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# 1 **Fluid seepage associated with slope destabilization along the Zambezi**

## 2 **Margin (Mozambique)**

3

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13

### 14 **ABSTRACT**

15

16 Evidences for active fluid seepages have been discovered along the Zambezi continental slope  
17 (offshore Southern Mozambique). These seepages are mostly associated with pockmarks  
18 which are aligned along a trend parallel to the slope and running closely upstream of the  
19 headwall scarp of a wide zone of slope destabilization. Fluid seepages are interpreted as a  
20 potential trigger for the slope destabilization. Acoustic anomalies within the water column  
21 have been interpreted as related to moderate bubble seepages mostly located outside and only  
22 punctually inside the destabilization zone. Exploration with the SCAMPI towed camera  
23 system in the widest pockmark (diameter 200 m wide) has shown fluid seepages associated  
24 to authigenic carbonate crusts and bacterial mats. These fluid seepages are also associated to  
25 the presence of chemosynthetic organisms (Vesicomidae and Thyasiridae bivalves,  
26 Siboglinidae tubeworms). The sampled gas in the sediment corresponds mainly to CH<sub>4</sub> of  
27 microbial origin, generated by hydrogenotrophic methanogenesis from a substrate of organic  
28 origin, *i.e.* a conventional process of genesis of microbial gas in the marine domain. No  
29 evidence for thermogenic gas was detected. Another type of pockmarks has been observed  
30 within the core of the slope destabilization zone. Most of these pockmarks are inactive in  
31 terms of fluid seepage at present time and are associated to carbonate buildups forming  
32 chimney geometries. They probably correspond to diagenetic chimneys of former fluid  
33 migration pathways that have been exhumed during the mass sliding and the surrounding  
34 depression are related to recurrent activity of strong lateral slope currents which have scoured

35 the sediments around. The spatial organization of the slope destabilization features is  
36 considered as representative of the temporal evolution of the landslide giving information  
37 about the dynamics of slope instability processes. This proposed evolution started by scattered  
38 seepages of formation water with dissolved gas. Then free gas seepages appeared notably in  
39 the upper part of the slope. This was followed by progressive shallow deformation in the  
40 sediments downslope of the main gas seepages. Finally, the whole slope was destabilized  
41 forming imbricated landslides exhuming locally former diagenetic chimneys.

42

## 43 **1. Introduction**

44

45 Marine cold fluid seepages commonly develop along continental margins worldwide.  
46 Seepages are found from shallow to deep water domains and they are especially common in  
47 the external platform to the upper continental slope (King and MacLean, 1970; Deville et al.,  
48 2006; Gay et al., 2006; Judd and Hovland, 2007; Prinzhofer and Deville, 2013; Dupré et al.,  
49 2007, 2010, 2014, 2015; Mascle et al., 2014; Riboulot et al., 2018; Marsset et al., 2018). The  
50 widespread occurrence of fluid seepages along margins has been largely emphasized by  
51 increasing multibeam seabed coupled with water column studies during the last decades  
52 (Dupré et al., 2010, 2014). Fluid seepages are commonly associated with the precipitation of  
53 authigenic carbonates around the vents associated with the microbially driven oxidation of  
54 methane present within the fluid seepages by sea water sulfate (Naehr et al., 2000; Aloisi et  
55 al., 2002; Peckmann et al., 2001; Bayon et al., 2013; Rongemaille et al., 2011; Pierre et al.,  
56 2012, 2014, 2017). Fluid overpressure along continental slopes are commonly associated with  
57 sedimentary instabilities responsible for slope destabilization (Sultan et al., 2004a and b; Bunz  
58 et al., 2005; Urlaub et al., 2015; Elger et al., 2018). Reciprocally, slope destabilization is also  
59 locally a possible trigger for fluid seepage (Kramer et al., 2017). The present study focuses on  
60 fluid seepages and slope destabilization processes which have been observed along the  
61 Zambezi continental slope. It is based on the geophysical characterization of seep-related  
62 structures, water column acoustic anomalies, fluid emissions analysis and authigenic  
63 carbonate analysis. The objective of this paper is to better characterize these fluid seepages  
64 and to show how they are closely associated with a wide zone of destabilization of the  
65 sediments along the continental slope. The study area appears to correspond to a typical case  
66 where the spatial organization of the slope destabilization features seems directly

67 representative of the temporal evolution of the landslide providing information about the  
68 dynamics of slope instability processes.

69

## 70 **2. Geological framework**

71

72 The sediment accumulation on the Zambezi platform has occurred progressively during more  
73 than 140 Ma on the western continental margin of the Mozambique channel (Salman and  
74 Abdula, 1995; Walford et al., 2005) which developed since the breakup of Gondwana and the  
75 formation of the oceanic lithosphere of the Mozambique Channel during Jurassic times  
76 (Leinweber and Jokat, 2012; Reeves, 2014; Key et al., 2015; Mueller and Jokat, 2019;  
77 Thompson et al., 2019). The deep water area of the Mozambique basin is characterized by the  
78 development of an oceanic lithosphere which began to develop during the Mid Jurassic-  
79 Cretaceous drift of Antarctica with respect to Africa (Rabinowitz et al., 1983; Coffin and  
80 Rabinowitz, 1987). Nowadays, the central part of the Mozambique Channel is still  
81 tectonically active (Marsset et al., 2018; Deville et al., 2018) and presents an anomalously  
82 high topography (Castelino et al., 2016; Deville et al., 2018). The Zambezi River is the fourth  
83 main river of Africa in terms of water flux (after the Nile, the Congo and the Niger) and it is  
84 the main one along the east African coast. The solid particles transported by the Zambezi river  
85 have largely been deposited along the Zambezi platform which corresponds to a major  
86 accumulation of sediments (locally more than 6000 m) located along the east African  
87 transform passive margin, in the offshore of southern Mozambique (Walford et al., 2005;  
88 Mahajane, 2014; Ponte, 2018, 2019 and references therein) (Fig. 1). The oceanic domain of  
89 the Mozambique basin is also largely covered by sediments deriving from the Zambezi  
90 turbidite system (Kolla et al., 1980; Droz and Mougnot, 1987; De Ruijter et al., 2002;  
91 Walford et al., 2005; Kolla et al., 1991; Mahanjane, 2012; Mahanjane et al., 2014; Halo et al.,  
92 2014; Breitzke et al., 2017). The Zambezi river delivered more than  $16 \times 10^3$  t/Ma of  
93 sediments during Quaternary times (Walford et al., 2005) but this flux has been disturbed  
94 recently by several dams trapping sediments in the Zambezi water shed (Moore et al., 2007).  
95 Nowadays, the Zambezi turbidite system is disconnected from the Zambezi river system  
96 (Schulz et al., 2011; Fierens et al., 2019; Miramontes et al., 2019). The sediments are  
97 dispersed by strong NNE-SSW trending coastal currents on the continental shelf (Schulz et  
98 al., 2011; Wiles et al., 2017a and b). A recent modeling approach suggested the activity of  
99 strong bottom current along the Zambezi continental slope mainly from NNE to SSW along

100 the Zambezi shelf (Mozambique current) and from SSW to NNE along the lower Zambezi  
101 slope (Mozambique undercurrent; Miramontes et al., 2019). The Zambezi margin is not  
102 affected by massive gravity shale tectonics processes like it is the case in similar shale-rich  
103 systems as the Niger Delta (Corredor et al., 2005), the Amazon (Cobbold et al., 2004) or the  
104 northern margin of Mozambique in the Rovuma basin (Mahanjane and Franke, 2014). One of  
105 the characteristics of the Zambezi platform and continental slope is that only the uppermost  
106 part of the sedimentary pile is affected by wide marine landslides which occurred repetitively  
107 (Ponte et al., 2018a and b). The sedimentary architecture of the Zambezi platform and  
108 continent slope correspond to a massive (> 2 km thick) prograding system from Early Miocen  
109 to present time (Ponte et al., 2018).

110

### 111 **3. Material and methods**

112

#### 113 *Geophysical acquisitions*

114

115 The data presented in this study were acquired during PAMELA-MOZ04 (2015) survey on  
116 board the R/V *Pourquoi pas?* (Jouet and Deville, 2015) in the framework of the PAMELA  
117 research project (PAssive Margins Exploration Laboratories; Bourillet et al., 2013).  
118 Multibeam echosounder data were used for bathymetry mapping (Fig. 2) but also for the  
119 detection and location of free gas emissions in the water column through water depths ranging  
120 from 61 to 1021 m in the studied area (Fig. 3). The multibeam dataset was collected with a  
121 Reson Seabat 7111 for shallow waters (5 to 500 m, 100 kHz) and a Reson Seabat 7150 for  
122 deeper waters (200 to 4000 m, 24 kHz, across and along-track beam width of 0.5°). Beyond  
123 water depths of 500 m, the Reson 7150 (24 kHz) was used with the following configuration:  
124 multiping option (4 swaths per ping) with 880 beams and nominal swath coverage of 150°  
125 (effective average of 145°). The multibeam acoustic coverage was acquired at an average  
126 speed of 9 knots which allows an average inter-ping distance of 4.3 m. Also, 24-channel mini  
127 GI-gun seismic reflection data were acquired during the PAMELA-MOZ04 survey. In  
128 addition, hull mounted Sub-Bottom Profiler (SBP) was operated in a chirp configuration (1.8-  
129 5.2 kHz) that offers a vertical resolution of 0.30 m and a maximal penetration of 100 m.

130

#### 131 *SCAMPI system*

132

133 The SCAMPI (Système de CAméras Ponctuel Interactif) is a towed system devoted to make  
134 direct observations at the sea bottom and to acquire submarine photos and video shooting. It is  
135 designed to operate between 3 and 10 m above the seabed and down to 6000 m of water  
136 depth. A CTD sensor was also mounted on the frame, monitoring water depth and  
137 temperature along the SCAMPI track. In the study area, it was operated during two dives  
138 (SCB01 and SCB03) on two different areas where pockmarks are present (Fig. 2).

139

#### 140 *Gas sampling and geochemical study*

141

142 Gas was sampled in three Calypso sediment piston cores (MOZ04-CS18 and MOZ04-CS19,  
143 and also MOZ04-CS17 made north of the study area; see supplementary material Fig. S1, S2,  
144 S3). The gas samples were collected using two different procedures: either directly as free gas  
145 that degassed from the sediment in the liner of core MOZ4-CSF19, or in the form of adsorbed  
146 gas in the sediment collected at the bottom of the cores MOZ4-CS17, MOZ4-CSF18 and  
147 MOZ4-CSF19. The free gas was sampled from the holes made in the PVC liners at the base  
148 of the piston cores to fix the corer bits. The sediments collected at the bottom of the cores, in  
149 the corer bits (*i.e.* at the deepest part of the cores), were placed in 200 ml glass bottles in order  
150 to recover the adsorbed gas in the sediment. The samples were conditioned with a 10 ml air  
151 head-space, 90 ml of sediment and 90 ml of water with 10 drops of mercury dichloride ( $\text{HgCl}_2$   
152  $\sim 1/1000$ ) in order to stop microbial activity after sampling. Samples were stored at 4°C. The  
153 gas was recovered in 10 ml Labco vials using a double needle for analysis.

