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# The evolution of Santa Maria Island in the context of the Azores Triple Junction

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## Abstract

Santa Maria is the oldest island in the Azores, formerly belonging to the Eurasia plate and currently the only one sitting on the Nubia Plate, thus sharing a geodynamic evolution with the Azores Triple Junction. It is therefore important to evaluate the effects of active tectonics on the evolution of Santa Maria, for example on its vertical movements. We present new stratigraphic, geomorphologic, structural and geochronological data from Santa Maria which shed further light on how a volcanic ocean island evolves in a tectonically active setting. Santa Maria island started with a first shield volcano (Old Volcanic Complex) that emerged ca. 6.0 Ma ago and was active until ca. 5.3 Ma. The short time span between the first and second shield volcanoes (ca. 0.3 Ma) and the preservation of only the western flank of this first shield volcano indicate an initial flank collapse at ca. 5 Ma. The collapse scar was covered by an eastwards dipping sedimentary complex (Intermediate Sedimentary Complex), with a likely tsunami deposit at the base. A second shield volcano (Young Volcanic Complex) rapidly grew on these

25 sediments from 4.8 to 3.8 Ma, and the island subsided by more than 100 m. At 3.7 Ma, a second  
26 flank collapse occurred, as inferred from the missing summit and eastern flank. Volcanism then  
27 resumed (3.6 to 2.8 Ma), giving rise to Strombolian cones lying unconformably on the collapse  
28 scar, and conformable parasitic cones on the unaffected flank. Submarine lavas occurring at up  
29 to 200 m altitude with a youngest age of 3.0 Ma indicate major uplift of the island since, at most,  
30 that time. Here we interpret uplift as the result of rift flank uplift on the southern shoulder of the  
31 nearby Terceira Rift in the last ca. 1.5 Ma.

32

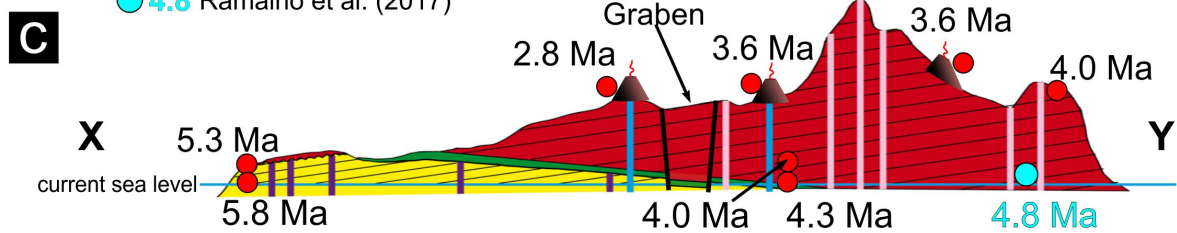
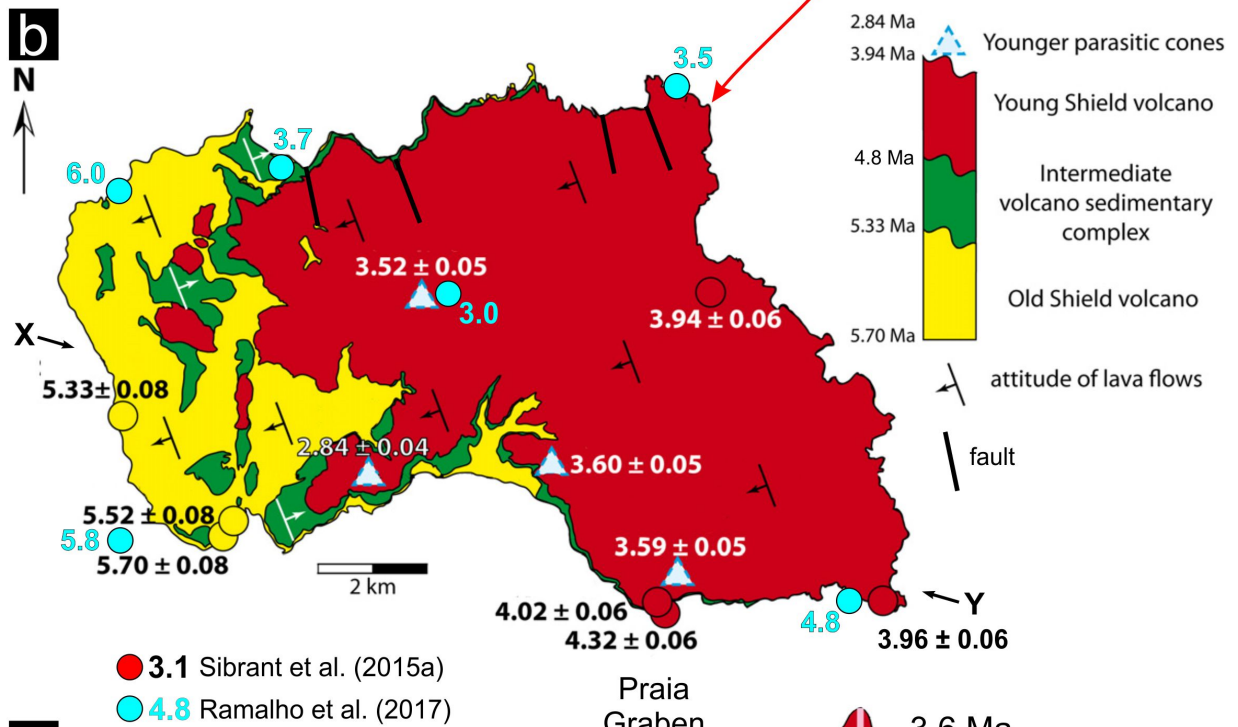
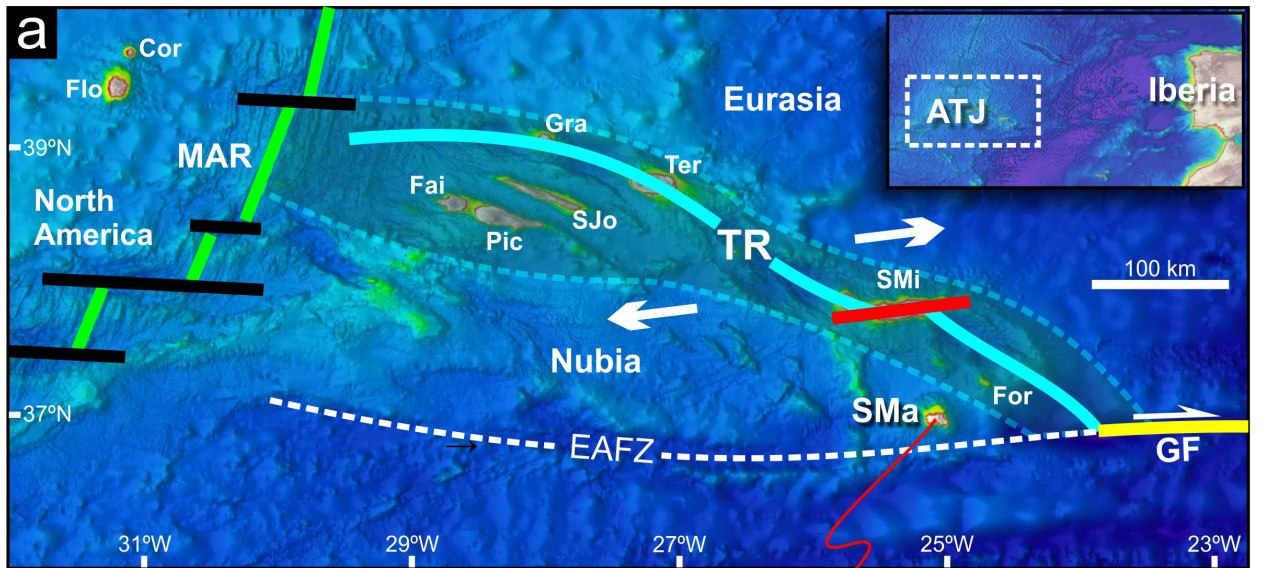
33 *Keywords:* Santa Maria Island; Azores Triple Junction; large-scale mass wasting; flank collapse;  
34 island subsidence and uplift; age fossils

35

## 36 **1. Introduction**

37 An outstanding problem in volcanic ocean islands close to major plate boundaries is that  
38 of evaluating the effect of active tectonics on their evolution. This is particularly so when the  
39 island is small and is located in a changing geodynamic setting where the stress field has  
40 undergone major changes (Luís et al., 1994; Mitchell, 2003; Vogt and Jung, 2004; Sibrant et al.,  
41 2015a). Additionally, although many volcanic islands around the world record evidence of  
42 important vertical displacements, the rates and mechanisms of the associated movements are still  
43 debated (e.g. Cas and Wright, 1987; Jones, 1969; Jones and Nelson, 1970; Porebski and  
44 Gradzinski, 1990; Ramalho et al., 2010a, b, c, 2013, 2017; Marques et al., 2020).





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Figure 1. (a) – Tectonic setting of the Azores Triple Junction. MAR and TR (thick green and cyan lines) are the Mid-Atlantic ridge axis and the Terceira Rift, respectively. The light blue shaded area delimited by cyan dashed line marks the diffuse Nubia/Eurasia plate boundary in the Azores (Marques et al., 2013a). Azores islands from west to east: Flo – Flores; Cor – Corvo; Fai – Faial; Pic – Pico; SJo – S. Jorge; Gra – Graciosa; Ter – Terceira; SMI – S. Miguel; SMa – Santa Maria. For – Formigas islets. White arrows on opposite sides of the TR represent the plate velocities (ca.  $3.5 \pm 0.5$  mm/yr; Marques et al., 2013a). White half arrow indicates the

54 *dextral strike-slip motion in the Gloria Fault (GF). The East Azores Fracture Zone (EAFZ) is*  
55 *currently inactive, therefore Santa Maria belongs to the Nubia Plate. Black solid lines –*  
56 *transform faults related to the MAR. Red solid line – transform fault related to the TR.*  
57 *Background shaded relief from EMODnet portal (<https://www.emodnet-bathymetry.eu/>). (b) –*  
58 *Simplified geological map of Santa Maria Island adapted from Sibrant et al. (2015a), including*  
59 *previous relevant ages (Sibrant et al., 2015a; Ramalho et al., 2017). (c) – geological profile*  
60 *along X-Y in B showing the relationships between the main units, which includes the dip of the*  
61 *lava flows as measured in the field and inferred from the ages. Note the consistency between*  
62 *lava flow dip and younging to the west at sea level in the YVC on the southern coast.*  
63

64 Santa Maria is the easternmost island in the Azores, and lies close to the junction  
65 between the East Azores Fracture Zone, the Terceira Rift and the Gloria Fault (Fig. 1). Santa  
66 Maria has long been recognized as the oldest island in the Azores archipelago (e.g. Zbyszewski  
67 and Ferreira, 1960; Abdel-Monem et al., 1975; Sibrant et al., 2015a; Ramalho et al., 2017). It is  
68 also the only island with clear evidence of submarine volcanism well above current sea level  
69 (e.g. Serralheiro et al., 1987; Serralheiro and Madeira, 1993; Serralheiro, 2003), and is the island  
70 with the most complete marine fossil record (Madeira et al., 2007; Ávila et al., 2018). Santa  
71 Maria can be viewed as a reference in the investigation of marine erosion shelves in the Azores  
72 and elsewhere (Marques et al., 2016; Ricchi et al., 2018), and the analysis of the shelves in the  
73 context of the long-term evolution of Santa Maria is critical to the present study. Constraining  
74 the age of marine fossils is very important to our study because they provide information on  
75 where the sea was at a given age (palaeoshoreline markers), and so help in the analysis of the  
76 vertical movements (mostly subsidence during YVC growth). We thus carried out our study in  
77 Santa Maria for three reasons: First, the island has grown in a tectonic setting that has changed  
78 over its > 6 Ma lifetime, thus possibly recording important steps in the evolution of the Azores  
79 Triple Junction (ATJ). Second, the evolution of the island is still not well understood, with gaps  
80 in our knowledge especially regarding stratigraphy, structure and tectonics, as well as strain and  
81 stress evolution. In this regard, geochronological data is used to constrain the age of the different  
82 volcanic complexes, the age of the inferred large-scale mass wasting (LSMW), and the age of the

83 different fossil deposits. Third, it is a very small island, therefore seemingly not prone to LSMW  
84 (Mitchell, 2003; Hildenbrand et al., 2018), which is in apparent contradiction with the LSMW  
85 inferred in Santa Maria.

86 In order to answer the questions about the tectonic evolution of this volcanic island, we  
87 needed to: first establish a well-constrained volcanic stratigraphy, from which we could infer the  
88 evolution of the island and, in particular, the ages of the abundant fossil deposits In parallel with  
89 this, we needed to constrain the geometry of the major shield volcanoes and the position of the  
90 main feeding centres, from which we could infer the missing portions of the shield volcano,  
91 discuss the origin of the major unconformities in terms of marine/meteoric and LSMW types of  
92 erosion, and discuss ages and triggering mechanisms. Second, we needed to identify probable  
93 tsunami deposits, and young smaller-scale landslides that shaped the marine shelves to the east,  
94 south and west of Santa Maria, as well as to analyse Santa Maria's vertical movements and  
95 discuss their rates and mechanisms. Third, we needed to determine the orientation of the stress  
96 field from the observed deformation and dykes, and to discuss the relationship between the  
97 evolutions of Santa Maria and the ATJ. To accomplish these objectives, we analysed aerial  
98 images and digital elevation models for geomorphological and geological interpretations. This  
99 was accompanied by fieldwork to identify the major unconformities and volcanic units, and to  
100 find and measure faults and dykes. These data were used to unravel the geometry and position of  
101 the main volcanoes, and to find the critical palaeodepth markers (palaeoshorelines). Finally,  
102 sampling for high-precision K-Ar dating was carried out and used to calibrate the volcanic  
103 stratigraphy and to constrain fossil ages and critical palaeodepth markers. The present work  
104 builds on that of Marques et al. (2013b) and Sibrant et al. (2015a), by adding new field,  
105 geochronological and structural/tectonic data, which together made it possible to accomplish the  
106 objectives listed above.

107

## 108 **2. Geological setting**

109 Early geological mapping of Santa Maria (Agostinho, 1937; Zbyszewski and Ferreira,  
110 1960) distinguished two main volcanic units separated by a volcano-sedimentary complex. The  
111 abundant marine fossils allowed Zbyszewski and Ferreira (1960) to propose minimum and  
112 maximum ages for the older (pre-Vindobonian) and younger (post-Vindobonian) volcanic  
113 complexes, respectively (Vindobonian – ca. 16 to 7 Ma). Serralheiro et al. (1987) later  
114 introduced three additional units. As a result, the stratigraphy becomes, from the bottom up: (1)  
115 two very small and poorly outcropping formations, one submarine (Cabrestantes Formation) and  
116 the other sub-aerial (Porto Formation); (2) the sub-aerial Anjos Volcanic Complex; (3) a mixed  
117 sub-aerial and submarine volcano-sedimentary complex, the Touril Complex; (4) a submarine  
118 volcanic complex, the Facho Complex; (5) the mixed submarine and sub-aerial Pico Alto  
119 Complex; and (6) the Feteiras Formation, which is composed of sub-aerial Strombolian cones  
120 and widespread pyroclasts.

121 Based on the recognition of major unconformities and K-Ar dating, Sibrant et al. (2015a)  
122 identified three main units: the Older Shield Volcano (ca. 5.7 to 5.3 Ma, which corresponds to  
123 the Anjos Complex and includes the Cabrestantes and Porto formations of Serralheiro et al.,  
124 1987), the Intermediate volcano-sedimentary Complex (5.3 to 4.3 Ma, far from Vindobonian,  
125 which corresponds to the Touril Complex of Serralheiro et al., 1987), and the Younger Shield  
126 Volcano (ca. 4.3 to 2.8 Ma, which encompasses the Facho and Pico Alto complexes of  
127 Serralheiro et al., 1987) with parasitic Strombolian cones on top (which correspond to the  
128 Feteiras Formation of Serralheiro et al., 1987). Based on lava flow geometry, as well as the  
129 geometry and location of the two shield volcanoes, plus the nature and shape of the major  
130 unconformities, Marques et al. (2013b) and Sibrant et al. (2015a) inferred the existence of two  
131 large-scale flank collapses. The first occurred between ca. 5.3 and 4.3 Ma, and the second at ca.  
132 3.6 Ma. Ramalho et al. (2017) dated submarine rocks in SE Santa Maria at ca. 4.8 Ma (Fig. 1),

133 which constrains the volcanic stratigraphy, since it is the oldest age of the Younger Shield  
134 Volcano. The 4.8 Ma age thus narrows the age interval for the first flank collapse, which lies  
135 between the youngest age of the Older Shield Volcano and the oldest age of the Younger Shield  
136 Volcano.

137

### 138 **3. Methods**

139 We started with a morphological analysis of the island using a digital elevation model  
140 (DEM) with a spatial resolution of 10 m, in order to identify the main morpho-structural units  
141 and better define areas of interest for fieldwork. The DEM was produced from a digital  
142 topographic map of Santa Maria Island made by the Centro de Informação Geoespacial do  
143 Exército (CIGeoE), and the full process is described in Costa et al. (2014). Given that most of  
144 the outcrops are on the coast, we went around the island by boat to get a full picture of the main  
145 volcanic sequences and their first-order unconformities, faults and dykes. Field work was then  
146 carried out over the whole island on road cuts, quarries, and those sea cliffs accessible from the  
147 landward side. We systematically measured the attitude of lava flows, faults and dykes, and  
148 reconstructed the geometry of major unconformities (mostly landslide scars).

149 We measured 225 dykes, mostly on the coast, and plotted their dip and strike on graphs.  
150 We also used previous geological maps where dykes had been mapped in detail inland. In many  
151 dykes we also measured thickness and noted the number of dykes in multiple intrusions. We  
152 measured the attitude of 41 faults and striations mostly on the coast, and plotted them on graphs.  
153 When visible, we also measured fault striations and noted kinematic indicators for fault  
154 movement.

155 We took advantage of Santa Maria's high coastal cliffs to investigate and sample the base  
156 and top of lava flow piles. We collected many more samples than reported here and in Sibrant et  
157 al. (2015a). However, due to limited funding in our project only critical samples were dated to

158 complement the K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  ages acquired on separate phases in Santa Maria (Sibrant et  
159 al., 2015a; Ramalho et al., 2017). We focused on the oldest age and setting of the OVC (samples  
160 SMA16B, G and K; Fig. 2a for location) to better constrain the oldest stratigraphy and vertical  
161 displacements, as well as the age of the submarine YVC close to sedimentary deposits with  
162 marine fossils (sample SMA16O; Fig. 2a for location) to better constrain their age and the  
163 vertical displacements in Santa Maria. For a detailed description of the K-Ar method used in this  
164 study see Appendix 1 in the supplementary material.

