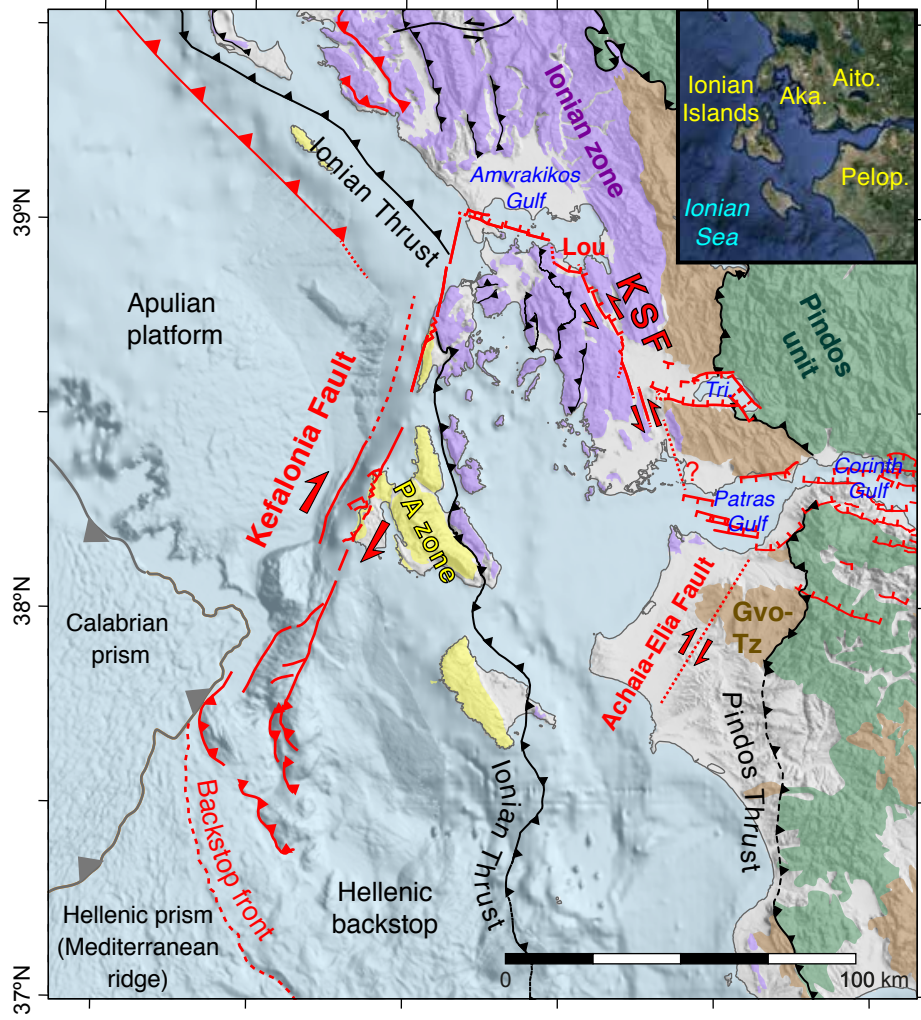


Figure 4

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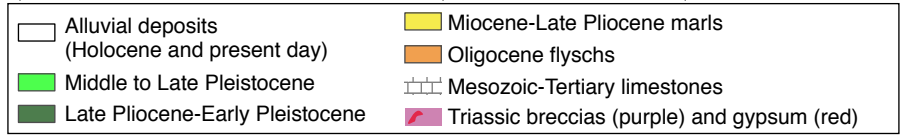
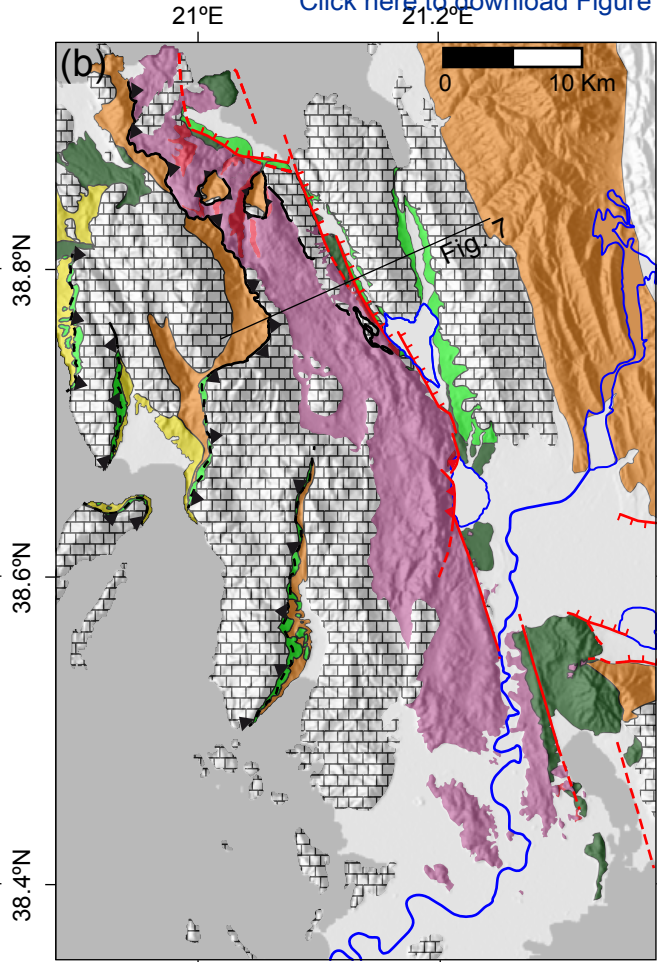
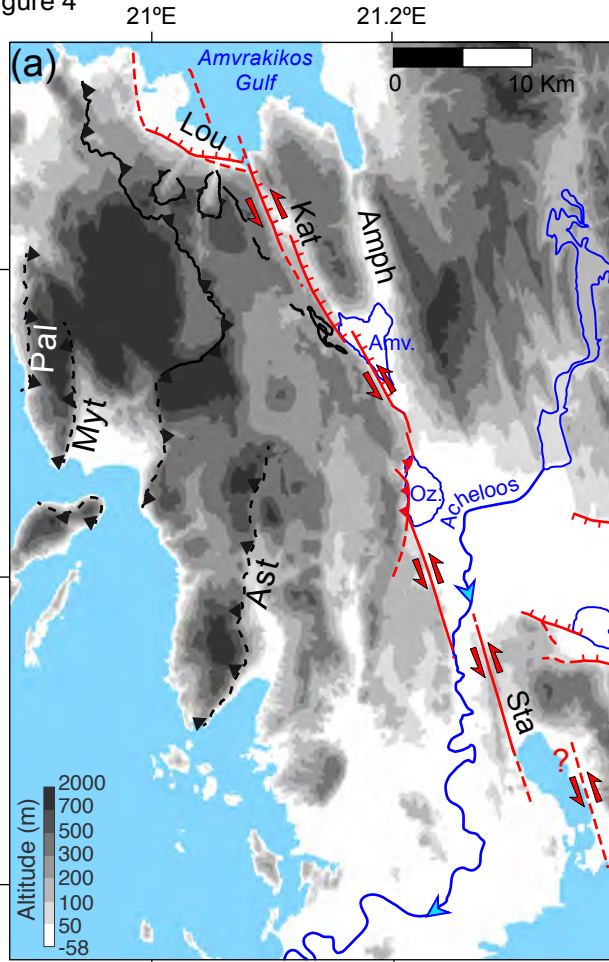