154 The chemical compositions of the gases were determined by gas chromatography (GC). The  
155  $^{13}\text{C}/^{12}\text{C}$  isotopic ratio measurements ( $\text{CH}_4$  and  $\text{CO}_2$ ) were determined on a MAT253 (Thermo  
156 Fischer) mass spectrometer coupled to a gas chromatograph (GC-C-IRMS for Gas  
157 Chromatography Combustion Isotope Ratio Mass Spectrometry. Detailed procedure is  
158 available in Appendix 2 in supplementary material.

159

#### 160 *Carbonate sampling and geochemical study*

161

162 Carbonate concretions have been recovered with multitube sampler inside the main pock-  
163 mark where MOZ04-MTB5 has been cored (Fig. 4). Attempts to recover carbonates with a  
164 Warren dredge were not successful. The mineralogy and the respective contents of the  
165 different carbonates have been determined by rock-eval method (Pillot et al., 2015). Isotopic

166 measurements were made on the bulk rock powder using a standard continuous flow Isotope  
167 Ratio Mass Spectrometry at the Erlangen University.

168

#### 169 **4. Results**

170

##### 171 *Morphobathymetric features*

172

173 Geophysical data have shown that the area studied, running parallel to the continental shelf  
174 trend from SW to NE, corresponds to a portion of the Zambezi margin covering parts from the  
175 shelf-break of the Zambezi platform to deep water areas along the Zambezi slope (down to -  
176 1200 m; Fig. 2). This area shows a NE-SW segmentation of the geomorphological features.  
177 The NE area corresponds to a sedimentary slope dipping towards the South-East which is  
178 preserved from any gravitational destabilization. The southwest area shows a more complex  
179 pattern and the slope exhibits massive evidences of gravitational destabilization made of  
180 imbricated mass-transport complexes with coarse outrunner blocks downslope (Fig. 2). The  
181 destabilized area is localized south of the Zambezi River mouth. The thickness of the  
182 destabilized sediments varies from less than 25 m to more than 150 m (Fig. S5 and S6 in  
183 supplementary material). The topography of the destabilized zone exhibit some gullies  
184 trending dip-slope with smooth morphology (Fig. 2). Globally, from the NE to the SW, the  
185 slope shows a progressive evolution from (1) a stable area to (2) an area of moderate  
186 destabilization characterized by progressive deformation of the slope, to finally (3) imbricated  
187 and polyphase system of landslides toward the southwest. Each individual landslide unit  
188 forms elongated tongue along the slope for which the detachment level varies from one  
189 tongue to another. In the different domains from the stable area to the massive destabilization  
190 area, different types of pockmarks with distinctive characteristics have been discovered,  
191 providing evidences for active or fossil fluid seepage.

192

##### 193 *Pockmarks outside the destabilization zone*

194

195 The pockmarks identified on geophysical data which are located outside of the destabilization  
196 zone are shown in Figs. 2, 4 and 5. Some of these pockmarks are located northeast and partly  
197 upstream of the northeast extremity of the zone of slope destabilization. A relatively well  
198 organized alignment exists between the pockmarks located to the northeast of the slope  
199 destabilization zone and the pockmarks located immediately upstream of the scarp of the

200 upper part of the SW slide area (Fig. 2). Several pockmarks are associated with acoustic  
201 anomalies in the water column (Fig. 3). The morphology of these anomalies, as observed with  
202 a RESON 7150 MBES, is characteristic of free gas emissions in the water column and their  
203 weak backscattering amplitude may indicate a low flow of bubbles (Fig. 3).

204 Northeast of the destabilization zone, the multibeam data acquired allowed us to identify  
205 several tens of pockmarks. The main ones are mapped in figure 2 and SBP profiles crossing  
206 them are presented in figures 4 and 7. During the SCAMPI dive MOZ04-SCB03,  
207 observations at the sea bottom have been made within and around the largest pockmark which  
208 corresponds to an isolated depression of 200 m in diameter located at 300 m of water depth  
209 (Fig. 4). Sampling with a multitube core system (MOZ04-MTB5) was made inside this  
210 pockmark, and a Calypso piston core (MOZ04-CSF19) was recovered 150 m south of this  
211 pockmark. The center of this pockmark is characterized by a more reflective character on the  
212 SBP data (see supplementary material; Fig. S4). The multitube coring (MOZ04-MTB5) made  
213 in the center of this structure collected sandy sediments with carbonate concretions (Figs. 5,  
214 6). The MOZ04-CSF19 Calypso core shows sandy levels in the upper 2 meters and clay-rich  
215 sediments below (supplementary material Fig. S1). When it returned on deck, the base of the  
216 core was degassing and free gas was directly flowing out from the liner of the core. The  
217 SCAMPI dive (MOZ04-SCB03: Figs. 4, 5) carried out in this pockmark area has shown a  
218 moderate activity of fluid seepages (water) without apparent free gas bubbling. In the center  
219 of the structure, we observed several active vents piercing the sandy surface of the seafloor.  
220 These vents were characterized by the presence of reduced gray/blue sediments and white  
221 areas (mineral precipitation and/or bacterial mats). Carbonate concretions (of maximum  
222 metric horizontal size) have also been observed (Fig. 5). Episodic turbid flows emerging from  
223 these vents have been punctually observed on video shooting (Fig. 5, arrows). The  
224 temperature of the water near the bottom during the SCAMPI dive MOZ04-SCB03 in the  
225 seepage area, where the carbonate samples were collected, was relatively constant between  
226 12.07 and 12.21°C (no obvious thermal anomaly). No acoustic anomalies in the water column  
227 were observed along the profiles acquired over this pockmark. This is probably due to the fact  
228 that no free gas bubble is expelled from this pockmark. The peripheral zone of the pockmark  
229 is mainly populated by Cnidarians (Pennatulles). Their density is low but increases towards the  
230 border of the pockmark. They are associated to ripple marks related to bottom current that  
231 suspend organic matter issued the pockmark area. OM is then used by these suspension-  
232 feeders organisms. Low densities of mollusks (Buccinidae and Ranellidae gastropods),



233 crustaceans (Inachidae), echinoderms (crinoids, asterids) were also observed in this peripheral  
234 zone of the pockmark.

235 At the border of the pockmark depression, the Pennatula density increases and in the center of  
236 the depression, a lobster colony (*Palinurus delagoae*) was observed. The presence of bivalve  
237 shells belonging to the families Vesicomidae and Thyasiridae is also abundant. These  
238 bivalves are common in methane seepage area as they host in their gills symbiotic bacteria  
239 whose metabolism is based on chemiosynthesis (sulfide oxidation) (Dubilier et al., 2008;  
240 Duperron et al., 2013). Also, bouquets of polychaete tubeworms belonging to the family  
241 Siboglinidae (vestimentiferans) were observed. These tubicolous worms are also common in  
242 methane seepage area as they have also the particularity of living in symbiosis with chemo-  
243 autotrophic bacteria, which use sulphides produced in the sediments (Dubilier et al., 2008).  
244 Hydrogen sulphide is produced by anaerobic methane oxidation coupled to sulfate reduction  
245 at cold seeps (Boetius et al., 2000). . The pockmark visited during the MOZ04-SCB03  
246 SCAMPI dive is among the wider of the NE part of the study area but other similar structures  
247 are also present in this area (Fig. 2). They are also associated with characteristic subvertical  
248 seismic anomalies seen in SBP data (see examples in Fig. 7A and B). Note also that clear and  
249 localized reflectivity anomalies are probably related to the presence of free gas as they are  
250 present only locally in thin antiformal layers of the uppermost sediments of this area and they  
251 are not related to characteristic sedimentary structures which might be responsible for the  
252 reflectivity anomalies (Fig. 7C).

253

#### 254 *Pockmarks inside the destabilization zone*

255

256 Different types of pockmarks have been found inside the destabilization zone. Some of them  
257 are located in the northeast most area of the destabilized area. They have a relatively small  
258 size (lower than 200 m), they have elongated shapes and they correspond shallow deformation  
259 structures possibly associated to a dewatering process during the slope deformation (Figs. 2;  
260 S5). Locally, inside the destabilized zone, some moderate positive reliefs are associated with  
261 acoustic anomalies in the water column above (see supplementary material; Fig. S6). They  
262 possibly correspond to moderate gas bubbling associated with the precipitation of carbonate  
263 buildups or mud volcanoes. The pockmarks which are located in the center of the destabilized  
264 zone immediately below the main landslide headwall scarp (Fig. 2, 8, 9, 10, 11) are more than  
265 200. Only the main ones are plotted on figure 2. Their size does not exceed 50 m in diameter.  
266 The location of these pockmarks in the center of the landslide area strongly suggests a

267 potential link between them and the origin of the slope destabilization process. The most  
268 characteristic pockmarks inside the slope destabilization zone are formed by comet-shaped  
269 depressions (Fig. 11). Despite of their small size, on multibeam data, it is possible to  
270 distinguish small positive reliefs in the center of some of these structures (Fig. 11). The center  
271 of these pockmarks also presents high reflectivity on sub-bottom profiler data (see  
272 supplementary material, Fig. S7). During the SCAMPI MOZ04-SCB01 dive in the area,  
273 carbonate buildups have been observed in the center of the pockmarks with circular  
274 depressions around (Fig. 11). Some carbonate buildups present pipes geometries. The most  
275 characteristic have cylindrical shapes with vertical sides and are 3 to 4 m in diameter at their  
276 base, for a height of up to about 8 m. No evidence for active fluid flows at these chimneys  
277 was observed during the dive neither in the water column above. Calypso coring CSF18  
278 sampled dark clay-rich homogeneous sediments without sedimentary structures (see  
279 supplementary material; Fig. S2). The sediments sampled in this core correspond to an  
280 Holocene cover deposited in the bottom of the depression formed during the slide. A Warren  
281 dredging collected also mainly dark mud in which were present many dead organisms but it  
282 was not possible to collect any of the carbonate material seen during the SCAMPI dive.

283 The density of pockmarks with chimney inside is higher near the scarp and decreases  
284 downslope towards the southeast. Some groups of these pockmarks are aligned according to a  
285 dip-slope direction (Figs. 9, 10). These pockmark alignments in the direction of the slope  
286 suggest a subsurface control of the orientation of these lineaments by NW-SE buried  
287 structures (possibly buried channels or canyons, or faults). Down along the slope (below 600  
288 m of water depth), blocks are visible on multibeam data (Fig. 9). These translated blocks are  
289 probably mainly made of carbonates issued from the platform (the main outcropping solid  
290 rocks along the Zambezi margin) and so they are regarded as having a different origin than  
291 the chimneys located upslope (mainly above - 600 m; Fig. 9).

