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Romain Jatiault, Lies Loncke, Damien Dhont, Dominique Dubucq, Patrice Imbert. Geophysical characterisation of active thermogenic oil seeps in the salt province of the lower Congo basin. Part II: A regional validation. *Marine and Petroleum Geology*, 2019, 103, pp.773-791. 10.1016/j.marpetgeo.2019.02.002 . hal-03403132

HAL Id: hal-03403132

<https://univ-perp.hal.science/hal-03403132>

Submitted on 20 Dec 2021

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1 **Geophysical characterisation of active thermogenic oil seeps in the salt** 2 **province of the Lower Congo Basin. Part II: A regional validation**

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7 **Key words:** *Oil slicks, Thermogenic fluid seeps, Pockmarks, Asphalt, Salt diapir, Lower Congo Basin, Gas*
8 *hydrates, Double BSR*

9 **Abstract**

10 The Lower Congo Basin is known to discharge a substantial volume of oil towards the sea surface, from
11 more than one hundred seafloor seep sites distributed throughout the deep province of the Lower
12 Congo Basin. A large geochemical coring survey confirmed the presence of oil on the seabed. The
13 combination with the seismic data considerably improved the identification of the origin of the oil
14 slicks on the seabed. Multiple specific geophysical characteristics of thermogenic hydrocarbon seep
15 sites were highlighted in a previous detailed analysis of seismic datasets. This study aims to test the
16 characteristics previously identified at regional-scale. The active discharge zone is limited to the distal
17 province of the basin. It is characterized by strong compression / shortening due to the sliding of the
18 post-salt super-sequence, resulting in numerous salt diapirs that control the location of seafloor oil
19 seep sites. The paper describes the bathymetric, reflectivity, amplitude and sub-bottom profiler
20 characteristics of a group of thermogenic seep sites. They correspond essentially to submarine mounds
21 or pockmarks of complex and irregular shape surrounded by hummocky mounds. Active oil pockmarks
22 are systematically associated with positive amplitude anomalies on the seabed and are linked to
23 vertical high-amplitude columns rooted in the seismic reflector and associated with the base of the gas
24 hydrate stability zone. The sub-bottom profiler data shows that the hummocky mounds are connected

25 by a network of faults to high-amplitude bodies buried under a consistent sediment thickness. Based
26 on the definition of specific geophysical features (seafloor mounds, complex shape and irregular
27 pockmarks, positive anomalies of seafloor amplitude, high-amplitude vertical pipes), we identified a
28 series of potential oil seep sites at basin scale. The mounds are particularly recognizable using the
29 seismic curvature attribute; we have identified 2946 individual hummocks that are grouped in 50 zones
30 with a density of 35 to 240 per km². They are believed to be associated with asphalt storage on the
31 seafloor and related to the biodegradation of heavy oils during hydrocarbon dysmigration through the
32 sedimentary pile. Unusual double BSRs occur over the study area; these are also a specific feature of
33 thermogenic seep sites. Barely half of the potential sites identified on the seismic datasets are
34 associated with recurrent oil slicks at the sea surface. The proportion of remaining anomalies may be
35 associated with inactive seep sites over the period of satellite-based monitoring or gas-dominated seep
36 sites.

37 **1. Introduction**

38 Characterizing the natural transfer of hydrocarbons from petroleum reservoirs to the seafloor has
39 strong implications on the understanding of the evolution of sedimentary basins (*Gay et al., 2006a*;
40 *Cartwright et al., 2007*; *Andresen et al., 2011*, *Anka et al., 2013*; *Marcano et al., 2013*; *Serié et al.,*
41 *2017*), deep marine ecosystems inventories (*Charlou et al., 2004*; *Ondreas et al., 2005*; *Jones et al.,*
42 *2014*) or submarine geohazards (*Bünz et al., 2005*; *Hill et al., 2011*), see the review by *Anka et al.*
43 *(2012)*. Pockmarks are among the most common expression of focused fluid flow at the seafloor (*King*
44 *and MacLean, 1970*; *Hovland and Judd, 1988*; *Judd and Hovland, 2007*). Their size and geometry
45 depend on sediment host properties and hydrocarbon flux (*Hovland et al., 2012*). The ascent of fluids
46 through the sedimentary series causes vertical successions of acoustic anomalies on seismic sections
47 (*Cunningham and Lindholm, 2000*; *Heggland, 2002*; *Gay et al., 2006b*). They are called either pipes,
48 defined as vertical successions of increasing reflection amplitudes (typically narrow, i.e. up to a few
49 100m diameter) and known to commonly form large clusters, or chimneys, defined as large-scale

50 (typically > 1 km diameter) and solitary features without any particular internal reflection (**Løseth et**
51 **al., 2001; Loncke et al., 2004; Cartwright et al., 2007; Løseth et al., 2009; Hustoft et al., 2009; Moss**
52 **and Cartwright, 2010; Løseth et al., 2011; Ho et al., 2012; Karstens et al., 2015**). In the case of
53 abundant gas migration towards the seabed, hydrates precipitate at the interface between free gas
54 and hydrate domains. This forms a seismic reflector with a polarity opposite to that of the seabed,
55 known as the Bottom Simulating Reflection (BSR) (**Shipley, 1979; Hovland et al., 1997; MacKay et al.,**
56 **1994; Berndt et al., 2004; Haacke et al., 2007**). The identification of sea surface oil seepage slicks is
57 used throughout the petroleum exploration workflow to validate source rock maturation, from
58 targeting (**Kornacki et al., 1994; Thrasher et al., 1996; Williams and Lawrence, 2002; O'Brien et al.,**
59 **2005; Stalvies et al., 2017**) to prospect validation (**Jauer and Budkewitsch, 2010**). Positioning the
60 outlines of multi-temporal slicks on the same map commonly shows radiating features from the central
61 source area (**De Beukelaer et al., 2003; Jatiault et al., 2017**). The spatial imagery was able to detect
62 50% of potential oil-supplying seep sites identified on exploration seismic in the Gulf of Mexico (**Garcia-**
63 **Pineda et al., 2010**).

64 Recently, **Serié et al. (2017)** set out a methodology to study hydrocarbon fluid flow by combining
65 remote sensing, seafloor coring campaign and industrial seismic data. The present study relies on this
66 pre-existing methodology that we complemented with a denser dataset of sea surface natural slicks
67 together with high resolution sub-seafloor data. More recently, **Jatiault et al. (2019, Part I)** presented
68 seafloor and sub-seafloor high-resolution characteristics of one active oil seep in the Lower Congo
69 Basin (see details in section 2.2). This complementary study aims at testing the recognition criteria
70 defined for a single oil seep on a larger seep population recognised in the Lower Congo Basin. The
71 combination of sea-surface slicks database, geochemical cores and geophysical anomalies (high-
72 resolution surveys used for geo-hazards evaluation and exploration 3D seismic) made it possible to
73 inventory oil-seep sites over a 35*50 km wide area. The comparison of oil-supplying seeps with the
74 whole set of fluid-flow features at the seafloor and in the shallow subsurface will be used to better
75 discriminate and define seismic features that can potentially be diagnostic of oil seep sites. This study

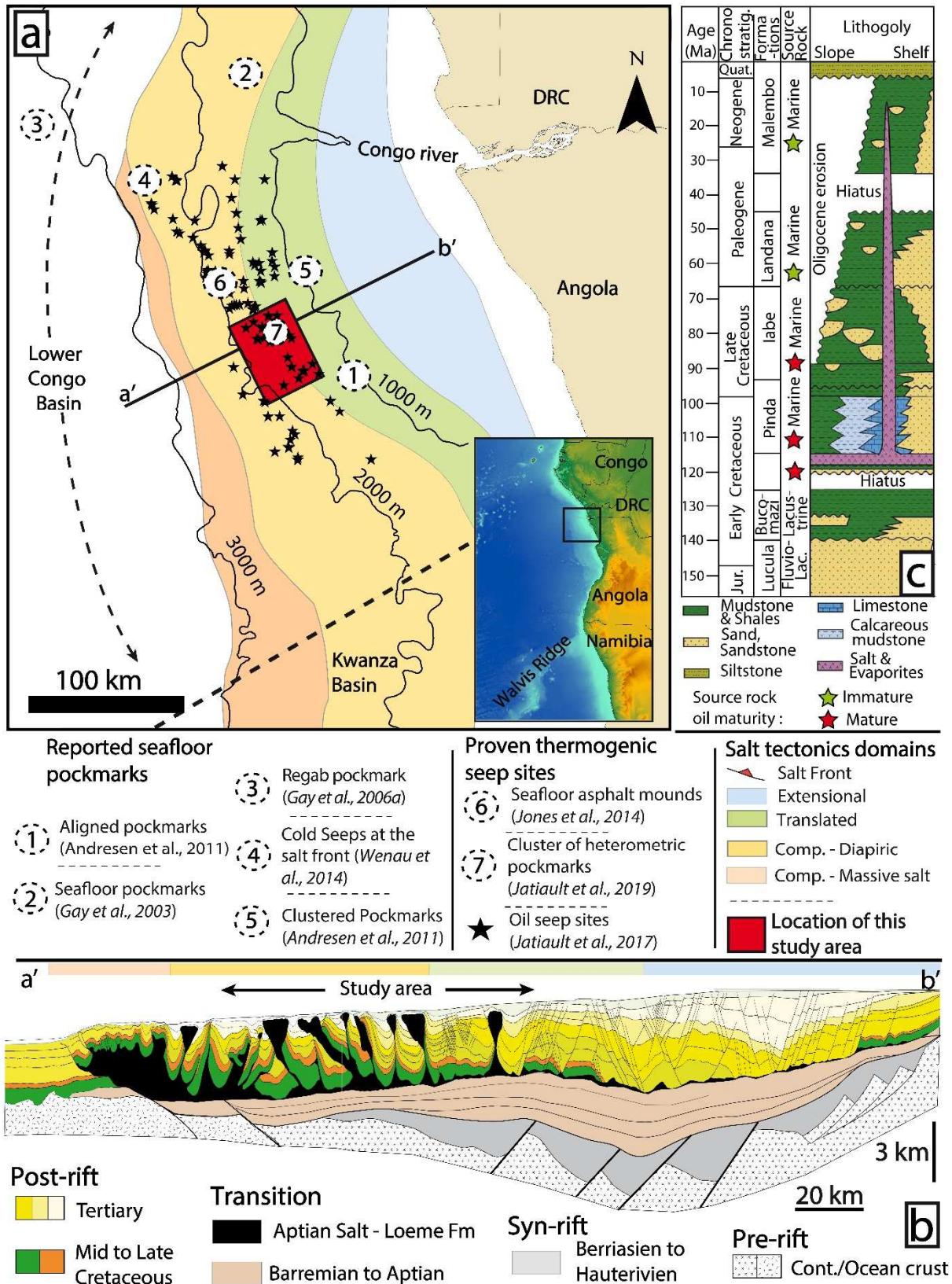
76 discusses about the significance of fluid-related seismic features with an updated methodology
77 integrating for the first time sea surface slicks and geophysical data in the Lower Congo Basin. Active
78 oil seep sites will be compared with potential seep sites identified from geophysical attributes in the
79 Lower Congo Basin.