Figure 5

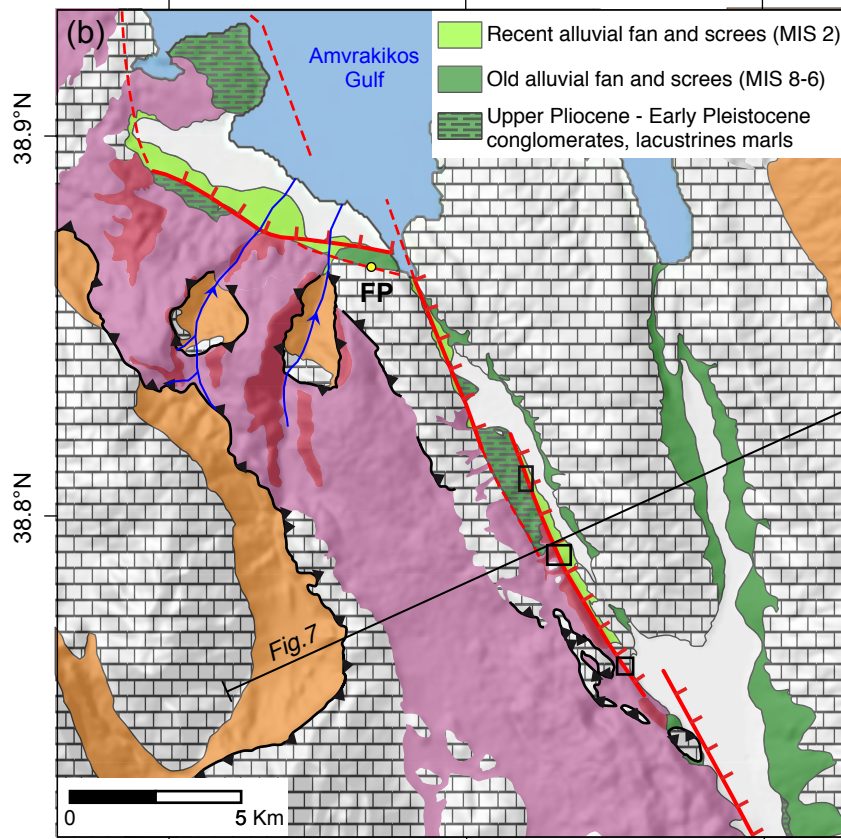
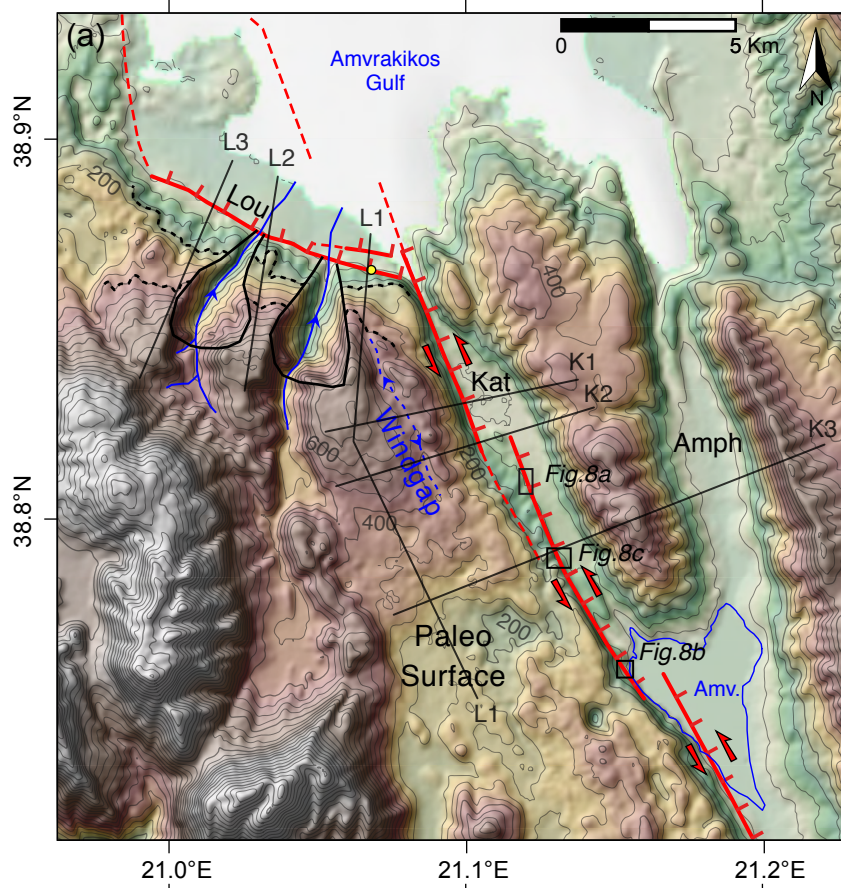