292 Acoustic anomalies in the water column are associated with some of these pockmarks. The  
293 anomalies correspond to sub-horizontal diffusive layers on sonar data (see supplementary  
294 material; Fig. S8) which are elongated downstream, *i.e.* in the direction of the bottom current  
295 flowing SE (the direction of strong bottom current has been directly observed during the  
296 towing of the SCAMPI). These acoustic anomalies initiated at pockmarks with carbonate  
297 inside correspond probably to flows of particles issued from the pockmarks and carried by the  
298 bottom current toward the southeast. Some of these pockmarks are comet tail-shaped,  
299 pointing towards the southeast, which is in good agreement with erosion related to this  
300 direction of downslope current. The trend of several gullies is also compatible with erosion

301 associated with this downslope current (Figs. 8, 9). The calypso coring (CSF18) made in the  
302 area of this pockmark cluster did not reveal any particular evidence that could be associated  
303 with active fluid flows (supplementary material Fig. S2).

304

#### 305 *Gas study*

306

307 Since the gas sampling was done on coring equipment which was largely in contact with the  
308 atmosphere during the recovery of the cores onboard, a significant proportion of air  
309 contributed, in all cases, to dilute the initial gas composition (Tables 1 and 2). The chemical  
310 composition of the gas which was degassing from the core MOZ4-CSF19 made close the  
311 active pockmark of the SCAMPI dive MOZ04-SCB03 (*i.e.* where fluid seepage have been  
312 observed) shows mainly methane and for a minor part CO<sub>2</sub> with traces of C<sub>2</sub> + (contents less  
313 than 0.01%). The isotopic composition of the methane collected in the core MOZ4-CSF19  
314 shows  $\delta^{13}\text{C-CH}_4$  values of -92.2‰ for the free gas seeping out from the liner of the core and -  
315 86.7‰ for the gas adsorbed in the sediments of the corer bit, at the most bottom of the core  
316 (Fig. 12; table 2) and  $\delta\text{D-CH}_4$  from -182.2‰ for the free gas to -170.5‰ in the sediments of  
317 the corer bit (Fig. 13; table 2). The isotopic composition of the CO<sub>2</sub> collected in the core  
318 MOZ4-CSF19 shows values of  $\delta^{13}\text{C-CO}_2$  of -44.5‰ for the free gas and -23.8‰ at the lowest  
319 part of the core (Fig. 14; table 2). No important degassing was observed in cores MOZ4-  
320 CSF17 an MOZ4-CSF18, only adsorbed gas was sampled. Geochemical signatures of these  
321 gas samples are very similar to those of core MOZ4-CSF19 (Figs. 12, 13, 14).

322

#### 323 *Authigenic carbonates*

324

325 Carbonates in the fluid conduits, which have been recovered with multitube sampler inside  
326 the main pockmark of the preserved northern area (MOZ04-MTB5), are made of calcite and  
327 aragonite (RE6 determination; see supplementary material Fig. S9). Isotopic composition of  
328 these carbonates show  $\delta^{18}\text{O}$  bulk rock values ranging between 2.89 and 3.47‰ vPDB and  
329  $\delta^{13}\text{C}$  bulk rock values between -48.87 and -52.50‰ vPDB (Fig. 15, table 3).

330

## 331 **5. Discussion**

332

### 333 *Pockmark activity*

334

335 North-east of the slope destabilization zone a system of pockmarks has been characterized  
336 forming (1) depressions aligned NE-SW between 200 and 300 m of water depth and (2)  
337 scattered depressions in the slope below 300 m of water depth (Fig. 2). Active fluid seepage  
338 corresponding to water escape has been characterized by direct observation thanks to the  
339 SCAMPI in the wider pockmark in the NE of the study area. Acoustic anomalies in the water  
340 column corresponding most probably to free gas bubbles seepages have been characterized  
341 close to the northeast border of the landslide area and upslope of the landslide area. Inside the  
342 landslide, active seepages are rare except punctual seepages but most of the pockmarks are  
343 inactive today. These depressions do not show typical characters of active fluids seepages at  
344 the seabed. It is probable that to the center of these depressions is the place of fossil deep  
345 diagenetic chimneys exhumed during the sliding. They probably correspond to former fluid  
346 migration pathways. These chimneys have probably been active partly after the landslide  
347 because they appear inside the Holocene sedimentary cover that is preserved at the center of  
348 the landslide area (Fig. 10C) but they are inactive today. They would then correspond to  
349 exhumed ancient fluid chimneys similar for instance to those described onshore in Bulgaria  
350 by De Boever et al. (2006). The peripheral depression of the chimneys could be recent and  
351 linked to the action of the currents which scour the sediment around the rigid chimneys. This  
352 would explain the turbidity of the water observed during the SCAMPI dive (MOZ04-SCB01)  
353 and the diffusive layer detected by multibeam acquisition in the water column (see  
354 supplementary material; Fig. S8). The fluids which have circulated in these ancient chimneys  
355 could have been at the origin of overpressures which initiated the gravitational mass  
356 movements (Sultan et al., 2004a and b; Bull et al., 2009). Overpressure are prone to develop  
357 at relatively shallow depths (few tens of meters) taking into account the low permeability of  
358 the sediments and the high sedimentation rate along the Zambezi platform and slope. A  
359 seismic reflection profile acquired upstream of the landslide area provides an image of what  
360 could have been the initial geometry before the slide (Fig. 10A). The landslide tends to be  
361 sealed by the Holocene sediments and it was possibly active mainly during lower stand of sea  
362 level. Indeed, the conjunction of overpressure in the sediments with decreasing load above  
363 (associated in this case with a drop of sea level) is classically considered as favorable to reach  
364 failure condition and so to initiate landslide (Hubbert and Rubey, 1959, Byerlee, 1978).

365

366 *Origin of fluids*

367

368 Geochemical analyses have shown that the gas has a typical microbial origin mainly  
369 generated according to a CO<sub>2</sub> reduction pathway from a substrate of organic origin (Fig. 12,  
370 13, 14), *i.e.* a conventional microbial gas genesis process in the marine domain (Whiticar,  
371 1999). No isotopic evidence for thermogenic gas was detected. The  $\delta^{13}\text{C-CO}_2$  values are  
372 indicative of the degradation of an organic source consisting of solid organic matter rather  
373 than liquid hydrocarbons (in this case the  $\delta^{13}\text{C-CO}_2$  are generally  $> -10\text{‰}$ ; Milkov and  
374 Etiope, 2018). CH<sub>4</sub> is the dominant gas in both the free gas and the adsorbed/dissolved gas in  
375 sediment porewater. Note that the fauna composition observed during the MOZ04-SCB03  
376 SCAMPI dive is in good concordance with the presence of fluid seepage associated with  
377 dissolved methane. Differences are noticeable between the free gas taken from the liners and  
378 the gas adsorbed in the sediments of the base of the core and recovered in head-spaces.  
379 Indeed, there is a difference of about  $+20\text{‰}$   $\delta^{13}\text{C-CO}_2$  and  $+5\text{‰}$   $\delta^{13}\text{C-CH}_4$  between,  
380 respectively, the free gas and the gas recovered in the head-spaces of the corer bits (Fig. 14;  
381 full arrows). The fact that methane  $\delta^{13}\text{C}$  shows low values in offshore Mozambique suggests  
382 that the organic substrate of the methane source is composed of isotopically light carbon  
383 (probably very rich in moist forest C3 plants, O'Leary, 1988). Values of  $\delta^{13}\text{C-CO}_2$  are  
384 between  $-23.8$  and  $-44.5\text{‰}$ . The <sup>13</sup>C depletion of CH<sub>4</sub> is also linked to a decrease in the  
385 CH<sub>4</sub>/CO<sub>2</sub> ratio and the <sup>13</sup>C depletion of CO<sub>2</sub> is accompanied by an increase in the CH<sub>4</sub>/CO<sub>2</sub>  
386 ratio (Table 2). Similar characteristics have been previously interpreted either as microbial  
387 production of very light methane immediately below the Sulfate-Methane Transition Zone  
388 (SMTZ) (Whiticar, 1999), or as related to a moderate anaerobic oxidation process of the  
389 methane in the zone of very low sulfate concentration below the SMTZ and a light methane  
390 back-production process under the SMTZ (thermodynamic process, Yoshinaga et al., 2014).  
391 Indeed, the reactions catalyzed by enzymes being reversible, with the approach of  
392 thermodynamic equilibrium, in the zone with low concentration of sulfates, an inverse  
393 reaction to the Anaerobic Oxidation Methane (AOM) is probable therefore with reduction of  
394 dissolved CO<sub>2</sub> and production of methane (Yoshinaga et al., 2014). The isotopic carbon  
395 separation values between CH<sub>4</sub> and CO<sub>2</sub> ( $\Delta\text{C}_{\text{CH}_4\text{-CO}_2}$ ), are between 62.9 and 47.7 in the core  
396 MOZ4-CSF19 in the Zambezi offshore which is a classical fractionation value for microbial  
397 gas related to biogenic CO<sub>2</sub> reduction in marine sediments (Whiticar, 1999).  
398 The isotopic analysis of the authigenic carbonates inside the sampled pockmark have shown  
399 very low  $\delta^{13}\text{C}$  values (Fig. 15), which are very typical of microbial methane derived carbonate  
400 precipitations (Aloisi et al., 2002; Peckmann et al., 2001; Peckman and Thiel, 2004; Bayon et

401 al., 2013; Pierre et al., 2017). In cold seep environments, authigenic carbonate formation is  
402 driven by the activity of microbial consortium of sulfate-reducing bacteria and  
403 methanotrophic archaea (Boetius et al., 2000; Orphan et al., 2001). A mixture of fluids between  
404 organic matter and DIC of seawater is not suitable to explain the very enriched in  $^{12}\text{C}$   
405 compositions (marine carbonates which are not derived from microbial methane oxidation  
406 have  $\delta^{13}\text{C}$  value commonly higher than  $-30\text{‰}$ ). It is necessary to invoke another source of  
407 carbon with low  $\delta^{13}\text{C}$  values to explain these isotopic compositions of the carbonates. In the  
408 near subsurface below the sea bottom, sulfate is prone to be reduced to sulphide while  
409 anaerobic oxidation of methane produces dissolved  $\text{CO}_2$  in the SMTZ. The related increase of  
410 DIC concentration is prone to react with  $\text{Ca}^{2+}$  (and  $\text{Mg}^{2+}$ ) of sea water in the uppermost  
411 sediments (in the oxic zone) generating carbonates. Thus, microbial methane as the source of  
412 carbon can explain the isotopic compositions of the carbonates discovered within the  
413 pockmark where the MOZ04-MTB5 was cored. Indeed, in this site, methane is extremely rich  
414 in  $^{12}\text{C}$  ( $\delta^{13}\text{C}\text{-CH}_4$  between  $-92.2\text{‰}$  and  $-86.7\text{‰}$ ; see above) as it is the case for the carbonates.  
415 The isotopic fractionation between  $\text{CO}_2$  and calcite precipitation ( $\Delta\text{C}_{\text{CO}_2\text{-calcite}}$ ) at  $12^\circ\text{C}$  is equal  
416 to  $-10\text{‰}$  (Emrich et al., 1970). This is consistent with the value measured here which is  
417  $\Delta\text{C}_{\text{CO}_2\text{-calcite}} = -8.1$ . Thus, the isotopic compositions of the gas and of the carbonates are both  
418 consistent with a microbial origin of the gas seepages.