80 **2. The Lower Congo Basin**

81 **2.1. Geological setting and petroleum systems**

82 The study area located between 10 to 12 °E and 6 to 8°S corresponds to a large oil-seeping province in
83 deep offshore Angola characterised by water depths ranging from roughly 1000 to 3000 m. The
84 chrono-stratigraphic framework of the LCB is divided into 3 major phases after the South Atlantic
85 opening during the Early Cretaceous (144 - 140 Ma). The pre-salt (Berriasian to Barremian) succession
86 consists of extensive lacustrine deposits including the oil-prone (mix type I/II kerogens) **Bucomazi Fm**
87 (Fig. 1c; *Burwood, 1999; MacHargue, 1990; Schoellkopf and Patterson, 2000; Brownfield and*
88 *Charpentier, 2006*). The transitional phase (Late Barremian to Aptian) marks the end of the crustal
89 extension followed by a period of thermal subsidence (*Brice et al., 1982; MacHargue, 1990; Fort et al.,*
90 *2004*). The confined environment of the margin together with a drop in the main sea level enabled the
91 deposition of a thick evaporite layer (1000 m thick in average; *Marton et al., 2000*; Fig. 1b). The post-
92 salt super-sequence is subdivided into three main episodes. The aggrading stage started with the
93 development of a carbonate-ramp (**Pinda Fm**; 113 - 95 Ma) under stable climatic and restricted marine
94 conditions (*Haq et al., 1987; Séranne, 1999; Séranne and Anka, 2005*). This period continued with a
95 progressive deepening of the basin due to thermal subsidence, leading to the deposition of the oil-
96 prone **Iabe Fm** (99 - 65 Ma, ~10 % TOC; *Burwood, 1999; Cole, 2000*) and subsequent (~4% TOC)
97 **Landana Fm** (65 - 45 Ma; *Cole et al., 2000, Schoellkopf and Patterson, 2000*; Fig. 1c). The pre-salt
98 series are the most prolific source intervals in the basin as Tertiary source rocks are immature over
99 most of it. The Eocene/Oligocene transition corresponds to a period of amplified sea level variations
100 ("Ice house" period; *Séranne, 1999*). It is marked by a regional unconformity, corresponding to a 10

101 Ma hiatus controversially interpreted as originating from the African superswell (**Nyblade and**
102 **Robinson, 1994**) or climate fluctuations. The 500 m thick eroded series were transported towards the
103 basin (**Teisserenc and Villemin, 1989; Séranne et al., 1992; Anka et al., 2009**). The prograding stage
104 (35 - 5 Ma) corresponds to the establishment of the paleo-Congo during the early Oligocene. It was
105 coupled with an "ice house" period, resulting in the deposition of siliciclastic sediments (**Malembo Fm**).
106 The Miocene-Pliocene transition is marked by the shift of the Congo River to its present-day location.
107 The development of an important upwelling system during the Early Quaternary (**Uenzelmann-Neben,**
108 **1998**) resulted in fining-upward sedimentation, leading to fine-grained deposits in the deep sea fan.
109 The post-salt super-sequence is affected by gravitational deformation, sliding over the Aptian salt
110 décollement layer. Salt tectonics subdivided the basin into an upslope extensional domain, a translated
111 area and a downslope compressive province characterised by salt diapirs, which confined the
112 sedimentation to minibasins (**Oluboyo et al., 2014**).



113

114 Fig. 1: a. Location map of the study area showing the main geological provinces of the LCB. The map

115 integrates the seafloor seeps reported in the literature (compiled from Gay et al., 2003; Gay et al.,

116 **2006a; Gay et al., 2007; Andresen et al., 2011; Wenau et al., 2014; Jones et al., 2014)** and recurrent
117 **oil slicks at the sea surface (black stars, from Jatiault et al., 2017).** Continuous black lines represent
118 **1000 m isobaths (Gebco).** **b. Regional cross section across the LCB displaying the pre-rift, syn-rift and**
119 **post-rift sequences (modified from Jatiault et al., 2017).** **c. Chronostratigraphic log and petroleum**
120 **system plays (modified from Anka et al., 2013).**

121 **2.2. Literature review of natural hydrocarbon seeps**

122 The LCB is affected by a large active fluid seepage system, as revealed during intensive petroleum
123 exploration over the last decade. Seabed outcrops of Miocene series, characterised by extensive high
124 amplitudes above the crest of the salt diapirs, correspond to preferential stratigraphic pathways for
125 migrating fluid in the salt provinces (*Serié et al., 2017*). In the salt minibasins, widespread classical type
126 I pockmarks (Conical; see definition of Type I in *Riboulot et al., 2016*) related to sediment pore
127 dewatering and biogenic methane venting are associated with the polygonal fault networks
128 (*Cartwright 2007; Andresen et al., 2011*). Aligned type I pockmarks commonly follow the maximal
129 flexural syncline axis of the minibasins (No. 1 in Fig. 1a; *Andresen et al., 2011*) or occur as sinuous
130 trends marking the ancient pathways of the Congo canyon (No. 2; *Gay et al., 2003*). A biogenic origin
131 is also suspected for the giant (~2000m diameter) Regab pockmark, located in the deep abyssal plain
132 at a water depth of 3150m (No. 3; *Gay et al., 2006a*). The origin of the gas expelled at the salt front
133 remains undetermined (No. 4; *Wenau et al., 2014*). A thermogenic contribution is highly suspected for
134 isolated pockmarks linked with Miocene turbidite channels (No. 2; *Gay et al., 2006 b*) and for clustered
135 pockmarks linked with salt diapirs (No. 5; *Andresen, 2012*). The migration of thermogenic hydrocarbon
136 is proven from the identification of a large number of seafloor asphalt mounds that spread on top of
137 salt diapirs (n°6; *Jones et al., 2014*). Seafloor asphalt mounds may reach approximately 1m in height
138 and host an abundance of biofauna. From the analysis of spaceborne SAR imagery, *Jatiault et al. (2017)*
139 calculated that the 100 oil seep sites of the compressive salt domain (black stars in Fig. 1a) emit a
140 volume of $4.38 \cdot 10^6$ litres of oil per year

141 The vertical association of sea-surface slicks and seafloor data show that seafloor seeps correspond to
142 clusters of pockmarks and seafloor mounds (n°7; *Jatiault et al., 2019, Part I*). One pockmark cluster
143 investigated in detail in *Jatiault et al., 2019, part I* consists of a complex of heterometric depressions
144 associated with asphalt mounds with diameters of 10 to 15 m in on the seafloor (*Unterseh et al., 2013;*
145 *Jones et al., 2014*). The subsurface is affected by several geophysical features including a shallow High
146 Impedance Layer (HIL) that reaches the seafloor at the location of depressions on the sub-bottom
147 profiler data. The HIL is interpreted as related to carbonate concretions with a possible contribution of
148 asphalt layers (*Hill et al., 2011*), (2) a set of two parallel reflections, about 50 ms apart, whose polarity
149 is opposite that of the seafloor. They are interpreted as a methane-related BSR overlying a second BSR
150 that could be related to a mix of heavier gas (*Jatiault et al., 2019*), (3) two different positive amplitude
151 anomalies horizontally delimited by the BSR; massive high-amplitude bodies below and vertical pipes
152 that connect the BSR with the seafloor above.

153 **3. Data and Methods**

154 This study adopts the methodology of *Serié et al. (2017)* to characterize the fluid flow phenomena in
155 the Kwanza basin. We refined it by integrating a detailed slicks inventory together with AUV-based
156 sub-bottom profiler data. Precise location of oil slicks origins at the sea surface better locates the
157 location of the active seeping vents at the seafloor (*Jatiault et al., 2017*) and to evaluate the seepage
158 activity. In addition, the SBP provides greater discrimination between seafloor fluid-related
159 morphotypes and shallow acoustic anomalies. All the maps shown in this publication (Fig. 3a, b; Fig.
160 6a, b; Fig. 7f; Fig. 9a, b and Fig. 11 a, b) cover the exact same area (red square location in Fig. 2) which
161 has been upscaled to enhance the quality of maps although the study was conducted over a larger
162 area that corresponds to the province imaged with 3D seismic.

163 **3.1. SAR data and seepage slicks inventory**

164 The entire SAR collection consists of long-range monitoring integrating 156 scenes acquired over 21
165 years. The variability of the SAR acquisition data distribution is high, both temporally and spatially, as

166 seen in Table 1 and Fig. 2, respectively. The oil-seeping province is imaged with a stack of SAR scene
 167 collection varying from 50 to 150 overlapping scenes (Fig. 2). The SAR dataset consists of a combination
 168 of X-band (wavelength of 2.5 to 3.75 cm) and C-band (3.75 to 7.5 cm) data that are known to be the
 169 most suitable wavelengths to detect oil slicks at the sea surface, enabling the recognition of the
 170 thinnest oil films (*Gade and Alpers, 1998*). The oil at the sea surface reduces the wind-induced capillary
 171 waves, thereby locally decreasing the radiometric values on SAR data. The discrimination of look-alikes
 172 (i.e. platform or boat spill, low wind effects, algal blooms) is primarily based on object features
 173 (radiometric values, edge sharpness and sinuosity), the remaining potential seepage slicks database is
 174 stacked on a compilation map. The variable orientation of surface slicks controlled by the sea surface
 175 water displacement (wind and currents) creates diverging patterns whose centres identify the oil
 176 surfacing area (black stars in Fig. 2; *Jatiault et al., 2017*). The proximal terminations of individual slicks
 177 in the oil surfacing area are called Oil Slick Origins (*OSO; Garcia-Pineda et al., 2010*). When there is no
 178 predominant current, the vertical projection of the average location of the OSO on the seafloor
 179 provides the most accurate location of the source on the seafloor.