Figure 6

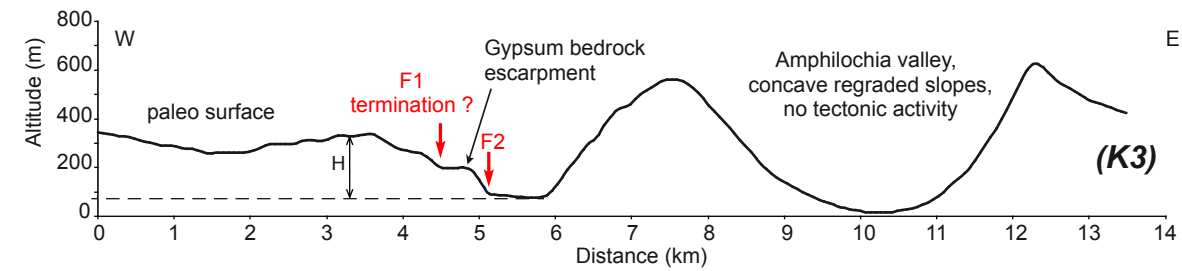
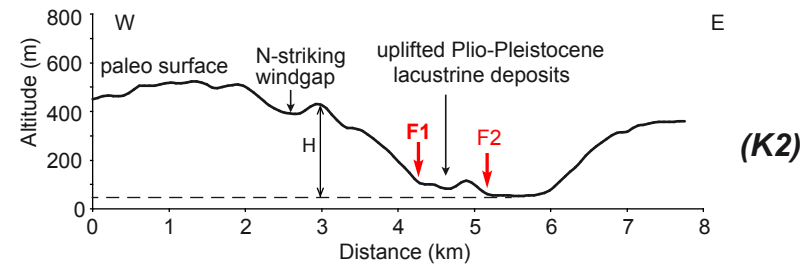
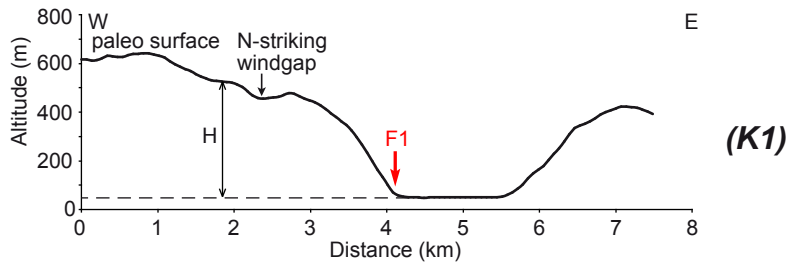
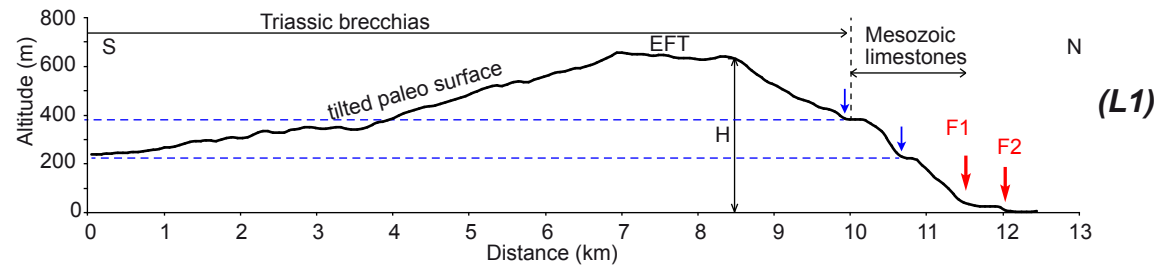
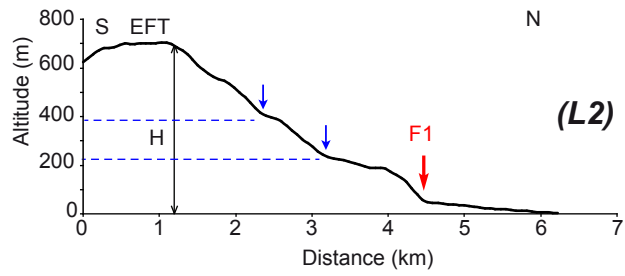
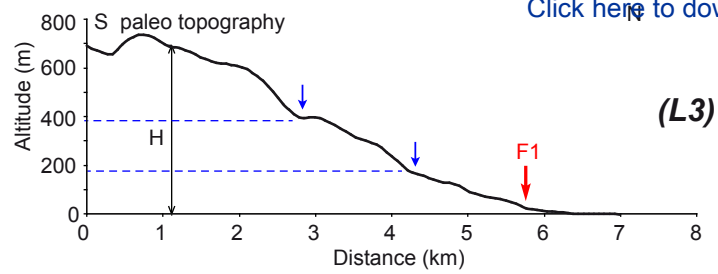
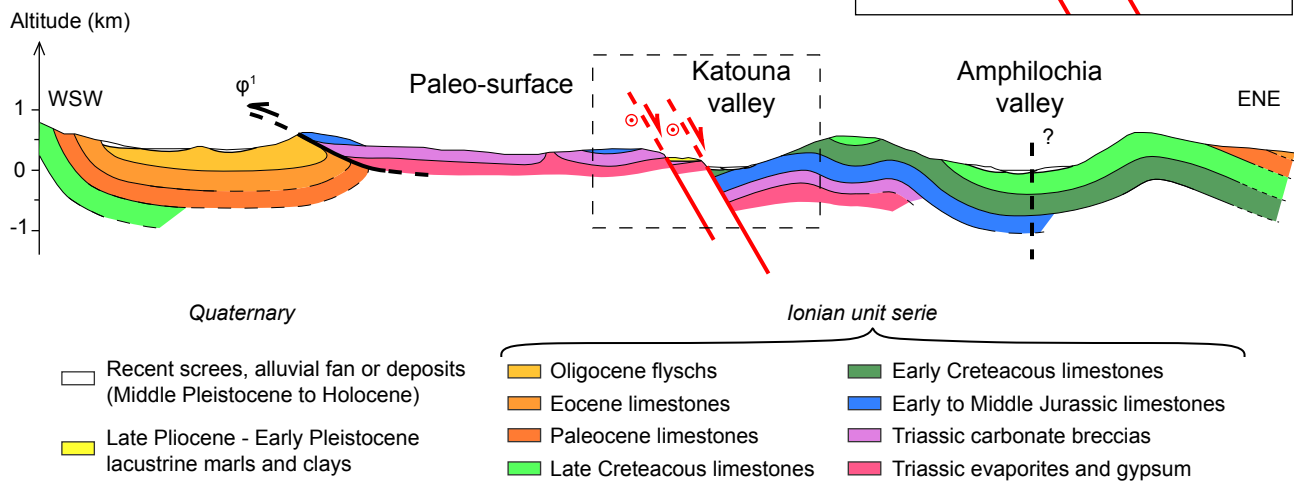
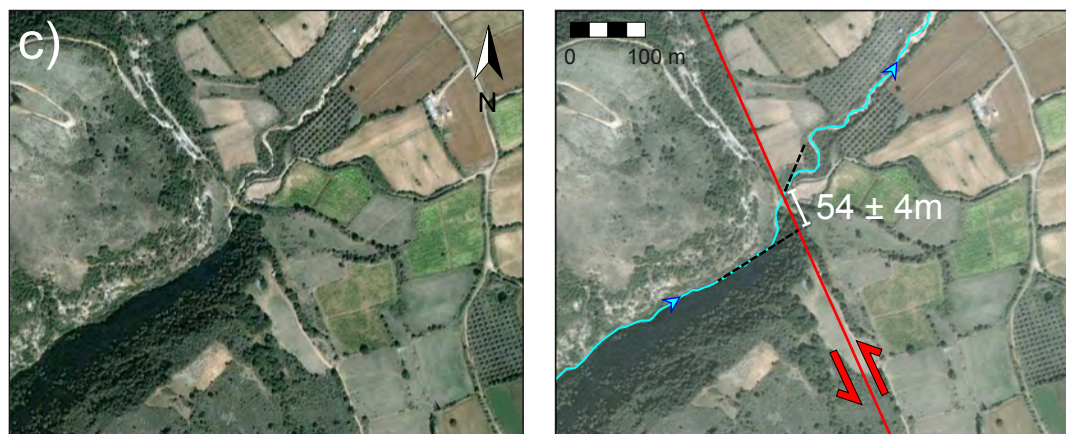
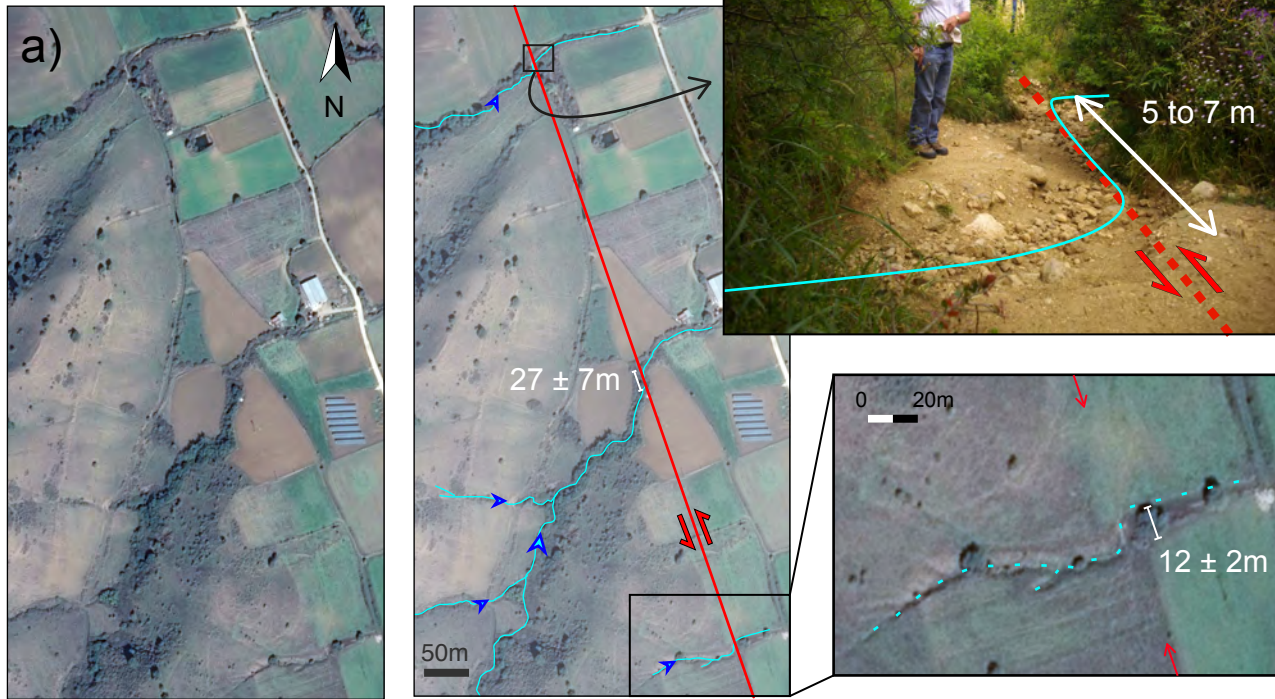


