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5 **Innovative tidal notch detection using TLS and fuzzy logic: implications for palaeo-shorelines from**  
6 **compressional (Crete) and extensional (Gulf of Corinth) tectonic settings**

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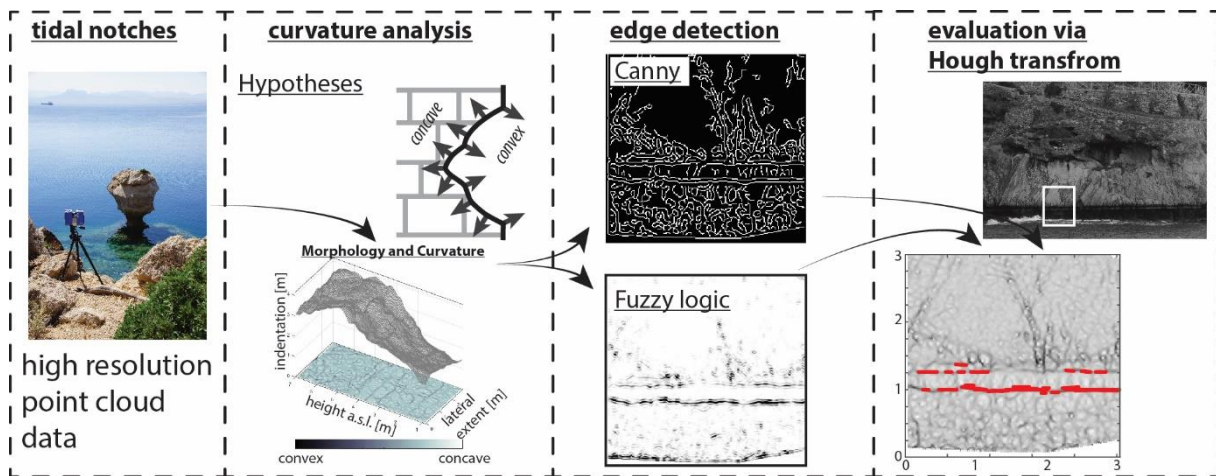
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16

17 **Abstract**

18 Tidal notches are a generally accepted sea-level marker and maintain particular interest for  
19 palaeoseismic studies since coastal seismic activity potentially displaces them from their genetic  
20 position. The result of subsequent seismic events is a notch sequence reflecting the cumulative coastal  
21 uplift. In order to evaluate preserved notch sequences, an innovative and interdisciplinary workflow is  
22 presented that accurately highlights evidence for palaeo-sea-level markers. The workflow uses data  
23 from terrestrial laser scanning and iteratively combines high-resolution curvature analysis, high  
24 performance edge detection, and feature extraction. Based on the assumptions that remnants, such  
25 as the roof of tidal notches, form convex patterns, edge detection is performed on principal curvature  
26 images. In addition, a standard algorithm is compared to edge detection results from a custom Fuzzy  
27 logic approach. The results pass through a Hough transform in order to extract continuous line features  
28 of an almost horizontal orientation. The workflow was initially developed on a single, distinct, and  
29 sheltered exposure in southern Crete and afterwards successfully tested on laser scans of different  
30 coastal cliffs from the Perachora Peninsula. This approach allows a detailed examination of otherwise  
31 inaccessible locations and the evaluation of lateral and 3D geometries, thus evidence for previously  
32 unrecognised sea-level markers can be identified even when poorly developed. High resolution laser  
33 scans of entire cliff exposures allow local variations to be quantified. Edge detection aims to reduce  
34 information on the surface curvature and Hough transform limits the results towards orientation and  
35 continuity. Thus, the presented objective methodology enhances the recognition of tidal notches and  
36 supports palaeoseismic studies by contributing spatial information and accurate measurements of  
37 horizontal movements, beyond that recognized during traditional surveys. This is especially useful for  
38 the identification of palaeo-shorelines in extensional tectonic environments where coseismic footwall  
39 uplift (only 1/2 to 1/4 of net slip per event) is unlikely to raise an entire notch above the tidal range.

40 Keywords: Tidal notches; Terrestrial laser-scanning; Computer vision; Fuzzy logic; Hough  
41 transformation; Palaeoseismology.



42

### 43 1. Introduction

44 In microtidal seas, such as the Mediterranean, tidal notches can be used to derive and quantify relative  
45 coastal movements during the Holocene (Pirazzoli, 1991). To develop these prominent strandlines,  
46 ranging from a few centimetres to several metres deep, the sustained action of physical, chemical, and  
47 biological erosion within the tidal range is necessary. Therefore, exposure to wave action, lithologic  
48 resistance to quarrying, and the strength of the rock able to support the weight of the overburden are  
49 key parameters effecting the shape of resultant notches (Trenhaile, 2015). In tectonically active  
50 regions, these distinct ecological and morphological features define the modern shoreline, and when  
51 equivalent older features are different from the present-day sea-level coseismic activity can be  
52 inferred (Fig. 1) (i.e., Boulton and Stewart, 2015). However, a direct correlation of individual sea-level  
53 markers to palaeoearthquake parameters is an outstanding challenge especially in extensional tectonic  
54 settings. For example, the shoreline of western Crete was uplifted by up to 9 m during the  
55 compressional  $M$  8.5 Hellenic earthquake in 365 A.D., forming a classic example for a lifted prominent  
56 strandline as a consequence of rapid emergence (Shaw et al., 2008). This distinct palaeoshoreline is  
57 well-preserved and has not been affected by wave attack or midlittoral erosion. By contrast, shorelines  
58 that experienced rapid emergence due to extensional tectonic movements, such as those from  
59 Perachora Peninsula in the Gulf of Corinth, are not likely to preserve fully developed tidal notches. In  
60 these settings, the amount of coseismic displacement is usually up to an order of magnitude lower  
61 than in megathrust events, and moreover the uplift component is estimated to be only 1/4 to 1/2 of  
62 the net slip per earthquake (e.g. Armijo et al., 1996; McNeill et al., 2005; Papanikolaou et al., 2010)  
63 and thus not likely to exceed the tidal range of  $\sim 0.4$  m in the Mediterranean Sea (Evelpidou et al.,  
64 2012). Therefore, it is suggested that apparent notches reflect the cumulative effect of multiple seismic  
65 events and individual notch levels cannot usually be attributed to specific earthquakes in regions of  
66 tectonic extension (e.g. Stewart and Vita-Finzi, 1996; Cooper et al., 2007; Boulton and Stewart, 2015).  
67 The identification of a palaeoshoreline is, among bioerosional remnants or consolidated beach  
68 deposits, based on the recognition of distinct erosional marks of former midlittoral zones (Pirazzoli et  
69 al., 1994). Typically, the notch position is mapped on a 1:5000-scale map (Cooper et al., 2007) and  
70 measurements are made to create morphometric profiles. Profiles are usually collected by tape  
71 measure (e.g. Kershaw and Guo, 2001) and include the average vertical extent of a notch and the  
72 maximum indentation (e.g. Antonioli et al., 2015). Vertical sheltered coasts are preferred for precise

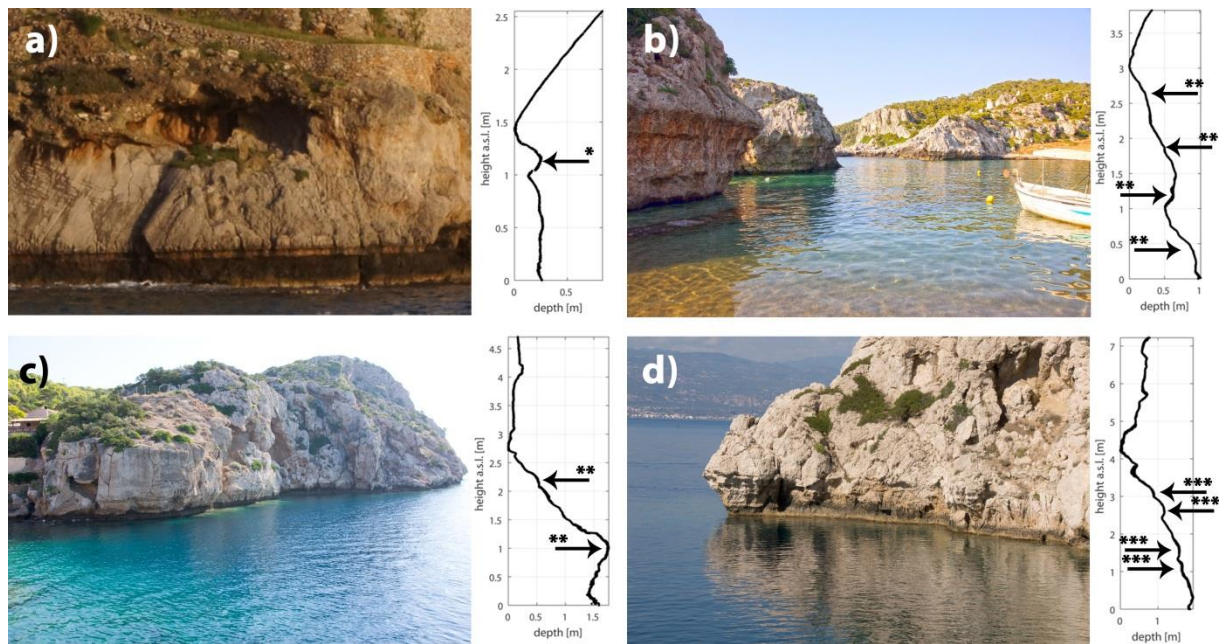
73 notch measurements (Pirazzoli, 1986), yet often these cliffs are inaccessible, and for that reason mid-  
74 range profiling using a handheld laser distance meter allowing evaluation of inaccessible and  
75 dangerous cliffs has also been employed (Kázmér and Taboroši, 2012). To address morphometric  
76 variations, a structure-from-motion (SfM) approach is also presented by Bini et al. (2014), which  
77 produces high resolution 3D models from a surface using a series of overlapping photographs.