419

#### 420 *Fluid seepages and slope destabilization*

421

422 The study of the distribution of fluid seepages (active and fossil) in the Zambezi slope  
423 suggests a strong interaction between fluid dynamics and gravitational slope destabilization.  
424 Active pockmarks are seen mostly outside of the destabilized zone. The pockmarks are  
425 scattered in the northeast of the study area (stable slope area). Close to the destabilized area,  
426 they tend to form an alignment trending parallel to the upslope boundary of the landslide area.  
427 Within this alignment, acoustic anomalies in the water column, which are probably related to  
428 bubble flows, appear close to the landslide area (northeast and upslope of the landslide; Fig. 2,  
429 3). The pockmarks visible in the center of the destabilized zone correspond mainly to  
430 carbonated chimneys interpreted as ancient fluid conduits which are inactive today. The  
431 spatial evolution of the structure of the study area, from the northeast to the southwest, seems  
432 directly representative of the temporal evolution of the progressive fluid-landslide interaction  
433 processes (Fig. 16). Following this interpretation, stage 1 corresponds to a situation of stable

434 slope only pierced by scattered moderate cold fluid seepages of formation water with  
435 dissolved microbial methane. This seepage generates pockmark depressions paved by  
436 authigenic carbonates close and at the sea bottom. Stage 2 corresponds to a situation of higher  
437 density of fluid seepages, some of them being related to free gas bubbling. At this stage, an  
438 alignment of active pockmarks is formed in the upper part of the slope. This alignment is  
439 probably related to the development of an open fracture system at the initial stage of the  
440 destabilization process which has evolved at stage 3 as the headwall scarp of the landslide.  
441 Stage 3 corresponds to a moderate gravitational mass movement of the upmost sediment  
442 associated locally with free gas fluxes. At this stage, the headwall scarp of the landslide is  
443 initiated immediately downslope of active pockmark trend and below a zone of deformed  
444 sediments is formed, possibly related to a progressive gravitational creeping. The fact that gas  
445 seepages develop first and that only after landslide and headwall scarp fault appear suggests  
446 that the fluids are the trigger to the landslide and, in this case, the seepage cannot be  
447 considered as a simple consequence of the landslide. We interpret the fluid seepages as a  
448 consequence of overpressure at depth, high enough to breach the seal rocks. Finally, stage 4  
449 corresponds to a situation of massive destabilization of the slope, with polyphased and  
450 imbricated mass-transport complexes involving deeper decollement levels compared to stage  
451 3. This process is responsible for the exhumation of the pre-existing fluid conduits. At this  
452 stage fluid seepages tend to be not active anymore.

453

## 454 **Conclusion**

455

456 Active fluid seepages which have been discovered along the Zambezi continental slope  
457 correspond to water flows with dissolved methane in the stable parts of the slope and they  
458 tend to form water and free gas seepages trending parallel to the slope and running upslope of  
459 the headwall scarp of a wide zone of slope destabilization. Geochemical analyses indicates a  
460 microbial origin of the gas and this interpretation is supported by the geochemistry of  
461 associated authigenic carbonates. In the center of the zone of massive slope destabilization, no  
462 active seepages have been characterized. The fluid seepages have been interpreted as a  
463 consequence of fluid overpressure related to the huge accumulation of sediments below the  
464 Zambezi platform and the continental slope. Overpressure has been interpreted as the  
465 potential trigger for fluid migration and slope destabilization. The spatial organization of the  
466 slope destabilization features appears as representative of the temporal evolution of the

467 landslide history giving information about the dynamics of slope instability processes.  
468 Following this interpretation, it is suggested that it is the fluid dynamics including free gas  
469 seepage which occurred first before the progressive destabilization of the slope.

470

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472

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480

481

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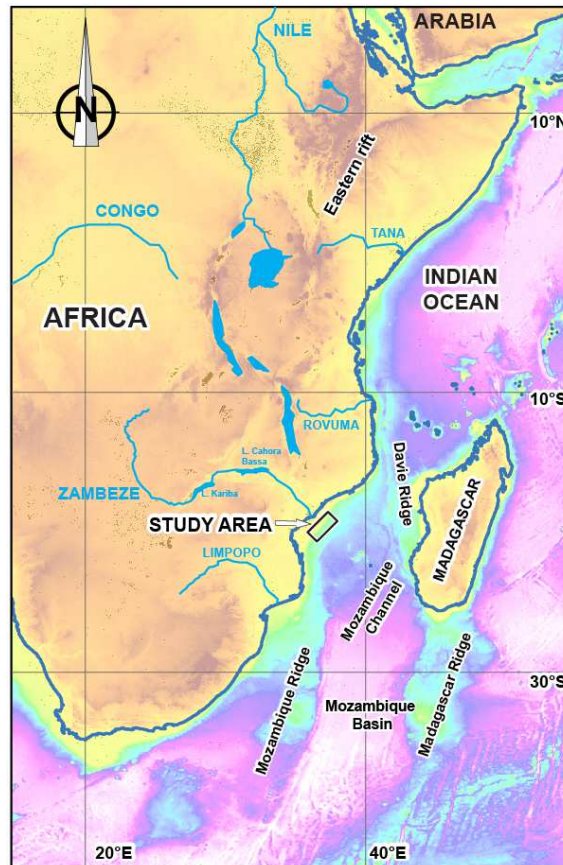


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756 **FIGURES CAPTION**

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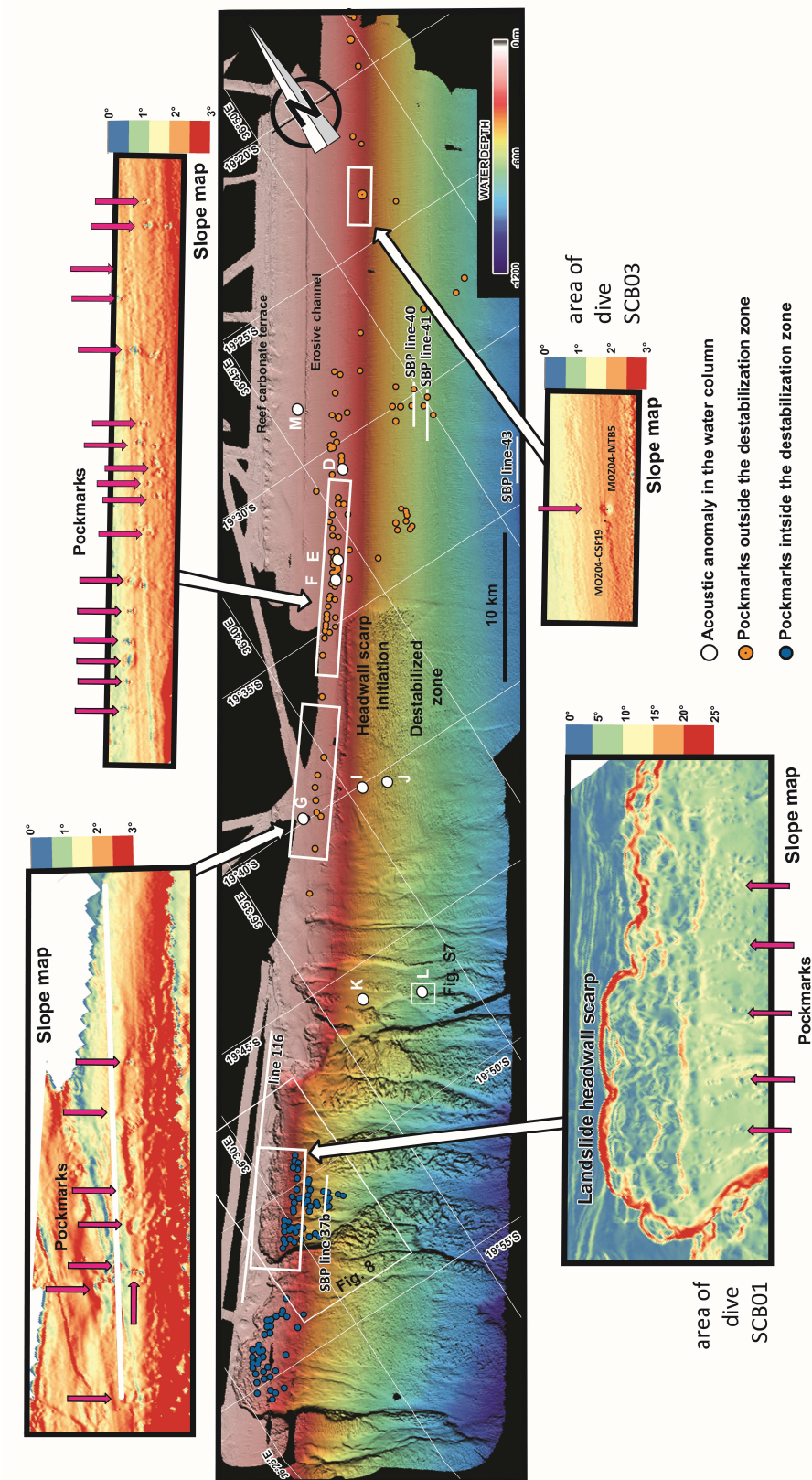


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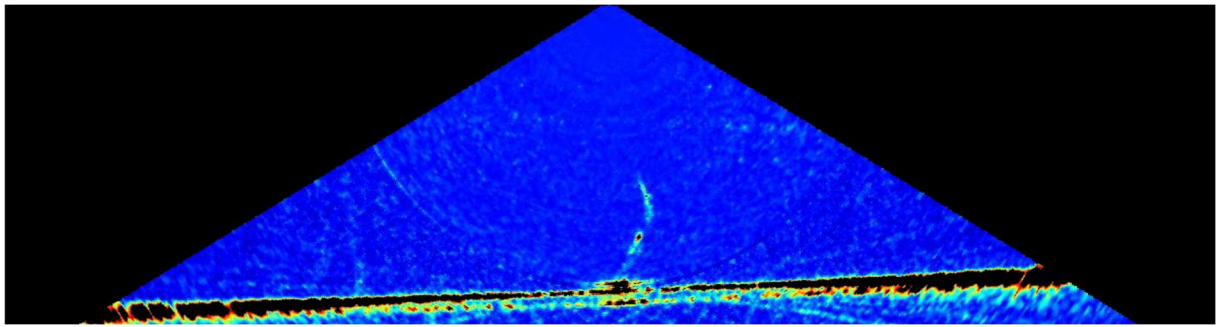
761 **Figure 1.** Location of the study area along the East African coast.