Figure 7



- |  |   |  |
|--|---|--|
| <ul style="list-style-type: none"> <li><span style="display: inline-block; width: 15px; height: 10px; border: 1px solid black; margin-right: 5px;"></span> Recent scree, alluvial fan or deposits (Middle Pleistocene to Holocene)</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: yellow; margin-right: 5px;"></span> Late Pliocene - Early Pleistocene lacustrine marls and clays</li> </ul> | <p style="text-align: center;"><i>Ionian unit serie</i></p> <ul style="list-style-type: none"> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: #FFD700; margin-right: 5px;"></span> Oligocene flyschs</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: #FFA500; margin-right: 5px;"></span> Eocene limestones</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: #FF8C00; margin-right: 5px;"></span> Paleocene limestones</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: #90EE90; margin-right: 5px;"></span> Late Creteaceous limestones</li> </ul> | <ul style="list-style-type: none"> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: #6B8E23; margin-right: 5px;"></span> Early Creteaceous limestones</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: #4169E1; margin-right: 5px;"></span> Early to Middle Jurassic limestones</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: #DDA0DD; margin-right: 5px;"></span> Triassic carbonate breccias</li> <li><span style="display: inline-block; width: 15px; height: 10px; background-color: #E91E63; margin-right: 5px;"></span> Triassic evaporites and gypsum</li> </ul> |
|--|---|--|