180 **Table 1 : Inventory of SAR scenes collection characteristics.**

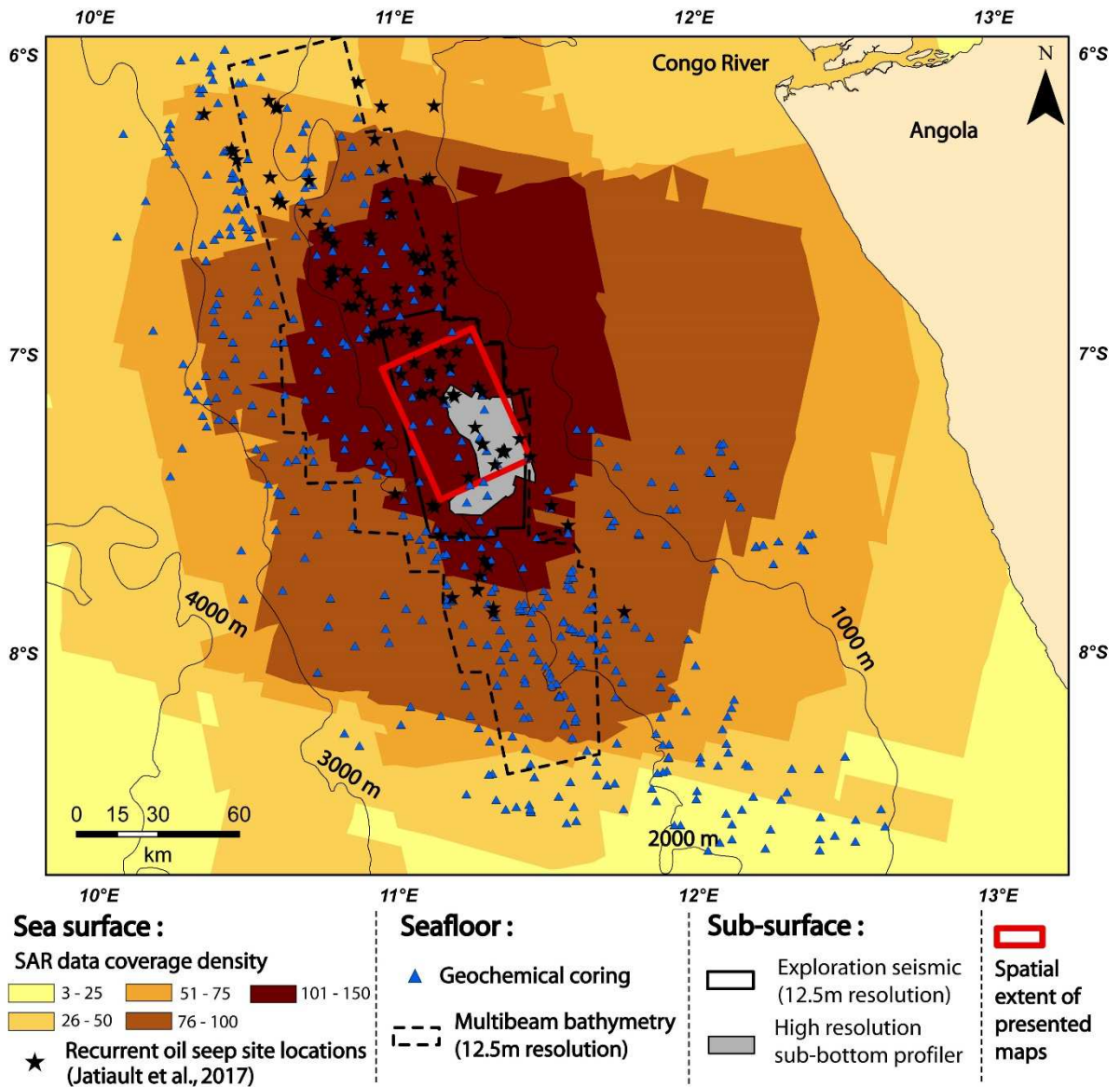
Satellite/ Sensor	Period of imagery	Wavelength	Pixel Spacing (m)	Amount of SAR data
Envisat /WSM	2002 - 2012	C (5.8 cm)	75	46
ERS/IMP	1994 - 2001	C (5.8 cm)	12.5	17
Cosmo-SkyMed	2009 - 2014	X (3.1 cm)	3-15	80
TerraSAR – X	2011	X (3.1 cm)	20	6
RADARSAT-2	2005 - 2012	C (5.3 cm)	25-50	7

181 **3.2. Geochemical coring**

182 The seafloor coring campaign was based on regional 2D seismic sections, across the deep
 183 transitional/compressive province of the LCB (blue triangles in Fig. 2). Piston cores were collected prior
 184 to the acquisition of high resolution 3D seismic presented in this paper. The entire dataset consists of

185 488 piston cores recovered during several coring campaigns between 1998 and 2010 by TDI Brooks.
186 The piston cores consist of a vertical succession of 20 cm-long sub-sections with a maximum depth of
187 5.6 m. The geochemical analyses include:

- 188 - Gas Chromatography - Mass Spectrometer (*GC - MS*) which provides the distribution of alkane
189 composition (Sn alkane) assessed from the retention time (performed for 423 cores out of the
190 whole set). The sum of individual extractible alkane portions provides an estimation of the
191 concentration of high molecular-weight hydrocarbon (C_{15+} hydrocarbon concentration).
- 192 - Unresolved Complex mixture (UCM) defined as the unextractable organic carbon with
193 chromatogram (C_{15+}).
- 194 - Total Scanning Fluorescence (TSF) intensity measured with spectrometry technique, which helps
195 quantify the fluorescence of aromatic components (**Abrams, 2005**). The maximum intensity (*I max*)
196 corresponds to the maximal values of fluorescence between emission (*EM*) spectrum and
197 excitation (*EX*) spectrum (e.g. **Barwise and Hay, 1996**). The ratio (R_1) between maximal value of
198 EM and EX provides an indirect estimation of °API (American Petroleum Institute; API gravity =
199 $- 0.1 * R_1 + 59.8$).



201

202 **Fig. 2: Geographical localisation of the study area and compilation of available dataset. The red**
 203 **square refers to the spatial extent of maps displayed in Fig. 3a, b; Fig. 6a, b; Fig. 7f; Fig. 9a, b and Fig.**
 204 **11 a, b.**

205 **3.3. Seismic dataset**

206 The available seismic dataset consists of a 3D seismic cube used for petroleum exploration,
 207 complemented by a high-resolution survey used for geo-hazards evaluation acquired with an
 208 Autonomous Underwater Vehicle (AUV).

209 **Table 2 : Characteristics of the available datasets including seafloor and sub-seafloor imagery.**

Data type		Line spacing (m)	Maximum Penetration (ms TWT)	Dominant frequency	Horizontal Resolution	Vertical Resolution	Covered area
Sub-seafloor	3D exploration seismic	12.5*12.5	4500	20 - 100 Hz	12.5 m	~4 m	3300 km ²
	AUV Sub-bottom profiler	175*1000	100	1.5 - 4.5 kHz	1.5 m	~10 cm	5500 km ²
Seafloor	Multibeam	-	-	12.5 kHz	12.5 m	-	16 000 km ²
	AUV HR bathymetry	-	-	200 kHz	1.5 - 3 m	-	830 km ²
	AUV Seafloor Reflectivity	175*1000	Few centimetres	120 - 410 kHz	3 m	-	830 km ²

210 The seismic cube covers a 3300 km² area with a maximum record length of 4500 ms TWT (Fig. 2). The
 211 source system is composed of two airgun clusters, 50 m separated with shot interval of 25 m. The
 212 sensor system consists of 10 parallel, 100 m separated streamers, and composed of 396 individual
 213 receiver groups separated by 25 m. We used the near-offset seismic trace.

214 The Sub-Bottom Profiler (SBP) dataset followed a grid with a line spacing of 1000m in the slope
 215 direction and 175m in the strike direction, and was acquired in two surveys operated in 2009 by C&C
 216 and in 2011 by Fugro (Table 2). The combination of the two datasets consists of an 830 km² gridded
 217 area and 5500 km of SBP sections. The high-frequency SBP is characterised by a 10 cm vertical
 218 resolution whereas the penetration is limited to the first 100 ms TWT below seafloor. We used the
 219 amplitude attribute to display the 3D seismic impedance contrast at lithological interfaces. The RMS
 220 (Root Mean Square) amplitude was used to display SBP sections and to identify geophysical anomalies
 221 on 3D seismic. Seafloor curvature maps are computed from the first arrivals of the 3D seismic cube,
 222 using a window size of 3 profiles and an interpolation length of 5 samples.

223 The high-resolution survey includes bathymetry (EM2000 multibeam echo-sounder) and seafloor
 224 reflectivity acquired along the acquisition tracklines of the vehicle. In areas not surveyed by the AUV,
 225 lower-resolution seafloor data (bathymetry, seismic amplitude) were taken from the seafloor
 226 reflections picked on the 3D seismic using Sismage software (**Guillon and Keskes, 2004**). In addition,