78 The problem of lateral profile heterogeneity is extensively discussed by Kershaw and Guo (2001),  
79 demonstrating that active fault segments crossing cliffs, local variations of different wave and surf  
80 regime, and/or bedrock heterogeneity result in different notch profiles even in nearby sites (see also  
81 Evelpidou et al., 2012). Furthermore, collecting multiple profiles manually is time consuming and  
82 contains potential error sources. For instance, the correlation of different extracted levels from  
83 morphometric profiles is challenging and requires a constant reference datum over the time period of  
84 profile collection. We suggest that terrestrial laser scanning (TLS) provides all requirements for  
85 palaeoseismological studies on emerging coasts. The data are of high precision and resolution, and  
86 enables the analysis of the surface curvature of a whole cliff in a reasonable amount of time.

87 This paper aims to present an interdisciplinary study of computer vision and palaeoseismology. High  
88 resolution data from TLS is investigated utilising multiscale image analysis and semi-automatic edge  
89 detection. Conventional gradient analysis is compared to modern modelling from Fuzzy logic  
90 methodology. Afterwards, feature extraction by Hough transformation gives spatial evidence for the  
91 existence of tidal notches within an entire sequence of palaeo-strandlines on a cliff.

92 In their comprehensive analysis of tidal notches in the Mediterranean, Antonioli et al. (2015) concluded  
93 that notch formation processes have not changed during the last 125 kyrs. Similar widths of both last  
94 interglacial and modern notches suggest equivalent tidal ranges as zones of notch formation. Hence,  
95 the retreat zone of a tidal notch representing mean sea-level can be inferred by knowing the local tidal  
96 amplitude and the position of either roof or floor. Particularly in the Mediterranean, the use of tidal  
97 notches as palaeo-sea-level markers to determine rates of tectonic activity is widespread, since  
98 potential errors are limited by low tidal ranges and the lack of strong waves (Pirazzoli and Evelpidou,  
99 2013). Therefore, the coastline at Perachora Peninsula in the eastern Gulf of Corinth provides suitable  
100 conditions to apply an innovative method improving tidal notch identification and comparison on local  
101 and regional scales. In order to verify and calibrate the method, which focusses on changing curvature  
102 at the roof or bottom of a notch, a distinct tidal notch in southwestern Crete ~1 m above recent sea-  
103 level uplifted by the 365 A.D. earthquake (Shaw et al., 2008) is investigated as reference model.

104



105

106 Fig. 1. Collage of raised shorelines on Crete and Central Greece and associated notch profiles extracted  
 107 from TLS data. The tidal notch at Agios Pavlos (a) was raised by the 365 A.D. earthquake and forms the  
 108 reference for notch detection (\* Shaw et al., 2008). Exposures at the coast of Perachora Peninsula (Gulf  
 109 of Corinth) are known from literature (\*\* Kershaw and Guo, 2001; \*\*\* Pirazzoli et al., 1994) and pose  
 110 testing targets in this study: b) Mylokopy Bay; c) Heraion Harbour, and d) Heraion Lighthouse.

111

112

## 113 2. Study sites

### 114 2.1. Agios Pavlos, SW Crete

115 The island of Crete is directly adjacent to the Hellenic subduction zone between Europe and Africa (Fig.  
 116 2) and comprises a complex geological and tectonic structure that results from successive thrusting of  
 117 alpine geotectonic units and the activity of major detachment faults. Crustal extension orientated both  
 118 arc-parallel and arc-perpendicular has led to the development of Quaternary carbonate bedrock fault  
 119 scarps throughout the island (Caputo et al., 2010). These normal faults mainly juxtapose Mesozoic  
 120 carbonates of the Pindos unit in their footwall against hanging-wall flysch and /or post-alpine  
 121 sediments. Vertical tectonic movements along the western part of the island are associated with both  
 122 fault populations, causing earthquakes along the nearby Hellenic trench and on normal faults onshore.  
 123 As a result, clearly visible emerged shorelines are developed on the limestone cliffs. The 365 A.D.  
 124 earthquake rapidly uplifted the well indented strandline by ~1 m at Agios Pavlos, located  
 125 approximately 70 km eastwards from the activated structure and evidences the recent regional uplift  
 126 phase (Stiros, 2010). Crete has experienced ~2.5 km of uplift since the Early Tortonian (Miocene) in  
 127 several different phases (Meulenkamp et al., 1994). The most recent phase of uplift, as evidenced by  
 128 uplifted Messinian deposits (Krijgsman, 1996), began at around 6 Ma and continues to the present day.  
 129 The study location is located inside a 200 m wide bay and is protected from rough seas in accordance  
 130 with official nautical cartographies and data from oceanographic buoys  
 131 (<http://utmea.enea.it/energiadalmare/>).

132

133       2.2. *Perachora Peninsula, eastern Gulf of Corinth*

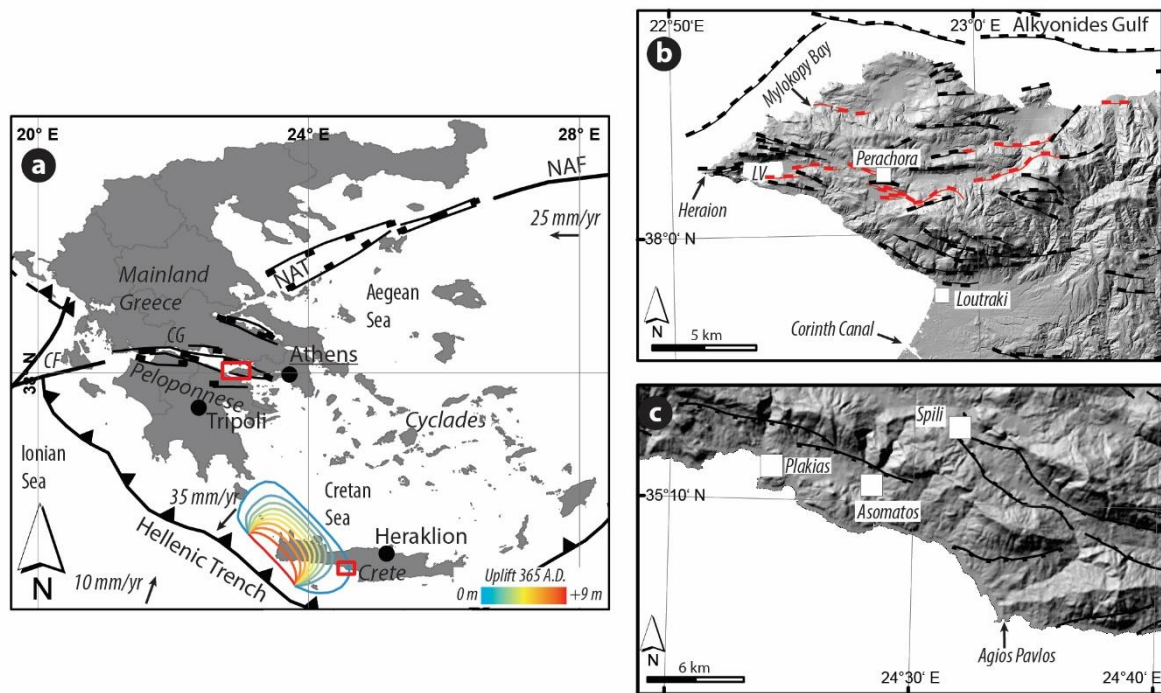
134 North-South directed extension with rates of 10–15 mm yr<sup>-1</sup> makes the Gulf of Corinth one of the most  
135 rapidly extending areas on Earth. Along the southern shore of the graben are active north-dipping  
136 normal faults uplifting coastal regions in the footwall. Rates of fault motion lie in the range of 1–10  
137 mm yr<sup>-1</sup> and are evidenced by Quaternary and Holocene palaeoshorelines (Armijo et al., 1996;  
138 Morewood and Roberts, 1999; Cowie and Roberts, 2001; McNeill and Collier, 2004; Leeder et al., 2003;  
139 Cooper et al., 2007; Roberts et al., 2009). Leeder et al. (2005) estimate slip rates of ~2.5 mm yr<sup>-1</sup> for  
140 normal faulting structures in the Alkyonides Gulf and the Perachora Peninsula over a period of 0.6 Myrs  
141 (Fig. 2). However, the authors also postulate that onshore faults (Schinos and Pisia) are more active  
142 than parallel offshore structures.