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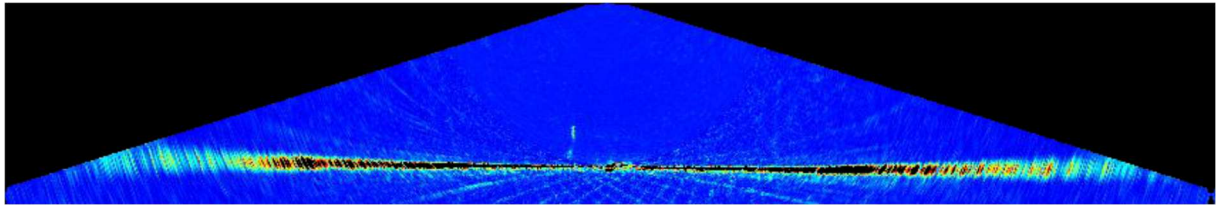


763  
764 **Figure 2.** Location of the pockmarks and water column acoustic anomalies in the detailed  
765 study area (red arrows indicate the pockmark locations on slope maps; letters refer to sites  
766 where acoustic anomalies interpreted as free gas seepages have been detected in the water  
767 column).

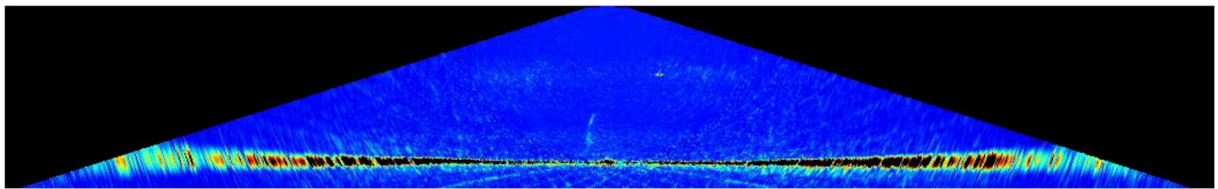
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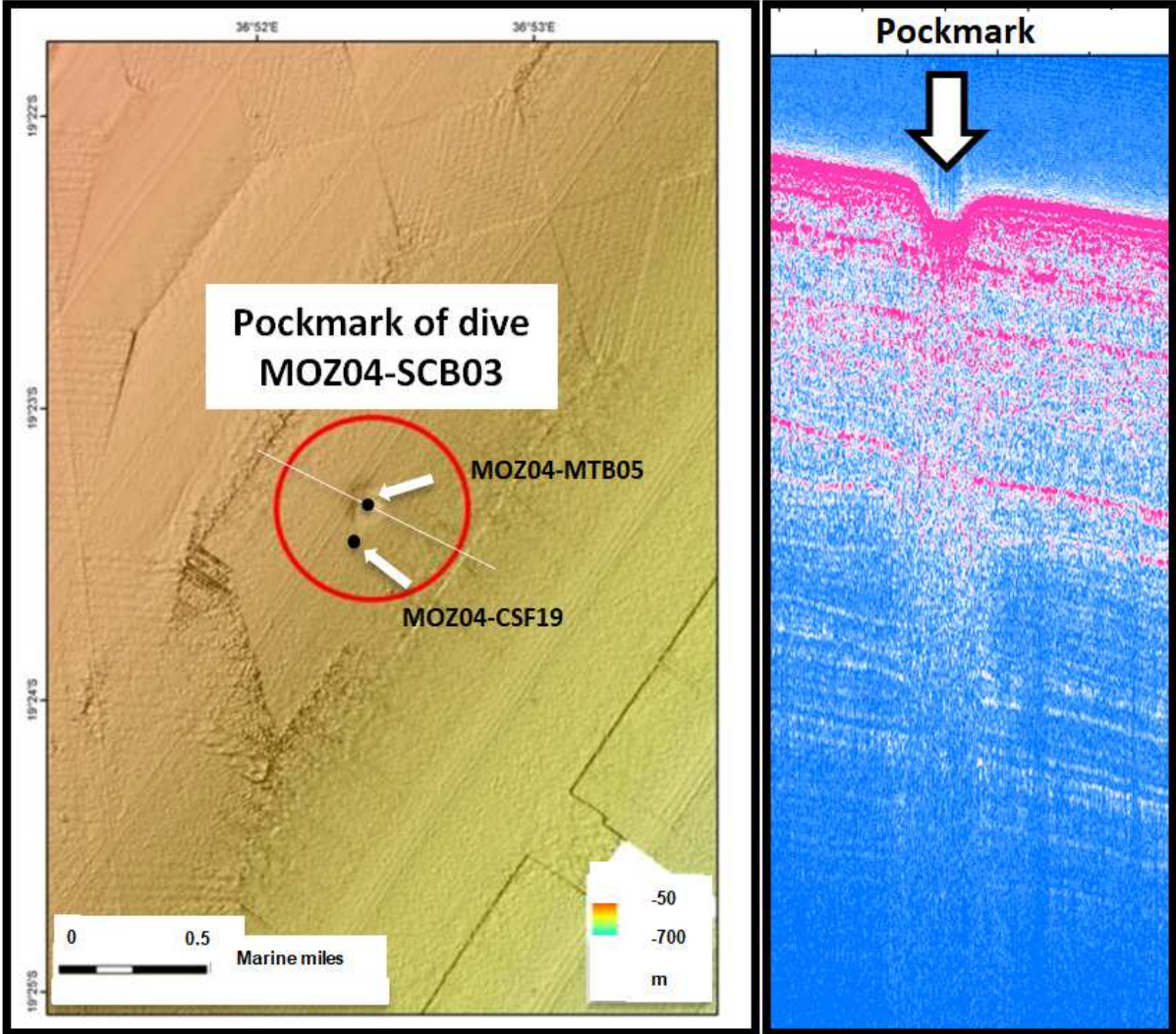


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772 **Figure 3.** Examples of multibeam polar echograms of the water column with acoustic  
773 anomalies interpreted as fluid seepages associated with bubble fluxes corresponding to sites  
774 G. (top image), I (middle image) and J (bottom image). See figure 2 for locations.



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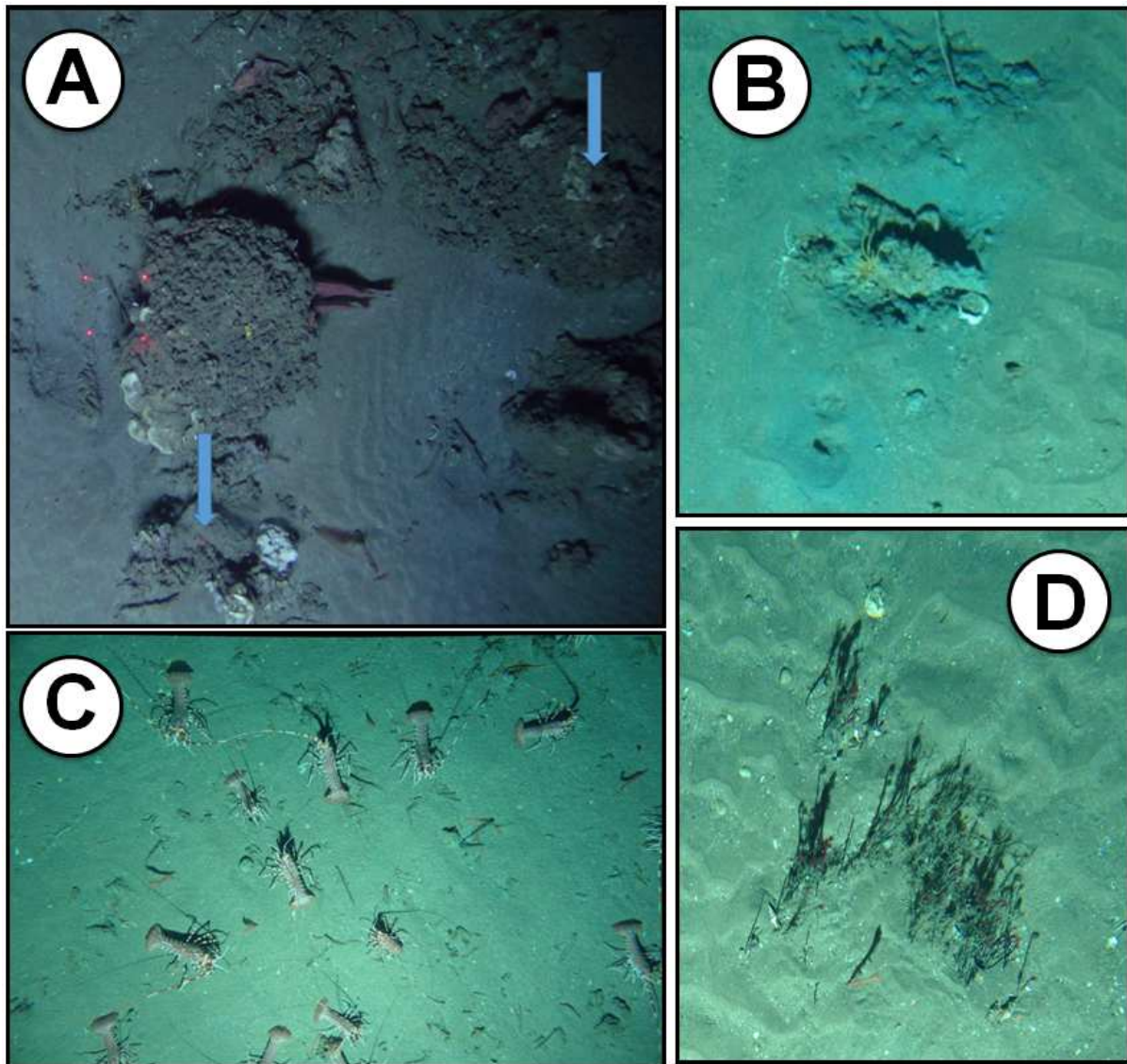


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778 **Figure 4.** The pockmark of SCAMPI dive MOZ04-SCB03 (location in Fig. 2). Note the  
779 seismic anomalies on the SBP profile crossing this feature.

780



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782

783 **Figure 5.** **A.** Authigenic carbonate crust in the pockmark of dive MOZ04-SCB03 (location in  
784 Fig. 2), the two arrows indicate places where turbulences associated with fluid seepages have  
785 been observed. **B.** Punctual seepages associated with expelled reduced sediments. **C.** Colony  
786 of lobsters. **D.** Tubeworms (Siboglinidae) characteristic of methane seepages.