165

## 166 **4. Results**

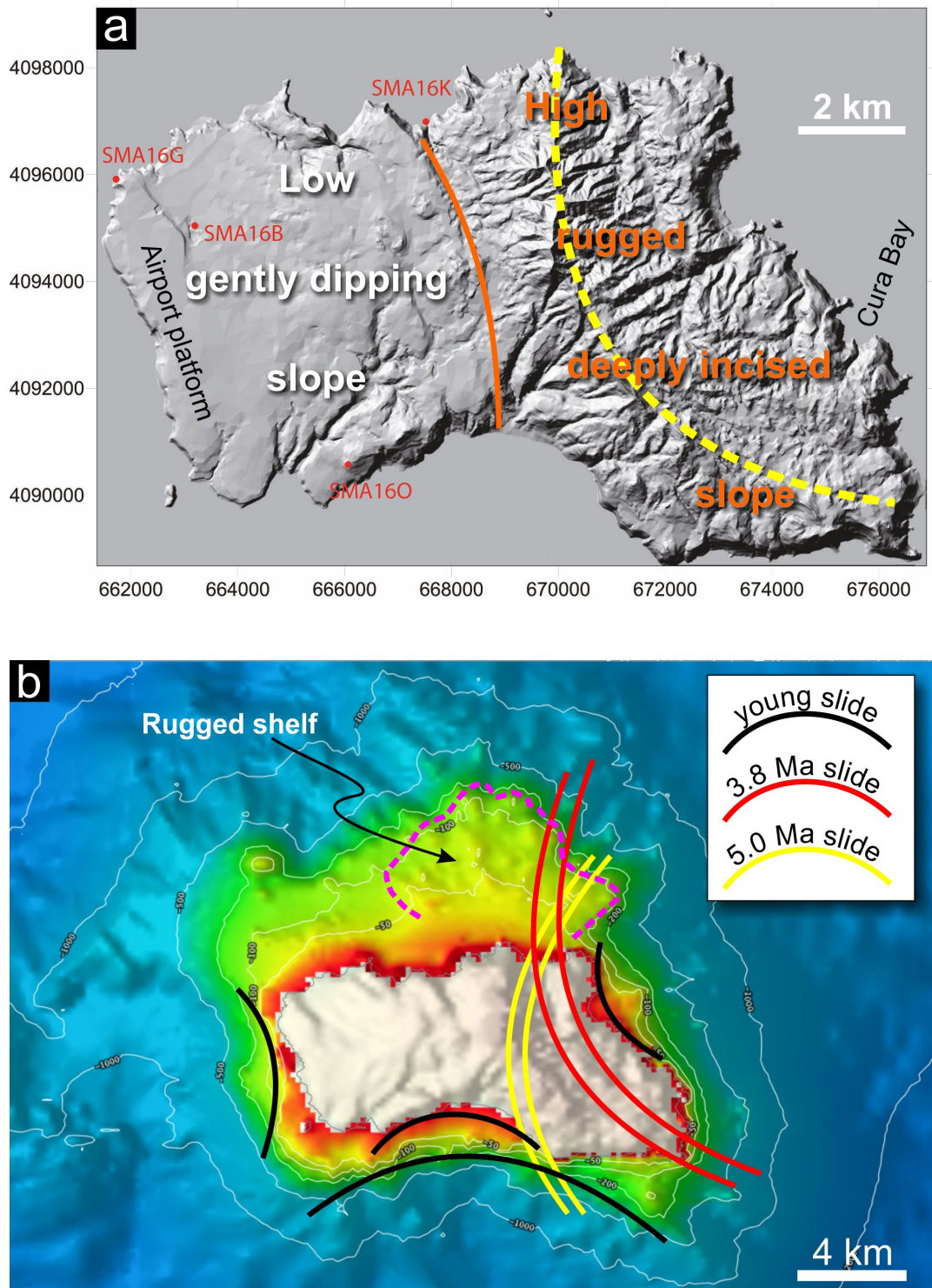
### 167 *4.1. Topography/bathymetry*

168 Morphologically, Santa Maria can be divided into two distinct parts (Fig. 2). The first is  
169 the low-lying western half, which is gently sloping to the west. This surface is most likely  
170 structural, as it generally follows the westward gentle dip of the OVC and YVC lava flows (Fig.  
171 S-1). The flat shelf on which the airport lies, close to the western coast, could be a palaeoshelf,  
172 as proposed by Ramalho et al. (2017). (2) The second part is the higher and more rugged eastern  
173 half of the island, whose highest peak is at an altitude of ca. 590 m and comprises a deeply  
174 eroded portion of the YVC. The divide between the two parts is rather sharp and arcuate, and  
175 concave to the east (Fig. 2).

176 In detail, there are other curved, concave seaward topographies that shape the coast line  
177 (Fig. 2b). These could well correspond to eroded scars of smaller scale landslides. Offshore,  
178 there is also a topographic asymmetry, with the marine shelf being much wider in northern Santa  
179 Maria than elsewhere around the island. The shelf edge to the north lies between ca. -120 m and  
180 -200 m, and extends up to 7 km offshore (Fig. 2b). In contrast, elsewhere around the island the  
181 edge of the marine shelf is at  $< -100$  m, locally even  $< -50$  m, and is much narrower ( $< 1.5$  km)  
182 (Fig. 2b). Ricchi et al. (2018) analysed in detail the marine shelf, and concluded that the spatial



183 distribution of marine terraces around Santa Maria depends on the complex interplay between  
 184 sea level fluctuations, vertical displacements, and the intensity of marine erosion.

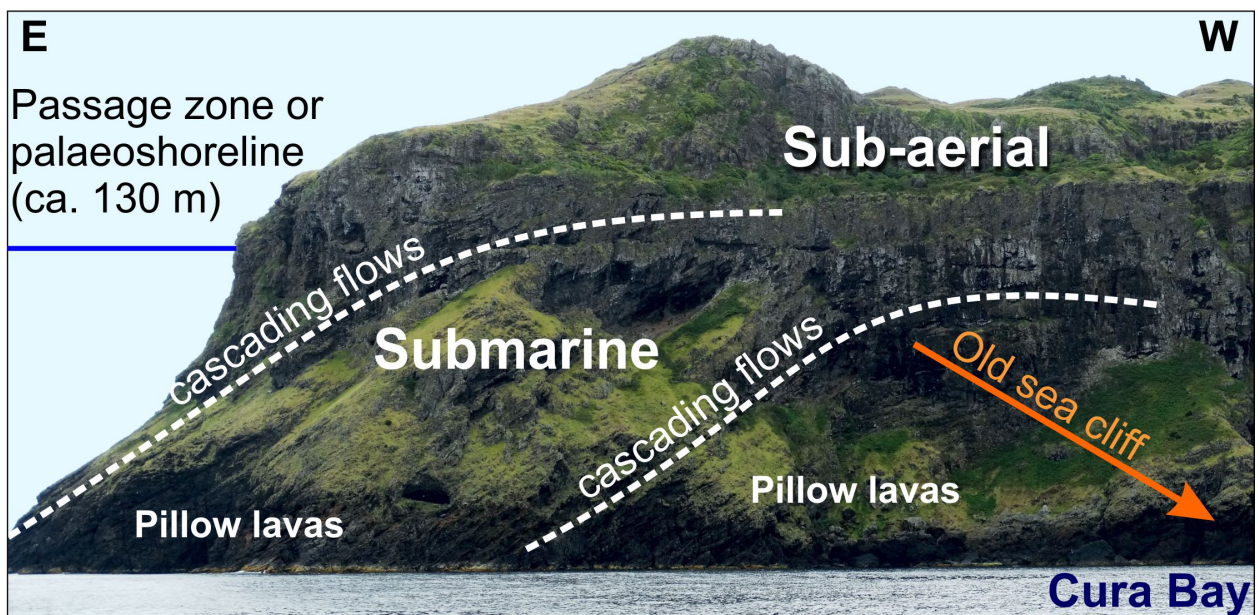


185  
 186 *Figure 2. Shaded relief maps to show the main features of the onshore (a) and offshore (b)*  
 187 *topography. (a) – the onshore shaded relief shows that the island is morphologically made up of*  
 188 *a low, westward gently dipping slope in the western half, and a high (590 m maximal altitude),*  
 189 *steep and deeply incised slope in the eastern half. Yellow dashed line marks the position of the*  
 190 *divide. (b) – position of here inferred young (black lines, small-scale slides partly destroying the*  
 191 *island and younger than 2 Ma), intermediate (red lines, large-scale slide partly destroying the*

192 island at ca. 3.8 Ma), and old (yellow lines, large-scale slide partly destroying the island at ca.  
193 5.0 Ma) landslides. Note that the coast where we infer young slides has very narrow shelves,  
194 despite the long-term erosion (> 3 Ma). Background shaded bathymetry from EMODnet portal  
195 (<https://www.emodnet-bathymetry.eu/>).  
196

#### 197 4.2. Field data

198 Critical to our objectives are: (1) the attitude of lava flows in the older and younger  
199 volcanic complexes (to constrain volcano geometry, and detect major unconformities and  
200 missing volcano flanks); (2) the composition and distribution of sediments in the sedimentary  
201 complex, and the geometry of its base (to detect landslide scars and tsunami deposits); (3) the  
202 original and current position of sub-aerial and submarine rocks (to analyse vertical  
203 displacements); (4) the distribution and attitude of dykes, and geometry and kinematics of faults  
204 (to infer stresses); and (5) the shape of the marine shelves (to detect recent collapses).



205  
206 *Figure 3. Photograph showing the geometry of lava flows at Baía do Cura in eastern Santa*  
207 *Maria (see Fig. 2a for location). From the geometry, we deduce that flows cover an old sea cliff*  
208 *to the west (orange arrow).*  
209

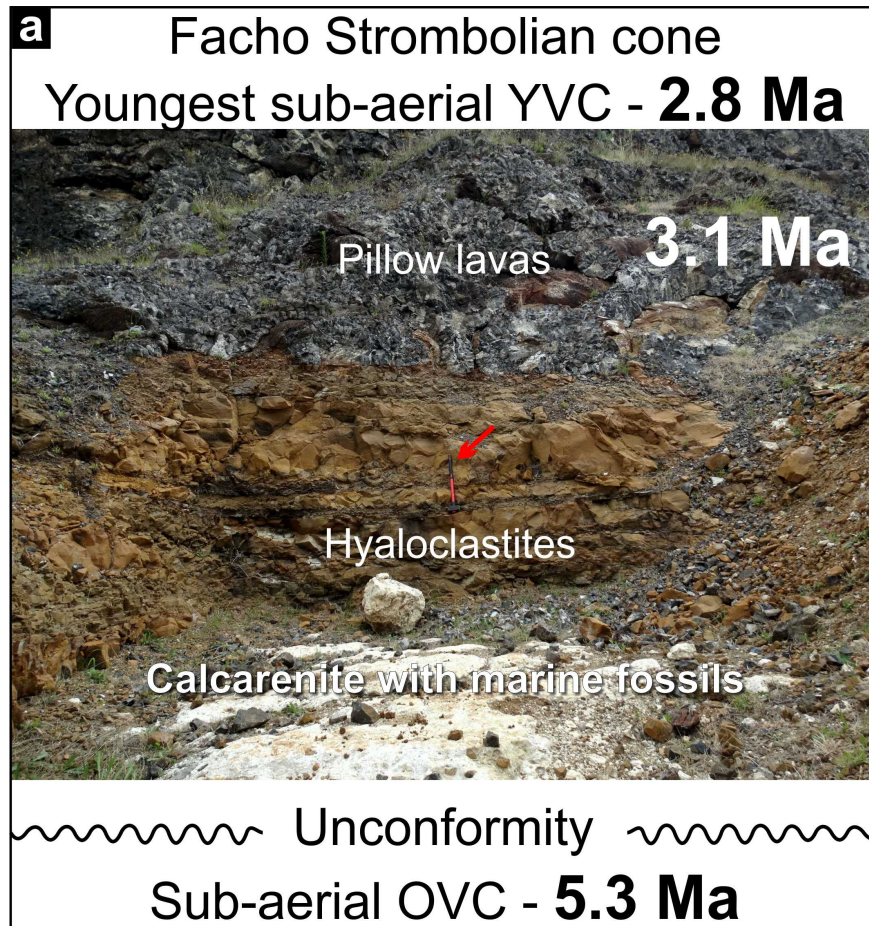
210 In an abandoned quarry NE of the north end of the airport runway (site of sample  
211 SM16B, Fig. 2a), the sub-aerial OVC overlies steeply eastward-dipping submarine flows  
212 intruded by dykes, which might correspond to an OVC passage zone (palaeoshoreline) or to the



213 basement complex. The OVC occupies the western half of Santa Maria, and the lava flows dip  
214 gently to the W or WSW (Fig. 2 and Fig. S-1). In contrast to the westerly dip in the OVC, the dip  
215 of the unconformity above the OVC is to the east. This unconformity is covered by the  
216 Intermediate Sedimentary Complex (ISC), which, at its base, shows chaotic conglomerates  
217 composed of polygenetic, large, poorly sorted and poorly rounded boulders (Serralheiro, 2003;  
218 this study). To the east, the ISC may pass into marine conglomerates. Towards the top, the  
219 sediments become finer and the carbonate component increases. Filling the space removed from  
220 the original OVC (east flank), and lying unconformably on the ISC, is the Young Volcanic  
221 Complex (YVC), which is initially composed of submarine lava flows, and later of sub-aerial  
222 lavas as the volcano emerged out of the ocean. Submarine and sub-aerial lava flows dip to the  
223 west all along the southern and northern Santa Maria coasts. Eastern Santa Maria has a great  
224 number of Strombolian cones, the lava flows of which dip gently to the east and west. On the  
225 eastern coast, passage zones (palaeoshorelines) occur where gently dipping sub-aerial flows pass  
226 into steeply dipping submarine flows (Fig. 3).

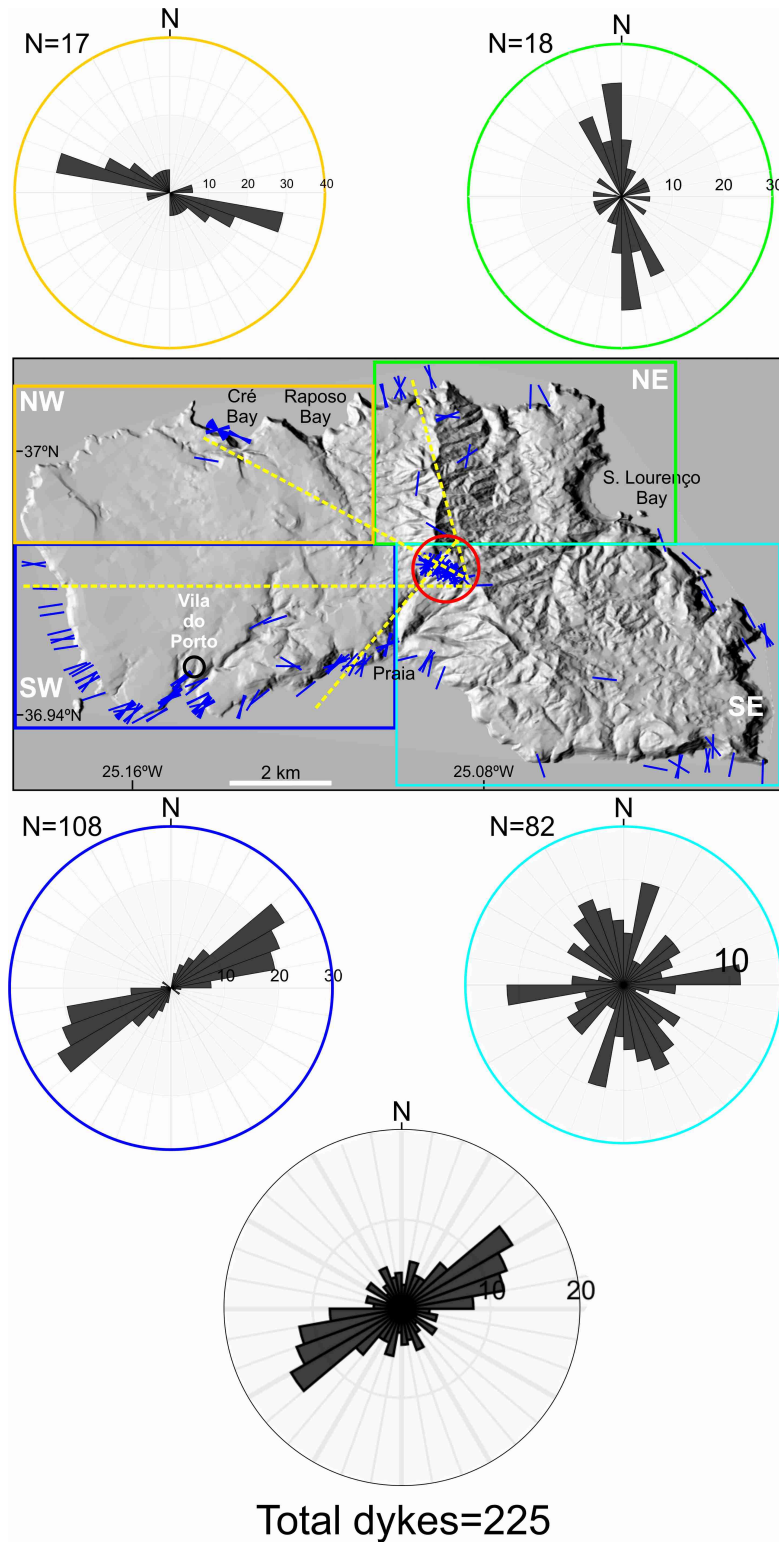
227         At Pedreira do Campo (site of sample SMA16O in Fig. 2a), the submarine YVC is seen  
228 to lie conformably on the fossiliferous marine ISC through hyaloclastites (Fig. 4), or perhaps  
229 with “*slight erosion prior to the deposition of the volcanic sequences above*” as recognised by  
230 Ramalho et al. (2017). From the nature of the contacts between marine sediments and underlying  
231 sub-aerial OVC (major unconformity covered with thick chaotic debris deposit), and the  
232 overlying submarine YVC (conformable with apparently similar marine environment), we infer  
233 that the age of the fossils is close to the age of the pillow lavas dated here (ca. 3.12 Ma).