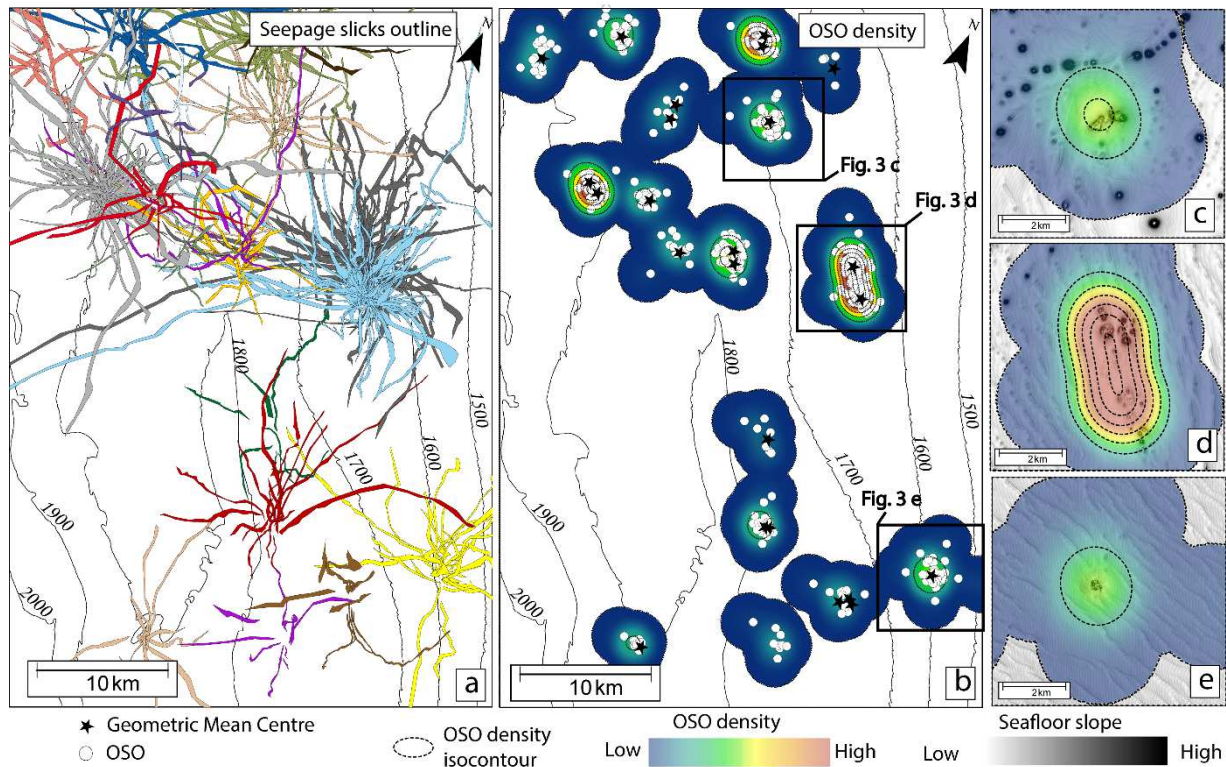
227 the seafloor origin of a large majority of (>80 %) of recurrent oil seep sites were imaged at large scale
228 (16 000 km²), 12.5m resolution multibeam bathymetry. The computation of the slope map with
229 superimposed seafloor isochrones enhances the imagery of seafloor features. Seafloor curvature maps
230 are computed from the first arrivals on the seafloor, extracted from the 3D seismic cube using Sismage
231 software and taking estimation window size of three samples and an interpolation length of five
232 samples.

233 **4. Analyses and results**

234 **4.1. Evidence of active oil seeps**

235 *4.1.1. Sea surface manifestations of oil presence*

236 The visual analysis of the 156 SAR scenes revealed more than 3000 seepage slicks characterised by
237 elongated/curvilinear trends with variable length (Fig. 3a). Diverging black streaks and OSO
238 concentration area within point clusters were used to identify active oil seep sites. The oil seepage
239 system consists of more than 100 seep sites distributed on the deep part of the Miocene Congo deep-
240 sea fan for water depths between 1200 to 2700 m. Observations of multi-temporal oil slicks at the sea
241 surface vary from 5 to 80 % from one seep site to another. The radius of the spatial scatter of OSO for
242 individual sea bottom seepage points has a mode radius of 750 m (*Jatiaux et al., 2018*), suggesting
243 that the lateral deflection due to underwater currents remains low compared to the water depth (Fig.
244 3b; *Jatiaux et al., 2019, Part I*). The vertical projection of OSO locations, the density and the geometric
245 mean centre coincide vertically at 98 % with seabed morphological anomalies, confirming the absence
246 of permanent deflection in the water column, which helps to identify active oil seep sites nearly at the
247 apex of OSO locations (Fig. 3c, d, and e).

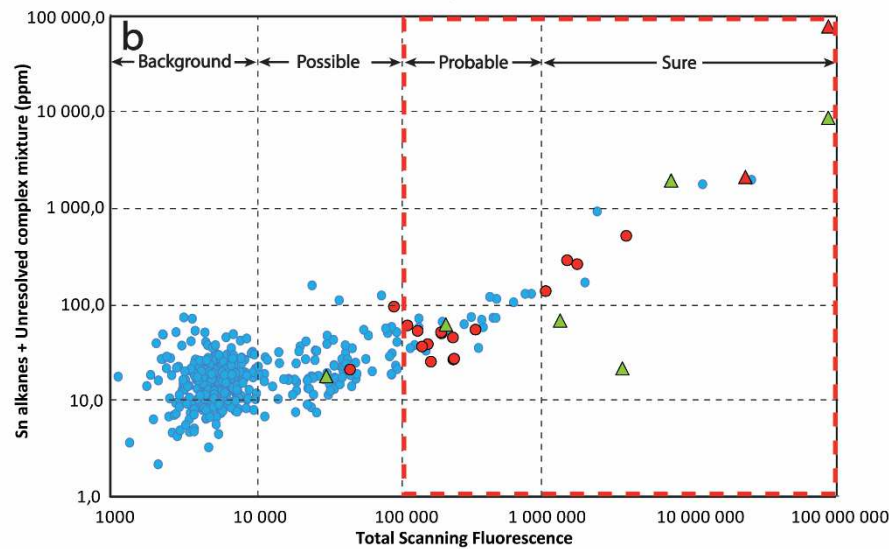
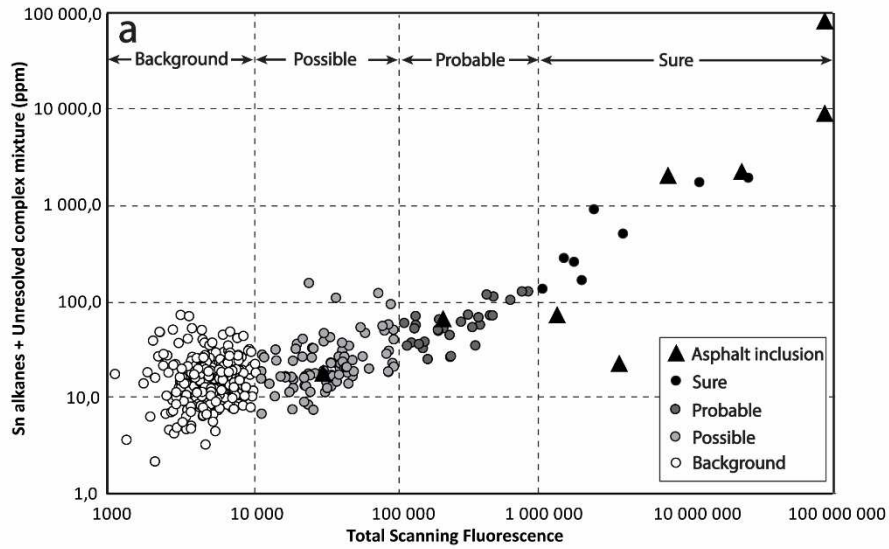


248

249 **Fig. 3: a. Compilation map of seepage slick outlines identified from the interpretation of 156**
 250 **overlapping SAR scenes. The colour corresponds to distinct active oil seep sites. b. Compilation of**
 251 **OSO pinpointed from diverging recurrent slicks in white dots, superimposed with the OSO density**
 252 **map and iso-contour. High values in warm colours correspond to frequent oil surfacing areas. c, d,**
 253 **e. Details of the OSO density map at frequent oil surfacing locations, superimposed in transparency**
 254 **with slopes map of the seafloor.**

255 **4.1.2. Seafloor geochemical coring**

256 The hydrocarbon content of seafloor piston cores is strongly variable (Fig. 4a). Geochemical analysis of
 257 heavy (C_{15+}) hydrocarbons shows that the sum of alkane (S_n) concentration ($C_{16} - C_{32}$) ranges from 0.1
 258 to 36 ppm while the concentration of UCM varies from 2 to 85 000 ppm. While the fluorescence (TSF)
 259 intensity changes from 1 116 to 87 240 000, 35 % of the cores have greater values than the regional
 260 background defined at 10 000 units (*Serié et al., 2017*). The plot of fluorescence vs. C_{15+} concentration
 261 is an indirect method for quantifying the presence of heavy hydrocarbons in sub-surface sediments
 262 (Fig. 4a).



Space-borne	Geochem.	No asphalt inclusion in cores	Asphalt inclusion in cores
No oil slicks at the sea surface	●	No oil slicks and no asphalt inclusion	▲ No oil slicks with asphalt core inclusion
Sea surface oil slicks	●	Oil slicks without asphalt core inclusion	▲ Combination of oil slicks and asphalt inclusion