Figure 8



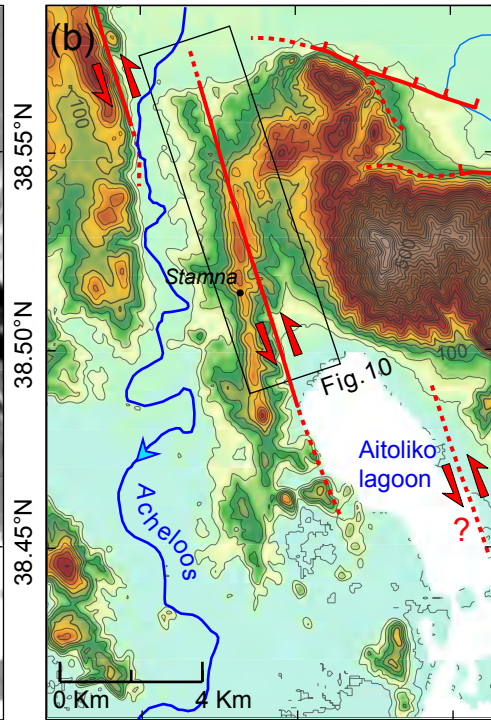
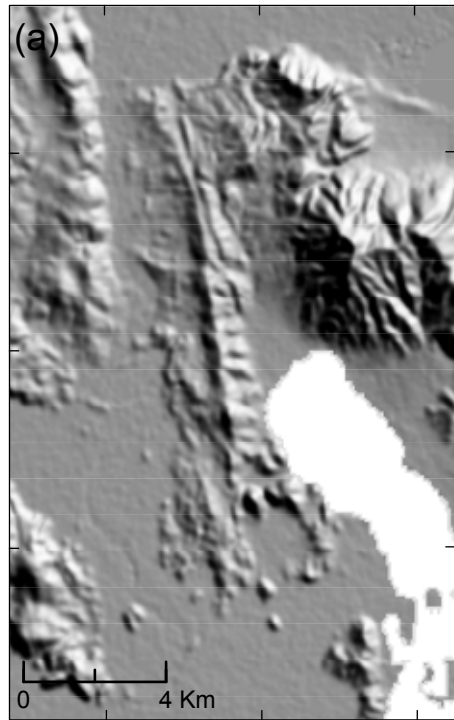