143 The coastline of the Perachora Peninsula is predominantly comprised of Mesozoic and Pleistocene  
144 carbonates. In some parts of the southwestern part of the peninsula, a thin composite  
145 volcanosedimentary series of basic rocks occurs. Occasionally, marine deposits of Tyrrhenian age  
146 comprising conglomerates crop out along northern coastlines (Bornovas et al., 1984).

147 The Heraion archaeological site is located at the northwestern tip of the Perachora Peninsula (Fig. 2b).  
148 The tidal notches at this site are described by several authors. Pirazzoli et al. (1994) identified four  
149 raised notches at the lighthouse between +1.1 and +3.2 m and dated them to 4.4–4.3 kyrs BP (+3.2 m),  
150 2.4–2.2 kyrs BP (+2.6 m), and 0.4–0.2 kyrs BP (+1.1 m) (see Fig. 1). Kershaw and Guo (2001) tried to  
151 correlate these notches to exposures at the harbour of Heraion only a few hundreds of metres to the  
152 east (+0.75 and +2.05 m). The authors conclude that differential uplift on cross-cutting faults causes  
153 dislocations of former strandlines and prevents a correlation between the two sites.

154 Another site mentioned by both studies is located along the northern shore of the peninsula. The  
155 Mylokopy beach actually consists of two small bays, separated by a tombolo. At the tip of the tombolo  
156 a massive limestone block contains up to five notch generations, which vary in height from the  
157 surrounding cliffs because of fault activity. In addition, three different notch morphometric profiles  
158 (identified notches at +0.4, +1.2, +2.0, and +2.6 m) can be extracted due to varying exposure to the sea  
159 and abrasional components (Kershaw and Guo, 2001).

160



161  
 162 Fig. 2. Overview map of studied sites. a) Map of Greece showing simplified large-scale tectonic  
 163 structures (CG, Corinthian Gulf; CF, Cephalonia Fault; NAF, North Anatolian Fault; NAT, North Aegean  
 164 Trough; black lines with barbs show active thrusts; black lines with marks show active faults) (after  
 165 Papanikolaou and Royden, 2007; Shaw et al., 2008). Red boxes highlight study areas. b) DEM (from  
 166 10m contour lines) of the Perachora Peninsula. Red lines with marks indicate normal faults that have  
 167 been activated during the 1981 earthquake sequence (Bornovas et al., 1984). LV, Lake Vouliagmeni. c)  
 168 DEM (SRTM-1) of the southwestern coast of Crete. The morphology indicates tectonic structures (black  
 169 line with marks) that potentially down-throw coastal areas (Bonneau, 1985).

170  
 171 3. Methodology

172 The methods presented include data acquisition from TLS and processing for semi-automated edge  
 173 detection based on the surface curvature of a cliff. One scan from the distinct shoreline at Agios Pavlos  
 174 operates as a reference for a unique tidal notch at this particular cliff, since the 365 A.D. thrust event  
 175 raised the strandline > 1 m from the erosional zone. Thus, we assume this exposure is not affected by  
 176 ongoing erosion. Consequently, the method is developed from this exposure and then tested on sites  
 177 from the Perachora Peninsula.

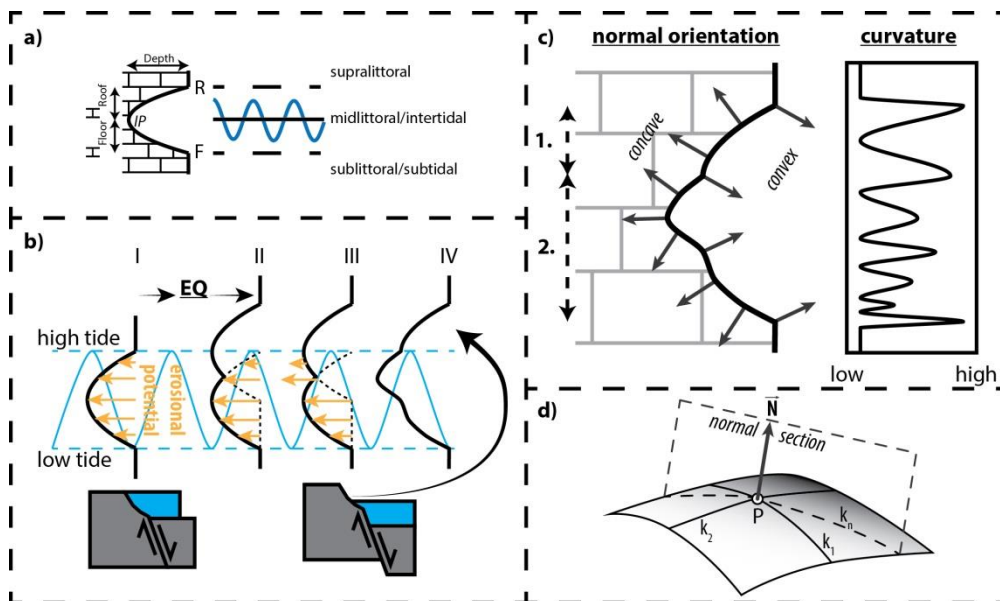
178 3.1 Theoretical assumptions

179 The term tidal notch refers to a horizontal erosion feature formed at sea-level due to coeval action  
 180 (Antonioli et al., 2015) of chemical, physical, and biological factors (Pirazzoli, 1986). However, the  
 181 predominant agent is commonly assumed to be bioerosion (Evelpidou et al., 2012), which is restricted  
 182 to carbonate rocks. Well-defined vegetational belts are the result of different grazing or boring  
 183 organisms each living in individual horizontal galleries. Therefore, Pirazzoli (1986) suggested a vertical  
 184 zonation (Fig. 3a) for notches, which also indicates maximum erosional potential at mean sea-level  
 185 (Fig. 3b). Moreover, the classical symmetrical notch profile (e.g. Laborel et al., 1999; Trenhaile, 2015)

186 is formed of three main sections (Fig. 3): I) A floor or base which extends to the limit of permanent  
 187 immersion at tidal low stand; II) a retreat zone of maximum concavity exhibiting the inflection point  
 188 near mean sea-level, and III) a roof near high tide level.

189 In an area of extensional tectonics, such as the Gulf of Corinth, the ratio of footwall uplift to hanging-  
 190 wall subsidence is estimated to 1/4 to 1/2 where the total net slip is not likely to exceed ~2 m, since  
 191 normal faulting structures usually do not produce earthquakes >  $M$  7.0 (e.g. Jackson et al., 1982;  
 192 Stewart and Vita-Finzi, 1996; Papanikolaou et al., 2010). Offshore, but close to the coast, normal  
 193 faulting seismic activity causes rapid emergence of coastal cliffs; however, coseismic uplift exceeding  
 194 the tidal range of ~0.4 m is unlikely since it would require minimum mean displacements of  $1.6 \pm 0.4$  m  
 195 (based on Wells and Coppersmith, 1994; for  $M$  6.5–7.0 empirical maximum displacements range from  
 196 0.8 to 2.1 m) which are unrealistic values of surface faulting for the vast majority of normal faulting  
 197 earthquakes. Thus, the former and new erosional zone along the cliff would overlap, overprinting the  
 198 earlier notch (Fig. 3b). Pirazzoli (1986) labels features of this origin as ‘ripple notches’. However,  
 199 depending on the time and vertical displacement, the resulting shape is tantamount to a widened  
 200 single notch; due to the tidal range variation. Only at close range minor variations will be detectable  
 201 on the surface curvature and normal to the orientation of the roof (Fig. 3c).

202



203

204 Fig. 3. Theoretic assumptions. a) Zonation of a simplified tidal notch (R, roof; F, floor; IP, inflection  
 205 Point) following suggestions of Pirazzoli (1986). b) Evenly distributed erosional potential pointing at  
 206 mean sea-level causes a symmetrical shape of a tidal notch (I). When the erosional zone gets offset by  
 207 an earthquake (II–IV), the level-based erosional potential attacks the prior to this created cliff  
 208 morphology (III). The resulting shape comprising two notch generations (1 and 2) exhibits patterns of  
 209 convex or concave curvature (c). d) Visualisation of the estimate of the normal vector (N) at any point  
 210 (P) along a normal section from principal curvatures  $k_1$  and  $k_2$ .