263

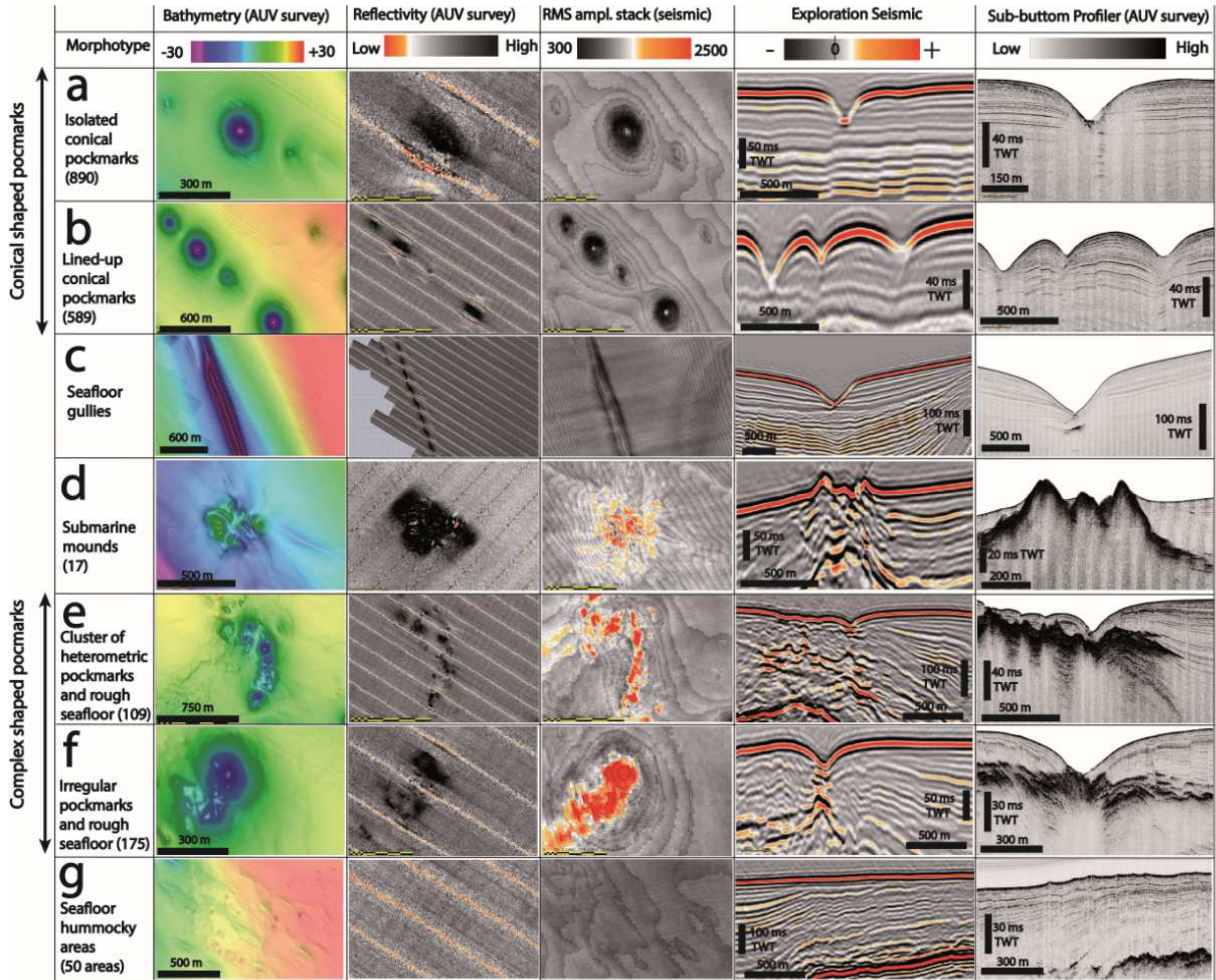
264 **Fig. 4: a. Graph (logarithmic scale) of the concentration of the high molecular-weight hydrocarbons**
 265 **(C₁₅₊) compared to the maximal intensity of the Total Scanning Fluorescence (TSF I_{max}); the circles**
 266 **colours reflects the uncertainty on the presence of hydrocarbons in cores. b. Same graph with color-**
 267 **coded symbols to show the correlation with sea-surface slicks; symbols are classified into 4**
 268 **categories depending on the geographical correspondence of oil at the sea surface (red circles) and**
 269 **visual inclusion in cores (triangles). The red dashed rectangle delimits the two categories "Sure" and**
 270 **"Probable" that we consider reliably contain oil traces.**

271 We considered that hydrocarbon traces are reliably present in cores for TSF values at least 100 times
272 greater than the regional background (Levaché, pers. com). Occurrence of hydrocarbons is possible for
273 114 cores (TSF values less than 100 000, Fig. 4a). For 38 cores, hydrocarbon traces are probable when
274 the TSF intensity is at least 10 times greater than the regional background ($100\,000 < \text{TSF} < 1\,000\,000$).
275 The presence of hydrocarbon is qualified as being sure for 20 cores having TSF values greater than 10^6 .
276 The observation of asphalt inclusions for 10 piston cores also confirms the migration of oil towards the
277 seafloor (black triangles in Fig. 4a). Even if they represent only 2% (10/488) of the total core array, they
278 correspond to the highest TSF and UCM values.

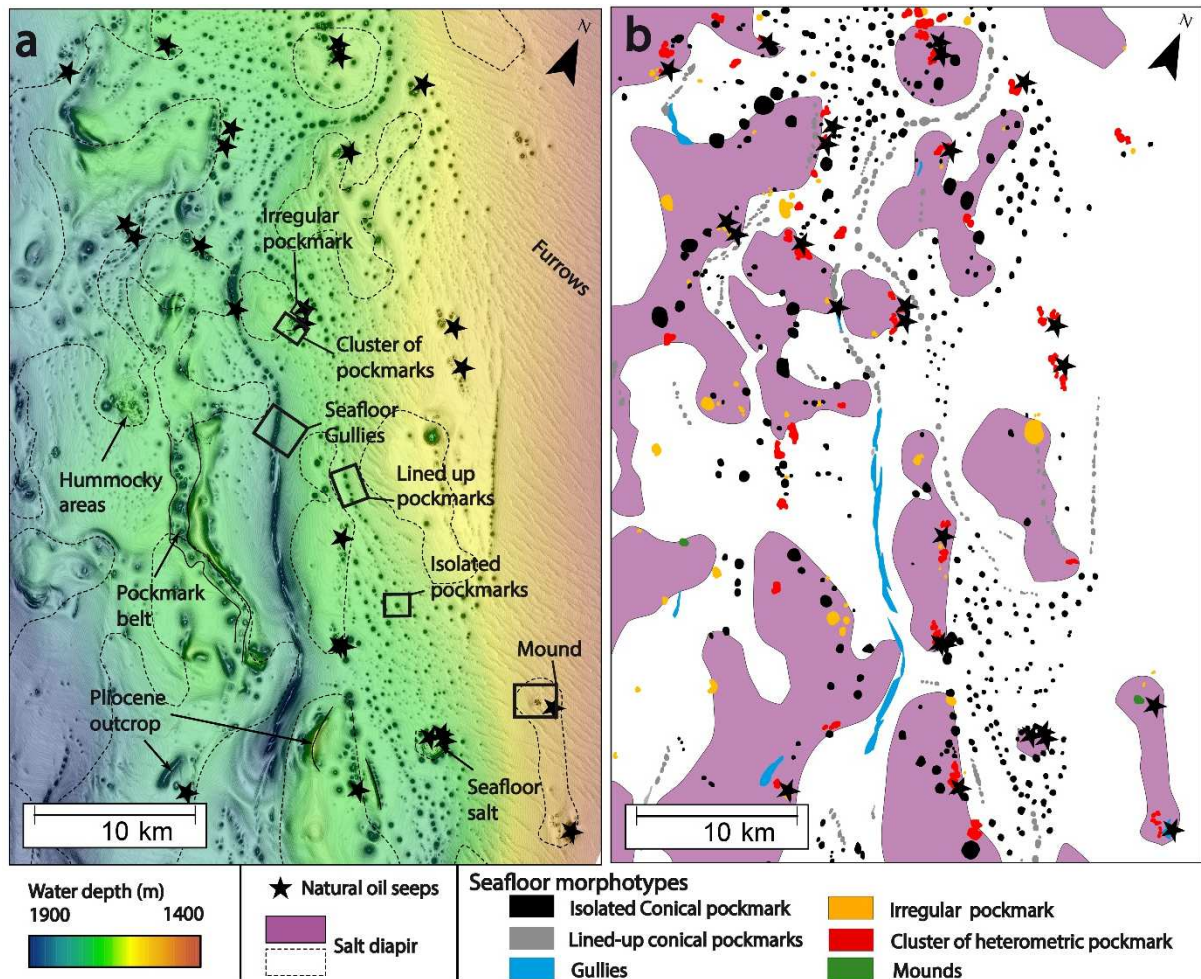
279 **4.2. Fluid flow features on the seafloor**

280 Seafloor features that may be related to fluid venting are categorised into 7 main families: conical
281 pockmarks (isolated and lined-up), seafloor gullies, complex-shaped pockmarks (clusters of
282 heterometric pockmarks and irregular isolated pockmarks), submarine mounds and scattered positive
283 topographic hummocky features (Fig. 5).

284



286 Fig. 5: Compilation of major fluid vents morphotypes observed on the seafloor in the Lower Congo
 287 Basin. The bathymetric colour scale was normalised with a 60 m dynamic range to better distinguish
 288 the different morphologies. High amplitudes are displayed in black on the reflectivity map and in red
 289 on the seafloor amplitude extracted from 3D seismic.



290
 291 Fig. 6: a. Map of the seafloor (dip + isochron) showing the distribution of fluid flow features. b.
 292 Interpretative map of focused fluid flows sorted according to their morphotypes. Black stars show
 293 the positions of the mean impact points of oil slicks at the sea surface.

294 4.2.1. The conical pockmark-gully continuum

295 Conical pockmarks can reach km-scale diameters with maximum depth of 150 m and are characterized
 296 by gentle slopes of $\sim 15^\circ$ (Fig. 5a). With a total number of 890, they are widespread throughout the
 297 study area and mostly occur in salt minibasins (Fig. 6).

298 Lined-up conical pockmarks (Fig. 5b), defined as a succession pool of at least 3 conical pockmarks along
299 a main direction, occur in 3 main settings. First, they are sparsely distributed along the maximal flexural
300 axis of salt minibasins (Fig. 6). Increase of their number and density can ultimately lead to form
301 curvilinear gullies (Fig. 5c) corresponding to deep (>50 m) and elongated (> 1 km) incised depressions
302 on the seafloor. Second, conical pockmarks can occur at the tip of normal faults on the seafloor in
303 association with the sagging of minibasins. Third, they are located at the seafloor interface
304 unconformity between uplifted slabs of Miocene-Pliocene series at diapirs and Quaternary siltstones
305 in minibasins. The total amount of conical pockmarks, including isolated ones and aligned sets, is
306 significant in the study area (1 750 individual features) (Table 3), which represents 85% of the total
307 fluid escape features identified on the bathymetric data.

308 ***4.2.2. Submarine mounds***

309 Submarine mounds are bathymetric highs on the seafloor with a typical relief of 5 to 20m above the
310 surrounding seabed and diameter up to 500m (Fig. 5d). We identified only 17 such mounds; the only
311 one of these that is imaged on HR data appears as a cluster of smaller individual mounds, whose slopes
312 range from 10 to 30°. The high-resolution bathymetry map reveals fault sets diverging radially away
313 from the seafloor mounds; similar radial patterns have been observed around salt diapirs by
314 ***Carruthers et al. (2013)***. Submarine mounds are clearly discernible on the seafloor as patches with
315 higher reflectivity compared to the surrounding seabed, indicating that they are formed of higher
316 impedance material than the background silts and clays. Seafloor mounds are located above
317 allochthonous salt diapirs like the irregular pockmark clusters (Fig. 5). Most of the submarine mounds
318 are associated with spiky diapirs (needle-shaped salt protrusion), and have not been observed above
319 bulbous ones. No clear distinction in terms of seepage proficiency (occurrence rate) could be
320 established between submarine mounds and other active features.