234



235

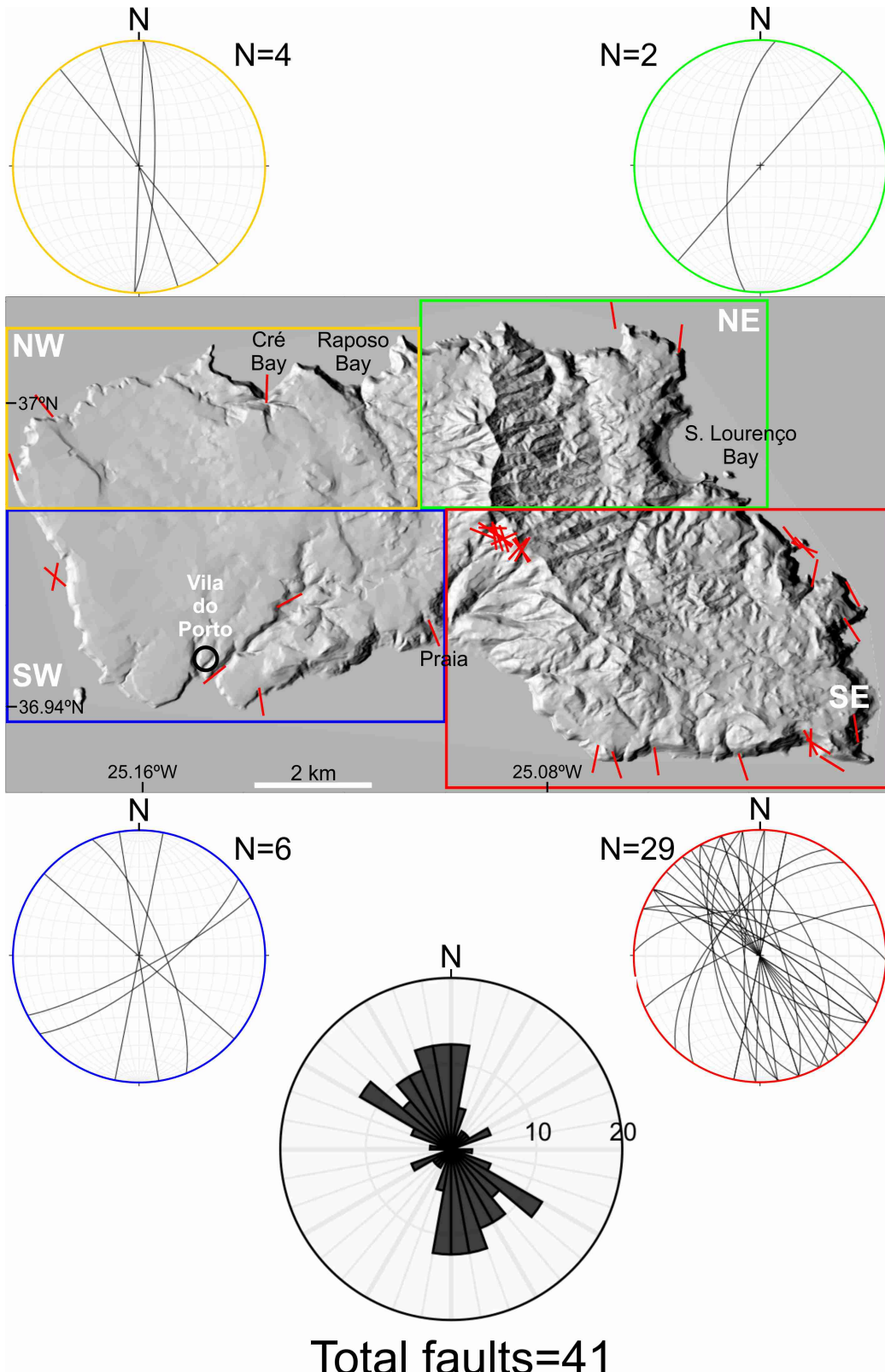
236 *Figure 4. Images of the outcrop at Pedreira do Campo, where we collected sample SMA160 (see*  
 237 *Fig. 2a for location). (a) – contact between pillow lavas, hyaloclastites and calcarenite with*  
 238 *marine fossils, all showing a marine setting of deposition. No appreciable unconformity, e.g.*  
 239 *erosion surface or angular unconformity, was observed in these outcrops. (b) – detail of*  
 240 *collected pillow lavas. Red arrow in (a) points to sledgehammer (ca. 1 m long handle) for scale.*  
 241 *Geologist on outcrop in (b) is 180 cm tall.*



242

243 *Figure 5. Distribution and attitude of dykes in Santa Maria (blue short lines), and statistics of*  
 244 *dyke attitude by quadrants (coloured stereoplots) and total (stereoplot at the bottom). Note that*  
 245 *dykes in the OVC (SW, NW and NE quadrants) converge to a small triangular area, marked with*  
 246 *a red circle.*  
 247





248

249 *Figure 6. Heterogeneous distribution of faults in Santa Maria. Compare with Fig. 5 for*  
 250 *relationships between dykes and faults.*

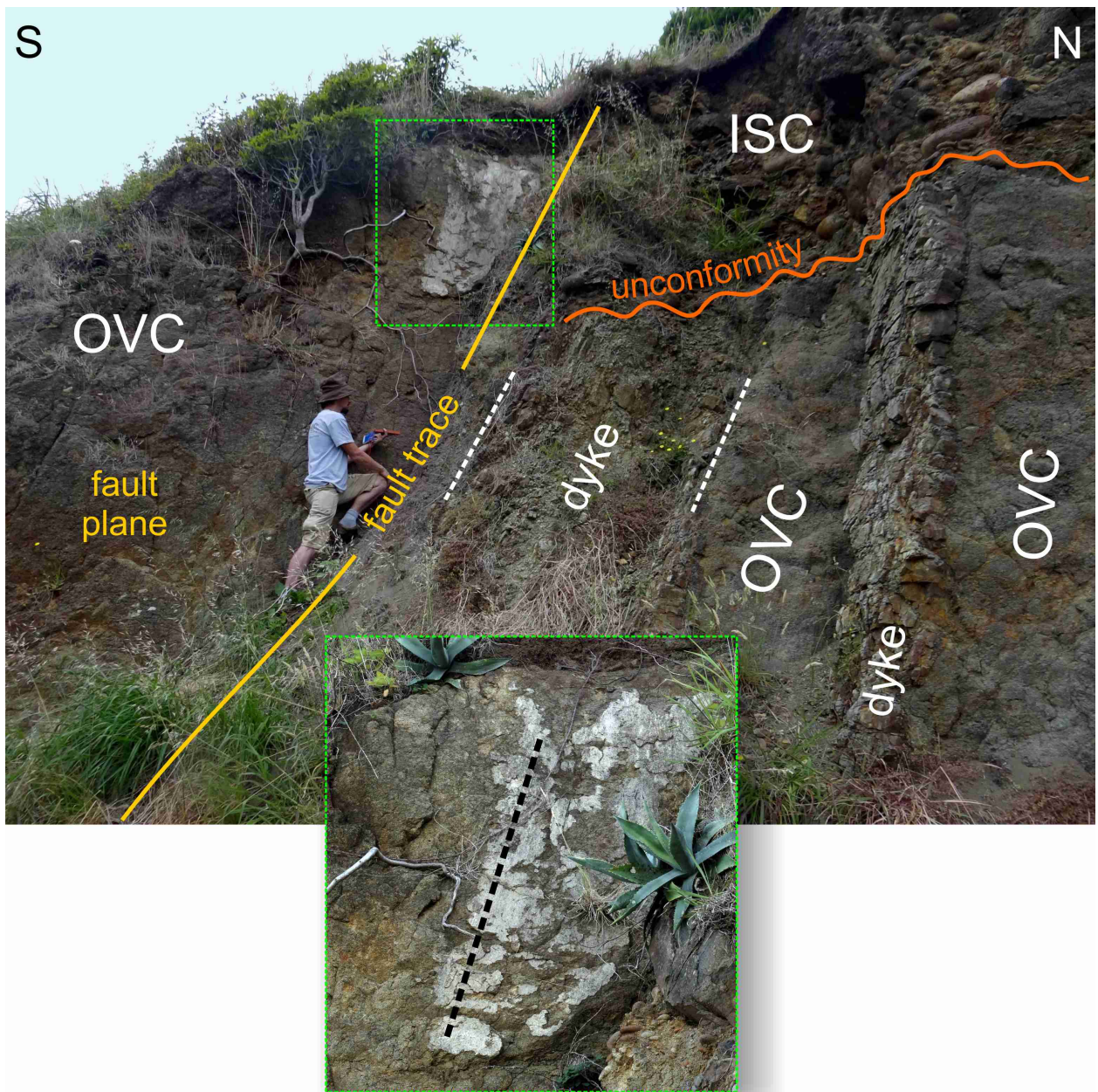
251

252 Dykes show a heterogeneous distribution around the island, with the greatest density of

253 dykes in the SW quadrant, and the least dykes in the NW quadrant. There is an overall dominant  
254 ENE-WSW trend to their orientation within the OVC, which is largely due to the dominant SW  
255 quadrant. Dykes older than the YVC are radial (cf. Fig. 5), and there is a convergence of these  
256 older dykes towards a triangular area (inside red circle in Fig. 5), which we infer to have been  
257 the approximate position of a major feeding centre for the OVC. A high concentration of dykes  
258 with different orientations can be observed within a very small area in the YVC (1-2 km<sup>2</sup>, inside  
259 red circle in Fig. 5), which we interpret as a main feeder for the YVC, which is coincident with  
260 the inferred main feeding centre for the OVC. In the southern YVC (i.e. over most of the SE  
261 quadrant where there is only YVC), the dykes show a generally scattered trend, but a NW to N  
262 main trend is apparent. In the northern YVC (i.e. over part of the NE quadrant on the coast and  
263 inland where there is only YVC), the young dykes trend mostly N-S to NNE-SSW. Young dykes  
264 in eastern Santa Maria have a dominantly curved pattern (concave eastward) in the YVC,  
265 gradually changing from NW-SE in the south to NNE-SSW in the north (Fig. S-3).

266         Faults have a heterogeneous distribution around the island (Fig. 6), with most faults  
267 outcropping in the SE quadrant, although the number of faults in the NE quadrant might be  
268 significantly underestimated (due to the poor outcrop conditions, even on the coast). There are  
269 many more faults in the eastern half of the island, which is dominated by the YVC, implying a  
270 heterogeneous distribution in both space and time. Faults have an overall dominant NNW-SSE  
271 trend (Fig. 6). Most of the observed tectonic faults have only small displacements (< 10 m), but a  
272 few have significant (> 50 m) displacements (Figs. 7, 8, S-5). These higher displacement faults  
273 trend mostly around NNW-SSE, and dip either to the east or to the west. The striations are dip-  
274 slip, or steeply plunging to north or south, thereby defining dominant normal faulting with a  
275 small strike-slip component (either dextral or sinistral). Two new pairs of conjugate faults have  
276 been identified that define, as named here, the Praia and Maia Grabens (Figs. 1c and 7). The  
277 Praia Graben in central Santa Maria is bounded to the west by an eastward-dipping fault (Fig. 7),

278 and to the east by a westward-dipping fault. This can be inferred from the different altitude of the  
279 base of the ISC in the graben (ca. 50 m) and on the eastern shoulder (ca. 85 m), where it should  
280 be at lower altitude given the east dip of the base of the ISC. The Maia Graben in eastern Santa  
281 Maria is bounded to the west by eastward-dipping faults (Fig. 8), and to the east by westward-  
282 dipping faults (Figs. S-4, 9 and 10). Note that the fault in Fig. 9 only affects the older YVC, but  
283 does not seem to cut through the ca. 3.6 Ma lava flows.

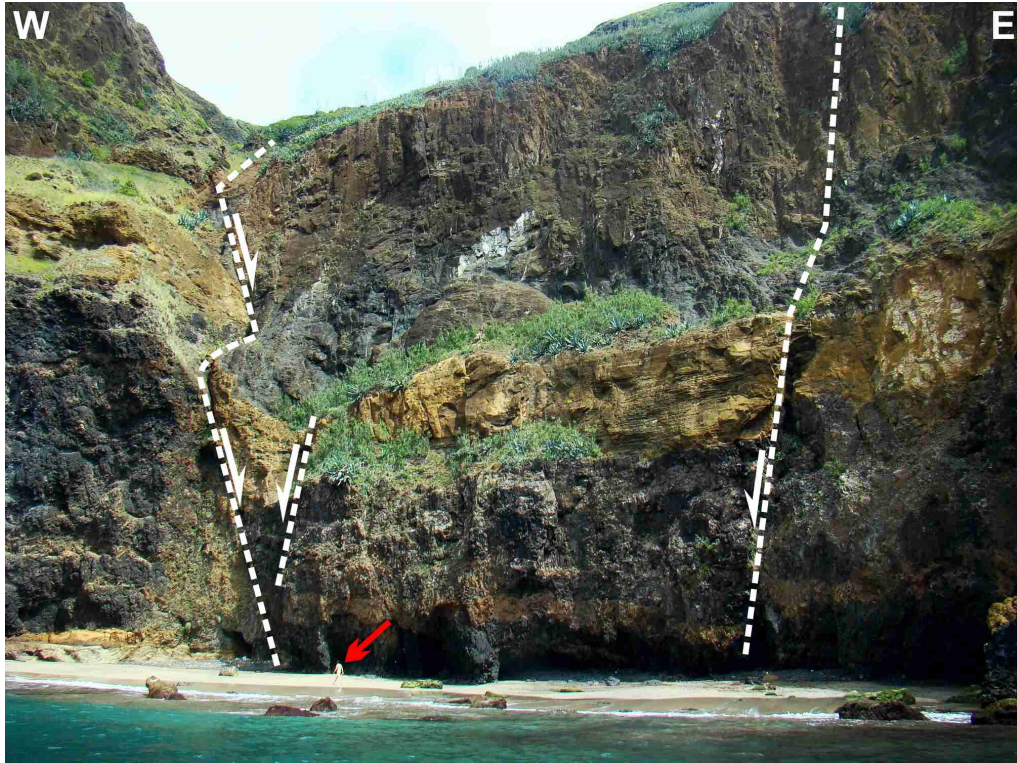


284

285 *Figure 7. Image of outcrop of the fault bounding the Praia Graben in the west. The fault strikes*  
286 *N158 and dips 70° toward the observer (ENE), and is normal dextral given the plunge of the*

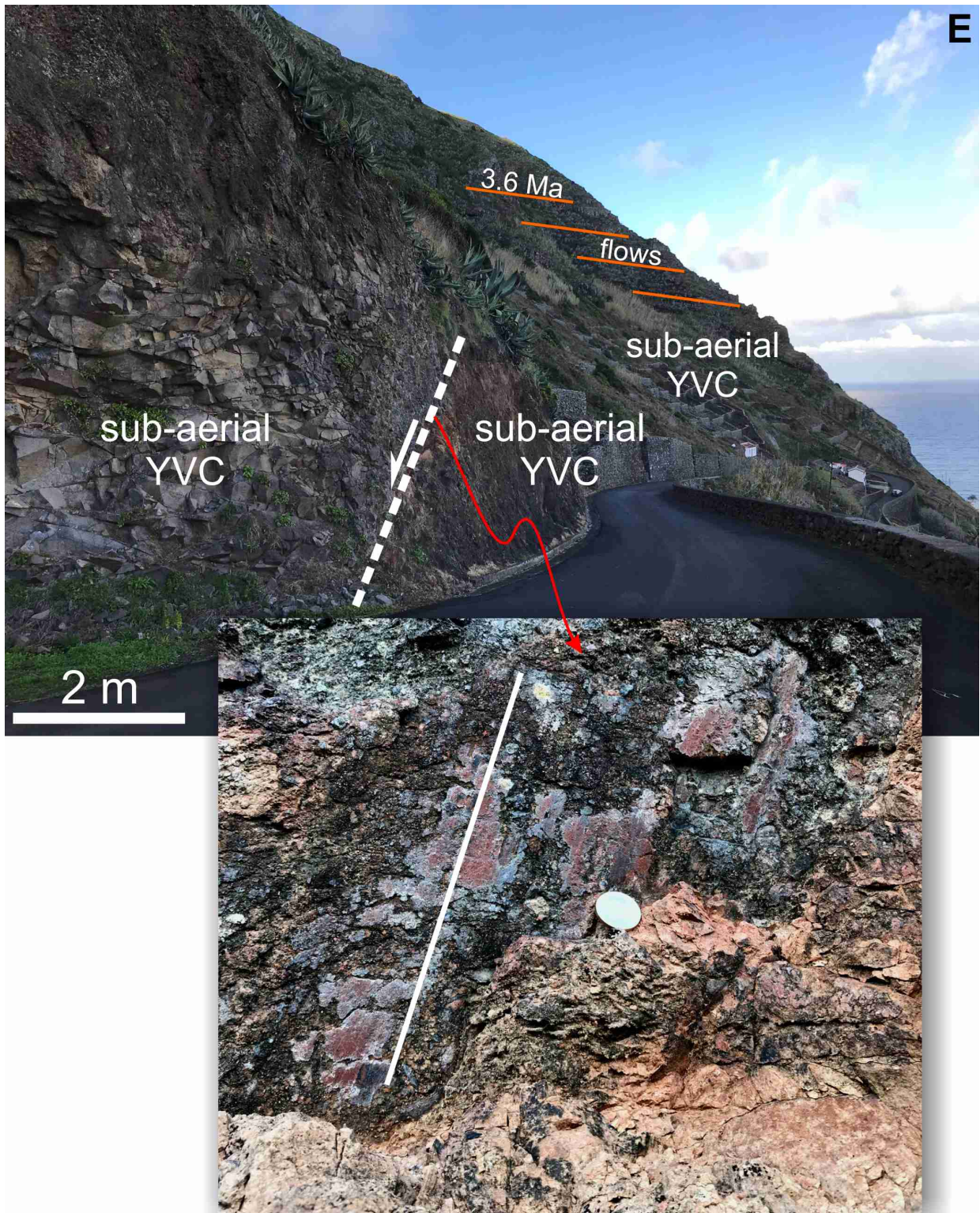


287        *striations (dashed black line zoomed on the inset at the bottom) and the displacement of the*  
288        *unconformity. The dykes strike N60 and dip 70° to the south, and do not propagate through the*  
289        *major unconformity into the Intermediate Sedimentary Complex (ISC, here composed of chaotic*  
290        *conglomerates). OVC – Old Volcanic Complex. Geologist on outcrop is 183 cm tall.*  
291



292  
293        *Figure 8. Normal faults dipping to the east (main fault) and west (minor), outcropping on the*  
294        *central southern coast and defining the west boundary of the Maia Graben. Red arrow points to*  
295        *geologist (180 cm tall) on the beach for scale.*  
296





297

298 *Figure 9. Photo of fault outcropping upslope the village of Maia (Fig. 10 for location), eastern*  
 299 *Santa Maria, trending N170 and dipping 70° to the west. The striations (highlighted by white*  
 300 *line on inset) and shear criteria indicate dominant normal faulting with a sinistral strike-slip*  
 301 *component. Note that the fault only affects the Young Volcanic Complex (YVC), but does not*  
 302 *seem to cut through the ca. 3.6 Ma lava flows.*

303



304 *Table 1 – Summary of the new ages obtained in this study, with uncertainty at 1σ confidence*  
 305 *level. Final age in bold character, obtained by weighing by the amount of radiogenic Ar (<sup>40</sup>Ar\*).*  
 306

Sample reference	Longitude (W)	Latitude (N)	K%	<sup>40</sup> Ar* (%)	<sup>40</sup> Ar* (10 <sup>12</sup> at/g)	Age (Ma)	Uncertainty 1σ (Ma)
SMA16K	25.11723	37.00413	1.645	15.9	10.30	5.99	0.09
				15.0	10.35	6.02	0.09
					mean	<b>6.00</b>	<b>0.09</b>
SMA16G	25.18262	36.99545	1.510	74.1	8.706	5.51	0.08
				76.5	8.689	5.50	0.08
					mean	<b>5.51</b>	<b>0.08</b>
SMA16B	25.16627	36.98736	1.474	50.1	8.361	5.42	0.08
				51.0	8.383	5.44	0.08
					mean	<b>5.43</b>	<b>0.08</b>
SMA16O	25.134978	36.946560	1.178	25.6	3.867	3.14	0.05
				24.2	3.818	3.10	0.05
					mean	<b>3.12</b>	<b>0.05</b>