211

212 3.2 TLS

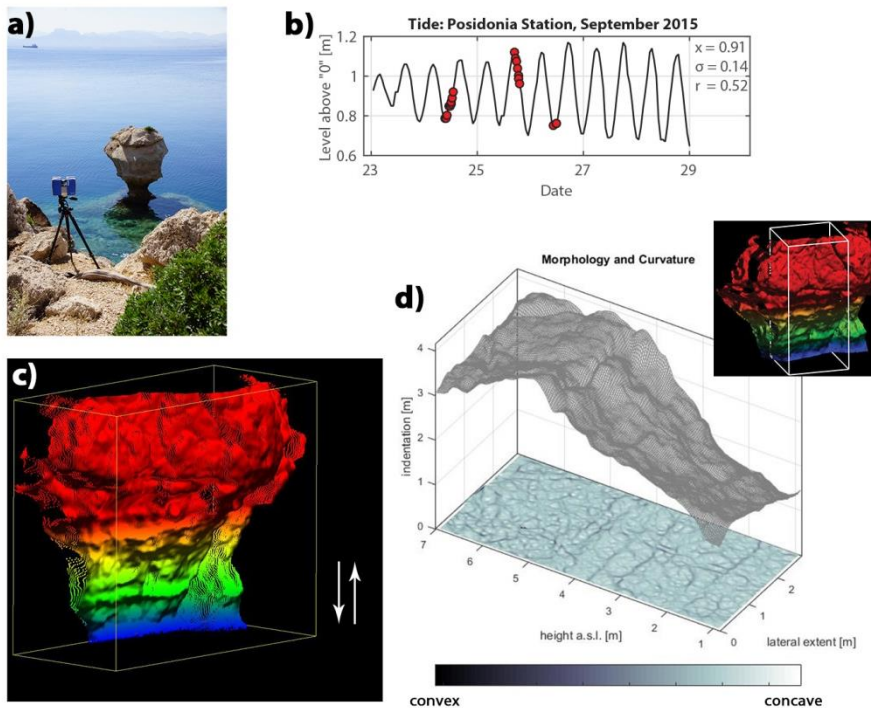


213 Terrestrial laser scanning (TLS) is a commonly used remote sensing technique with a high spatial and  
214 temporal resolution and is highly effective for reconstructing morphology (Wilkinson et al., 2015),  
215 interpreting trenches and outcrops (Schneiderwind et al., 2016), monitoring movements (Rosser et al.,  
216 2013), extracting slip vectors (Jones et al., 2009), and recording smoothness along fault planes (Wiatr  
217 et al., 2015).

218 The fundamental principle underlying TLS is rapid measurement of one-dimensional distances using a  
219 model-specific wavelength within the electromagnetic spectrum. A coherent laser beam with little  
220 divergence propagates dominantly in a well-defined direction and is reflected off surfaces, forming a  
221 non-contact and non-penetrative active and stationary recording system. Most common are systems  
222 that make use of the time-of-flight principle, where the instrument measures the time delay between  
223 emission, reflection and receiving the laser pulse. Phase-based TLS bypass the requirement of a high-  
224 precision clock by modulating the power of the laser beam and measuring the phase difference  
225 between the emitted and received waveforms (Smith, 2015). The result is an irregular but dense point  
226 cloud ( $x,y,z$  coordinates) representing a highly detailed digital 3D surface model. In both systems, the  
227 data quality is controlled by the range between sensor and target, surface properties (e.g. moisture,  
228 roughness), and also the angle of incidence.

229 In this study we used a time-of-flight mode operating Optech ILRIS 3D system for scans collected on  
230 Crete and a Faro Focus 3D system (phase-based mode) during the survey in central Greece due to  
231 logistical constraints. All scans were undertaken during calm sea conditions and from close-range to  
232 mid-range (max. 100 m). In order to correlate the data from multiple sites at the Perachora Peninsula,  
233 hourly tide gauge data from the Posidonia station (Hellenic Navy Hydrographic Service) was applied to  
234 the individual point clouds referenced to mean sea-level (Fig. 4).

235



236

237 Fig. 4. Data acquisition and processing. a) Close- to mid-range laser scanning. b) Tide gauge data  
238 provided by the Hellenic Navy Hydrographic Service ( $x$  = mean sea-level,  $\sigma$  = standard deviation,  $r$  =

239 tidal range) from the moment of scanning (red dots). c) High resolution point cloud data adjusted to  
240 mean sea-level using the tide gauge data as a reference datum. d) Segments prepared for surface  
241 curvature analysis (d). Extraction of two-dimensional information about the surface curvature reduces  
242 error sources from interpreting 3D surfaces.

243

244 Once the point clouds are corrected for their individual spatial information, principal curvature analysis  
245 is performed. In general, curvature is the second derivative of a function  $f(x)$  and describes the amount  
246 by which a geometric object differs from being flat. Depending on the sign, the object is either convex  
247 or concave at any point  $P$ , and the surface normal  $\vec{N}$  is oriented perpendicular to the surface towards  
248 maximum curvature. The magnitude  $k$  of difference from a flat object is quantitatively described by:

249 
$$k = \frac{f''(x)}{[1+(f'(x))^2]^{\frac{3}{2}}} \quad (1)$$

250 The mean curvature at a point on a third dimension uses both the maximum and minimum normal  
251 curvatures. These principal curvatures are orientated mutually perpendicular with  $k_1 > k_2$  (Fig. 3d).  
252 However, since tidal notches are a horizontal sea-level marker, only the vertical principal curvature is  
253 respected for the analysis. Moreover, the minimum curvature  $k_2$  highlights exclusively convex patterns  
254 corresponding to features such as the roof of a tidal notch. This automatically excludes sources of  
255 misinterpretation (e.g. joints or cracks) and focuses on horizontal differences (Fig. 4d).

256 To calculate the surface curvature, TLS data provides surface information with  $x$ ,  $y$ ,  $z$  coordinates,  
257 where the  $z$ -coordinate describes the lateral indentation value. To sharpen the principal curvature  
258 information, standard averaging and 2D median filtering are applied.

259

### 260 *3.3 Edge detection*

261 The curvature defines a parameter essential for curve sketching. However, this value does not have a  
262 primary link to neighbourhood relationships. Indeed, the curvature at any point is calculated from the  
263 adjacent points but it does not quantify geometric alignments, such as straight edges, and the  
264 curvature of neighbouring pixels is not compared. Therefore, methods of edge detection are applied  
265 which aim to identify points where abrupt changes and discontinuities in the surface curvature occur.  
266 Furthermore, the process reduces the curvature plot to its significant details that appear as convex  
267 objects.

268

#### 269 *3.3.1 Canny method*

270 Edge detection is an integral part of many computer vision systems and multiscale image analysis. The  
271 method results in a dramatic reduction of processed data, while preserving structural information  
272 about object boundaries (Canny, 1986). In general, an image contains edges where the gradients along  
273 the  $x$ - or  $y$ -axis show rapid changes in image intensity. For instance, the transition from black to white  
274 (which equals the values of 0 and 255 in an 8-bit array) within just two pixel cells depicts a sharp edge  
275 with the highest possible gradient. Ideally, the result is a binary image that only contains information

276 about edges within the initial intensity image. To decide whether an edge is located at a certain part  
277 of the image, one of the following criteria has to be fulfilled:

- 278 a) The first derivative of the intensity is larger in magnitude than a given threshold; or
- 279 b) The second derivative of the intensity has a zero-crossing (i.e. where the intensity of the image  
280 changes rapidly or the first derivative changes sign).

281 The built-in Matlab™ edge function provides several estimators that implement these rules.  
282 Furthermore, sensitivity for horizontal over vertical edges can be applied. The Canny edge detector  
283 has become standard in edge detection by defining two thresholds for strong and weak edges,  
284 respectively. Technically, the algorithm applies a Gaussian noise reduction and a non-maximum  
285 suppression to eliminate multiple responses. Edges classified as weak only persist in the resulting  
286 binary image when these are connected to strong edges. Therefore, the three criteria of edge  
287 detection (good detection, good localization, and low spurious response) are addressed (Canny, 1986;  
288 Bao et al., 2005).