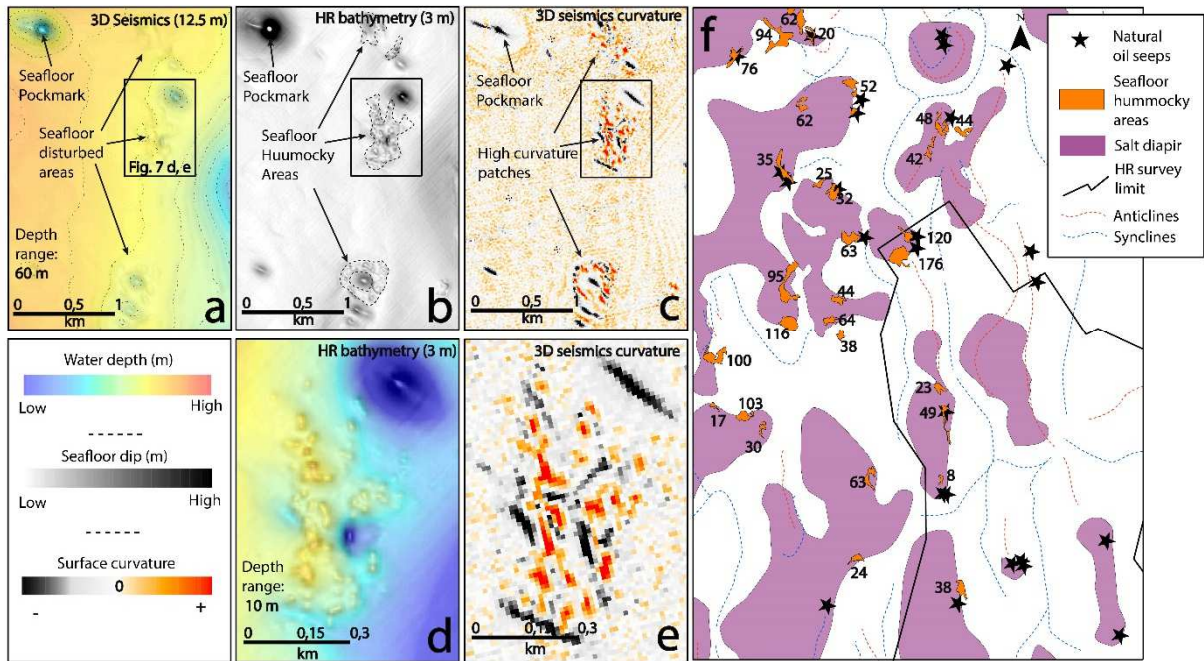
321 ***4.2.3. Complex shaped pockmarks***

322 Complex-shaped pockmarks are uneven fluid escape features on the seafloor with a main depression
323 whose depth does not exceed a few tens of meters. Complex-shaped pockmarks occur as two

324 distinctive patterns; (1) Clusters of heterometric pockmarks (Fig. 5e), defined as an aggregation of a
325 large number of unit pockmarks (*Hovland et al., 2010*), with clusters reaching 2-3 km and exceeding
326 1500m in length (*Jatiault et al., 2019, Part I*). They usually develop along the salt-related fault
327 networks at the rim of a salt canopy, thereby creating a complex-shaped depression at broader scale,
328 that contains different heterometric pockmarks; (2) Irregular pockmarks (Fig. 5f), corresponding to
329 sub-circular depressions with a rough aspect at the base. Local depressions are associated with a strong
330 high-amplitude anomaly on the seafloor reflectivity map (Fig. 5). In contrast with previously described
331 mounds, they are mostly found along landward flanks of bulbous diapirs, and never appear in
332 association with spiky ones. We identified 109 clusters of heterometric pockmarks and 175 irregular
333 isolated pockmarks.

334 ***4.2.4. Seafloor hummocky areas***

335 The seafloor is affected by rough patches clustering over limited-size areas (10-15m in diameter and
336 few meters high), on top of salt diapir. They were identified on high-resolution bathymetry maps and
337 therefore remain below the 3D seismic resolution (Fig. 7a). However, seafloor hummocky induces a
338 slight disturbance in the seafloor creating a rough aspect that may be discernible from the exploration
339 seismic resolution using specific seismic attributes such as seabed curvature (Fig. 7a). On the HR
340 bathymetry, hummocky areas consist of a numerous small hummocks (Fig. 7b). The discrimination of
341 hummocky features is particularly enhanced using the curvature attribute that measures the
342 bathymetric slope inflexions (Fig. 7c). On curvature maps, hummocky features are characterised by a
343 central (round or elongated; Fig. 7d) high positive value over topographic features, surrounded by sub-
344 circular medium values (~ 0) and by negative values at the rim (Fig. 7e).



345

346 **Fig. 7: a. Seafloor map from 3D seismic, the dynamic range of the seafloor colour scale is 60 m. b.**
 347 **Seafloor slope map of the 3m resolution multi-beam echo sounder affected by the meter-scale**
 348 **seafloor hummocky areas. c. Curvature map of the seabed from the 3D seismic data. d. Zoom of the**
 349 **3m resolution echo-sounder seafloor map (bathymetric range is 10 m) superimposed with the slope**
 350 **map. e. Zoom of the seabed curvature map from the 3D seismic data. f. Geographical inventory of**
 351 **the hummocky areas superimposed with salt diapir locations and natural oil seep sites. The numbers**
 352 **refer to the amount of detected individual hummocks.**

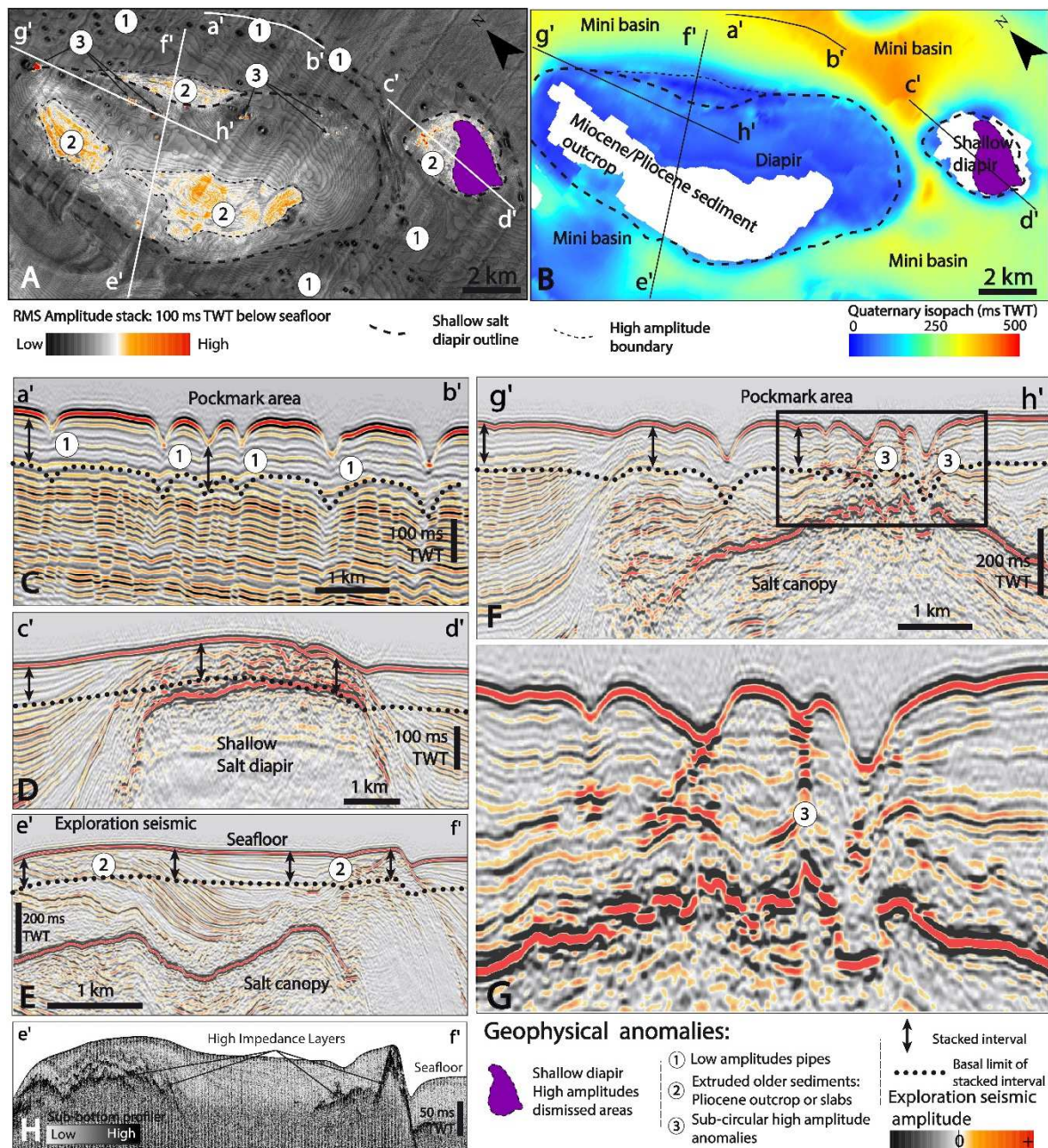
353 We assumed that rough patches correspond to zones with a high density of seafloor hummocks and
 354 individual positive sub-circular features correspond to individual hummocks. The presence of
 355 hummock clusters is associated with complex-shaped pockmarks (clusters of heterometric and
 356 irregular pockmarks) in most cases. Underlying HIL remains buried under few tens of ms below the
 357 seafloor and connected to hummocks by shallow faults (Fig. 5g). We identified 2946 possible individual
 358 hummocks over the area imaged with 3D seismic. Ten areas with a high hummock concentration were
 359 identified on the HR survey and an additional 50 on the wider 3D survey (12.5m resolution) (Fig. 7). 3D
 360 seismic data detects about 55% of individual hummock features visible on the HR survey. The number
 361 of discernible hummock features in clusters ranges between 10 to 210 on the 3D seismic, covering

362 surface areas from 0.12 to 3.45 km² and corresponding to a density of 35 to 240 hummocks per km².
363 One piston core was drilled inside a hummocky cluster visible on the 3D seismic and showed asphalt
364 inclusions in the sediment. Hummocks have the same morphology and geophysical characteristics as
365 asphalt mounds and their distribution is similar to that of those previously identified in the area
366 (*Unterseh et al., 2013; Jones et al., 2014*). Seafloor hummocks are interpreted as seafloor asphalt
367 storage that reached the seafloor through scattered emission points above the crest of salt diapirs,
368 following a stage of oil migration across sedimentary series.