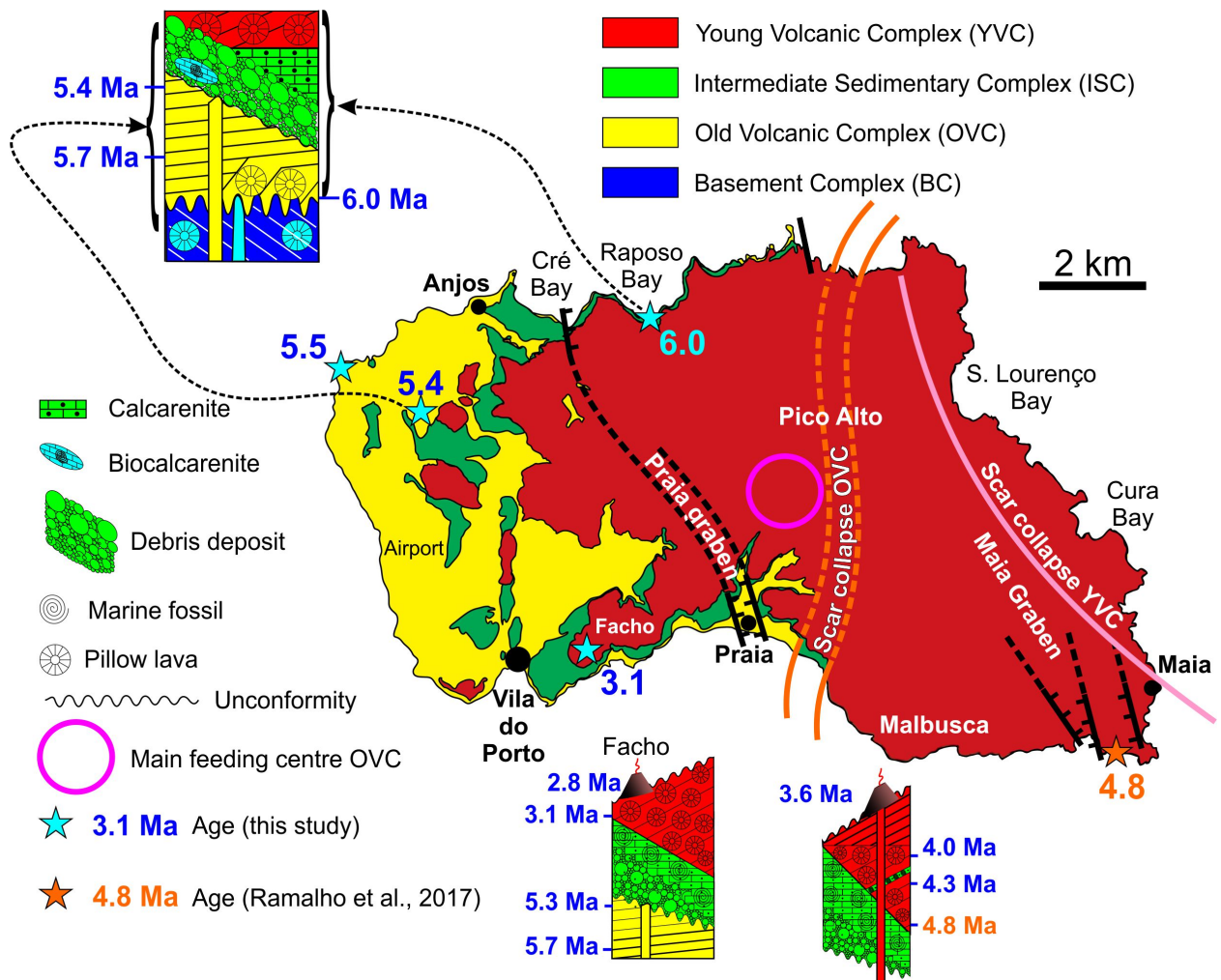
307

308

### 309 4.3. K-Ar dating

310 The new K-Ar ages obtained in this study range between  $3.12 \pm 0.05$  Ma and  $6.00 \pm 0.09$   
 311 Ma (Table 1 and Fig. 10). They are consistent with the available stratigraphic controls and with  
 312 previous K-Ar and <sup>40</sup>Ar/<sup>39</sup>Ar ages measured on separated groundmass (Sibrant et al., 2015a;  
 313 Ramalho et al., 2017). The new age of  $6.00 \pm 0.09$  Ma here obtained on sample SMA16K  
 314 collected at Baía do Raposo (Fig. 10), just below the ISC, extends the age of the OVC up to ca.  
 315 6.0 Ma. Previous and new ages make it possible to better constrain the stratigraphic sequences in  
 316 critical sections, and to better correlate well-exposed sections in different parts of the island (Fig.  
 317 10). The 6.0 Ma age in the OVC shows that the Cabrestantes (dated by Ramalho et al., 2017, at  
 318 ca. 6.0 Ma) and Porto volcanic cones belong to the OVC. They are not independent units as  
 319 defined by Serralheiro et al. (1987). The ca. 3.1 Ma age shows that the fossil deposits have  
 320 different ages at different altitudes and from east to west ( $> 4.8$  Ma to the east at sea level, and  
 321 ca. 3.1 Ma to the west and at 100 m altitude), thus helping in reconstructing the growth of the

322 YVC and the associated vertical displacements of the island.



323  
 324 *Figure 10. Proposed geological map with new stratigraphy calibrated by ages reported in*  
 325 *Sibrant et al. (2015a – ages in blue on the logs, and also cyan on the map), Ramalho et al. (2017*  
 326 *– ages in orange) and this study (light blue stars). Also note the newly proposed position of the*  
 327 *two large-scale landslide scars and of the two recognized main grabens. In the logs, vertical*  
 328 *lines represent dykes, and oblique lines represent dip of lava flows.*  
 329

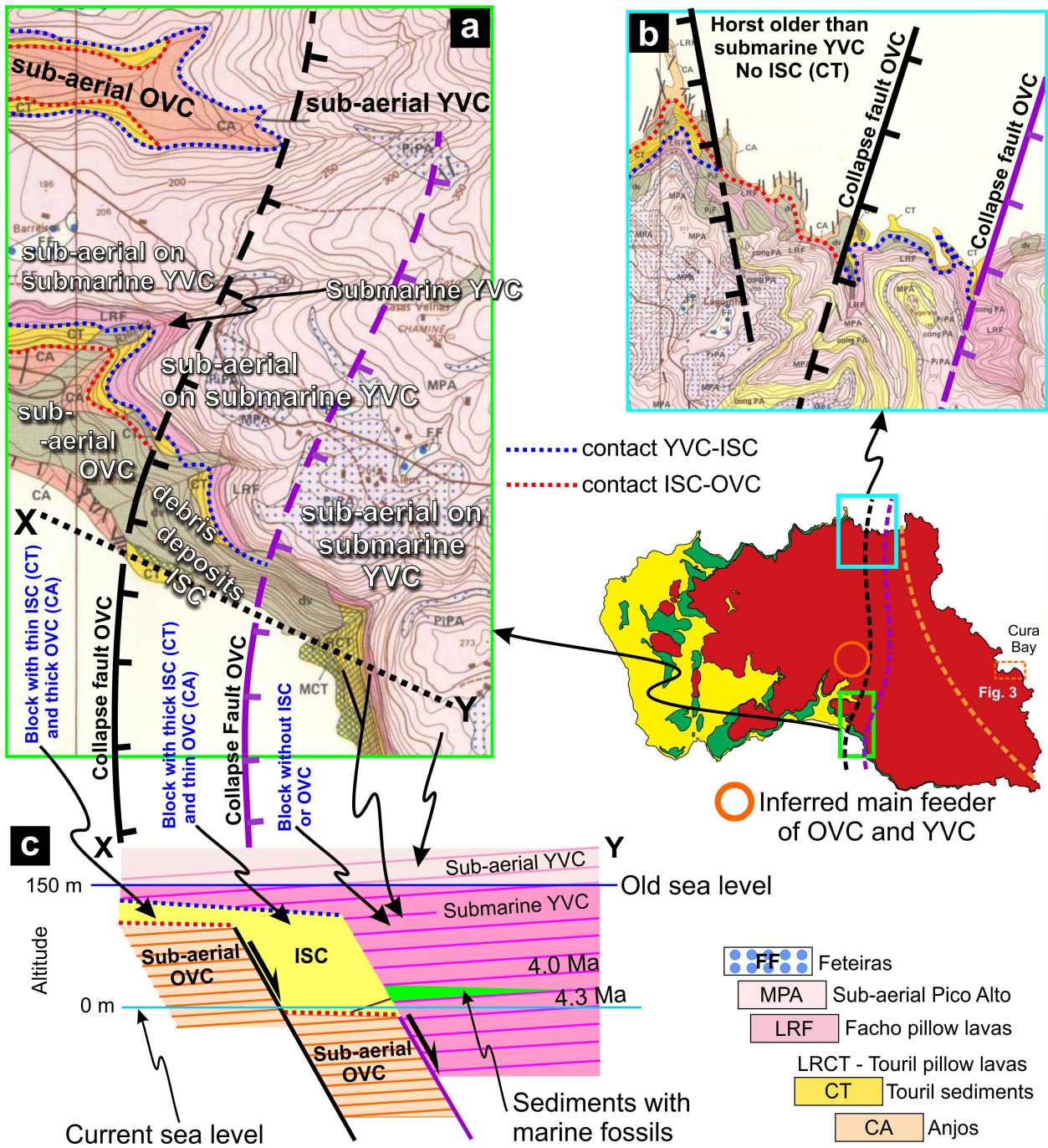
330 *4.4. Gravitational instability in Santa Maria*

331 Adding to the works of Marques et al. (2013b) and Sibrant et al. (2015a), we can now  
 332 give a much narrower age interval and location for the first and second flank collapses. Marques  
 333 et al. (2013b) and Sibrant et al. (2015a) proposed an age of between 5.3 and 4.3 for the first  
 334 collapse, and here we narrow the age interval down to 5.2-4.9 Ma. Marques et al. (2013b) and  
 335 Sibrant et al. (2015a) did not give a specific location for the faults produced by the first flank  
 336 collapse, which we do here. The first flank collapse at ca. 5 Ma has been inferred from the short

337 time span between first and second shield volcanoes (ca. 0.3 Ma) and the preservation of only  
338 the western flank of the first shield volcano (Marques et al., 2013b; Sibrant et al., 2015a; present  
339 study). The location of the first collapse is here deduced from fieldwork data, the position of the  
340 main feeding centre inferred from radial dykes, and the geological maps shown in Fig. 11. On  
341 the south coast (Fig. 11a), the sub-aerial OVC is in lateral contact with the ISC from sea level to  
342 ca. 100 m altitude (solid black line). Further inland, the sub-aerial OVC has a direct contact with  
343 the sub-aerial YVC at ca. 170 m altitude (dashed black line), or through an intervening ISC.  
344 These relationships are summarized in the X-Y cross-section shown in Fig. 11c. On the northern  
345 coast (Fig. 11b), the geological configuration is similar to that mapped on the southern coast, but  
346 with a more complex structure, i.e. the landslide fault apparently has a graben-horst structure,  
347 instead of the two, simple east-dipping normal faults inferred for the southern coast. Here we  
348 better constrain the age of the collapse at ca. 5.0 Ma, using the youngest OVC age (ca. 5.2 Ma)  
349 and the oldest YVC age (ca. 4.9 Ma). This allows us to infer a collapse of the summit and eastern  
350 flank of the first shield volcano, delimited by a concave fault running approximately N-S from  
351 the central/south coast to the NE coast of Santa Maria (Fig. 11).

352 Three pieces of evidence allow us to infer a second collapse. First, the position of  
353 younger (3.5-3.7 Ma) YVC cones on a surface that is concave to the east, which is the opposite  
354 of the general rule for well-preserved shield volcanoes, where parasitic cones sit on a convex  
355 conical surface. The adventive cones are therefore unconformable on the westward-dipping older  
356 (> 4.0 Ma) YVC, and their lava flows dip gently to the west and the east. Second, the summit  
357 crater or caldera is missing. Third, the passage zones in eastern Santa Maria (Fig. 3), which are  
358 made up of lavas flowing from the parasitic cones. The passage zone is here interpreted as the  
359 result of lavas flowing over a steep scarp (landslide scarp?), which must lie deeper to the west.  
360 Given that on the south and north coasts lavas dip to the west, and unconformable east-dipping  
361 lavas only occur on the east coast, we conclude that the second landslide fault must lie between

362 the SE and NE corners of Santa Maria, and be concave to the east (Fig. 11).



363

364 Figure 11. Panels (a) and (b) are extracts of the geological map of Serralheiro et al. (1987) with  
 365 our interpretation of the location of the main landslide faults affecting the OVC, based on the  
 366 distribution of the OVC, the ISC and the YVC, as represented in the X-Y cross-section in panel  
 367 (c). Note that we have put LRCT and LRF together as the submarine part of the YVC. Also note  
 368 that the old landslide faults are drawn where the OVC abruptly ends against the ISC and/or YVC  
 369 (black line), and where the ISC abruptly ends against the submarine YVC (magenta line). Red  
 370 lines plunging to the west in (c) represent lava flow dip.  
 371

372

373 *4.5. Gravitational instability around Santa Maria Island*

374           Given that LSMW in the area could be related to the tectonic evolution of the ATJ, as  
375 suggested for Santa Maria, it is important to have a complete view of LSMW around the island.  
376 At least one submarine slide has been recognized near Santa Maria in the Monaco Bank (Weiß et  
377 al., 2016) (Fig. S-5). Weiß et al. (2016) interpreted the slide using high-resolution bathymetry  
378 and seismic reflection, and concluded that it occurred as a slow LSMW event. In Fig. S-5b we  
379 re-interpret the Monaco Bank slide regarding the faults and the original volume/shape of the  
380 slide block. We used shaded relief bathymetry and a bathymetric profile to interpret the landslide  
381 faults, mainly based on the scars observed on the bathymetry and the distribution of the debris.  
382 We reconstructed the original wedge, the volume of which compares very well with the volume  
383 of the debris deposit. From the ratio ( $10 \text{ km}/2 \text{ km} = 5$ ) between the distance travelled by the  
384 debris (10 km) and the Monaco Bank height (2000 m), we infer that the slide was relatively  
385 slow, but maybe not as a slump as Weiß et al. (2016) suggested.

386

387 *4.6. Tsunami deposits*

388           Several conglomeratic deposits occur on Santa Maria, but here we only focus on two that  
389 are potential tsunami deposits (Figs. S-6 and S-7). The most widespread deposit is the one  
390 blanketing the unconformity atop the OVC and sealing the old dykes. This polygenetic chaotic  
391 debris deposit is very well exposed on the road into Praia from the west (Fig. S-6). It contains  
392 boulders from meters to centimetres in size, and comprises two main layers (Fig. S-6a): the  
393 bottom layer contains mostly well-rounded large boulders in a calcarenite matrix (Fig. S-6c), and  
394 the top layer contains smaller and more angular boulders in a grey clay matrix (Fig. S-6b).  
395 Moreover, the bottom layer comprises well-polished pebbles (Fig. S-6d), typical of a wind and  
396 sand polishing process in low-altitude coastal areas. From the nature of the matrix and pebble  
397 roundness and polish, we infer that the bottom deposit originated in the sea (tsunami runup), and

398 the top deposit originated in land (tsunami backwash).

399 A smaller deposit occurs at site SMA16B (see location in Fig. 2) and is shown in Fig. S-  
400 7. This deposit is also polygenetic, chaotic, very poorly sorted with large boulders in a matrix of  
401 pebbles, gravel, sand and clay. This deposit includes large blocks of marine sediments (Fig. S-  
402 7b) and pillow lavas (Fig. S-7c) attesting to its marine origin. Unfortunately, the relationship  
403 with the surrounding sub-aerial OVC is not clear. If it were to sit unconformably on the OVC  
404 and below the YVC, then it would have the same age as the deposit described above.

405

## 406 **5. Discussion**

### 407 *5.1. Stratigraphy calibrated by geochronology*

408 Given the similarity of the ages (ca. 6 Ma) of small and scattered outcrops of Porto,  
409 Cabrestantes (dated by Ramalho et al., 2017 at ca. 6 Ma) and Baía do Raposo (here dated at ca. 6  
410 Ma), we consider the Porto and Cabrestantes units as OVC. The new age at Baía do (Bay of)  
411 Raposo (ca. 6 Ma) better constrains the oldest age of the OVC, and shows the consistency with  
412 the general dip of the OVC flows to the west.

413 In addition, the Touril Complex, considered by Serralheiro et al. (1987) to include sub-  
414 aerial and submarine lava flows and sediments, is here reduced to the sedimentary rocks, and is  
415 renamed Intermediate Sedimentary Complex (ISC). The section at Pedreira do Campo (Fig. 4)  
416 shows the typical transition sequence from the OVC to the Young Volcanic Complex (YVC),  
417 through an unconformity between the OVC and sediments, which are conformably overlain by  
418 the YVC. Therefore, the sub-aerial lava flows belong to the OVC and the submarine flows  
419 belong to the YVC. We note that (Fig. S-8) extrapolation of the age of dated pillow lavas at  
420 Pedreira do Campo (Fig. S-8c) to similar settings (Fig. S-8b and d) along the same yellow unit to  
421 the east (CT, Complexo do Touril of Serralheiro et al., 1987) leads to major inconsistencies.  
422 Furthermore, the submarine lavas (LRF) here dated at 3.1 Ma at Pedreira do Campo (Fig. S-8c)



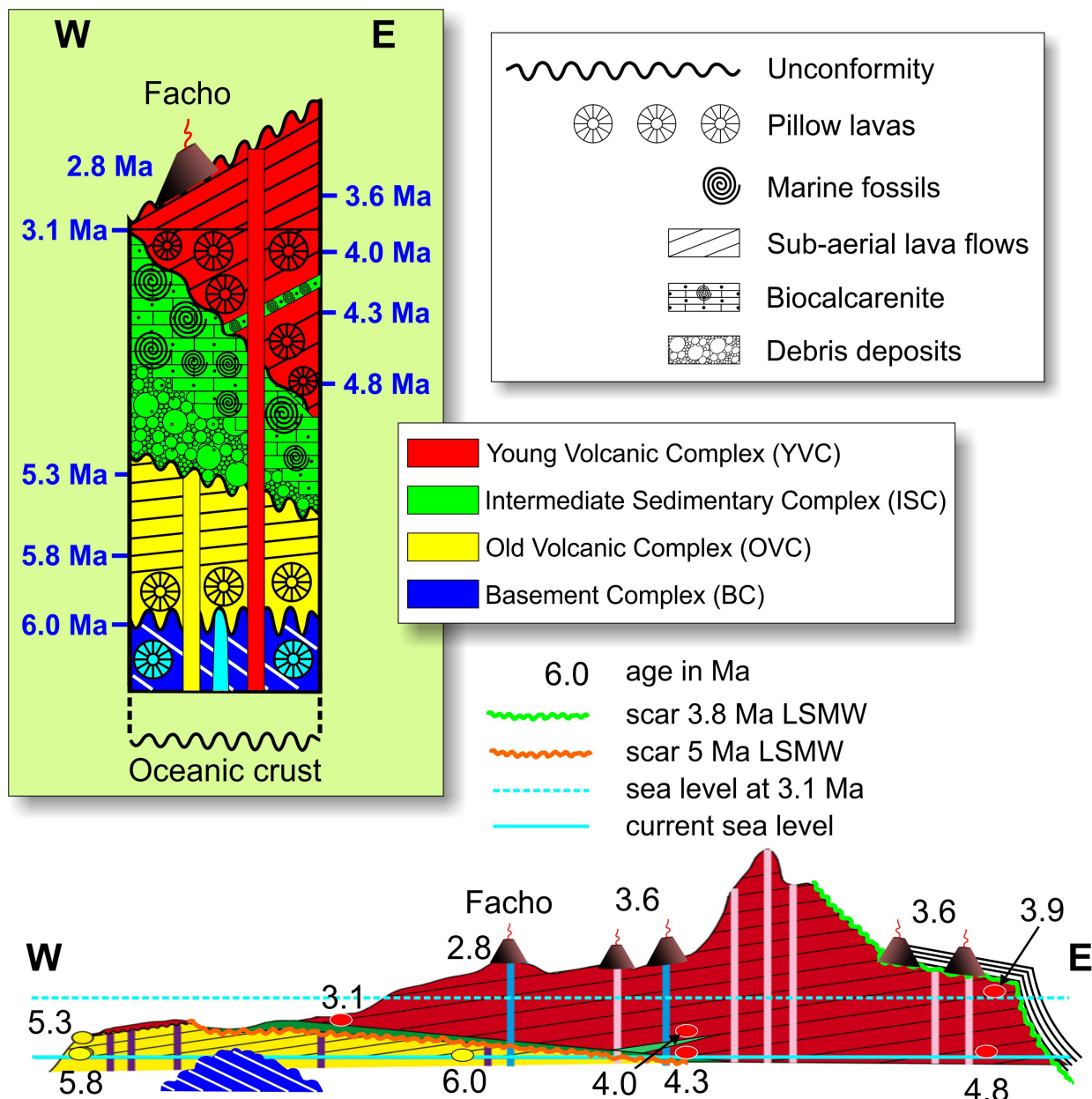
423 cannot be overlain by lava flows that are older (Fig. S-8b and d), and the CT sediments at  
424 Pedreira do Campo (ca. 3.2 Ma) cannot be the same as the CT sediments to the east atop Praia  
425 (Fig. S-8a) and at Malbusca (ca. 4.1 Ma) in Fig. S-8d. Therefore, there must also be a scarp  
426 where a thick black line marked F is drawn in Fig. S-8b, because the OVC (CA on the map) ends  
427 abruptly at sea level (whereas it reaches 150 m altitude immediately to the north). Likewise, the  
428 chaotic debris deposit (CT) also ends here, where the conglomeratic deposit passes into  
429 submarine lavas of the YVC (LRCT on the map in Fig. S-8d). This scarp/fault has to be older  
430 than the CT because it does not cross-cut it.