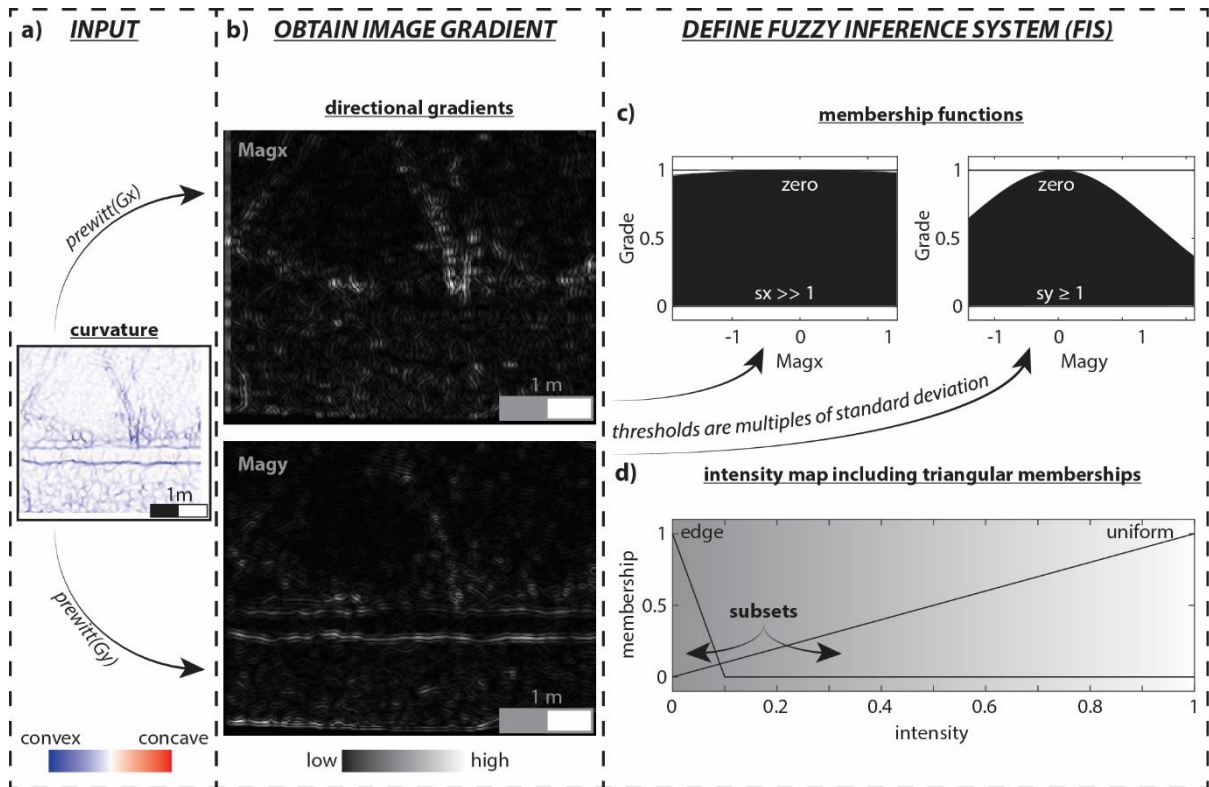
289

### 290 3.3.2 Fuzzy logic

291 Zadeh (1965) described a fuzzy set as a class of objects without a precisely defined criterion of  
292 membership. Within a fuzzy set each object is assigned to a grade of membership ranging between  
293 zero and one. Hence, approaches for decision-making (Bellman and Zadeh, 1970) and cluster analysis  
294 (Bezdek and Harris, 1978) were developed. Translated to edge detection from surface curvature the  
295 Fuzzy logic approach allows the use of membership functions to define the degree at which a pixel  
296 belongs to a convex edge or a different region. This is also the essential statement defining the  
297 membership function. Therefrom, other than from the Canny edge detector, the result is an intensity  
298 image and not a binary type. Consequently, edge detection and recognition still belongs to the user  
299 and is not the result of any blackbox approach securing transparency in the process.

300 Edge detection using Fuzzy logic comprises three steps. Firstly, directional gradients ( $G_x$ ,  $G_y$ ) and  
301 gradient magnitudes ( $Mag_x$ ,  $Mag_y$ ) serve as input information for a fuzzy set and have to be obtained  
302 from the curvature plot using the Prewitt gradient operator (Fig. 5). The Prewitt operator is a standard  
303 edge detection algorithm that accurately highlights vertical or horizontal alignments (Zhang et al.,  
304 2013) (Fig. 5b). Secondly, a fuzzy inference system (FIS) specifies a zero-mean Gaussian membership  
305 function for each input where the range of directional magnitudes depicts the limiting range values  
306 (Fig. 5c). If the gradient value is zero the pixel belongs to the zero membership function of grade 1. The  
307 grade along function quantifies the degree of membership of a certain element to the fuzzy set. In  
308 order to adjust the sensitivity of edge detection, multiples of standard deviation ( $s_x$ ,  $s_y$ ) of both zero  
309 membership inputs control the edge detector performance. Because of the high resolution of TLS data  
310 and dense point cloud, those values should be  $>1$  to decrease sensitivity for areas of minor interest  
311 (e.g. small cracks or joints). Furthermore, defining  $s_x \gg 1$  encompasses the majority of plan curvature  
312 within the zero-membership function and thus excludes those from analysis. Therefore, a triangular  
313 membership function is specified for the output intensity image. Start, peak, and end of the triangles  
314 influence the intensity of the detected edges and can be adjusted as required to improve edge  
315 detection performance.

316



317

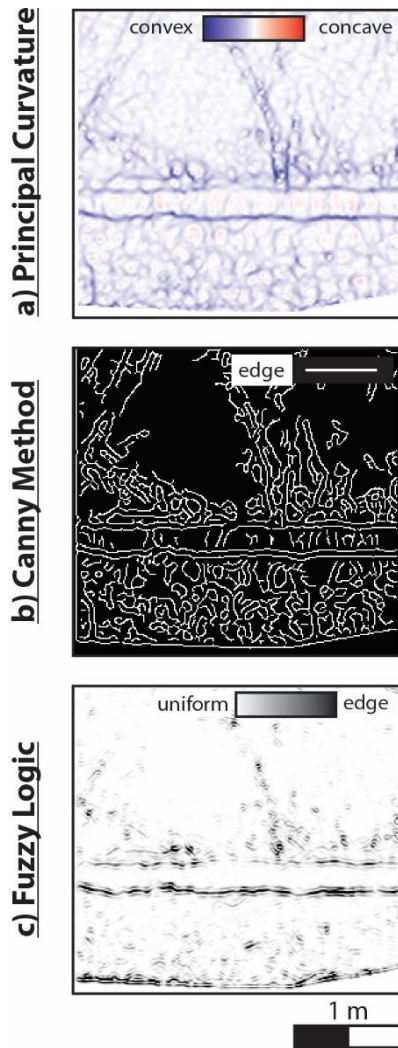
318 Fig. 5. Fuzzy set edge detection. Edge detection is performed on principal curvature images (a). Two-  
 319 dimensional gradients (b) are individually addressed in defined membership functions (c). The intensity  
 320 map (d) shows subsets of different memberships. White pixels belong to a uniform region; only very  
 321 dark pixels represent detected edges (Fig. 6c).

322 The third step of edge detection from Fuzzy logic includes rule specification and evaluation of the FIS.  
 323 For classification of the intensity map, two rules are necessary which access three simple principles of  
 324 set theory (If-then, AND, OR):

- 325 - If  $\text{Mag}_x$  is zero and  $\text{Mag}_y$  is zero then intensity is white
- 326 - If  $\text{Mag}_x$  is not zero or  $\text{Mag}_y$  is not zero then intensity is black

327 By this formulation a pixel of gradient different from zero depicts black and belongs to an edge (Fig.  
 328 6). Furthermore, the gradient is defined to be zero by Gaussian membership functions and forms the  
 329 input for the applied FIS.

330



331

332 Fig. 6. Comparison of applied analyses. a) Principal curvature depicting a high resolution image of the  
 333 cliff morphology. b) Edge detection after Canny. It is successful in notch detection but also highlights  
 334 small edges of minor interest. c) Edge detection from Fuzzy logic, highlighting rapidly changing  
 335 gradients in a horizontal manner.

336

### 337 3.4 Hough transform

338 The Hough transform is a popular tool for feature detection due to its robustness to noise (Fernandes  
 339 and Oliveira, 2008). The technique aims to find imperfect instances of objects representing line  
 340 features by a voting procedure. For this procedure image objects are compared to the parametric term  
 341 of a straight line. For some technical reasons, it is proposed to use its Hesse normal form since vertical  
 342 lines would give rise to unbounded values of the slope (Duda and Hart, 1972):

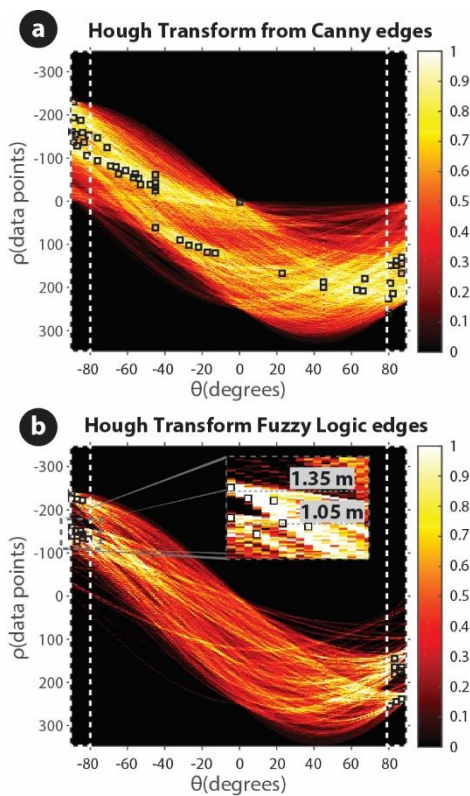
$$343 \quad \rho = x \cos \theta + y \sin \theta \quad (2)$$

344 where the variable  $\rho$  is the distance from the origin (0,0) to the line along a vector perpendicular to  
 345 the line, and  $\vartheta$  is the angle between the  $x$ -axis and this vector with a range of  $-90^\circ < \vartheta < 90^\circ$ . Thus, the  
 346 gradient of a line feature is the tangent of  $90 - \vartheta$ . The result of the Hough transformation is a parameter  
 347 space matrix comprising  $\rho$  and  $\vartheta$  vectors for each pixel  $(x, y)$ , where the algorithm determines evidence

348 of a straight line with respect to neighbouring pixels. Furthermore, it depicts a voting map [0 1]  
349 representing the discretised parameter space of detected objects (Fernandes and Oliveira, 2008). Local  
350 maxima (peaks) in this map represent parameters ( $\rho$ ,  $\vartheta$ ) of the most likely lines that can be extracted.