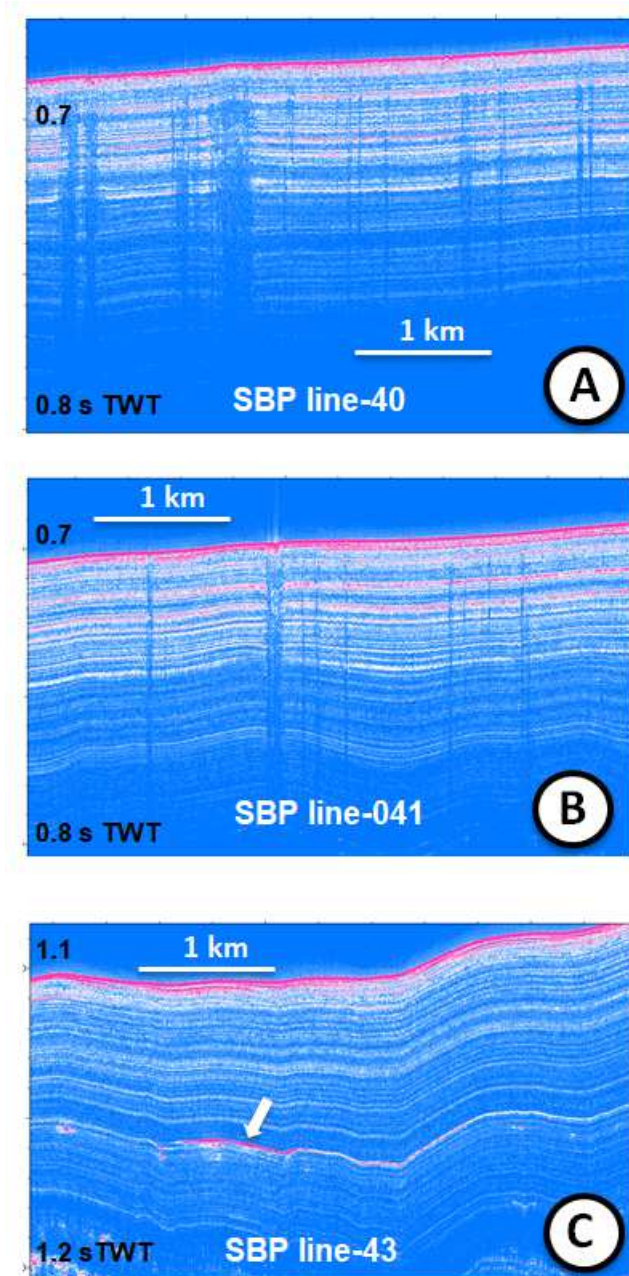
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789 **Figure 6.** Photo of a carbonate conduit recovered in multitube sampler (MOZ04-MTB5;  
790 location in Fig. 2).

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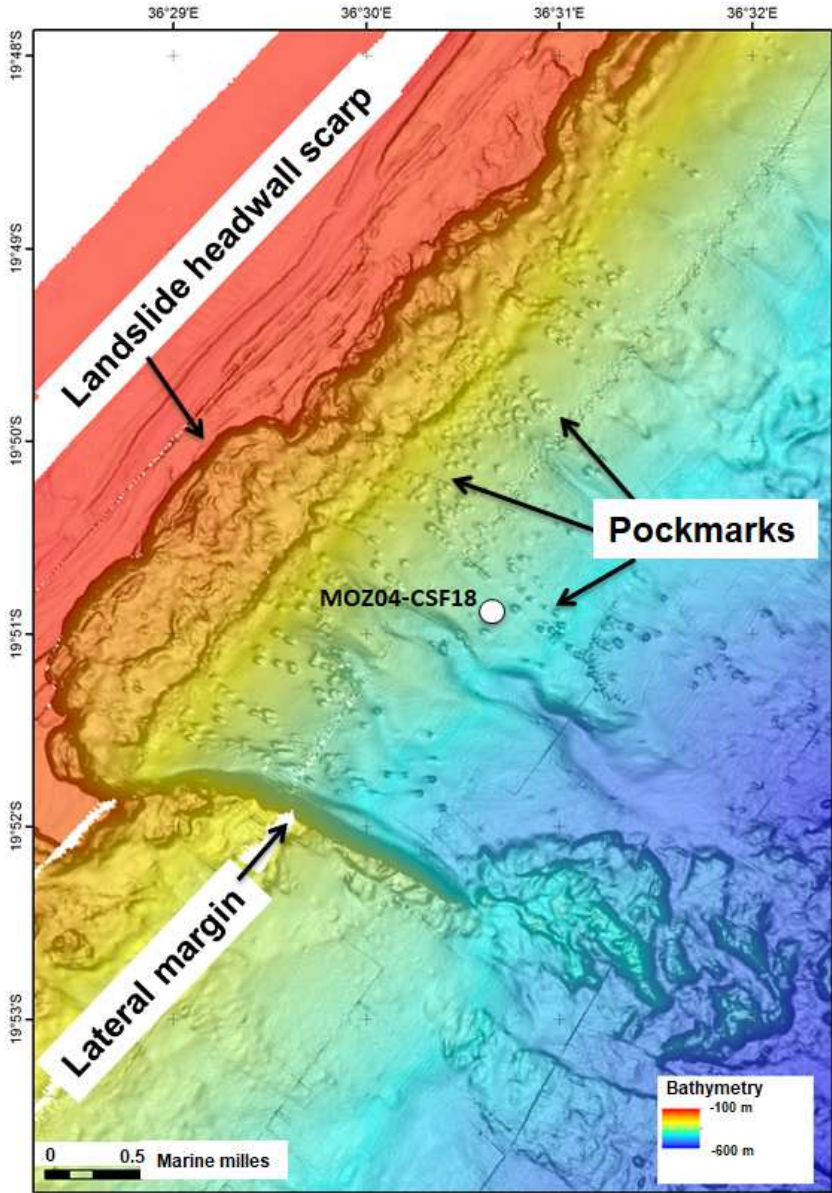




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794 **Figure 7.** **A** and **B.** Examples of SBP lines acquired in the slope north-east of the slope  
795 destabilization zone showing vertical seismic anomalies interpreted as gas escape pathways.  
796 **C.** Example of SBP line showing an amplitude anomaly (white arrow) in a stratigraphic layer  
797 which is interpreted as a possible free gas occurrence (location of the SBP lines in Fig. 2).



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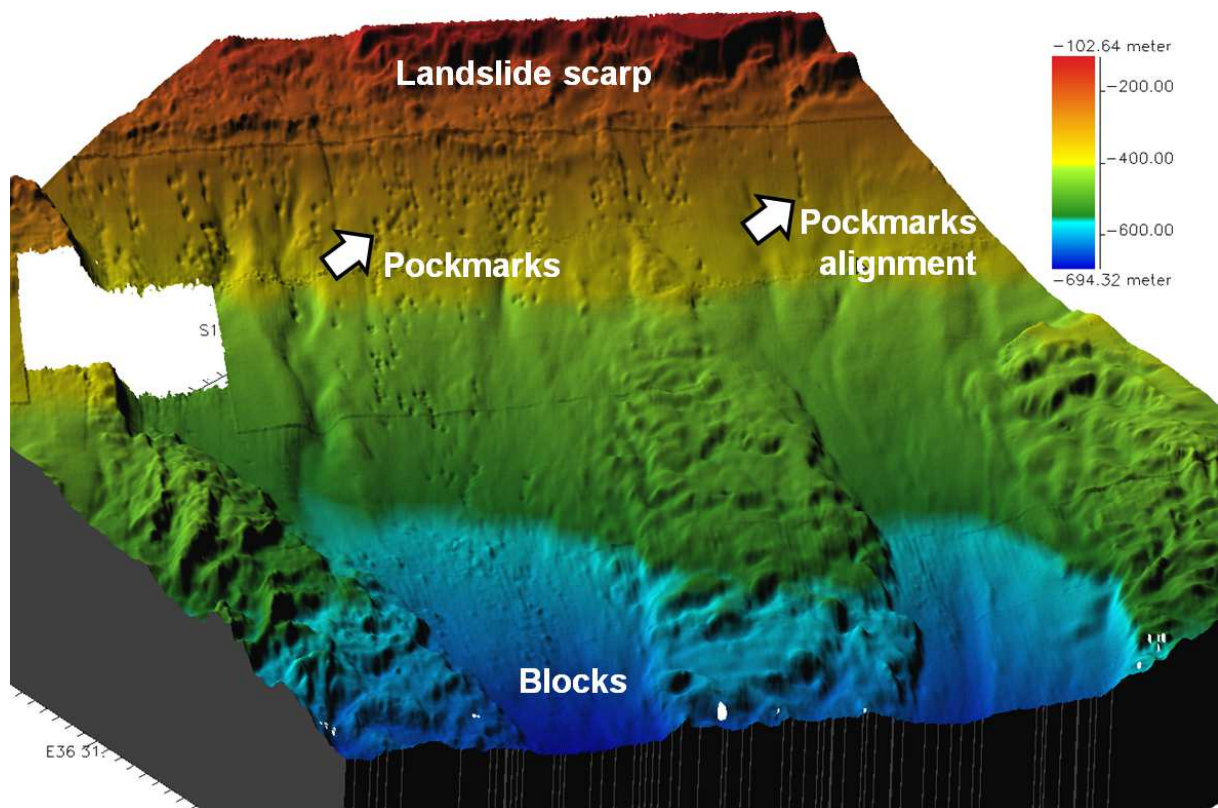
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800 **Figure 8.** Detailed bathymetric map showing the distribution of the pockmarks in the center  
801 of the slope destabilization zone.