431 We also find that the submarine Facho Complex cannot be below the Pico Alto Complex  
432 (4.8 to 2.8 Ma), as proposed by Serralheiro et al. (1987), because the Facho Volcano is sub-  
433 aerial, and it is the youngest volcanism on the island, dated by Sibrant et al. (2015a) at ca. 2.8  
434 Ma. The submarine lavas attributed to Facho actually lie below the Facho Volcano, and comprise  
435 the submarine volcanism of the YVC (4.8 to 3.1 Ma). Given the continuous (no unconformities  
436 recognized) age spread of submarine lava flows (4.8 to 3.9 Ma; Sibrant et al., 2015a; Ramalho et  
437 al., 2017), sampled in the Touril, Facho and Pico Alto complexes, there is no argument for  
438 attributing them to three distinct volcanic units. We therefore group them together as the early  
439 submarine stage of the YVC.

440 Finally, we find that the Feteiras Formation (“feteiras” means “the place where fern  
441 grows”; cf. Fig. S-9) is simply deposits from parasitic Strombolian cones that belong to the  
442 YVC, as indicated by the radiometric ages of Sibrant et al. (2015a) and Ramalho et al. (2017).  
443 The “pyroclasts” attributed to Feteiras are actually not pyroclasts, but instead a soil resulting  
444 from deep in-situ weathering of lava flows (Fig. S-9). The Feteiras Formation also cannot be  
445 stratigraphically above the Facho Complex, as proposed by Serralheiro et al. (1987), because the  
446 cones attributed to this unit are much older (ca. 3.6 Ma; Sibrant et al., 2015a) than Facho (ca. 2.8  
447 Ma; Sibrant et al., 2015a).

448 To summarize, the proposed new stratigraphy is, from bottom to top (Fig. 12): (1) The  
449 Basement Complex, which corresponds to the seamount stage (prior to 6 Ma); (2) the Old  
450 Volcanic Complex, which built the first sub-aerial shield volcano (maybe initially submarine; 6  
451 to < 5.3 Ma); (3) the Intermediate Sedimentary Complex, which comprises mixed sub-aerial and  
452 submarine conglomerates overlain by marine calcarenites with abundant fossils (< 5.2 to > 3.1  
453 Ma); (4) the Young Volcanic Complex, which built the second shield volcano, initially  
454 submarine with intercalated fossiliferous sediments, and gradually passing into sub-aerial, with  
455 late parasitic cones on top (> 4.8 to 2.8 Ma). These four complexes are each separated by major  
456 unconformities as shown in Fig. 12.





457  
 458 *Figure 12. Top panel – log with the new proposed stratigraphy calibrated with K-Ar data of*  
 459 *Sibrant et al. (2015a) and present study, and <sup>40</sup>Ar/<sup>39</sup>Ar data of Ramalho et al. (2017). Bottom*  
 460 *panel – geological cross-section summarizing all field and geochronological data. Note the*  
 461 *consistency between lava flow dip and younging to the west at similar altitude, and upwards, in*  
 462 *both OVC and YVC. Also note that the young volcanic cones in the east lie unconformably on the*  
 463 *basal YVC, through a LSMW scar, and in the west they lie conformably on the basal YVC as*  
 464 *parasitic cones.*  
 465

466 From the stratigraphic logs shown in Fig. 10 and 12, and supported by the new ages (see  
 467 also Fig. S-8), it is apparent that the fossil deposits cannot all have the same age. In fact, there is  
 468 a difference of ca. 1 Ma between the sediments at Malbusca Point (ca. 4.2 Ma) and at Pedreira do  
 469 Campo (ca. 3.2 Ma). This has major consequences regarding the palaeontology of the marine

470 fossils in Santa Maria (because the use of fossils for stratigraphy and correlation with similar  
471 fossils in other parts of the world depends critically on their age), and is vital to the interpretation  
472 of the evolution of the island and its vertical movements (especially subsidence during growth of  
473 the YVC).

474

## 475 *5.2. Structure, tectonics, strain and stress*

476 Comparison between Figs. 5 and 6 shows that dykes of the OVC do not follow mapped  
477 faults, and the quadrant with the most dykes (SW) is not the one with the most faults. In the  
478 YVC, the SE quadrant is dominated by both dykes and faults, where many have similar  
479 orientations. From this we infer that this second population of dykes were instead injected into  
480 fractures sub-parallel to faults (only locally do dykes intrude actual faults).

481 Our interpretation of the geometrical, spatial and temporal relationships of dykes and  
482 faults is that the stress field changed over time and in space, especially during the transition from  
483 the OVC to the YVC, the time of the older flank collapse (ca. 5 Ma). In support of this, older  
484 dykes (> 5.2 Ma) show a bulk radial distribution, similar to what Marques et al. (2019) observed  
485 in Fogo Island, Cape Verde, from which we infer the location of the main feeding centre and a  
486 radial stress field imposed by the first shield volcano (Marques and Cobbold, 2002). Then, there  
487 is a clear dominance of the WSW-ENE trend in the SW quadrant, which includes multiple-  
488 injection dykes (cf. Fig. S-2), attesting to preferential NNW-SSE opening (least compressive  
489 stress) due to the regional stress field. Next, the younger dykes (< 4.9 Ma) show a preferential  
490 trend along the NNW-SE to NNE-SSW direction, attesting to preferential ENE-WSW opening.  
491 Finally, the faults are mostly normal, heterogeneously distributed in space (across central and  
492 eastern Santa Maria), younger than ca. 4.8 Ma, and show a preferential NNW-SSE to N-S trend  
493 (ENE-WSW to E-W opening).

494 Dykes older than ca. 5 Ma could be related to the similarly trending East Azores Fracture

495 Zone, the old Nubia-Eurasia plate boundary. Instead, dykes younger than ca. 5 Ma could be  
496 related to ENE-WSW extension in the last 4.0 Ma (DeMets et al., 2010), and to the rift jump  
497 from the East Azores Fracture Zone to the Terceira Rift along several transient, short lived,  
498 grabens trending WNW-ESE (Vogt and Jung, 2004). Building on the work of Luís et al. (1994),  
499 Vogt and Jung (2004) and Sibrant et al. (2015a), here we can specify that the change in stress  
500 field orientation occurred at ca. 5 Ma, as supported by our new geochronological data and  
501 volcanic stratigraphy.

502         The trend of the ca. 5 Ma LSMW scar is approximately N-S, at a high angle to the  
503 dominant WSW-ENE dyke trend in the OVC, thus excluding a relationship between collapse and  
504 dykes. The N-S trend is perpendicular to the far field extension in the eastern Azores (DeMets et  
505 al., 2010). Therefore, we suggest that extension could have favoured the localization and the  
506 triggering of the two LSMW here proposed. It could also have produced the main grabens  
507 identified here. Finally, we propose that a transient Santa Maria Graben started opening at about  
508 5 Ma, and was responsible for the flank collapse inferred for Santa Maria at that age. Note that  
509 both inferred LSMW occurred along faults striking NNW-SSE to N-S, consistent with extension  
510 and the trend of the dykes younger than 5 Ma.

511

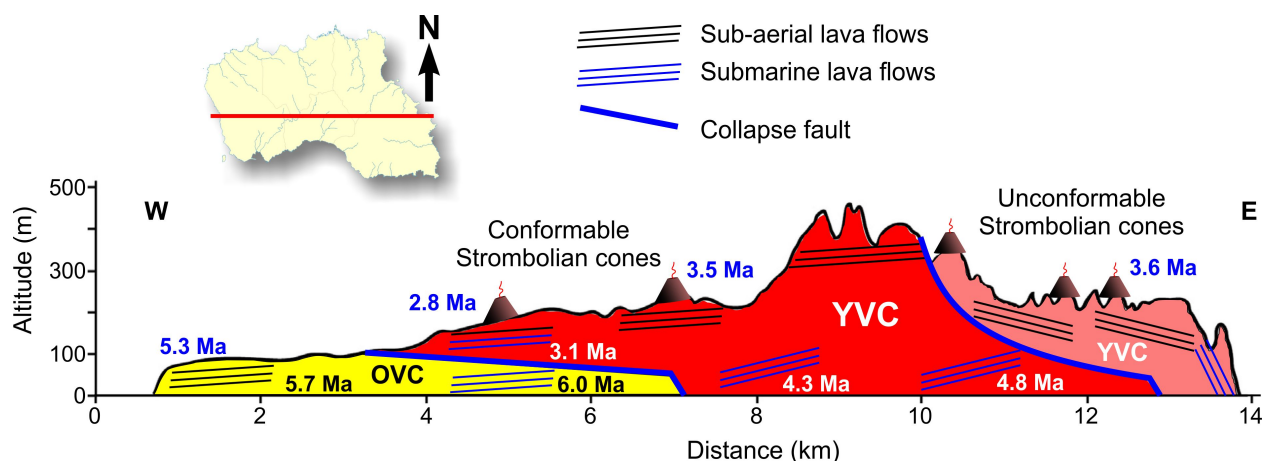
### 512 *5.3. LSMW events*

513         Despite the small size of the Azorean islands, several LSMW events have been described  
514 recently (Hildenbrand et al., 2012a; Marques et al., 2013b; Sibrant et al., 2014, 2015a, b, 2016;  
515 Costa et al., 2014, 2015; Marques et al., 2018; Hildenbrand et al., 2018). Exceptions in the  
516 eastern Azores are the islands of Faial (Hildenbrand et al., 2012b; Marques et al., 2014b;  
517 Trippanera et al., 2014) and Terceira (Marques et al., 2015; Quartau et al., 2014), where LSMW  
518 has not been described (Mitchell, 2003; Casalbore et al., 2015; Quartau et al., 2012, 2015).

519         From the bulk radial distribution of dykes at Santa Maria, we infer the position of

520 coincident OVC and YVC main feeding centres on the divide between the eastern and western  
521 parts of the island (cf. Fig. 5). If this interpretation is correct, then the summits and eastern flanks  
522 of the two shield volcanoes are missing, as can also be deduced from the lava flow geometry  
523 (Fig. 12). One can propose an evolution of Santa Maria's morphology based solely on meteoric  
524 and marine erosion (Ramalho et al., 2017). However, this view contains three inconsistencies.  
525 First, field and geochronological data (lava flow dip and younging to the west) show that both  
526 OVC and YVC only have their western flanks preserved. Second, Santa Maria has undergone  
527 meteoric and marine erosion, and probably also small-scale landsliding over the last 3.6 Ma, if  
528 not longer. This is 10 times longer than the period between the OVC and YVC), but both are still  
529 mostly preserved. Third, the difference in age between the lavas of the older and younger shield  
530 volcanoes (ca. 0.3 Ma) is clearly not long enough for meteoric and wave erosion to remove the  
531 large amounts of lava flows missing in the older shield volcano (eastern flank and part of the  
532 summit). In addition, marine erosion would not have been selective in removing only one half of  
533 the shield volcano and preserving the other, especially the half facing the dominant winds (NW,  
534 W and SW). Therefore, the alternative is that the missing portion of the original OVC shield  
535 volcano has been removed by large-scale sector collapse. The chaotic debris deposit at the base  
536 of the ISC could, in part, represent a tsunami deposit associated with this collapse.

537         The youngest age measured for the OVC is ca. 5.3 Ma (but could be younger further to  
538 the west, in the sea) and the oldest age for the YVC is ca. 4.8 Ma (but could be older below  
539 current sea level). Therefore, the age of the first flank collapse is bracketed between <5.3 and  
540 >4.8 Ma, i.e. at around 5.0 Ma. We could not improve the accuracy of the age of the second  
541 collapse, but we could provide more detail on its location. The YVC lava flows dip to the west  
542 on the southern and northern coasts, but dip to the east on the eastern coast (Figs. 3, 12, 13), thus  
543 constraining the position of the collapse fault between the SE and NE corners of the island.



544

545 *Figure 13. E-W topographic cross-section with drawn geometry of lava flows and position of*  
 546 *LSMW scars and young volcanic cones (< 3.7 Ma). Note that the cones in the west lie*  
 547 *conformably on the western flank of the YVC, as parasitic cones, in great contrast to the cones in*  
 548 *eastern YVC that lie at an altitude lower than the top of the west-dipping flows of the basal YVC,*  
 549 *therefore unconformable on a surface here interpreted as a LSMW scar.*  
 550

551 Given the tectonic position of Santa Maria, its age and the inferred geometry of the  
 552 landslide scars, the triggering mechanisms of the two inferred LSMW events may have been: (1)  
 553 high-magnitude earthquakes due to motion in the East Azores Fracture Zone, the Nubia-Eurasia  
 554 plate boundary in the Azores prior to the jump to the Terceira Rift; (2) NNW-SSE rifting in the  
 555 ocean floor and dyke intrusion parallel to the inferred landslide scars.

556 Given that the onshore ISC deposits lie on an eastward-dipping unconformity atop the  
 557 sub-aerial OVC, and that there is no evidence of a major palaeotopographic relief nearby, we  
 558 interpret these deposits to be in part the result of a tsunami produced by the first flank collapse.  
 559

#### 560 5.4. Vertical movements

561 The spatial and temporal distribution of sub-aerial and submarine lavas at Santa Maria is  
 562 good evidence that: (1) either the island has moved vertically by hundreds of meters (stationary  
 563 sea level), or (2) the sea level has changed by hundreds of meters (stationary island), or (3) both  
 564 processes acted together. Hypothesis (2) does not seem viable because sea level estimates (Miller  
 565 et al., 2005) do not show such sea level highstands (ca. 200 m) in the period 6 to 0 Ma.

566 At Baía da (Bay of) Cré (Fig. S-10), young island uplift has exposed critical outcrops for  
567 the analysis of vertical movements of the island, especially the ones that pre-date younger uplift.  
568 Sub-aerial lava flows of the OVC currently outcrop from sea level up to ca. 100 m (red ellipse in  
569 Fig. S-10). This sub-aerial OVC is unconformably overlain by submarine lavas of the YVC from  
570 ca. 100 m up to ca. 200 m (blue ellipses in Fig. S-10), where a palaeoshoreline exists at ca. 200  
571 m, in the upward transition to sub-aerial YVC. This current position of sub-aerial OVC at 100 m  
572 altitude, and overlain by 100 m thick submarine flows of the YVC, means that the sub-aerial  
573 OVC was submerged by at least 100 m (the minimum thickness of the sub-aerial OVC) to allow  
574 for the deposition of younger submarine flows of the YVC on older sub-aerial lavas of the OVC.  
575 This implies island subsidence between ca. 4.9 Ma (oldest YVC submarine flows close to sea  
576 level) and 3.1 Ma (youngest YVC submarine flows at ca. 100 m altitude), with undetermined  
577 influence of sea level change. YVC submarine flows found at an altitude of 200 m, and at the  
578 contact with overlying sub-aerial YVC flows (palaeoshoreline), indicate a 100 m thickness of  
579 submarine YVC, and that the sea level at the time of deposition of the uppermost submarine  
580 lavas of the YVC was at least 200 m higher than the present day, due to island subsidence after  
581 around 4.9 Ma, with undetermined influence of sea level change. The current exposure of the  
582 YVC palaeoshoreline at ca. 200 m altitude also means that uplift by at least 200 m must have  
583 occurred since emplacement, with undetermined influence of sea level change.

584 A similar situation occurs in SW Santa Maria, on the opposite coast of Baía da Cré,  
585 where young uplift has exposed YVC submarine lavas unconformably overlying OVC sub-aerial  
586 lavas with intermediate thick marine sediments. Again, submarine lavas on top of sub-aerial  
587 lavas means that the island was subsiding until at least ca. 3.1 Ma, with undetermined influence  
588 of sea level change. The ca. 3.1 to 2.8 Ma age of the pillow lavas WSW of Facho at ca. 170 m  
589 maximal altitude (Fig. 10 for location), where a palaeoshoreline exists at the transition from  
590 submarine to sub-aerial YVC, indicates that, prior to younger uplift the island subsided, with

591 undetermined influence of sea level change until ca. 3-2.8 Ma. Ramalho et al. (2017, their Fig. 6)  
592 estimated subsidence and uplift rates based on a palaeoshoreline located at about 3.5 Ma, but  
593 these rates could be significantly different if the palaeoshoreline age is put at ca. 2.8 Ma, as  
594 indicated by the new age (ca. 3.1 and younger) of the pillows west of Facho (sub-aerial, ca. 2.8  
595 Ma). Besides, 3.5 Ma is only an upper bound, because uplift could have started anytime between  
596 that age (or 2.8 Ma in the present study) and present day, in the absence of reliable markers  
597 younger than 2.8 Ma. On the other hand, subsidence starting at ca. 5.3 Ma (Ramalho et al., 2017)  
598 is not justified, because the first submarine lavas post-dating the sub-aerial OVC lie above an  
599 east-dipping major unconformity and are off-set to the east relative to the OVC, which means  
600 that they would be submarine even without any subsidence of the island (Fig. 14).