351 Since the Matlab™ Hough function requires a binary image input, the intensity map from Fuzzy Logic  
352 edge detection is converted using a global image threshold (Otsu, 1979). Beside that, line segment  
353 extraction from the Hough transform follows the same workflow for both data sets from edge  
354 detection (Canny Method and Fuzzy Logic) (Fig. 7). After the Hough transform is computed, peak values  
355 in the voting map are identified, where the user specifies the number of peaks to identify and thus,  
356 controls the influence of minor objects.

357



358

359 Fig. 7. Hough transform from detected edges. Dashed areas indicate potential line features with  
360 absolute  $\vartheta > 80^\circ$ . Due to its sensitivity, extracted line segments from Canny edge detector (a)  
361 are more spread and randomly orientated than from Fuzzy Logic edge detection (b). Peaks in the normalised  
362 voting map (squares) represent parameters for most likely lines. Zoom indicates to peak cluster of  
363 almost horizontal oriented line features corresponding to elevations of the notch's roof and floor,  
364 respectively.

365

## 366 4. Results

### 367 4.1. Developing methods, Agios Pavlos, Crete

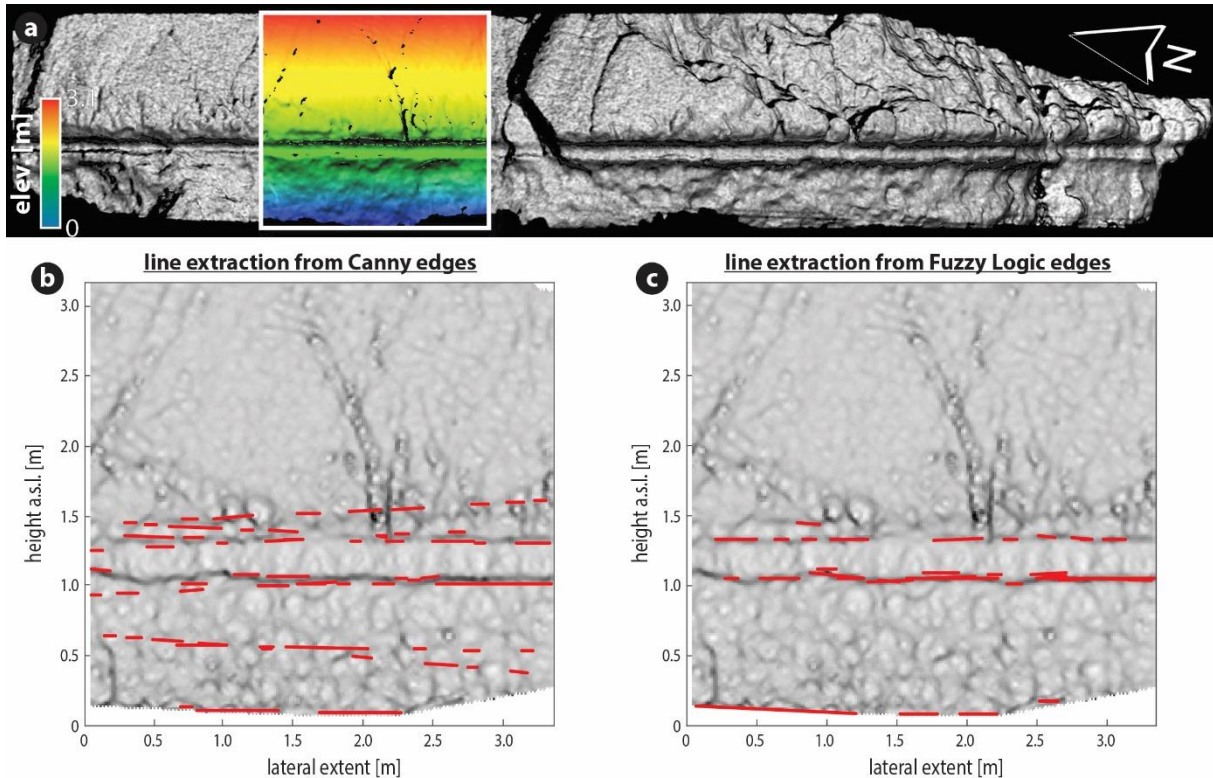
368 The workflow was developed utilising curvature analysis, edge detection using a Canny algorithm, a  
369 Fuzzy logic approach, and Hough line extraction on laser scan data from Agios Pavlos. The principal  
370 curvature analysis clearly highlights convex patterns (Fig. 6a) as expected from theoretical assumptions

371 (Fig. 3). The prominent strandline is obviously defined by an evenly convex roof and floor. However,  
372 not only horizontal asperities resulting from erosion at sea-level are registered. In order to reduce the  
373 image information and to focus on almost horizontal and continuous features, two individual edge  
374 detection approaches were applied. The conventional Canny edge detector predicts sharp changes in  
375 surface curvature suitable for the roof and the floor of the notch. Furthermore, minor morphological  
376 irregularities are ignored and not interpreted as a discontinuity. However, the algorithm does not  
377 sufficiently exclude information from plan curvature and consequently omits edges from features of  
378 minor interest, such as joints, cracks or weathering aspects (Fig. 6b). The Canny edge detector returns  
379 a bivalent set of uniform areas and edges and thus, does not differ for gradual irregularities within the  
380 subset "edge". Consequently, only the predominant horizontal orientation of edges detected at the  
381 extents of the notch is evidence for its existence. The membership functions of the Fuzzy logic  
382 approach allow outputs of quasi-probabilistic edge occurrence (Fig. 6c). This means detected edges,  
383 which are almost the same as from the Canny detector, are ranked towards the grade of conformance  
384 with formulated rules. Furthermore, focus is complied with horizontal features reducing image  
385 information once more towards the recognition of sea-level marker.

386 The Hough transform returns a matrix of a discretised parameter space displayed as a graph of line  
387 feature distance from the origin ( $\rho$ ) against line feature deviation from vertical ( $\vartheta$ ). Fig. 7 contrasts the  
388 resulting matrices from Canny edges with edges determined from Fuzzy logic. It is obvious that peaks  
389 and hot spots representing accumulations of  $\rho$ ,  $\vartheta$ -pairs are wider spread when Canny edges determine  
390 the input for Hough transform. Especially from  $\vartheta$ -values distributed edge orientations are confirmed  
391 (see also Fig. 6b). However, for almost horizontal line features the corresponding absolute  $\vartheta$ -value  
392 should be  $> 80^\circ$ , since it represents the normal vector orientation. When edges determined from the  
393 Fuzzy logic approach are input for the Hough transform the resulting peaks are clustered at highest  $\vartheta$ -  
394 values. Furthermore, hot spots are clearly separated from each other and enable correlation to  
395 corresponding heights in the laser scan (Fig. 7b). Peaks located at minimum or maximum  $\rho$ -values  
396 correspond to the upper or lower image extent. The laser scan at Agios Pavlos shows some minor wave  
397 action resulting in a lack of data in the lower part of the cliff section and causing detected edges and  
398 determined line features in this region (Fig. 8).

399 When comparing the results of line feature determination from different inputs, it is conspicuous how  
400 spread peaks in the parameter space influence the focus on distinct morphological features. Line  
401 structures extracted from Canny edges do not represent the roof and floor of the notch exclusively.  
402 Lines following edges from generic irregularities, such as those from weathering in the lower parts, are  
403 also extracted. Indeed, features with  $\vartheta$ -values  $< 80^\circ$  can be suppressed in the plot (see Fig. 8b) but this  
404 still does not provide a threshold for distinct features. Due to the membership functions of the Fuzzy  
405 logic approach gradual distinction of edge detection enables adjustment of such thresholds. As a result,  
406 only the notch at  $\sim 1.2$  m is highlighted (Fig. 8c). Therefore, it seems the identification of tidal notch  
407 morphologies on coastal cliffs is possible.

408



409

410 Fig. 8. Feature extraction from scan of the cliff at Agios Pavlos. a) Overall result. b) Extracted line objects  
 411 from Canny edges. c) Objects from Fuzzy logic edge detection representing the sea-level marker more  
 412 concentrated along the notch extent line.