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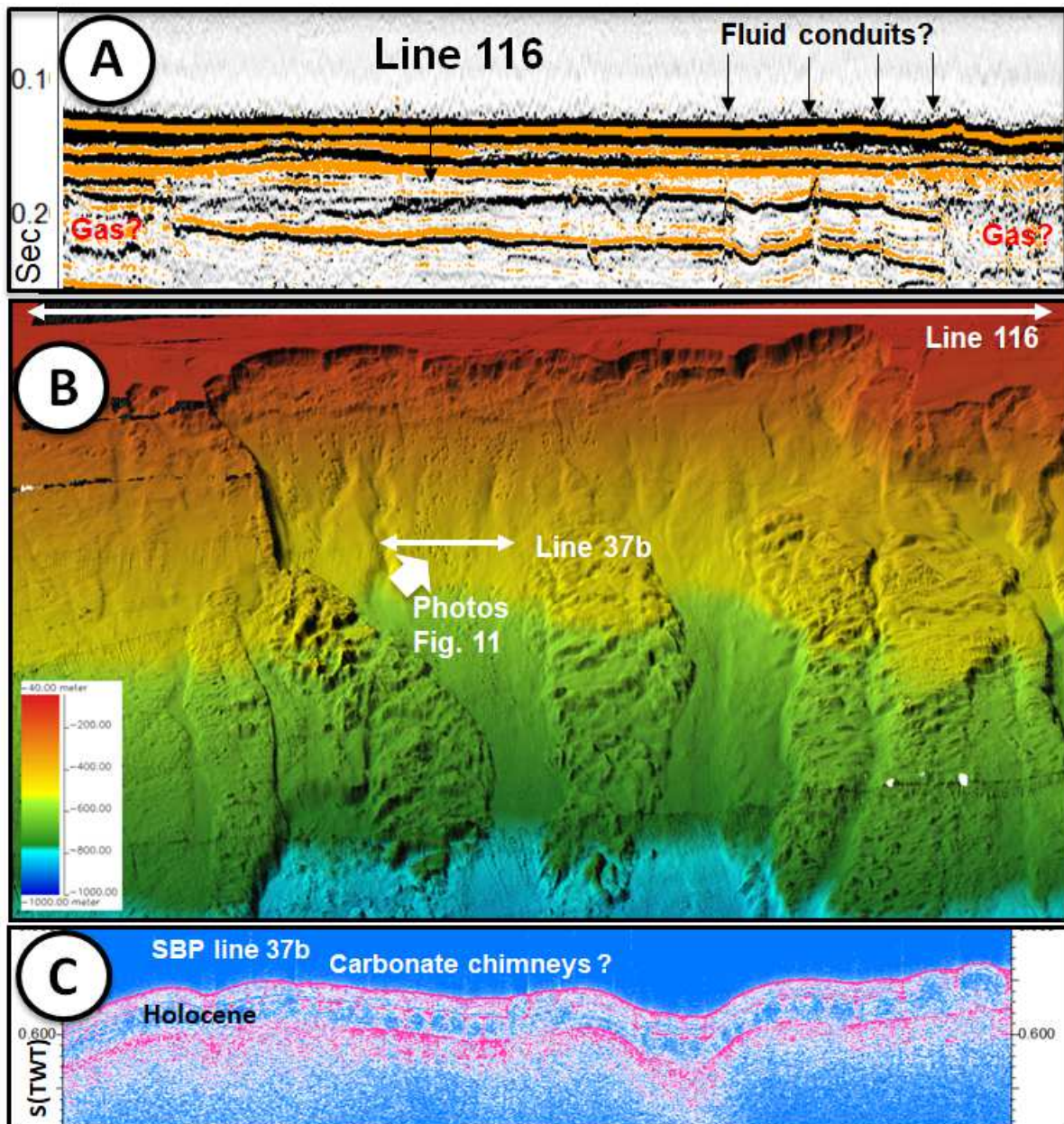
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805 **Figure 9.** Block-diagram illustrating the location of the pockmarks of the zone of slope  
806 destabilization. Note the alignment of some of the pockmarks (vertical exaggeration x3).

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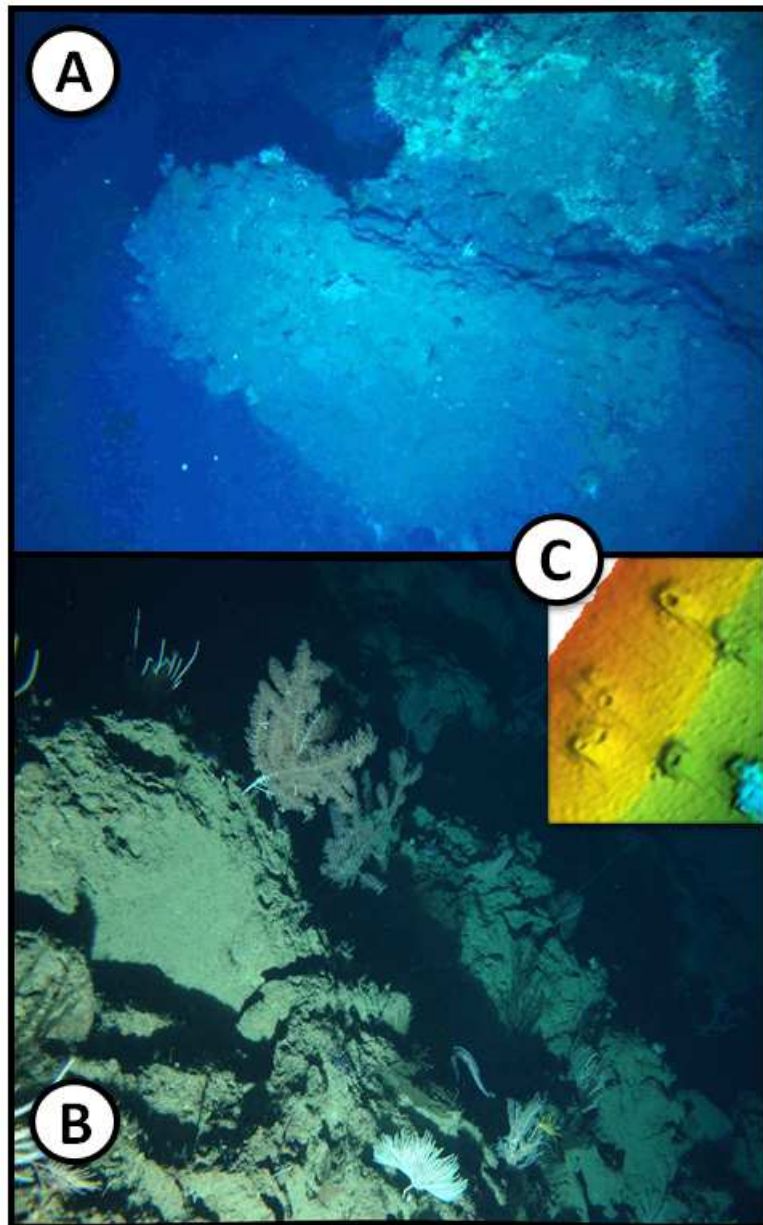


808

809 **Figure 10.** –A. High Resolution seismic line upstream of the destabilization area. Along this  
 810 line some vertical seismic structures are interpreted as probable fluid conduits and, locally,  
 811 zones of low amplitude chaotic seismic facies with acoustic mask are possibly related to the  
 812 presence of free gas within the sediments. **B.** A perspective view of the center of the  
 813 destabilization zone showing the distribution of the pockmarks and the location of seismic  
 814 reflection line 116 (Fig. 10A) and the SBP line 37b (Fig. 10C). Note also the presence of  
 815 gullies without any apparent correlation with the pockmarks alignments. **C.** SBP profile  
 816 showing vertical seismic structures below the pockmarks which are possibly related to  
 817 carbonate fluid chimneys.

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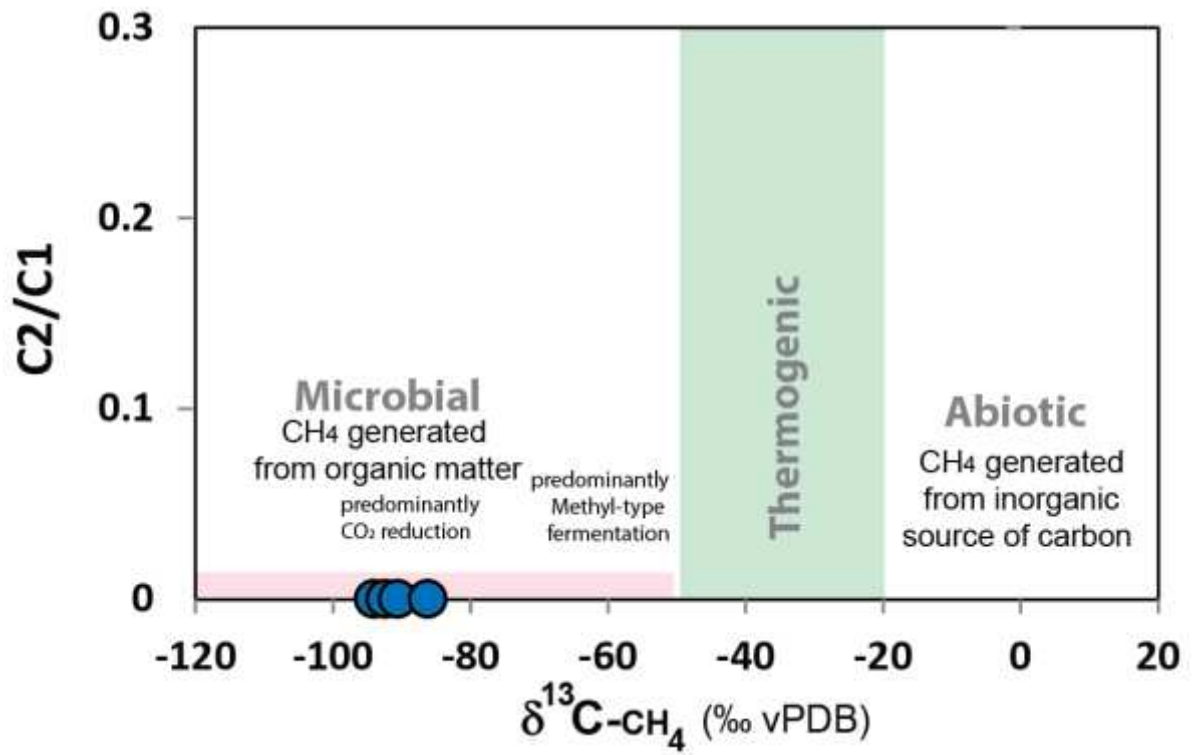


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821 **Figure 11.** – **A.** Picture of the top of a carbonate chimney observed in a pockmark of the  
822 center of the slope destabilization zone (this structure is about 4 m in diameter and 8 m high;  
823 location Fig. 10). **B.** A side of one of the carbonate chimney covered by gorgones. **C.** Detailed  
824 bathymetric map showing the internal geometry of the pockmarks depressions inside the  
825 destabilization zone with carbonate chimneys in the center of the comet-shaped depressions.