369 **4.3. Seismic geomorphology in the sub-surface**

370 ***4.3.1. Positive geophysical anomalies on the 3D seismic***

371 We computed the RMS amplitude stack of the first 100 ms TWT below the seafloor reflection to
372 identify geophysical anomalies (Fig. 8 A). Geophysical anomalies occur as three main distinct features,
373 or categories.



374

375 **Fig. 8: A. Map of amplitude root mean square (RMS) over the first 100 ms TWT below seabed,**
 376 **showing four types of seismic anomalies. The dotted ellipse is the outline of a shallow diapir that**
 377 **coincides with consistent high amplitudes close to the seafloor, the outcrop of Neogene series that**
 378 **creates a moderate amplitude anomaly, the sub-circular low amplitude anomaly in minibasins and**
 379 **smaller sub-circular high-amplitude anomalies associated above salt diapirs. Please note that the**
 380 **North arrow has been rotated to ensure optimal visibility. B. The quaternary sediment isopach**
 381 **reveals the differential sedimentation between minibasin area and diapir area. C, D, E, F. Seismic**

382 sections through the different geophysical anomalies identified on fig. 8A (see details in text and
383 locations on the Fig. 8 A, B). G. Zoom of from section F on high-amplitude pipes. H. SBP section across
384 the High Impedance layer.

385 Above shallow salt diapirs, the RMS interval cross-cuts the top of salt, making high-amplitude
386 anomalies that are unrelated to fluid effects. We dismissed these areas from the interpretation (purple
387 patches in Fig. 8).

388 The first type of acoustic anomaly (1 on Fig. 8 A) is defined as a vertical succession of low-amplitude
389 reflections. Low-amplitude pipes suggest acoustic dimming in the sedimentary pile where the
390 impedance contrasts are attenuated across successive lithologic interfaces. Low-amplitude pipes are
391 essentially spread across salt minibasins or aligned along the maximal flexural axis of salt minibasins
392 (Fig. 8 A; Fig. 9). We identified a large number of low-amplitude pipes (582) across the area imaged
393 using the exploration seismic (Fig. 9). The low-amplitude anomalies identified on the 3D seismic
394 correspond to the locations of conical shaped pockmarks (isolated and aligned) and gullies (Fig. 8 C).
395 The lithologic interfaces are disrupted by an acoustically transparent zone in the sub-bottom profiler
396 below the location of conical pockmarks (Fig. 5). Lithologic interfaces are either truncated by the
397 seafloor depression or associated with a slope inflection, stacked on successive lithologic interfaces. In
398 the former case, the active fluid seep probably corresponds to a recent initiation of the seepage
399 activity. In the latter case the deepest interval affected can be followed down to 600 ms TWT on the
400 exploration seismic. On the sub-bottom profiler, stratigraphic boundaries surrounding the low-
401 amplitude anomalies remain well organised down to the acoustic penetration. Most correspond to the
402 bulls-eye pockmarks defined by *Andresen et al. (2011)*.

403 The second type (2; Fig. 8 A) of acoustic anomaly corresponds to moderate positive amplitude
404 anomalies related to outcropping older sediments (mostly Neogene) above salt diapirs; these
405 anomalies gradually dim out laterally (Fig. 8 E). Affected areas range from 1 to 10 km². Moderate
406 amplitude anomalies are composed of consistent, extensive patches indistinctively downslope or

407 upslope (Fig. 8 E) in relation to the depocentre shift/tectonic inversion (**Quirk and Pilcher, 2012**).

408 Uplifting of older sediments can also be detected on the sub-bottom profiler sections where they occur

409 as strong threadlike reflections (Fig. 8 F).

410 The third type (3; Fig. 8 A) of acoustic anomaly corresponds to local, sub-circular and Positive High

411 Amplitude Anomalies (PHAA; **Ho et al., 2012**) that are vertically stacked on successive lithologic

412 interfaces, marking a vertical succession of strong impedance contrasts (bright anomalies; Fig. 8 G).

413 The PHAA diameters vary from 60 to 350m and occur either as multiple vertical pipe clusters (see

414 **Jatiaux et al., 2019, Part I**) or isolated chimneys (Fig. 8 G). We identified 75 individual PHAA on the

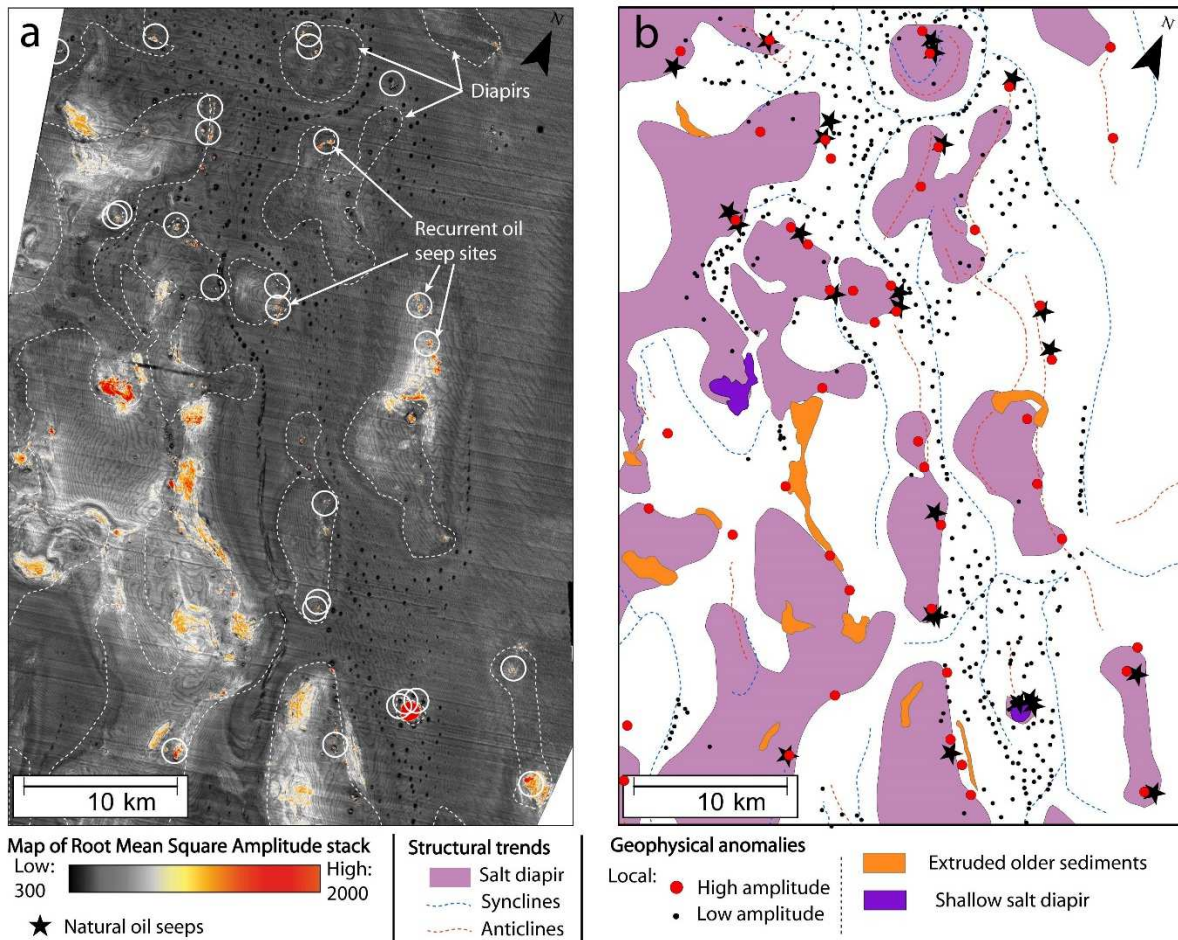
415 RMS amplitude stack of the first 100 ms TWT, mostly associated with diapirs (Fig. 9). They tend to

416 congregate along the upslope salt flank or minibasin edges. High-amplitude vertical pipes are mostly

417 associated with strong RMS amplitude in the central area surrounded by a moderate amplitude

418 peripheral anomaly. The seafloor expression of PHAA corresponds essentially to the complex shaped

419 pockmarks (clustered or isolated) and submarine mounds.



420

421 **Fig. 9: a. Map of the RMS amplitude stack of the first 100 ms TWT below seafloor. Geophysical**
 422 **positive amplitude anomalies are visible as warm colours. White circles show the average surfacing**
 423 **areas of recurrent oil seeps. b. Map of the allochthonous salt represented as purple polygons. The**
 424 **anticline/syncline of the Late/Early Pliocene transition is displayed as red and blue dashed polylines,**
 425 **respectively. The geophysical anomalies extracted from the RMS amplitude stack are categorised**
 426 **into four main families: shallow salt diapir, exhumed older and compacted sediments, pseudo-**
 427 **circular amplitude diming and vertical stack of pseudo-circular high-amplitude anomalies.**