413

414 *4.2. Testing methods, Perachora Peninsula, eastern Gulf of Corinth*

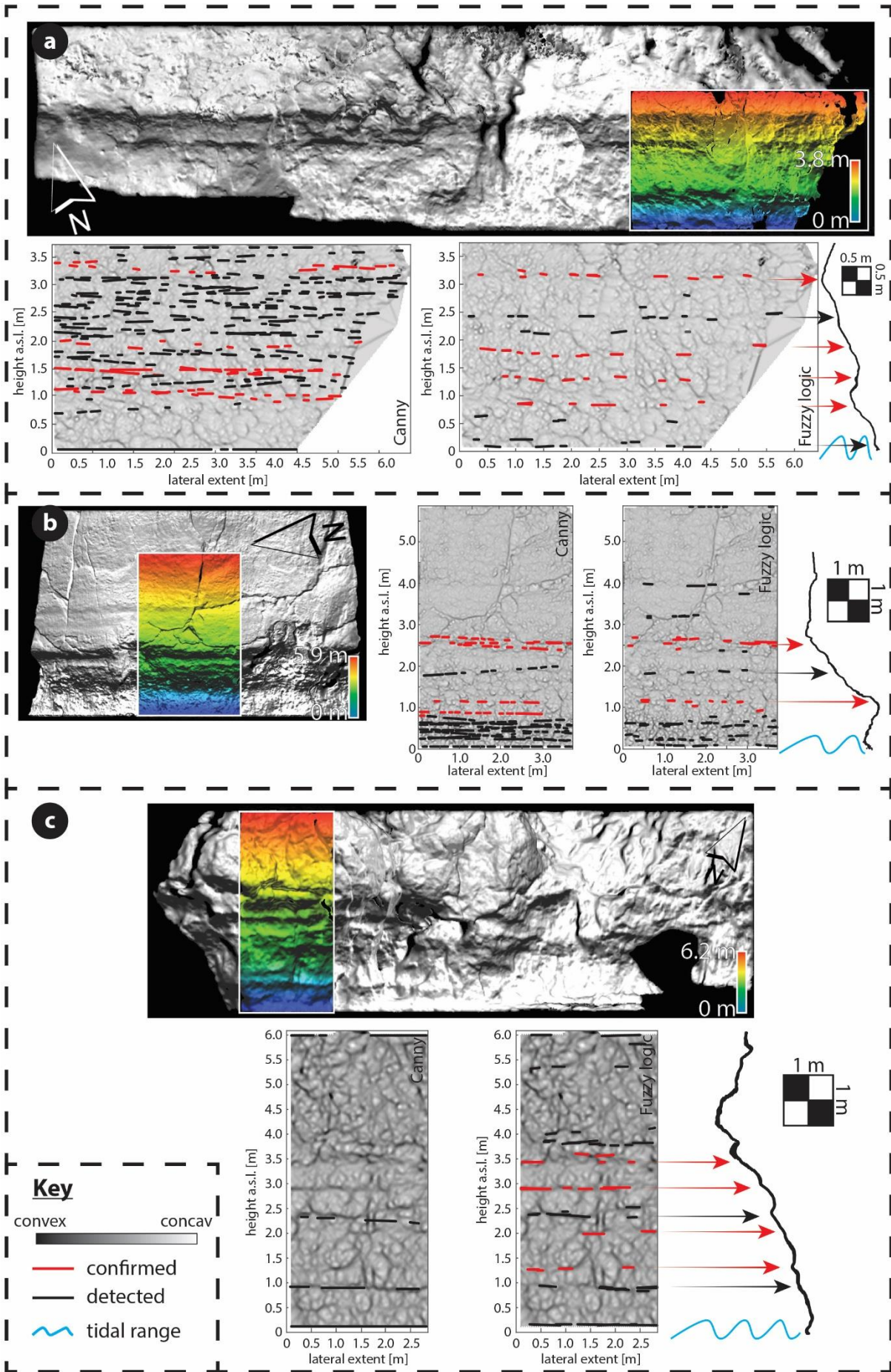
415 The entire workflow was tested at different sites along the coast of the Perachora Peninsula. This  
 416 setting has been extensively studied due to the 1981 earthquake sequence that attracted several  
 417 research groups, and Holocene tidal notches have been described. Kershaw and Guo (2001) recognised  
 418 five different notch generations ( $\sim 2.7$ ,  $\sim 2$ ,  $\sim 1.2$ ,  $\sim 0.4$ , and  $0$  m) at Mylokopy Bay (see Fig. 1b). Laser  
 419 scan data, covering an area of almost  $6.5 \times 3.8$  m of the cliff, was processed for curvature analysis. Line  
 420 feature extraction from Hough transformation confirmed evidence for all five levels (Fig. 9a).  
 421 Obviously, edges from the Canny detector result in many more line features across the scan than from  
 422 the Fuzzy logic approach. Canny edges produce line structures almost evenly spread from  $\sim +1$  m up to  
 423 the top of the scan window. Only insignificant line features are determined for the lower most part of  
 424 the scan data. A confirmation of published indentations is only possible because of their known  
 425 extents. Furthermore, the recently developing notch is only evidenced by Fuzzy logic edges. Thus,  
 426 Canny edges indicate remnants of tidal notches but are accompanied by noise which is the result of  
 427 morphological structures of minor significance. Due to the significant number of extracted lines from  
 428 Canny edges it is hard to identify distinct levels. Also, line orientation is predominantly not horizontal  
 429 but showing slight inclined trends although only features of  $\vartheta > 80^\circ$  are considered. Structures from  
 430 Fuzzy logic edges appear much more horizontal. It is noticeable that even Fuzzy logic edge detection  
 431 method produces line features of considerable length that do not belong to any of the published notch  
 432 morphologies, yet are located between two published notch levels ( $+2.4$  m).



433 Similar results can be noticed for both sites at Heraion. Kershaw and Gou (2001) identified two notches  
434 at the southern part of the Harbour and correlated them to four notches determined by Pirazzoli et al.  
435 (1994). The output for both sites supports the potential of tidal notch detection from Fuzzy logic edges.  
436 Lower parts at the Heraion harbour site are significantly rougher than from the rest of the scan and  
437 produce line structures without significant cluster levels. A horizontal and convex morphology  $\sim 2$  m  
438 a.s.l. evidences the remnant of a notch roof (Fig. 9b). Its remains are poorly preserved and only a few  
439 line features are extracted from Fuzzy logic edges. However, a conventional 2D profile supports its  
440 existence. A notch at +1.8 m in between both published notches might represent a so far unrecognised  
441 earthquake event.

442 At the cliff beneath the lighthouse, Canny edges only produce poor results (Fig. 9c). There is only one  
443 evidence for a notch provided as a line feature at  $\sim 1$  m. This feature matches to a convex edge that  
444 might represent the roof of a so far unpublished notch just below the lowermost notch identified by  
445 Pirazzoli et al. (1994) at +1.1 m (see also Fig. 1d). It is worth noting that the roof corresponding to the  
446 notch at +1.1 m was missed by the Canny algorithm. Contrastingly, Fuzzy logic edges provide evidence  
447 for the roofs (+3.5, +3.0, +2.0, and +1.3 m) of all four published notches at corresponding heights  
448 (inferred mean sea-levels at  $\sim 3.2$ ,  $\sim 2.6$ ,  $\sim 1.7$ , and  $\sim 1.1$  m). However, there is also evidence for a further  
449 notch roof at  $\sim 2.4$  m in between two recognised notch horizons. This evidence is supported by both  
450 edge inputs following same parameters in the Hough transform and the 2D profile (Fig. 9c).

451



453 Fig. 9. Results of testing methods along coast of the Perachora Peninsula. The locations of investigated  
454 data in each scan are indicated colourising the height levels. Published notches are provided and  
455 correlated to the results of line extraction at Mylokopy bay (a), Heraion harbour site (b), and Heraion  
456 Lighthouse site (c). Red arrows indicate the position of the roof of known notches. Black arrows point  
457 at morphological characteristics that could correspond to new notches.

458

## 459 5. Discussion and concluding remarks

460 TLS is a commonly used technique for morphological purposes (e.g. Rosser et al., 2014; Wilkinson et  
461 al., 2015). Due to its flexibility, quality, and accuracy, the resulting data highlights even minor evidence  
462 of spatial peculiarities. In this study, the detailed examination of tidal notches preserved owing to  
463 tectonic activity and coastal uplift has been undertaken. Thereby, uplift values in the order of a few  
464 decimetres are expected in extensional settings (Papanikolaou et al., 2010) and therefore, a high  
465 spatial resolution is required and this is offered by the TLS. Furthermore, a mesoscale downward  
466 widening of pre-existing tidal notches is likely. The former notch floor as well as biological markers,  
467 such as *Lithophaga* agents, could be overprinted by the newer tidal notch generation. Thus minor but  
468 horizontally consistent changes in the surfaces' curvature might be evidence for sea-level indicators  
469 that were eroded along their lower extent over time, or did not have enough time to develop because  
470 of short recurrence intervals between uplift events. Thereby, the local tidal amplitude (here: 0.2 m)  
471 forms the resolution limit. Traditional profiling with tape measures or laser distance meter (Kázmér  
472 and Taboroši, 2012) aims to identify tidal notches from a digital copy of the vertical cliff topography.  
473 When corrected for sea-level datum, information about elevation and notch dimensions can be  
474 inferred. This includes both horizontal and vertical extent per feature (Pirazzoli, 1986). Multiple profiles  
475 can only be correlated when referring to the same datum. However, spatial variations in cliff  
476 topography of closely positioned sites are hard to verify from horizontally stacked 2D profiles, as a  
477 consequence of bedrock heterogeneity, local variations of wave action, and/or fault movements  
478 (Kershaw and Guo, 2001). Utilising TLS measurements in notch studies presents the opportunity to  
479 collect high resolution spatial data from exposures (even from distance) in a rectified manner, which  
480 is not possible using conventional tape measurement or photogrammetry and SfM approaches (Bini et  
481 al., 2014). Even submerged notches down to 0.8 m are not excluded from TSL surveys when using  
482 systems operating at the green-wavelength (Smith, 2015).