Figure 10

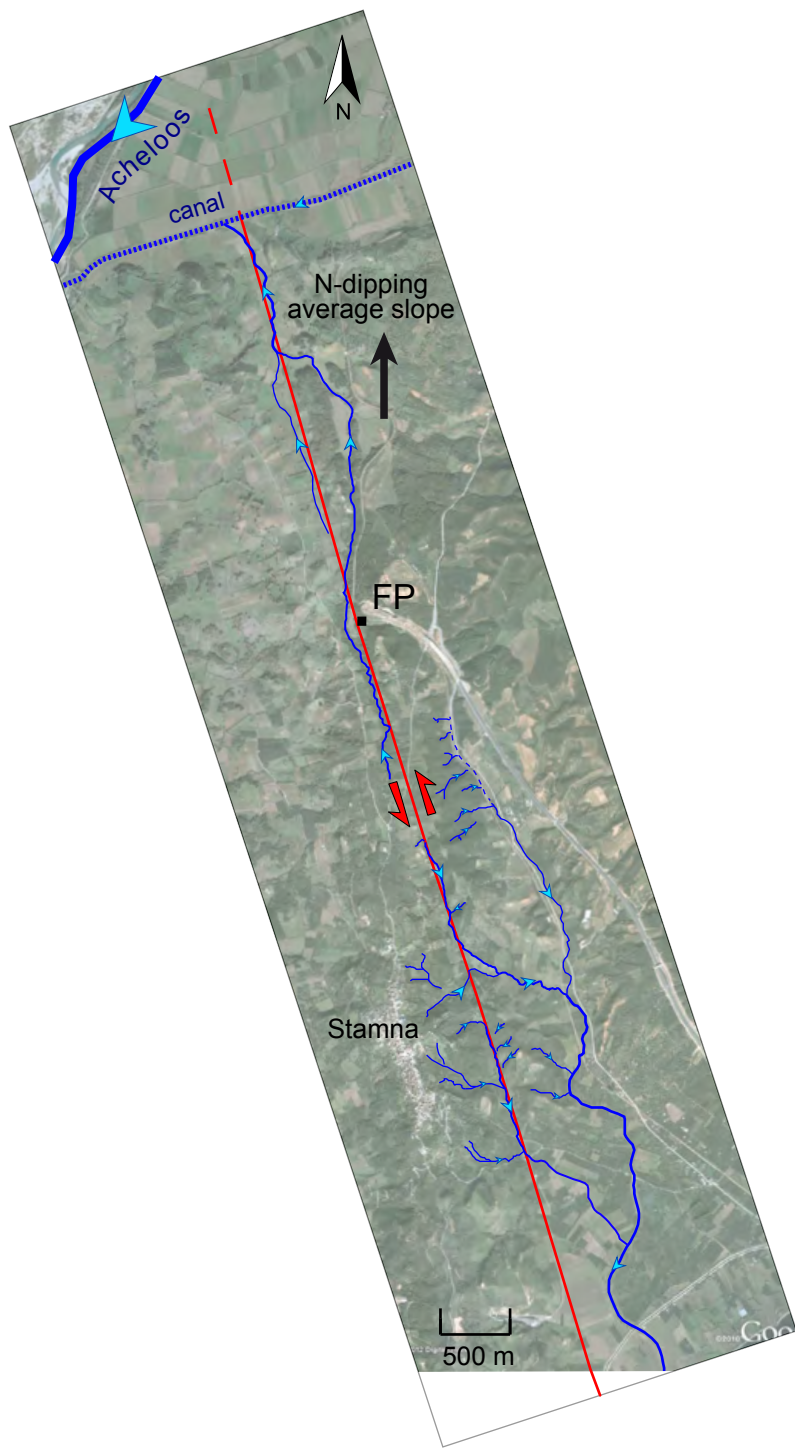




Figure 11



Figure 12  
W

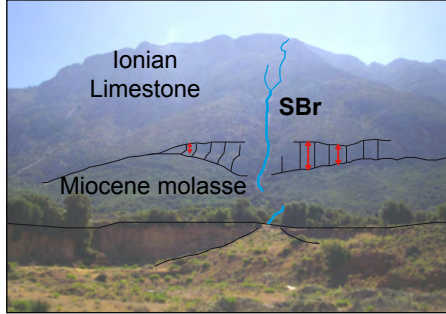
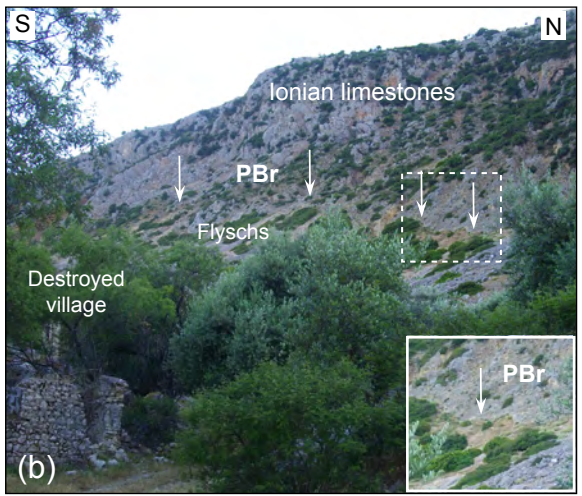
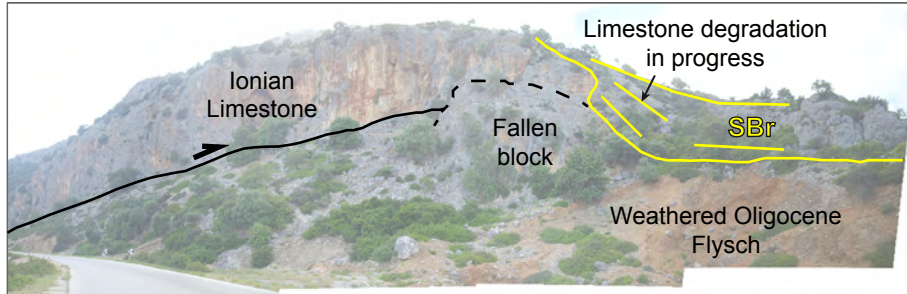