601         According to the scenario proposed here, subsidence resulted from significant loading by  
602 the YVC growth filling the scar of the first collapse (Fig. 14). We can estimate the isostatic  
603 effect of constructional loading by assuming Airy isostasy and a maximum 900 m thickness of  
604 the YVC (current 600 m + 200 m missing summit + 100 m estimated below sea level):

$$605 \quad \varepsilon = 900 - (900 * \rho_l / \rho_a) = 900 - 900 * 2800 / 3200 = 900 - 788 = 112 \text{ m}$$

606 where  $\varepsilon$  is the topography,  $\rho_l$  is the density of basaltic lavas, and  $\rho_a$  is the density of the  
607 asthenosphere. The result of 112 m is an upper bound calculation of the isostatic response to  
608 constructional loading, therefore capable of explaining the inferred subsidence.

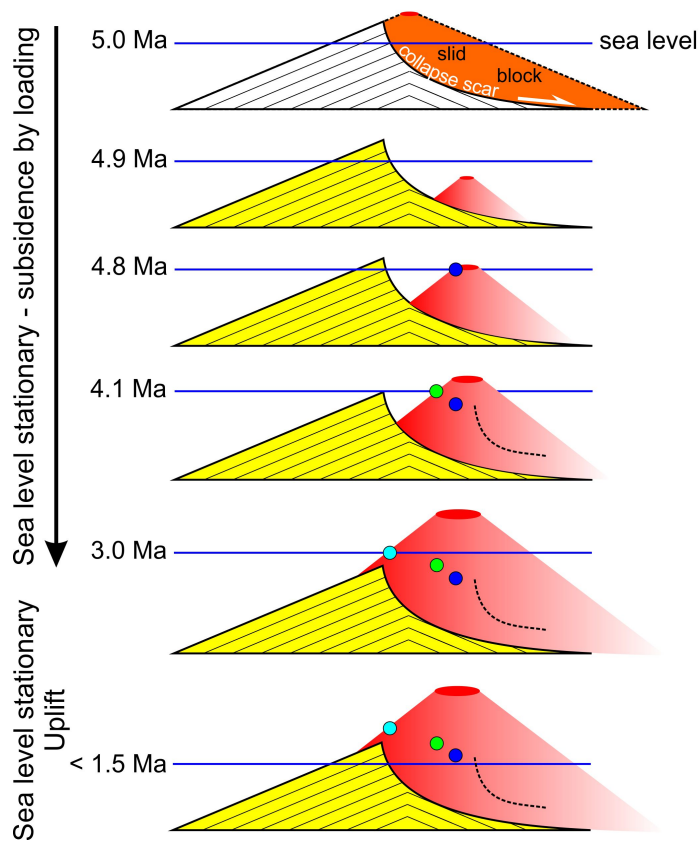
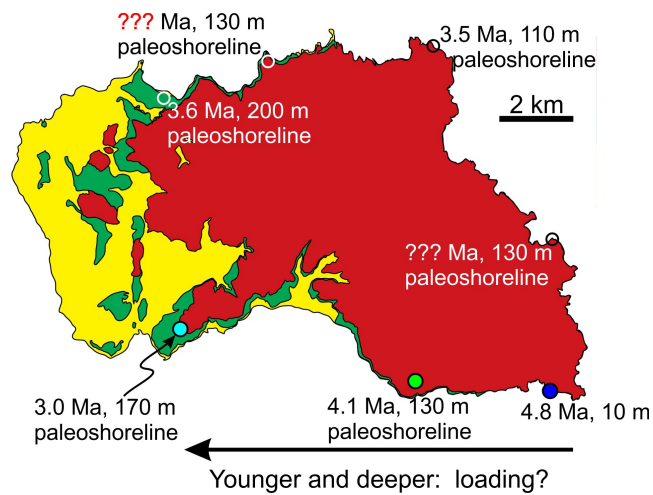
609         The new age ( $3.12 \pm 0.05$  Ma) obtained on YVC pillow lavas stratigraphically overlying  
610 marine carbonates of the ISC at Pedreira do Campo (Fig. 4), and underlying the sub-aerial ca. 2.8  
611 Ma flows of the Facho volcano, indicates a progressive filling of the first collapse scar by the  
612 YVC, initially submarine and later sub-aerial, as the YVC shield volcano grew out of the ocean  
613 from east to west over a scarp dipping to the east (Fig. 14). Therefore, subsidence would have  
614 been active until, at least, ca. 2.8 Ma. Given the topographic position of 4.8 Ma old submarine  
615 YVC close to current sea level to the east (location in Fig. 10) and 3.1-2.8 Ma old submarine

616 YVC to the west at ca. 170 m, we infer that, similarly to Baía da Cré, at least 200 m of  
617 subsidence occurred between 4.8 and 2.8 Ma. Subsidence rates at Santa Maria cannot be directly  
618 compared with the faster subsidence rates estimated for younger islands in the eastern Azores  
619 (Hildenbrand et al., 2012a; Marques et al., 2015), because they lie on younger lithosphere, and  
620 are thus subsiding faster due to faster lithospheric cooling (Turcotte and Schubert, 2014). They  
621 also lie on rifting lithosphere, where Graciosa, Terceira and S. Miguel islands lie inside the  
622 Terceira Rift, and Pico, Faial and S. Jorge islands lie in the area of diffuse rifting (Marques et al.,  
623 2013a, 2014a, and Miranda et al., 2014), and are thus currently undergoing additional vertical  
624 tectonic movements.

625         Ramalho et al. (2017) concluded that the only viable mechanism able to explain the uplift  
626 is crustal thickening by basal intrusions, and argued that uplift in response to the tectonic regime  
627 is unlikely because the area is under transtension. From a physical point of view, the argument of  
628 transtension is inconsistent with the known mechanics of rifting lithosphere, because rift  
629 shoulders are uplifted during rifting (Weissel and Karner, 1989). Although produced by  
630 lithospheric extension, rifts are known to have quite high shoulders, which are produced by uplift  
631 of rift flanks due to mechanical unloading of the lithosphere during extension and consequent  
632 isostatic rebound (Weissel and Karner, 1989). The Terceira Rift is no exception (Marques et al.,  
633 2015; Marques et al., 2018), as well illustrated by the topographic profile shown in Figure 10.  
634 Typically, magma ponding at the Moho (underplating) or higher (storing in magma chambers) is  
635 contemporaneous with volcanism at the Earth's surface, and differentiation during ponding can  
636 be responsible for the evolution of lavas from mafic to intermediate as observed in nearby S.  
637 Miguel Island. Santa Maria does not show significant differentiation (Beier et al., 2013), which  
638 means that magma found easy ways to reach the surface without significant ponding.

639





640

641 *Figure 14. Sketch illustrating subsidence by loading induced by the growing YVC until 2.8 Ma,*  
 642 *considering sea level stationary. Note the consistency between growth and subsidence using*  
 643 *passage zones along an E-W section on the southern coast (the best constrained).*  
 644

645 The topographic profile across the East Azores Fracture Zone, Santa Maria and the  
 646 Terceira Rift (Fig. 15) indicates conspicuous flank uplift in the Terceira Rift. Maximal uplift on  
 647 the NE flank is ca. 2,000 m, but on the SW flank, where Santa Maria lies, uplift seems much  
 648 smaller (hundreds of meters). Despite Santa Maria not sitting at the highest point of the rift

649 shoulder, the flank uplift could still account for the 200 m of uplift inferred for Santa Maria. If  
650 the age inferred for the Terceira Rift is correct (Vogt and Jung, 2004; Marques et al., 2015;  
651 Sibrant et al., 2016; Marques et al., 2018), and Santa Maria's upward movement is (at least in  
652 part) due to rift flank uplift, then some (or all) of the 200 m of uplift is younger than ca. 1.5 Ma.

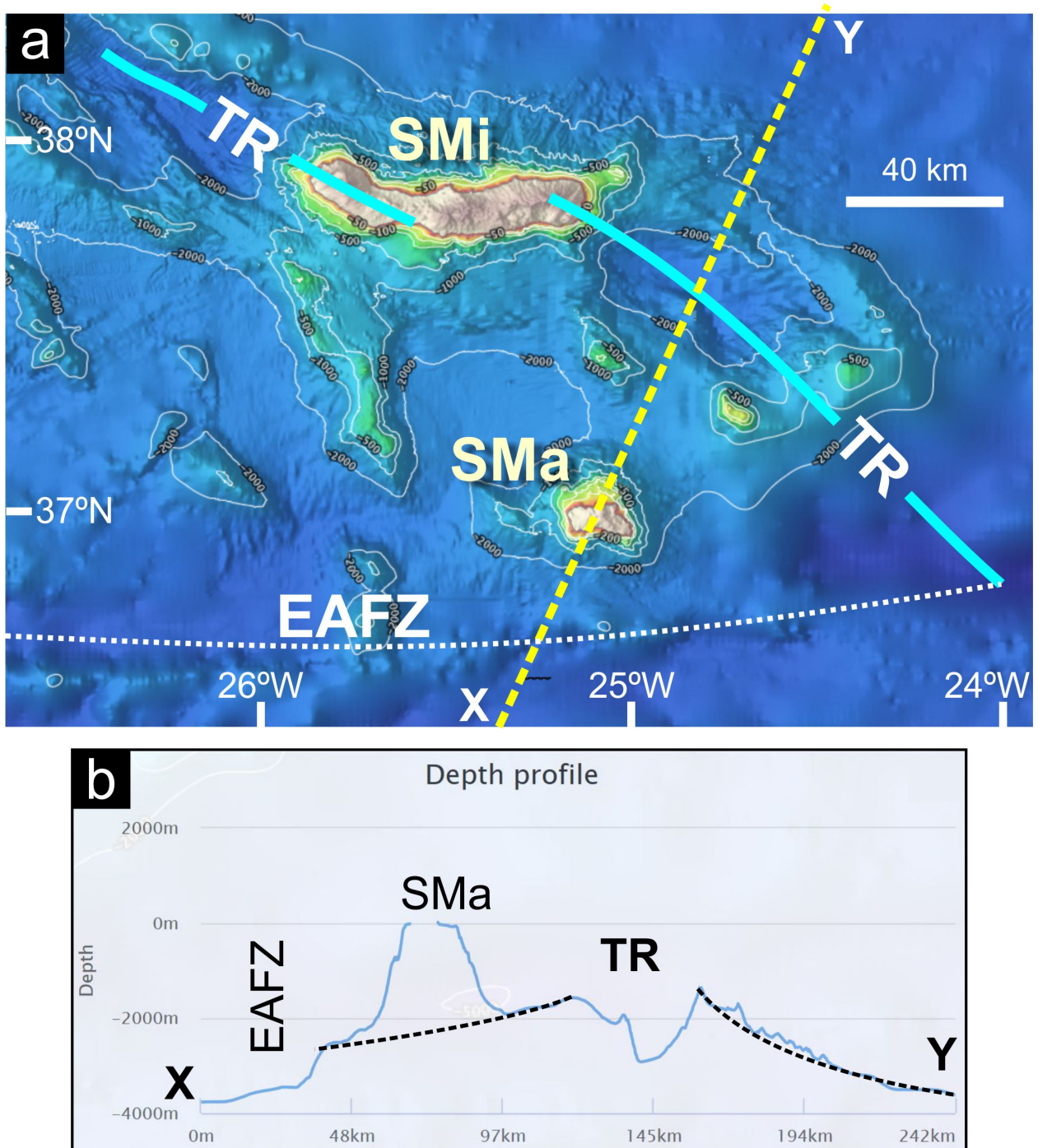
653 If we use this age and ca. 200 m altitude of the highest passage zone to calculate the  
654 uplift rate, we calculate a rate of ca. 0.133 mm/yr, which contrasts with the 0.057 mm/yr rate  
655 obtained using ca. 3.5 Ma (Ramalho et al., 2017).

656

### 657 *5.5. Marine erosion shelves*

658 Regarding the evolution of marine shelves, Santa Maria can be used as a reference in the  
659 Azores, because: (1) there is no evidence of current appreciable vertical motion; (2) it is  
660 similarly affected by the same sea level changes as the younger Azores islands; (3) it is mostly  
661 composed of basaltic lava flows and pyroclasts (as in most Azorean islands); (4) it has been  
662 volcanically inactive for a long period (> 2.8 Ma, Sibrant et al., 2015a); and (5) it is affected by  
663 similar weather, wave magnitude and propagation directions to the other Azorean islands. The  
664 youngest volcanism in Santa Maria (ca. 3.7 to 2.8 Ma; Sibrant et al., 2015a) occurs as small  
665 Strombolian cones scattered on top of the island; therefore, most of the coastal area is made of  
666 rocks older than ca. 3 Ma, and the western coast is made of rocks older than 5 Ma. We look at  
667 the first-order topography of the shelves, because we are looking at their relationship with the  
668 main evolution of the island (volcanic construction/major landslides). In the absence of volcanic  
669 construction in the last 2.8 Ma, the explanation for the narrow insular shelves all around Santa  
670 Maria, except to the NE, cannot be found in regular marine abrasion and meteoric weathering.  
671 We combine the observed short width of the shelf and age of rocks on the coast with the concave  
672 shape of the coast and/or shelf edge to propose that the shelf is narrow because of recent  
673 medium-scale landsliding. The slide to the south, centred on the village of Praia, could be

674 responsible for the development of the large canyon on the headwall, the mouth of which is at  
 675 Praia (due to sudden increase in potential energy), and for the slump currently creeping at Praia  
 676 (Fig. S-11).



677 *Figure 15. Shaded relief bathymetry around Santa Maria (a), and X-Y topographic profile (b)*  
 678 *across the East Azores Fracture Zone (EAFZ), the Santa Maria Island (SMa) and the Terceira*  
 679 *Rift (TR). The cross-section shows that Santa Maria sits on the uplifted SSW shoulder of the TR.*  
 680 *Background shaded relief from EMODnet portal (<https://www.emodnet-bathymetry.eu/>).*  
 681  
 682

683 **6. Conclusion**

684           The revised volcanic stratigraphy proposed here for Santa Maria comprises four units,  
685 involving three main volcanic complexes (Basement, Old and Young) and a sedimentary  
686 complex. The Old and Young volcanic complexes are separated by a major unconformity on  
687 which the sedimentary complex lies. The lava flows of the Old and Young volcanic complexes  
688 dip gently to the west (consistent with the younging of radiometric ages to the west), and the  
689 major unconformity separating them dips gently in the opposite direction, i.e. to the east.

690           Prior to ca. 6.0 Ma, a seamount (Basement Complex – BC) began growing from the  
691 ocean floor to eventually reach the sea surface and form a proto-Santa Maria Island. At around  
692 6.0 Ma, a shield volcano had emerged out of the ocean to form the original Santa Maria Island,  
693 which grew until ca. 5.2 Ma, the youngest age of the Old Volcanic Complex.

694           The time span between the youngest age of the Old Volcanic Complex (ca. 5.3 Ma or  
695 younger) and the oldest age of the Young Volcanic Complex (ca. 4.8 Ma or older) is < 0.5 Ma,  
696 inconsistent with marine and meteoric erosion being responsible for the selective removal of  
697 more than half of the first shield volcano. Therefore, we infer that, sometime between 5.2 and 4.9  
698 Ma, a sector collapse removed the whole eastern flank and part of the summit of the first shield  
699 volcano (Fig. 14). The east-dipping collapse scar was first covered by a tsunami deposit made of  
700 chaotic conglomerates, and later by shallow marine sediments reflecting increasing water depth  
701 and age of fossils to the east.

702           At around 4.9 Ma, the Young Volcanic Complex started filling the collapse scar from  
703 east to west (Fig. 14), initially as submarine volcanism. The new shield volcano grew out of the  
704 ocean to the east until ca. 3.8 Ma, and the island subsided by more than 100 m due to loading.  
705 Supported by the fact that more than half of the second shield volcano is missing, and that  
706 Strombolian cones aged ca. 3.6 Ma lie unconformably on the older Young Volcanic Complex,  
707 we infer that a second flank collapse at ca. 3.7 Ma removed the whole eastern flank and the

708 summit of the second shield volcano. This second collapse was soon followed by the  
709 emplacement of conformable (on the undamaged western flank) and unconformable (on the  
710 collapse scar to the east) volcanic cones from ca. 3.6 to 2.8 Ma (Fig. 13). Based on the position  
711 of the main feeding centres inferred from the distribution of radial dykes here, we constrain the  
712 location of the faults produced by the two inferred flank collapses. Smaller landslides, together  
713 with marine and meteoric erosion have further shaped Santa Maria through to its present-day  
714 topography, and are responsible for the great variability in marine shelf width around the island.

715         The stress field within the island changed from NNW-SSE to ENE-WSW oriented least  
716 compressive stress at around 5 Ma, because the orientation of dykes intruding only the Old  
717 Volcanic Complex (i.e. older than 5.2 Ma) is mostly WSW-ENE, and dykes intruding only the  
718 Young Volcanic Complex (i.e. younger than 4.9 Ma) are mostly oriented NNW-SSE.  
719 Coincidentally, the inferred collapse faults have an orientation similar to the normal faults mapped  
720 at Santa Maria, which suggests a genetic relationship between extension/rifting and large-scale  
721 mass wasting on the island.

722         From the current altitude occupied by sub-aerial and submarine lavas, we can conclude  
723 that Santa Maria has undergone important vertical movements throughout its evolution.  
724 Subsidence occurred during growth of the YVC, as attested by the diachronic deposition of  
725 marine sediments (which are younger to the west) and the distribution of marine and sub-aerial  
726 lavas of the YVC. Given that uplift postdates submarine volcanism (youngest at ca. 3.0 Ma),  
727 magma ponding as a mechanism to explain the inferred uplift is not consistent with the current  
728 data on Santa Maria. Instead, the major uplift experienced by Santa Maria, as indicated by  
729 submarine lavas outcropping at ca. 200 m asl, is here considered as being the result of rift flank  
730 uplift on the southern shoulder of the nearby Terceira Rift in the last ca. 1.5 Ma.

731         We conclude that one can identify large-scale sector collapses based on data collected  
732 onshore, mostly through the recognition of major unconformities and their interpretation, i.e. that

733 they represent the removal of large portions (more than half) of the earlier edifice. Here we show  
734 that the inferred flank collapses may have been triggered by tectonic stresses and strain, i.e.  
735 during a rifting stage active at around 5-3 Ma that produced the Santa Maria transient rift.  
736 Therefore, Santa Maria can be used as a case-study for similar oceanic islands in tectonically  
737 active settings.