483 The presented workflow aims to detect the roof and/or floor of raised tidal notches by reducing spatial  
484 information and focussing on horizontal continuities. Convex patterns, pointing towards the sea, pose  
485 evidence for remnants of tidal notches (see Fig. 3). The principal curvature analysis highlights such  
486 patterns but does not link those to the attributes of two-dimensional orientation or continuity.  
487 However, the magnitude of curvature can be utilised to describe significant morphological changes.  
488 Such information is input data for edge detection analysis. Herein, two methods of edge detection  
489 were tested in order to reduce spatial information towards its varying significance. In computer vision  
490 and image processing, the Canny edge detector algorithm depicts a standard operator (Bao et al.,  
491 2005) for tracking ridges in gradient magnitude images (Canny, 1986). A disadvantage of this method  
492 is that all extracted edges appear to have the same significance (see Fig. 6b). Thus, edges in areas of  
493 minor interest and oriented both vertically and horizontally, appear the same as those of relevance for  
494 tidal notch detection. Therefore, a Fuzzy logic sequence was constructed comprising of membership  
495 functions that enable exclusive focus on significant horizontal changes in surface curvature. Even if the

496 input information is incomplete or imprecise, the approach outputs predominantly continuous and  
497 horizontally oriented structures. Instead of crisp boundaries between two classes (e.g. edge or  
498 uniform), the membership functions are defined to give probabilistic information on edge existence  
499 (see Fig. 6c). However, resulting edge information from both algorithms were individually used as input  
500 data for the final Hough transform, which intends to extract continuous line features. Missing points  
501 on the desired curves as well as spatial variations between the ideal line and the noise edge points are  
502 the result of imperfections in either the image data or the applied edge detection algorithm. The Hough  
503 transform produces discrete parameter space matrices of the spatial data in which voting peaks  
504 indicate a continuous line object. Furthermore, minor restrictions to the objects orientation yield in  
505 spatial matching of identified lines and tidal notch extents (see Fig. 8). The ability to adjust the edge  
506 detection algorithm for individual requirements, using a Fuzzy logic approach appears to be more  
507 reliable for highlighting notch morphologies than the Canny edge detection. Due to the possibility of  
508 excluding plan changing curvature and defining membership grades, the line objects extracted from  
509 Fuzzy logic edge detection is most suitable.

510 As mentioned above edge detection and line object extraction target remnants of raised notches, such  
511 as their roof and/or floor. This should not be confused with the aims of traditional cliff profiling. Here,  
512 the depth of a notch is not analysed and thus the outcome does not allow any conclusion on the  
513 developing period as a function of the erosion rate. Only the vertical extent is measurable if the notch  
514 is completely preserved. In Agios Pavlos, it is possible to obtain estimates of the tidal range ( $\sim 0.35 \pm$   
515  $0.05$  m) which are consistent with estimates from Evelopidou et al. (2012). However, assuming a  
516 constant local tidal range throughout the Holocene allows the projection of the historic mean sea-  
517 levels with half the erosive zone beneath the detected roof and half above the detected floor,  
518 respectively. Hence, historic sea-levels can be reconstructed although the majority of their  
519 morphological footprints in a coastal cliff are no longer existent. Furthermore, data collection via TLS  
520 enables the extraction of multiple traditional profiles easily for conventional analyses as well (see  
521 profiles in Fig. 1) and adds coherent information on the third dimension to address local  
522 heterogeneities. Therefore, traditional and presented approaches validate and complete each other  
523 from the same data base.

524 Palaeoseismological studies are frequently assisted by tidal notch investigations in areas of coastal  
525 tectonic activity (e.g. Kershaw and Guo, 2001). In particular, in extensional tectonic settings the  
526 footwall coastal uplift is not likely to exceed several decimetres (e.g. Papanikolaou et al., 2010).  
527 However, Pirazzoli et al. (1994) identified a series of four tidal notches of Holocene age at Heraion (Fig.  
528 1d), each displaced by repeated uplifts of about  $0.8 \pm 0.3$  m. Assuming a ratio of 1/4 net slip per event,  
529 this would equate to 4 m total offset in an area where Jackson et al. (1982) reported just minor  
530 coseismic uplift of 0.2 during the Alkyonides earthquake sequence ( $M$  6.4–6.7) in February and March  
531 1981. If evidence for remnants of tidal notches in between more distinct features are detected by using  
532 high resolution data in high performance algorithms, palaeomagnitude estimates get more realistic.  
533 For instance, both Canny and Fuzzy logic edges provided evidence for notch roofs at +1.0 and +2.4 m  
534 at the cliff beneath the lighthouse, respectively. These positions fit in the idea of regular displacements  
535 during earthquakes and reduce mean notch offset yielding reliable values of coseismic uplift ( $0.5 \pm 0.2$   
536 m per event). A second example is obtained at Mylokopy. Including additional notch roofs ( $\sim 0.6$ ,  $\sim 1.3$ ,  
537 and  $\sim 2.25$  m) would result in repeated uplifts of about  $0.4 \pm 0.18$  m corresponding to magnitudes of  $M$   
538  $6.7 \pm 0.1$  in accordance with Wells and Coppersmith (1994). The results help to reconcile the  
539 discrepancy between the palaeoseismic record and the direct observations of co-seismic

540 displacements provided by Jackson et al. (1982). Minor but horizontally continuous remnants revealed  
541 by dense point cloud data are usually not validated in single 2D profiles. However, the identification of  
542 new notch levels would (partially) solve the paradox between large tectonic uplift values and plausible  
543 palaeomagnitudes.

544 The results show the possibility of tidal notch detection by curvature analysis and subsequent edge  
545 detection and line feature extraction. It is shown that morphologies accepted as tidal notches can be  
546 detected by reducing high resolution point cloud data towards the principal curvature pointing at the  
547 roof or the floor of a notch, respectively (see Figs. 8c and 9b). Even evidence for previously unidentified  
548 structures are extracted from the data. As a consequence more realistic uplift values would result if  
549 these features get proven as remnants of tidal notches. The workflow enables the objective validation  
550 of observations along coastline by evaluating coastal cliffs in three dimensions. Therefore, reliable  
551 statements on coast uplifting earthquake events are possible. The variability of conventionally  
552 collected tidal notch profiles (Kershaw and Guo, 2001) is circumvented by instant 3D data collection in  
553 high resolution and applied spatial analytics. Furthermore, the semi-automated workflow provides fast  
554 results once adjusted for individual needs. The benefits are as follows:

- 555 - Enhanced objectivity in recognising tidal notch morphologies on cliff faces.
- 556 - More insights from high-resolution 3D TLS by recognising undiscovered notches or features  
557 corresponding to multiple notches.
- 558 - Valuable information on morphological characteristics even of only minor distinction and their  
559 spatial distribution especially in extensional tectonic settings, where coseismic uplift is much  
560 less than in compressional environments.

561 However, data quality and thus the reliability of the outcome remain dependent on the preservation  
562 of individual tidal notches on a coastal cliff. Sheltered sites in microtidal seas provide perfect conditions  
563 for tidal notch preservation after emergence whereas inhomogeneous and disturbed cliffs exposed to  
564 the open sea (Pirazzoli, 1986) are not likely to be good archives of Holocene earthquake events.  
565 Furthermore, varying bedrock consistency or the presence of bedding planes may yield in the  
566 formation of minor structural notches. Especially when the bedding is horizontally oriented,  
567 misinterpretation by remote morphological analysis cannot be neglected (Kershaw and Guo, 2001).  
568 This implies that along coast a natural variance of tidal notches masked by surf processes and  
569 inhomogeneities yields different results of tidal notch identification. Therefore, careful site selection  
570 for palaeo-shoreline identification should consider constraints of marine attacks, tectonic influences  
571 on- and offshore and coastal geology. In order to consider such local lateral variations, 3D data  
572 acquisition helps to reduce sources of misinterpretation. Therefore, we show that TLS combined with  
573 up to date post-processing edge analyses can form a rigorous and useful approach to the interpretation  
574 of palaeoseismic records from Holocene tidal notches.

575

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583

584

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