Figure 13

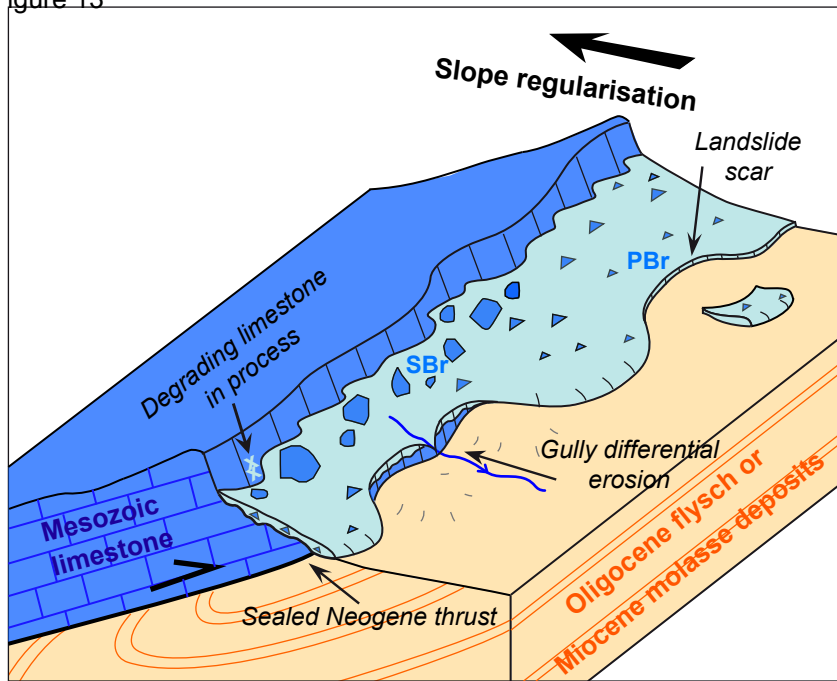


Figure 14

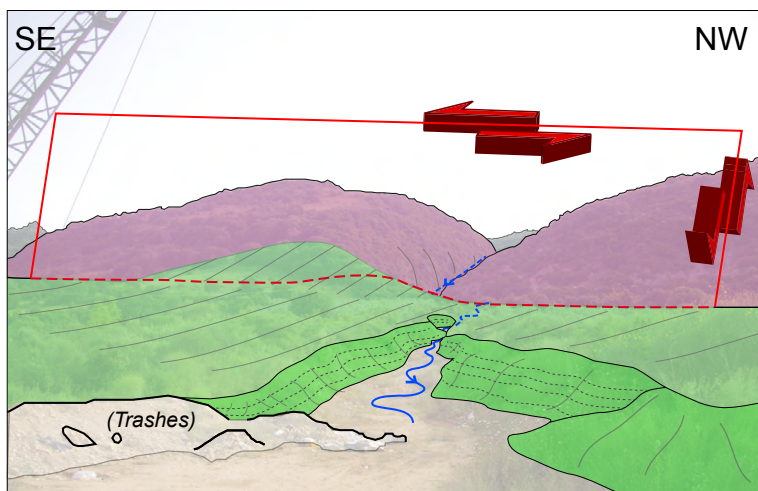
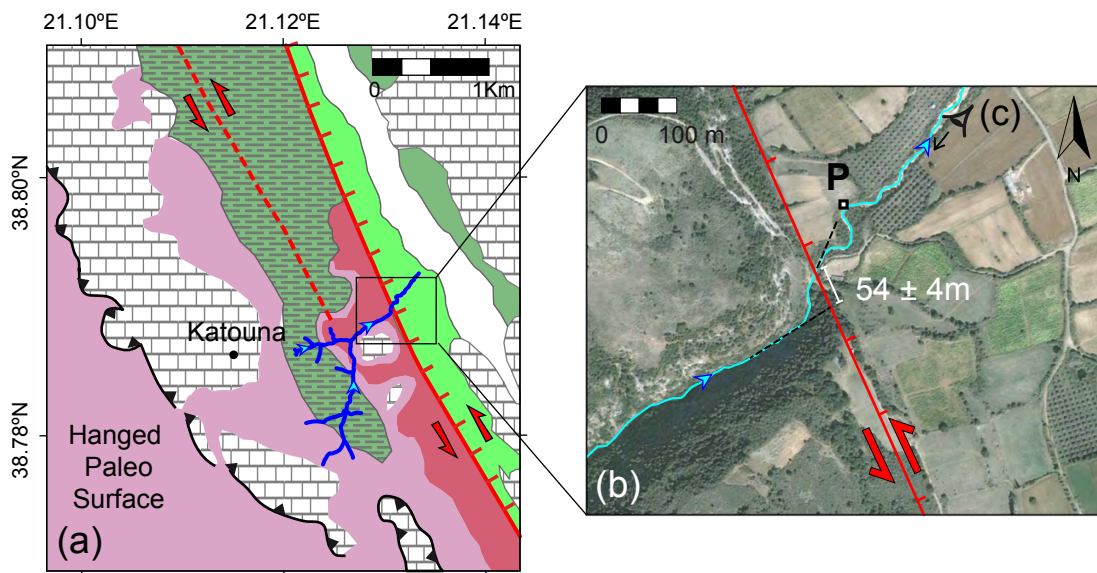


Figure 15

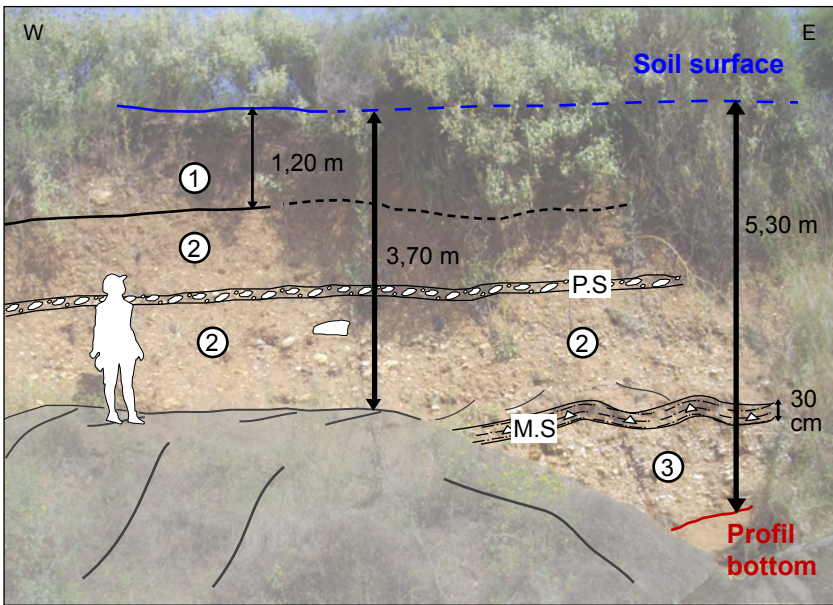
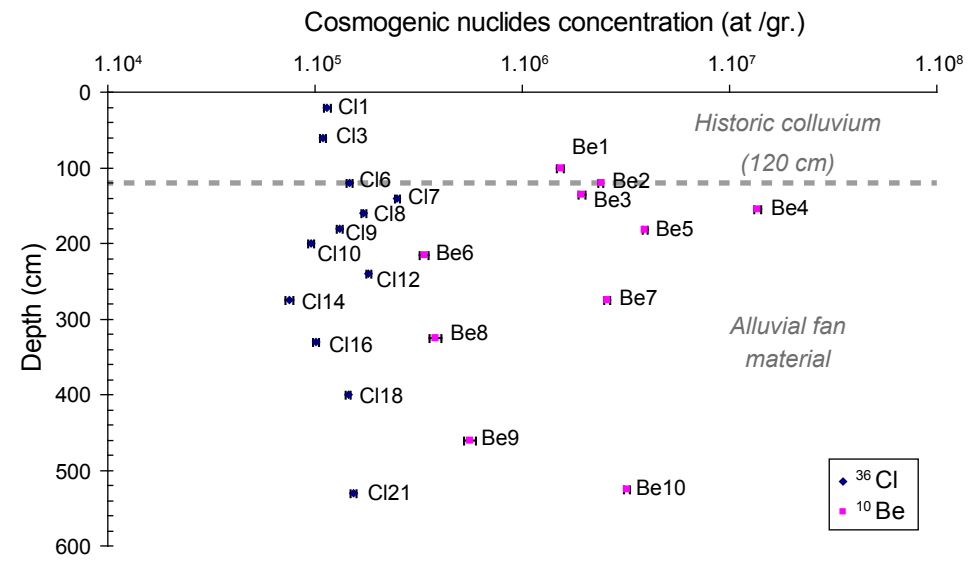
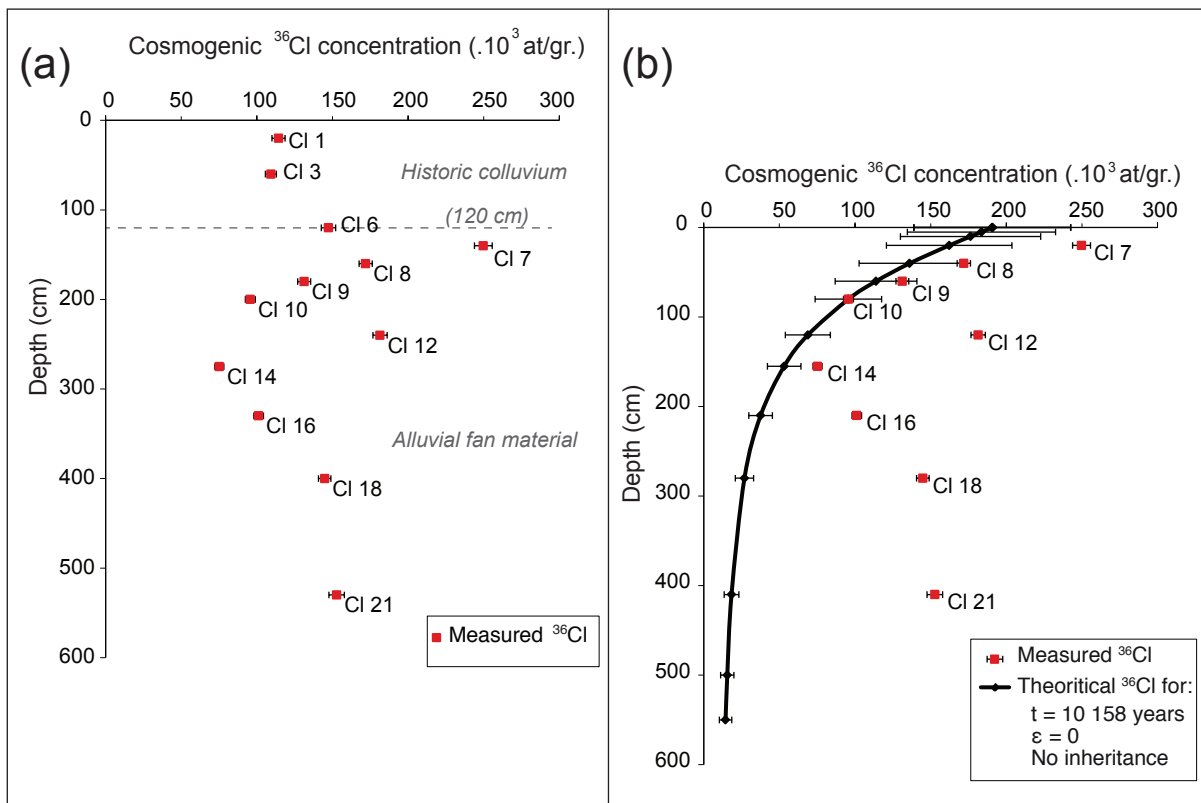