738

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747

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949



950 **Supplementary material**

951 *Appendix 1 – K-Ar dating method*

952 Careful microscopic examination of thin-sections was carried out to identify the textural  
953 and petrographic characteristics of the samples and ensure that they did not suffer any significant  
954 alteration. As all our new samples from Santa Maria are basic to slightly evolved lavas, the  
955 groundmass was selected. The samples were crushed and sieved to the chosen fraction (typically  
956 125-250  $\mu\text{m}$ , except sample SMA16O sieved at 125-250  $\mu\text{m}$ ). After ultrasonic cleaning in a dilute  
957 nitric acid solution (10%), followed by complete rinsing in distilled water and drying, heavy  
958 liquids were used to eliminate all the phenocrysts (e.g., plagioclase, pyroxene or olivine  
959 phenocrysts), which are K-poor and may carry potentially unsuitable inherited excess  $^{40}\text{Ar}$ . The  
960 samples were then dated with the K-Ar Cassinot-Gillot technique, which has been shown well-  
961 suited to date Quaternary volcanic products precisely, even low-K basalts and andesites (Gillot et  
962 al., 2006; Quidelleur et al., 2008; Germa et al., 2010, 2011; Boulesteix et al., 2012; 2013; Ricci  
963 et al., 2015; 2017). This technique has been extensively used in the last decade to constrain the  
964 age of volcanism and flank instabilities in the Azores (Hildenbrand et al., 2008; 2012a,b, 2012;  
965 Costa et al., 2014; 2015; Sibrant et al., 2014, 2015a,b, 2016). K was measured by flame  
966 absorption spectrometry and compared with standards MDO-G (Gillot et al., 1992) and BCR-2  
967 (Wilson, 1997), both attacked and measured in the same conditions as the samples. Ar was  
968 measured by sector mass spectrometry (Gillot and Cornette, 1986). Details about the analytical  
969 procedure and calculation of uncertainties can be found elsewhere (e.g. Gillot et al., 2006;  
970 Germa et al., 2010; Boulesteix et al., 2013; Hildenbrand et al., 2014; 2018). Decay constants and  
971 isotopic ratios of Steiger and Jäger (1977) were used.

972

973 **Supplementary figures**

974



975

976 *Figure S-1. 3-D Google Earth image to show that the gentle slope to the west is mainly*  
977 *structural, i.e. closely follows lava flow dip (dashed orange lines). The steps observed on the*  
978 *topography can therefore represent the front of successive lava flows that did not reach the same*  
979 *distance from the feeder. OVC, ISC and YVC stand for Old Volcanic Complex, Intermediate*  
980 *Sedimentary Complex, and Young Volcanic Complex, respectively. Data from SIO, NOAA, U.S.*  
981 *Navy, NGA, GEBCO.*

982

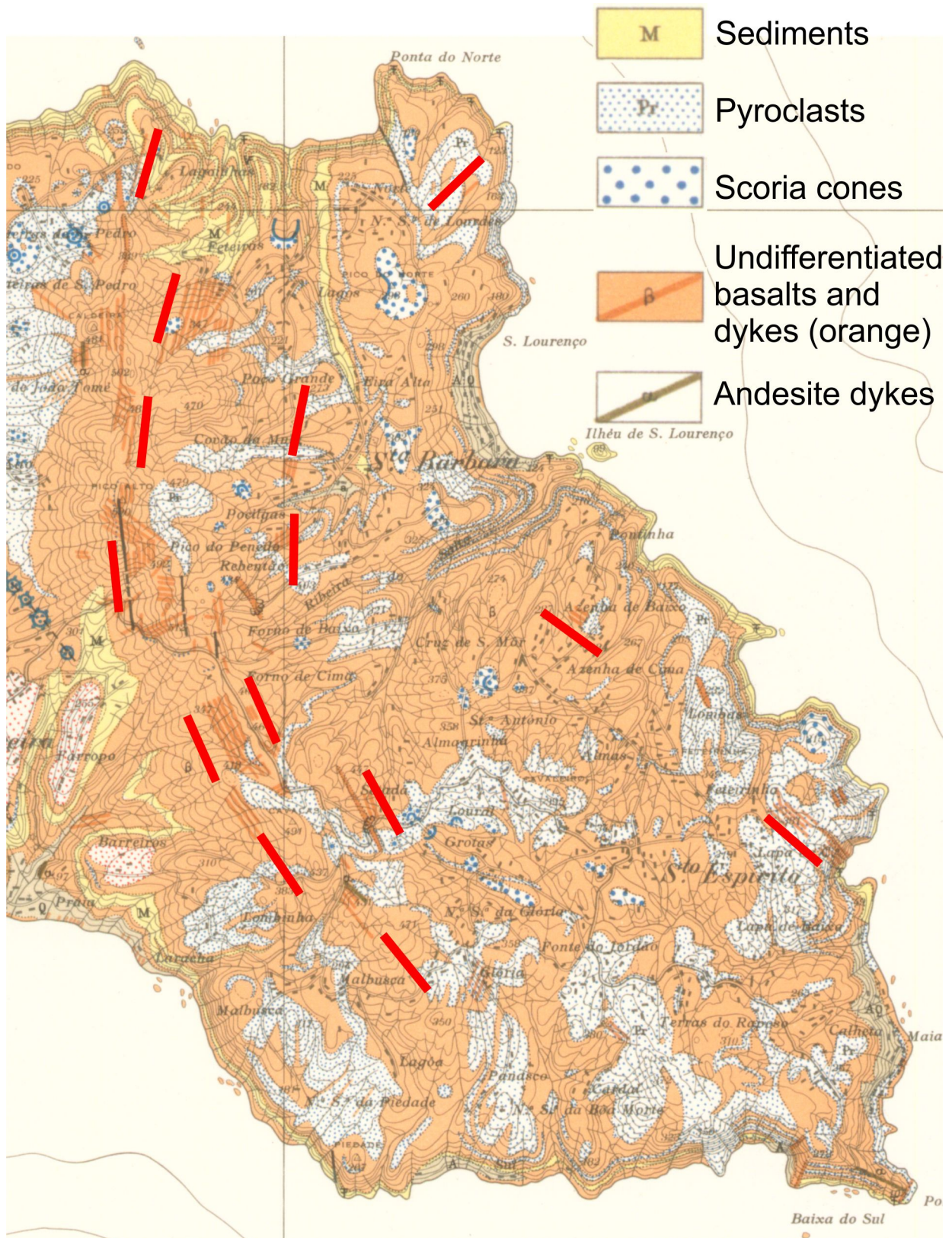


983

984 *Figure S-2. Multiple injection, sub-vertical dyke striking ENE-WSW, indicating preferential*  
985 *NNW-SSE opening.*

986





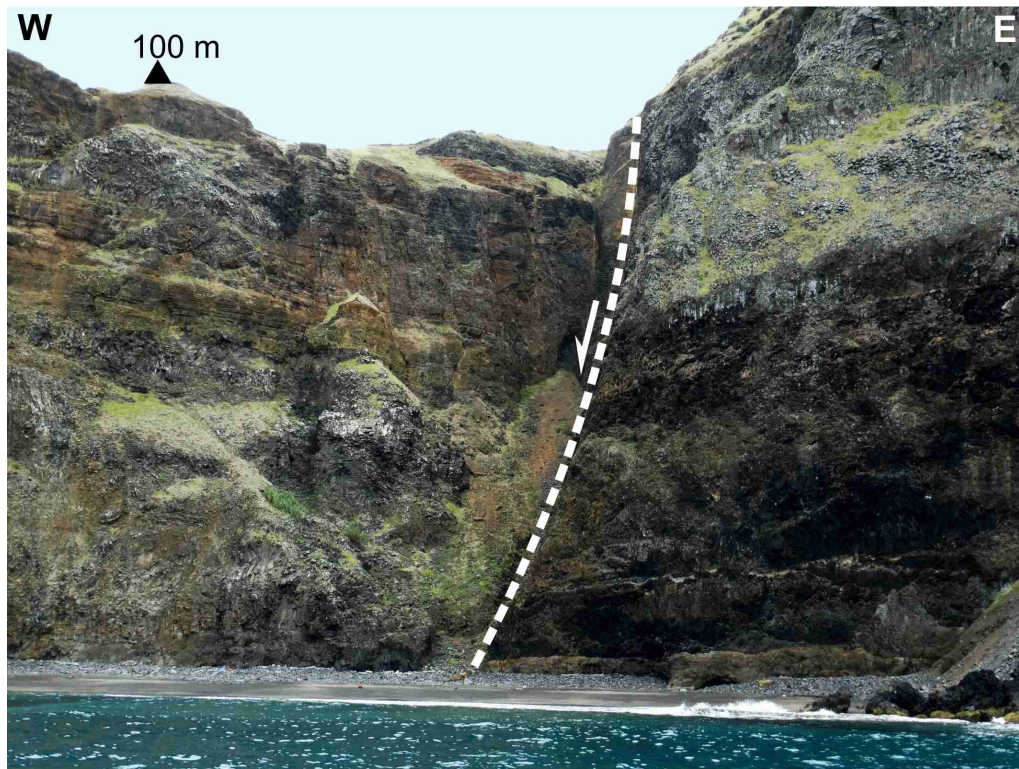
987

988 *Fig. S-3. Extract of the geological map of Zbyszewski and Ferreira (1960) in which dykes*  
 989 *(orange lines) display a curved, concave to east, trend (highlighted in red), varying from NW-*  
 990 *SE in the south, to NNE-SSW in the north.*

991

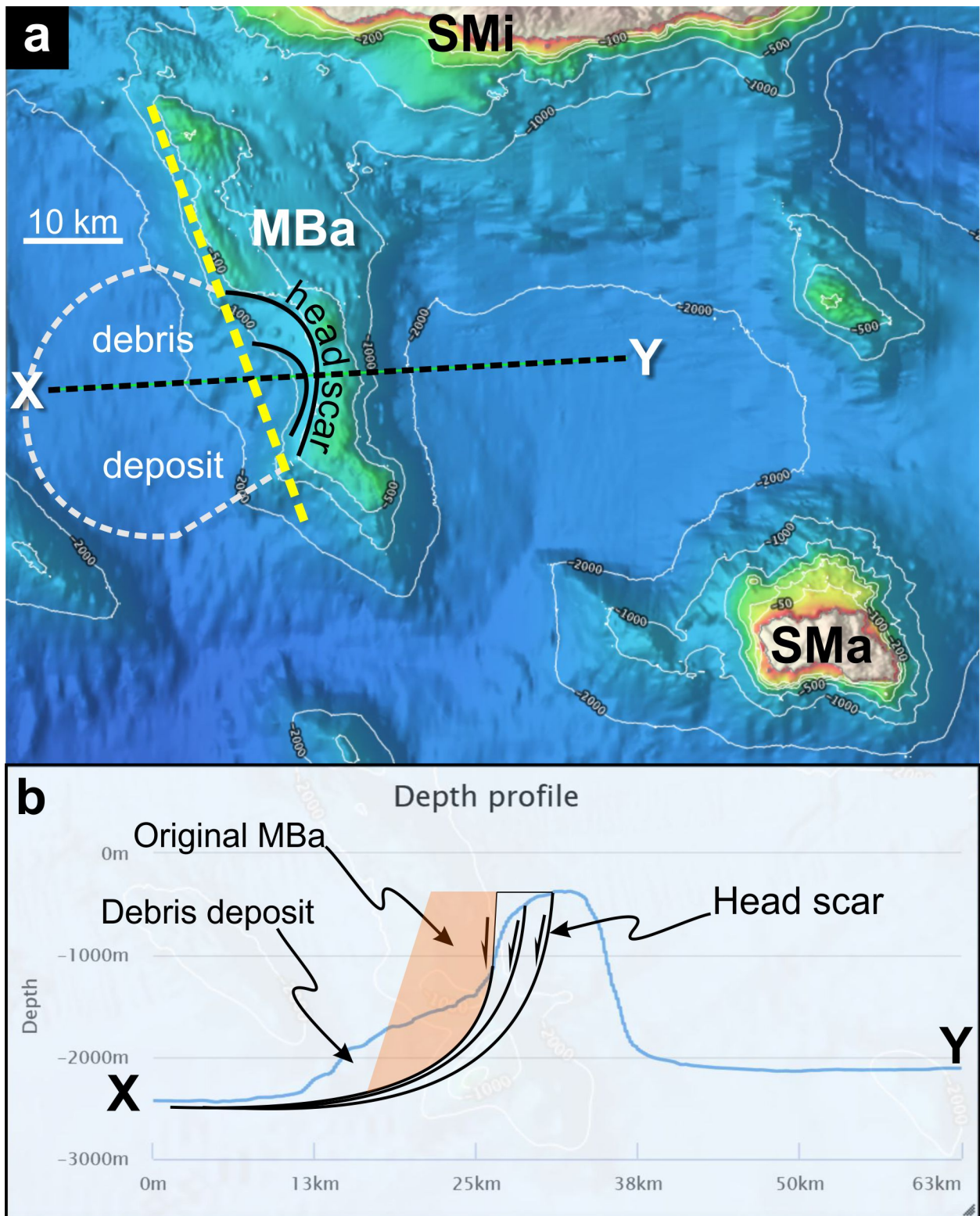
992





993

994 *Figure S-4. Normal fault dipping to the west. This normal faulting attests to the change in the*  
995 *stress field from NNW-SSE  $\sigma_3$  (dominant dykes of the OVC) to ENE-WSW  $\sigma_3$  (dominant normal*  
996 *faulting cutting OVC and YVC).*



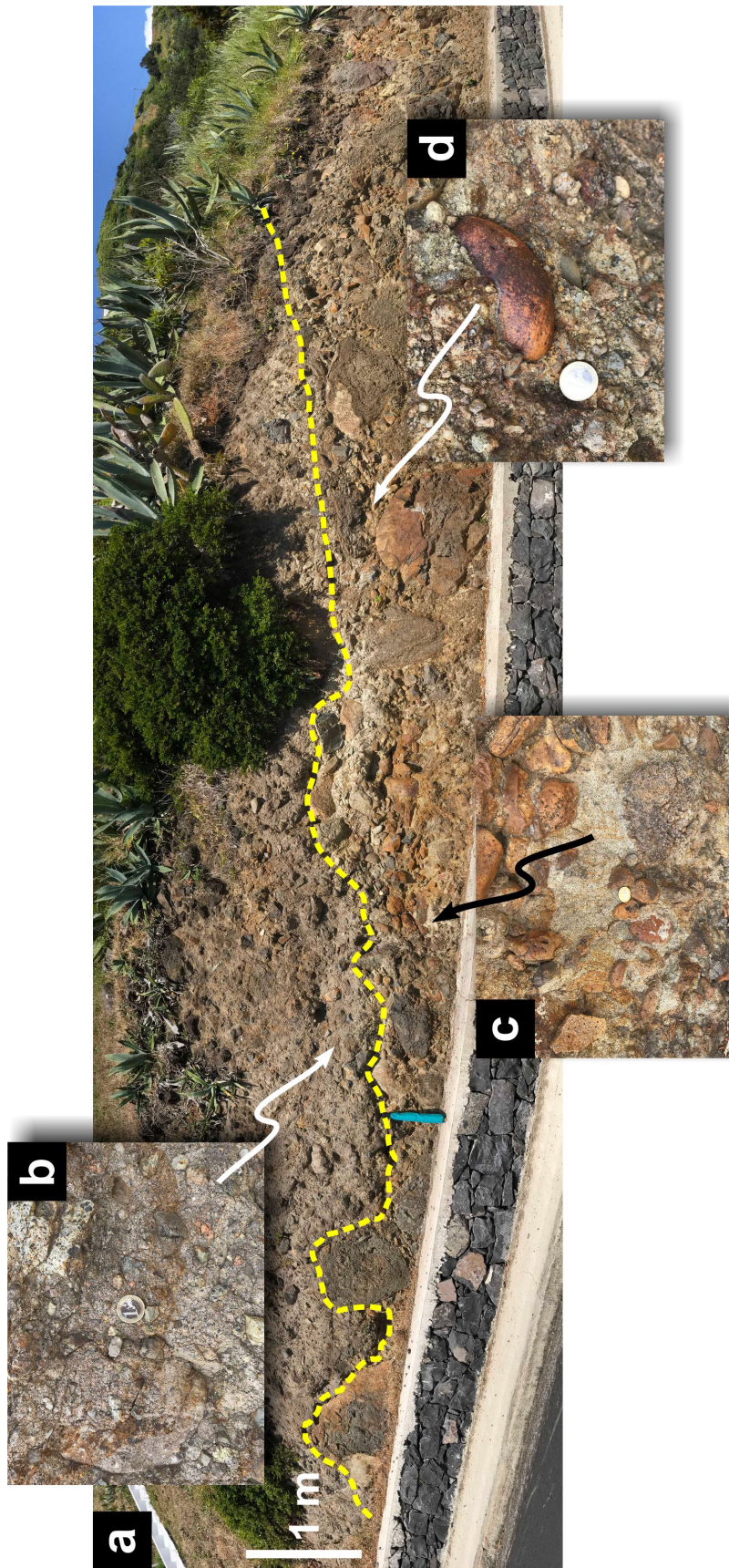
997

998 *Figure S-5. (a) – Shaded relief of the bathymetry around the Monaco Bank (MBa) and Santa*  
 999 *Maria Island (SMa). The flat and elongated top of the MBa is interrupted by a half-moon scar*  
 1000 *concave to the west, which, similarly to Weiß et al. (2016), we interpret as the scar of a LSMW,*  
 1001 *the debris deposit of which is visible in the bathymetric profile shown in (b). Note that the full*  
 1002 *Santa Maria Island fits inside the scar, which gives an idea of the dimension of the MBa LSMW.*

1003 *The yellow dashed line marks the original position of the western edge of the MBa. The X-Y*  
 1004 *dashed line marks the location of the bathymetric profile shown in (b). Background shaded relief*

1005 *from EMODnet portal (<https://www.emodnet-bathymetry.eu/>). (b) – Bathymetric profile with*  
1006 *interpreted landslide faults, mainly based on the scars observed on the bathymetry. Light orange*  
1007 *shaded wedge represents the original shape of the MBa in an E-W section, which compares very*  
1008 *well with the inferred debris deposit. The orange shaded wedge was drawn using the distance*  
1009 *from the original MBa western edge to the head scar, and the MBa eastern slope.*

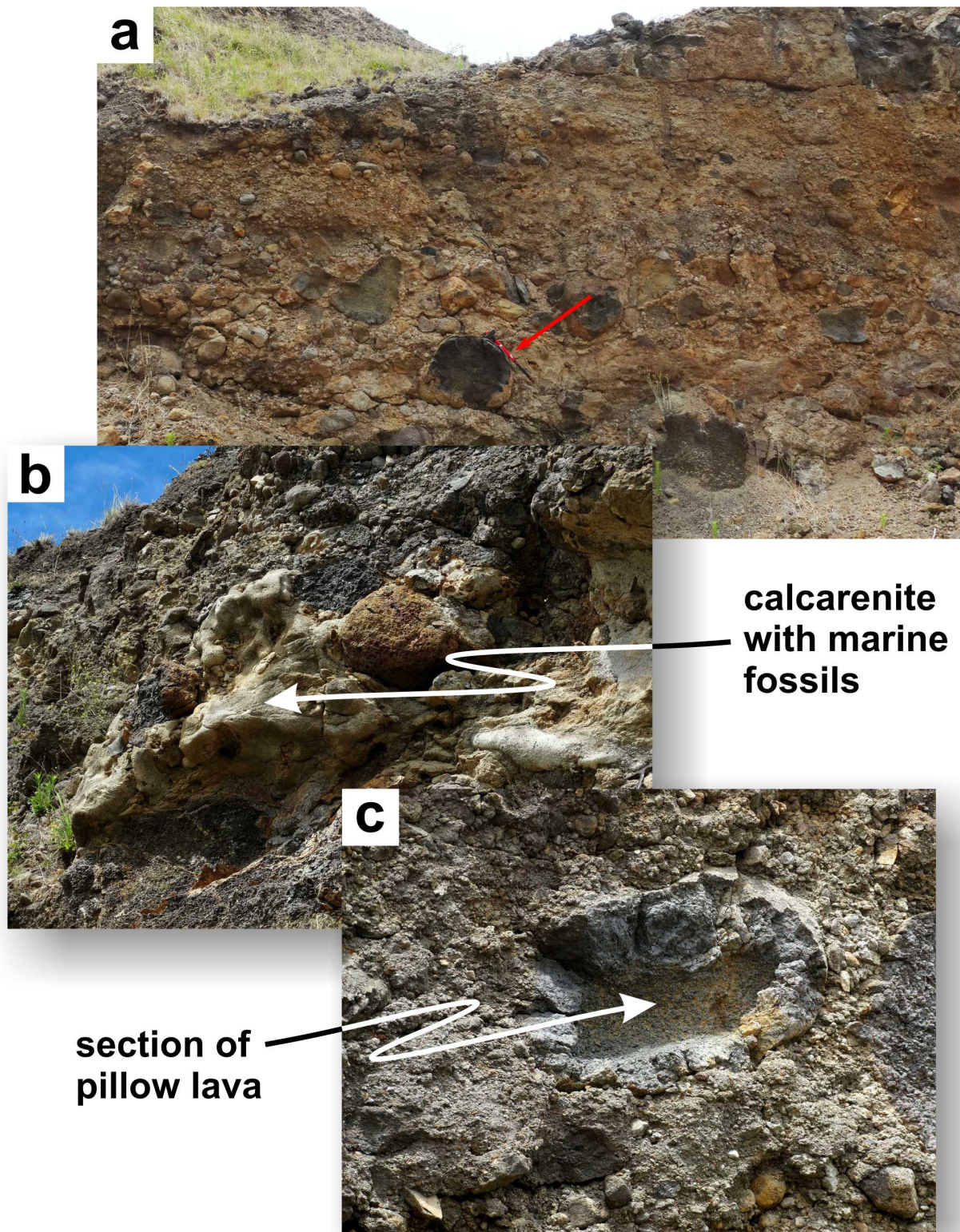




1010

1011 *Figure S-6. Image of the polygenetic chaotic debris deposit outcropping on the road going down*  
 1012 *to Praia. Insets to show details described in the text. Green umbrella (ca. 0.5 m long) for scale in*  
 1013 *(a).*