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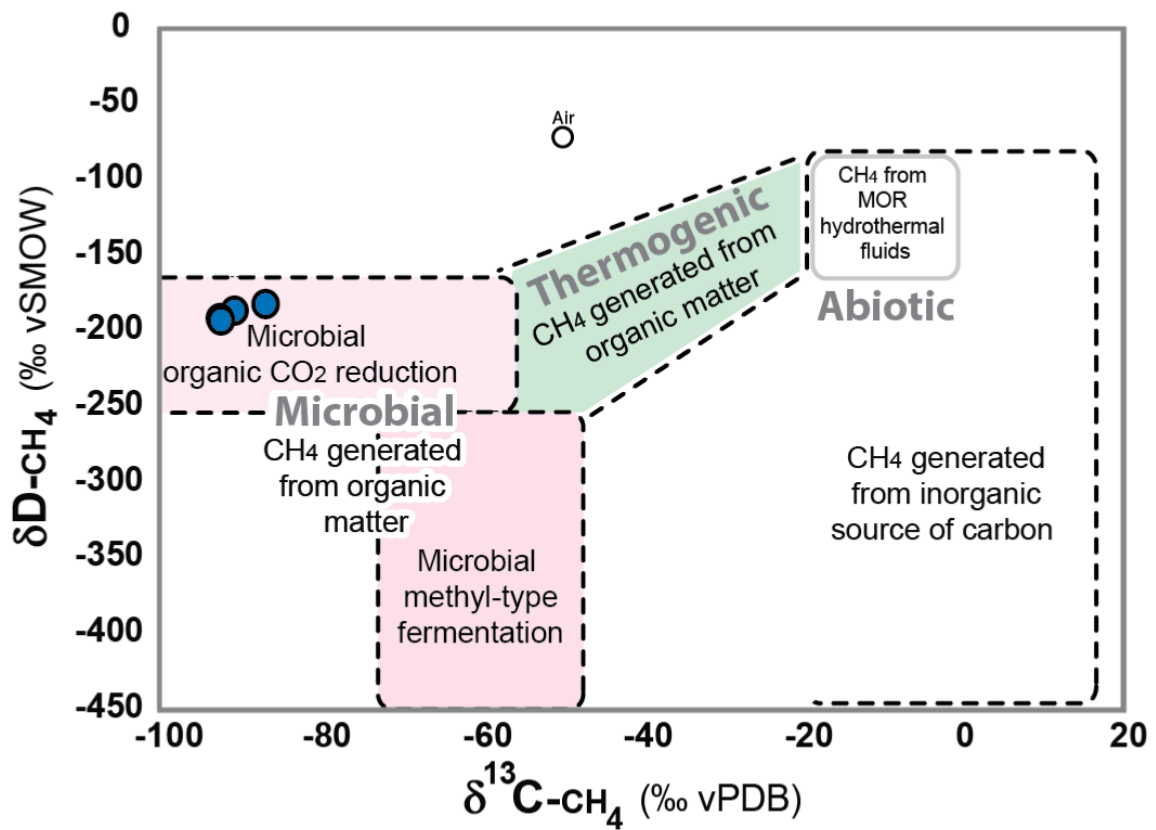


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828 **Figure 12.** Diagram  $\delta^{13}C$  of methane versus  $C2/C1$  for gases collected in the study area.

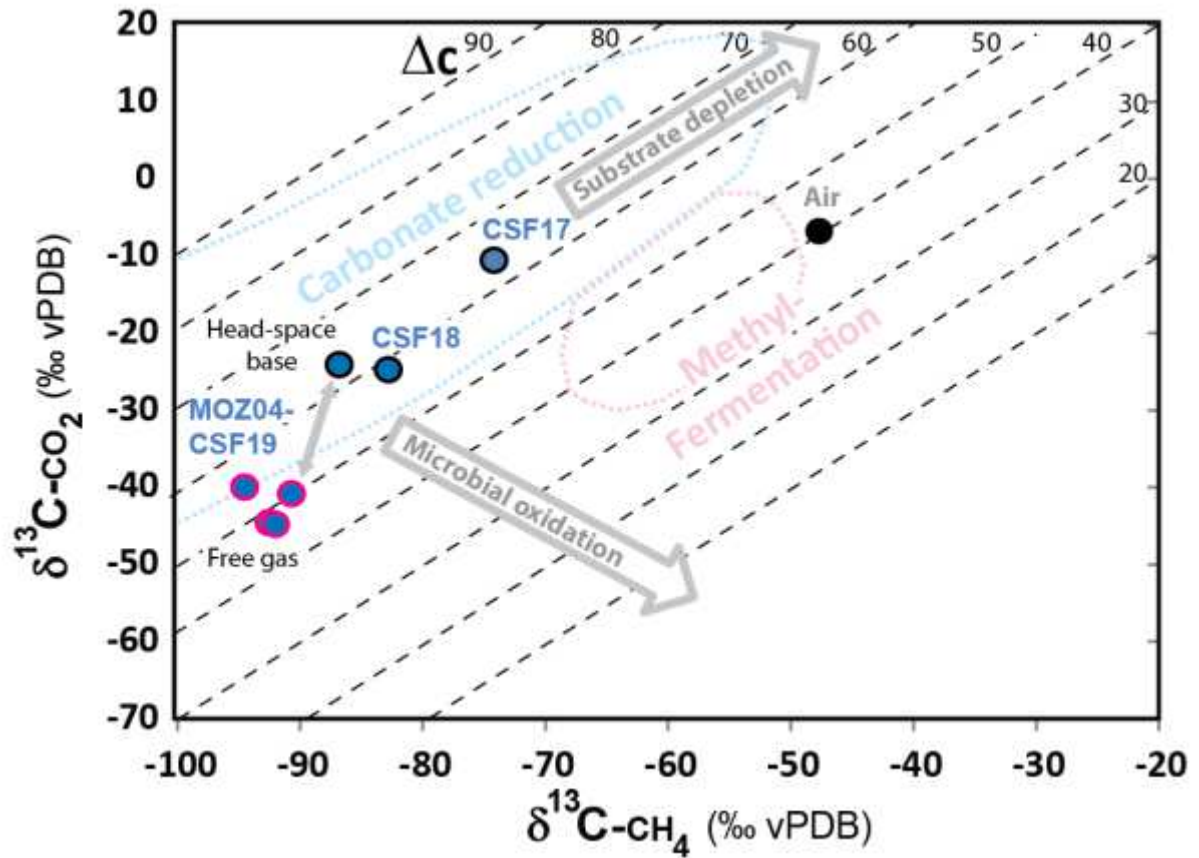
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832 **Figure 13.** Diagram  $\delta^{13}\text{C}$  of methane versus  $\delta\text{D}$  of methane for gases collected in the study  
 833 area.

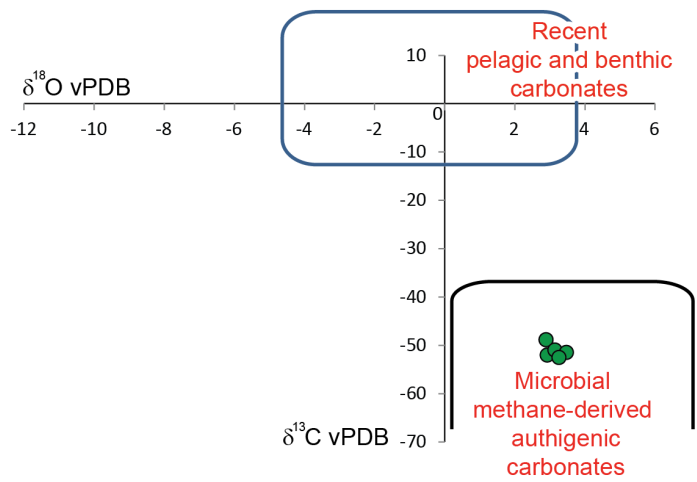


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835 **Figure 14.** Diagram  $\delta^{13}\text{C}$  of methane versus  $\delta^{13}\text{C}$  of  $\text{CO}_2$  for gases collected in the study area  
836 (domains after Whiticar, 1999).

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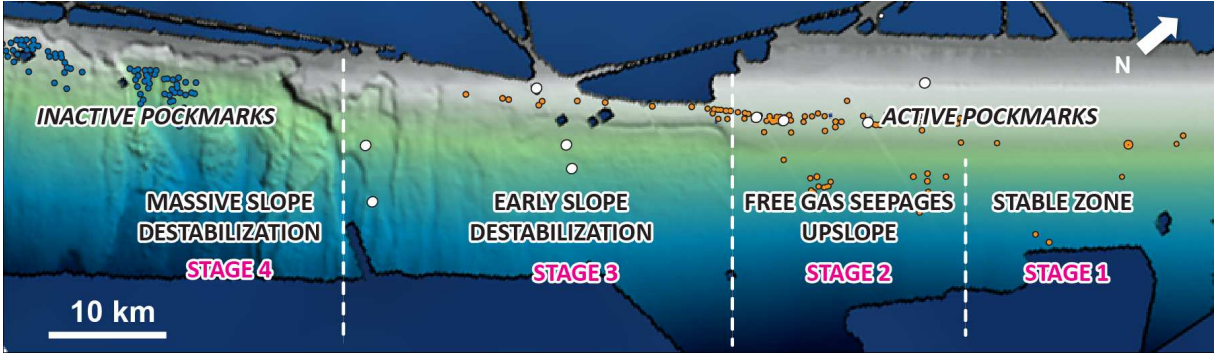


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840

841 **Figure 15.** Isotopic composition of the sampled carbonates in core MOZ04-MTB5 (location  
842 in Figs. 2 and 4).

843



844

845 **Figure 16.** Relationship between fluid seepages and slope destabilization.

846



Sample type	Sample	CH <sub>4</sub> (%)	CO <sub>2</sub> (%)	CH <sub>4</sub> /CO <sub>2</sub>	Air (%)
Free gas	MOZ4-CSF19-B(A)	96.62	3.38	28.63	62.74
	MOZ4-CSF19-B(B)	96.10	3.90	24.63	44.80
	MOZ4-CSF19-B(C)	96.26	3.74	25.72	54.70
	MOZ4-CSF19-B(D)	96.24	3.76	25.57	15.32
	MOZ4-CSF19-B(E)	95.72	4.28	22.38	61.82
	MOZ4-CSF19-B(I)	96.43	3.57	27.02	78.10

848 **Table 1.** Composition of the free gas sample on core MOZ4-CSF19.

Type of sample	Sample	$\delta^{13}\text{C-CH}_4$ (‰)	$\delta^{13}\text{C-CO}_2$ (‰)	$\delta\text{D-CH}_4$ (‰)	$\Delta\text{C}_{\text{CH}_4-\text{CO}_2}$
Free gas	MOZ4-CSF19-B(A)	-90.5	-40.5	-175.4	50.0
in liner	MOZ4-CSF19-B(B)	-92.4	-44.3	-180.5	48.1
	MOZ4-CSF19-B(C)	-92.2	-44.5	-182.2	47.7
Adsorbed gas at core base					
32.5m	MOZ4 CS17 (OG)	-74.1	-10.2	-178.7	63.9
9.5 m	MOZ4 CSF18 (OG)	-82.7	-24.4		58.3
9.5 m	MOZ4 CSF19 (OG)	-86.7	-23.8	-170.5	62.9

849 **Table 2.** Isotopic composition and isotopic carbon separation values between CH<sub>4</sub> and CO<sub>2</sub> of  
850 the gas samples collected on cores MOZ4-CSF17, MOZ4-CSF18 and MOZ4-CSF19.

	$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)
	V-PDB	V-PDB
MOZ4-MTB5-A	2.89	-48.87
MOZ4-MTB5-B	2.93	-52.02
MOZ4-MTB5-C	3.15	-51.00
MOZ4-MTB5-D	3.47	-51.48
MOZ4-MTB5-E	3.26	-52.50

851 **Table 3.** Isotopic composition of the carbonate samples collected on core MOZ4-MTB5.

852

853