Figure 16





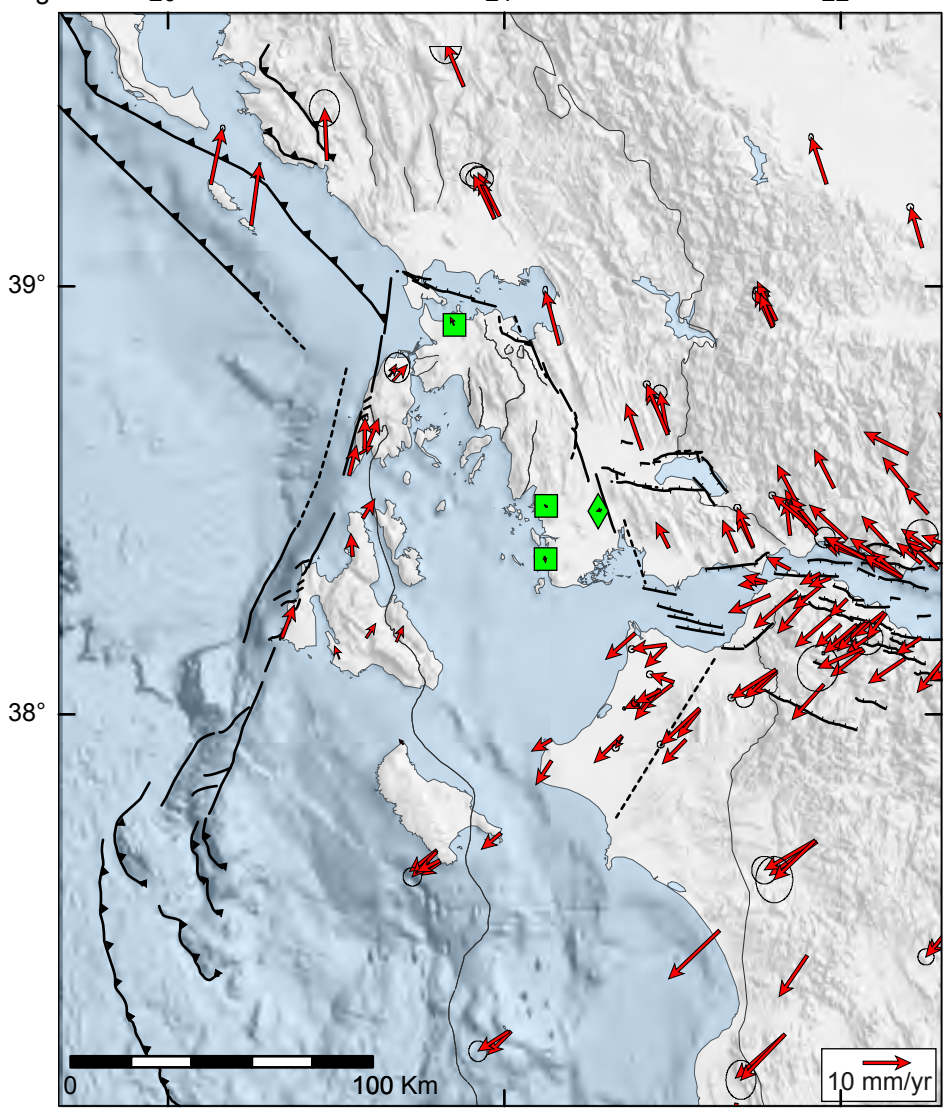




Figure 19

20.0

21.0

22.0

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