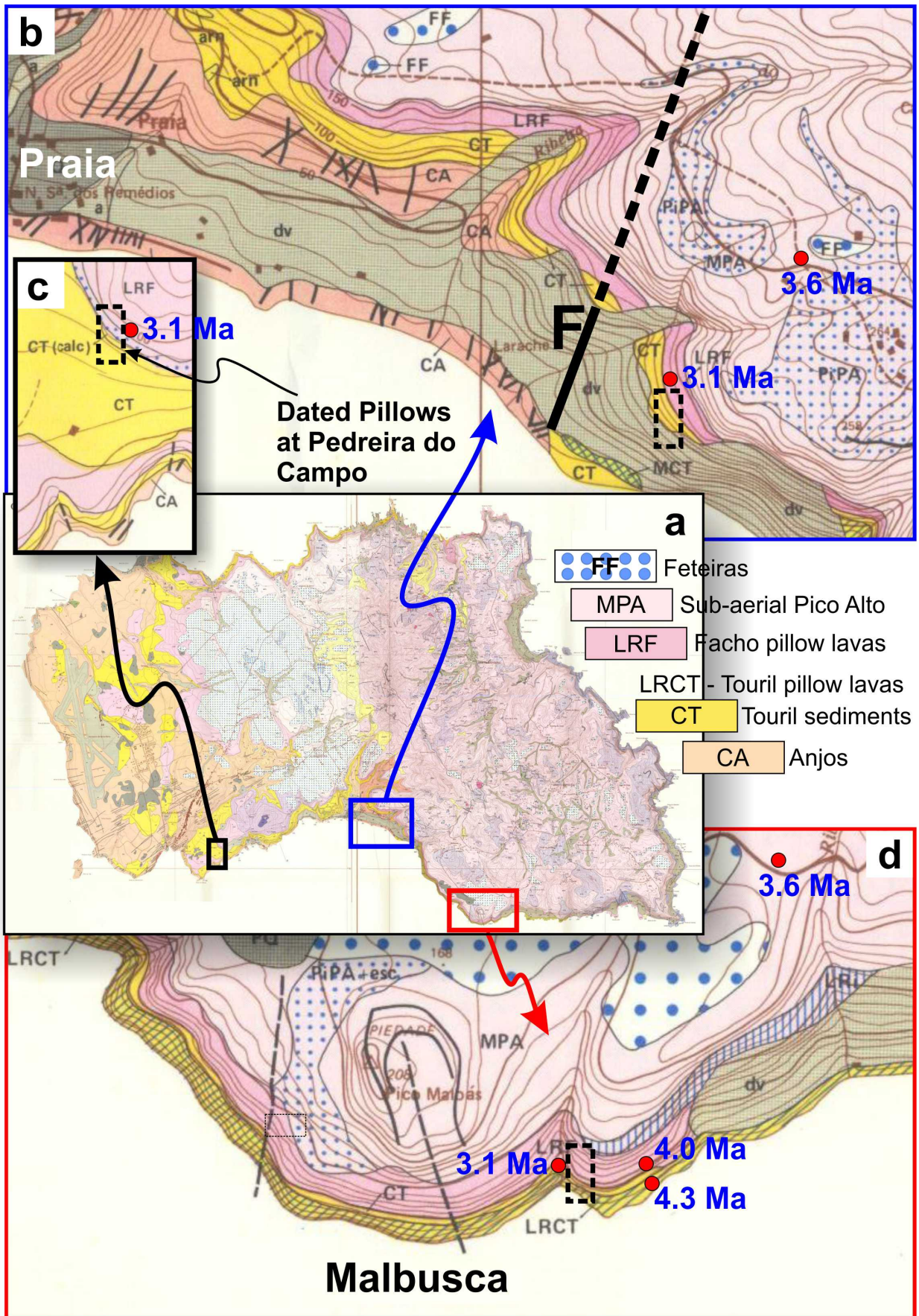




1014

1015 *Figure S-7. Image of chaotic debris deposit (a) containing large boulders originated in the sea:*  
 1016 *calcarenite with many marine fossils (b) and section of submarine pillow lava (c). The debris*  
 1017 *deposit lies unconformably on sub-aerial Old Volcanic Complex. Red arrow points to*  
 1018 *sledgehammer (ca. 1 m long handle) on pillow lava for scale.*



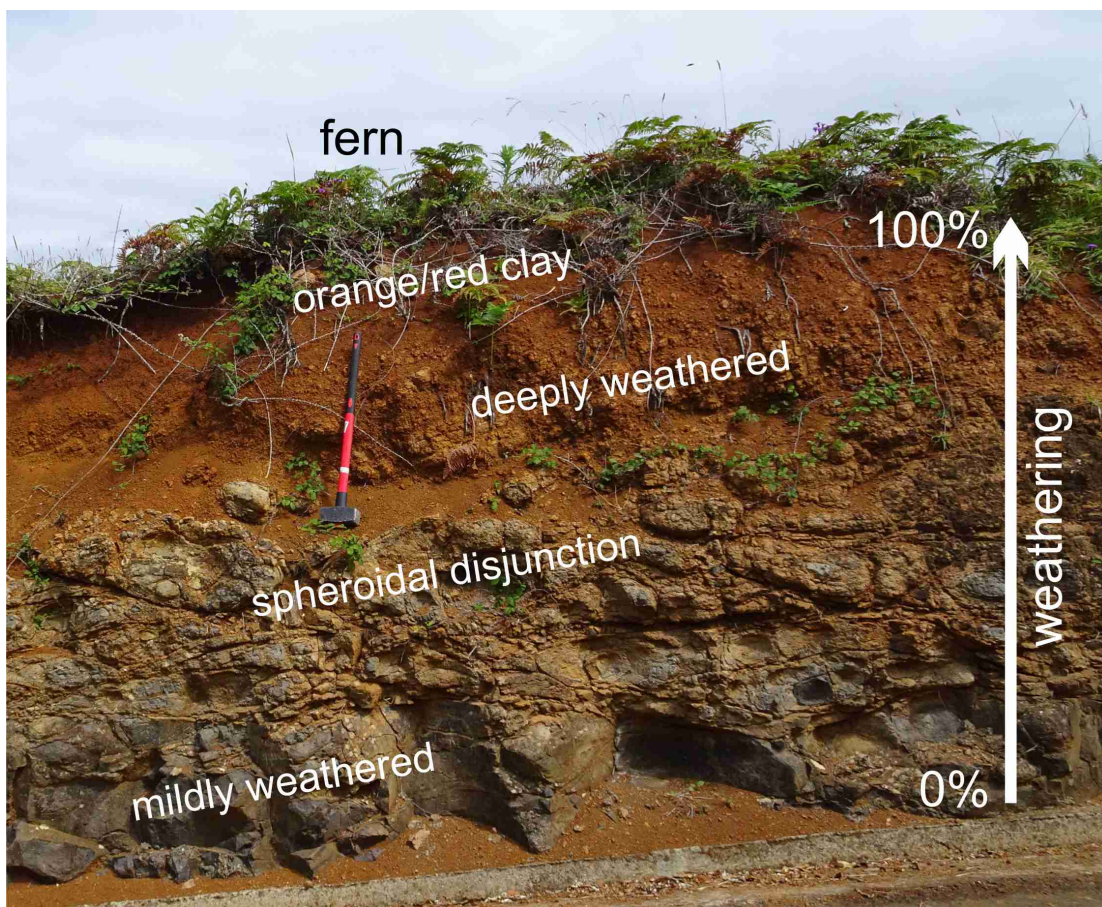


1019

1020 *Figure S-8. (a) – full official geological map made by Serralheiro et al. (1987), surrounded by*

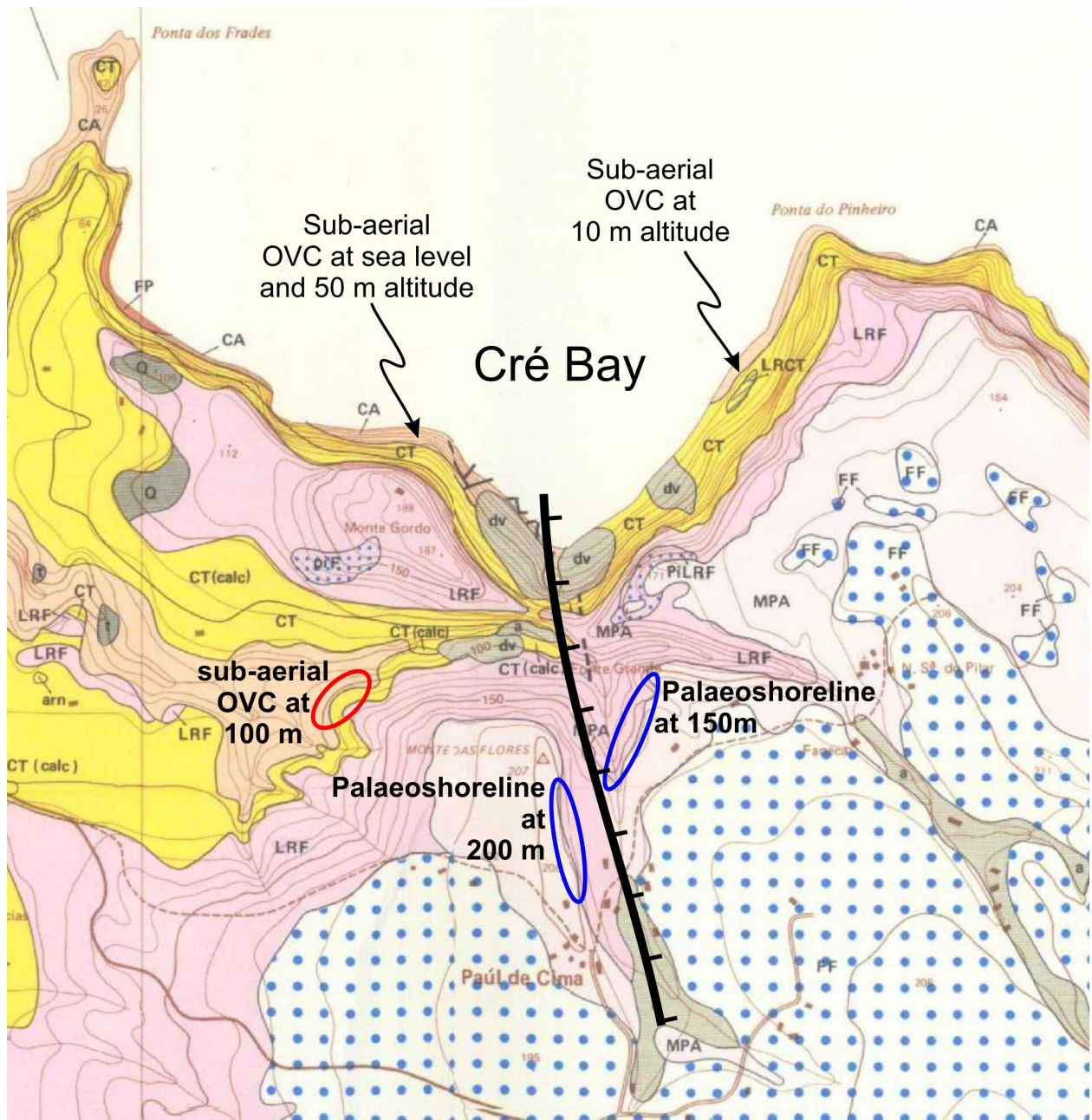


1021 *three extracts of the map to show inconsistencies between the stratigraphy established in 1987*  
1022 *and the stratigraphy constrained here and in Sibrant et al. (2015a) by K-Ar dating. Note that:*  
1023 *(1) extrapolation of the age of dated pillows at Pedreira do Campo (c) to similar settings (b and*  
1024 *d) along the same yellow unit to the east (CT, Complexo do Touril of Serralheiro et al., 1987)*  
1025 *leads to major inconsistencies; (2) the submarine lavas (LRF) here dated at 3.1 Ma at Pedreira*  
1026 *do Campo (c) cannot be overlain by lava flows that are older (b and d); (3) the CT sediments at*  
1027 *Pedreira do Campo (ca. 3.2 Ma) cannot be the same as the CT sediments to the east atop Praia*  
1028 *(b) and at Malbusca (ca. 4.1 Ma) in (d); (4) there must be a scarp where a thick black line is*  
1029 *drawn in (b) and marked F, because the CA unit ends abruptly at sea level, it reaches 150 m*  
1030 *altitude immediately to the north, and the chaotic debris deposit (CT) also ends here, where the*  
1031 *conglomeratic deposit passes into submarine lavas of the LRCT; this scarp/fault has to be older*  
1032 *than the CT because it does not cut it.*  
1033



1034  
1035 *Figure S-9. Typical outcrop of the “Feteiras Formation”. It is clear from this image that the top*  
1036 *orange clay is not a pyroclast, it is the product of deep weathering of a lava flow from the YVC.*  
1037 *This is a typical outcrop that can be found in tropical islands like Oahu, in Hawaii (cf. Google*  
1038 *image, red soil visible on the NW quadrant of Oahu where the Portuguese settlers grew sugar*  
1039 *cane and pineapple).*  
1040

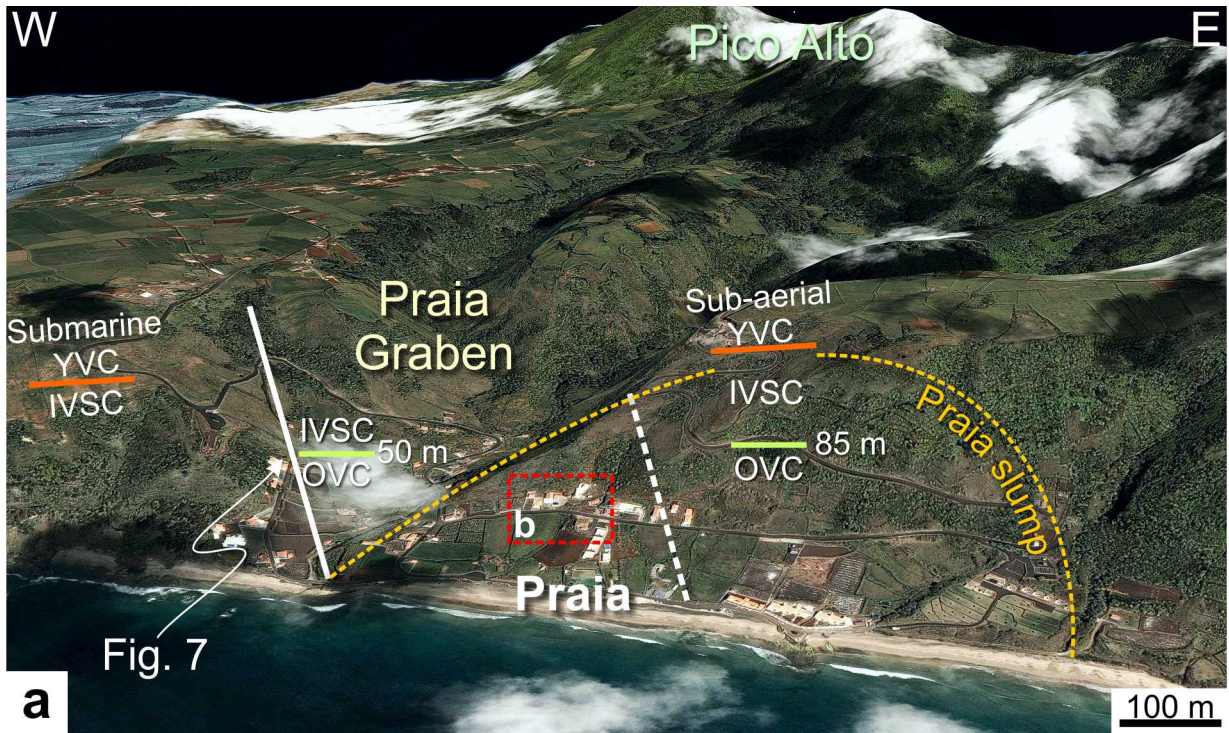




1041

1042 *Figure S-10. Extract of the geological map by Serralheiro et al. (1987; central-north Santa*  
 1043 *Maria) to show: (1) the altitude at which ca. 3.6 Ma palaeoshorelines outcrop (blue ellipses); (2)*  
 1044 *the Cré normal fault (ticks on downthrown block) that connects to the south with the Praia*  
 1045 *Graben; (3) the ca. 50 m displacement on the fault; (4) that the island subsided by, at least, 100*  
 1046 *m during deposition of the YVC (with stationary sea level), because this is the difference between*  
 1047 *the altitudes of the palaeoshoreline and the underlying sub-aerial OVC (red ellipse). See legend*  
 1048 *in Fig. S-8 for colour code.*





1049

1050 *Figure S-11. (a) – 3-D Google Earth image to show: (1) the position of the passage zone*  
 1051 *between sub-aerial (east) and submarine (west) lavas of the YVC; (2) the position of the Praia*  
 1052 *Graben, defined by an observed normal fault in the west (white solid line – see details in Fig. 7)*  
 1053 *and by an inferred fault (white dashed line) in the east (from different altitude of the base of the*  
 1054 *ISC); (3) the Praia Slump, currently creeping to the south. (b) – photo of house being torn apart*  
 1055 *by the internal creeping motion of the slump, and road showing small grabens in the foreground*  
 1056 *and background. Data from SIO, NOAA, U.S. Navy, NGA, GEBCO.*  
 1057