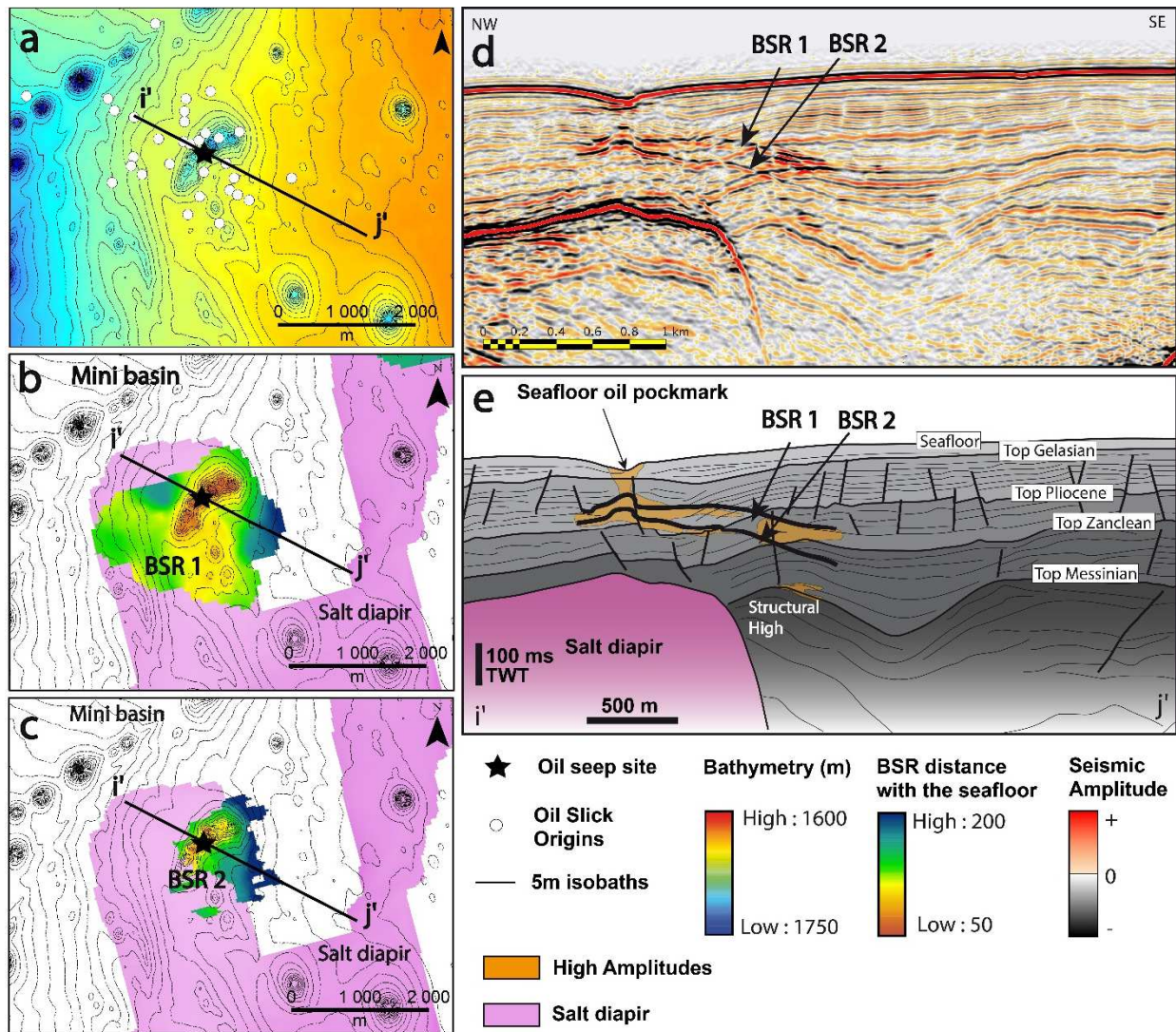
428 ***4.3.2. Negative polarity reflections***

429 Occasionally, consistent negative reflections crosscut stratigraphic series with all the characteristics of
 430 a methane hydrate BSR. The BSR occurs as extensive reflectors in minibasins with a distance from the
 431 seafloor ranging roughly from 250 to 500 ms TWT and is usually underlain by a thick High-Reflectivity
 432 Zone (**Andresen et al., 2011**).

433 Approaching the salt diapirs, the BSR shoals up to a range of 50 to 250 ms TWT below the seabed; it
434 generally occurs in discrete small patches (Fig. 10a). This difference between the overburden of the
435 diapirs and minibasins is known to be associated with the high thermal conductivity of the salt, which
436 concentrates heat above diapirs, resulting in a higher geothermal gradient there, and consequently a
437 thinner hydrate stability zone (*Lucazeau et al., 2004*). The BSR corresponds to the basal limit of pipe-
438 like features (type 3 anomalies) characterised by a vertical succession of PHAA and is underlain by a
439 100 ms-thick high-amplitude interval.

440 The sub-surface series are also locally affected by an occasional second negative polarity reflection.
441 The horizon occurs as a continuous, crosscutting surface and tends to be parallel to the first BSR. The
442 vertical distance with the BSR is mostly constant (~50ms), or occasionally increases towards the
443 minibasins (Fig. 10). The thermal effect associated with the presence of a salt diapir also affects the
444 vertical location of the second BSR by decreasing the distance from the seafloor. Double BSRs are
445 observed exclusively above salt diapirs. Both BSRs are concomitantly and locally deflected upward
446 below seafloor depressions, which also correspond to the locations of PHAA (Fig. 10).

447



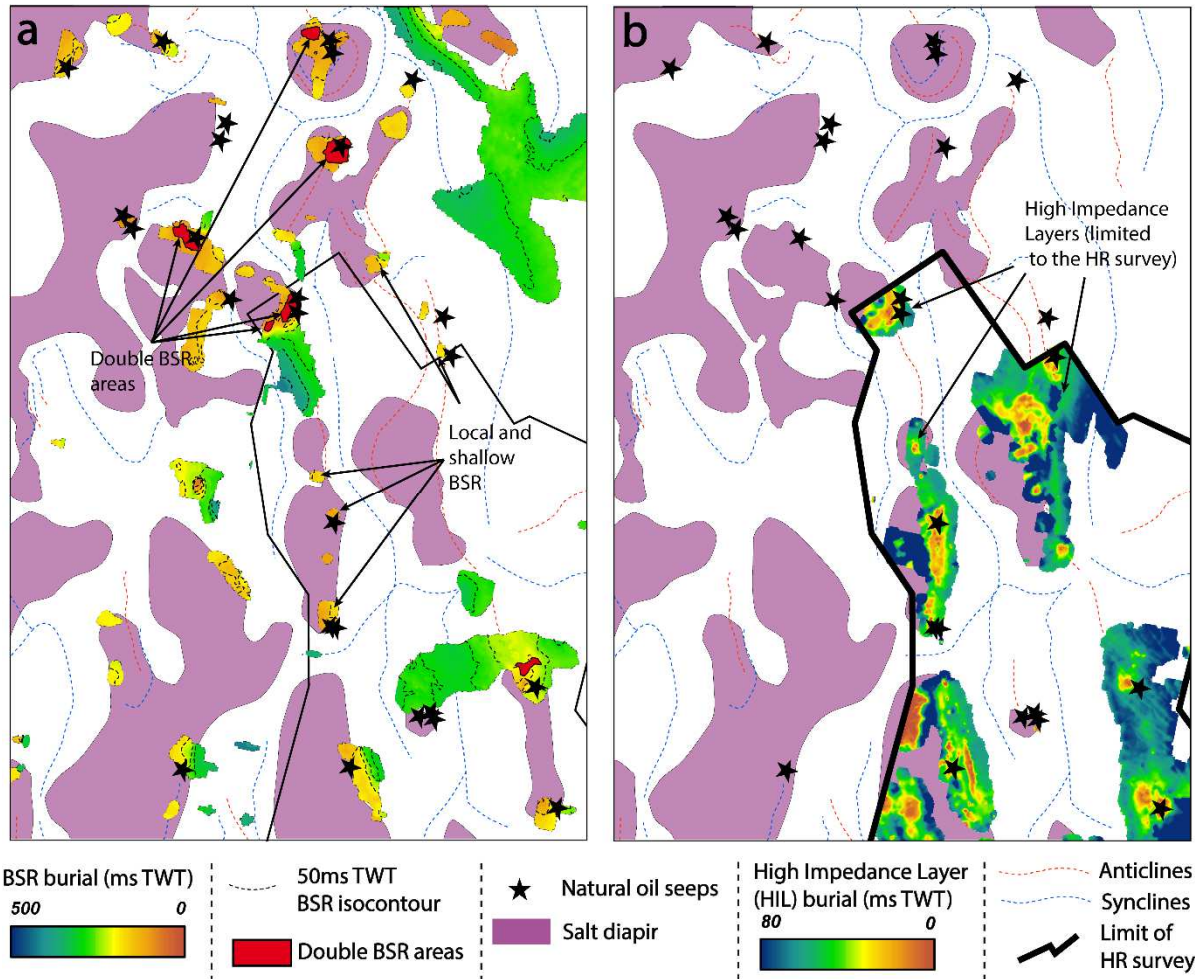
448

449 **Fig. 10: a.** Seafloor map superimposed with 5m isobaths, oil slick origins (OSO; Garcia-Pineda et al.,
 450 **2010** and location of oil seeps identified with the SAR system. **b.** TWT difference map between upper
 451 BSR and seafloor, superimposed with the extension of the underlying diapir and 5m isobaths. **c.** TWT
 452 difference map of the lower BSR with the seafloor, superimposed with the underlying diapir
 453 extension and 5m isobaths. **d.** Seismic section across a double BSR marked by two stacked black
 454 horizons (see location in Fig. 10.a) **e.** Interpretative line drawing.

455 **4.3.3. Subsurface high impedance layer**

456 A consistent High-Impedance Layer (HIL) frequently appears on sub-bottom profiler sections, in the
 457 shallow sub-surface above the salt diapirs (Fig. 8 H). HIL are only identified on the high-resolution
 458 survey and consist of a high-amplitude cross-cutting reflector. High-Impedance Layers occur in patches

459 whose surface areas can reach 120 km², the average being 20 km² (Fig. 11 b). They are located above
 460 diapiric areas, mostly at the upslope flank but can also be occasionally found downslope. The TWT
 461 difference with the seafloor ranges from 0 to 80 ms TWT above diapirs and can be higher (up to 200
 462 ms TWT) in minibasins.



463

464 **Fig. 11 : a. Extract of the Bottom Simulating Reflection (BSR) map with basin structure in background**
 465 **illustrating the relationship with hydrate and oil seep sites. b. Isochron map of the HIL in the shallow**
 466 **sub-surface from sub-bottom profiler data. The colour scale displays the distance between the**
 467 **seismic horizon and the seafloor.**

468

469 5. Synthesis and discussion

470 5.1. Integrative synthesis of the oil seepage situation

471 A subset of 22 cores spatially corresponds to the vertical projection of recurrent oil seep sites detected
472 from the SAR study, within a radius of < 1500 m (red dots and green triangles in Fig. 4b). Geochemical
473 analyses were successfully performed for 19 out of 22 cores. For these sampled oil seep sites, the C₁₅₊
474 concentration (Σn Alkanes + UCM) shows high concentrations of heavy hydrocarbons and TSF values
475 at least 50 times higher than the regional background. A large majority (17/19) of sampled oil seep
476 sites fall into the "Probable" and "Sure" categories and the remaining (2/17) into the "Possible"
477 category (red dots and green triangles in Fig. 4b). These observations validates the assumption that
478 lateral drift in the water column averages to nil over time and confirms that, without any systematic
479 offset, the pockmarks beneath the barycentre of OSOs corresponds to the source of expelled oils, on
480 a regional scale as demonstrated from integration of vertical mooring data (*Jatiault et al., 2018*).
481 Considering that 58 pistons belong to the "Probable" and "Sure" categories, 38% (22/58) correspond
482 to the location of recurrent seepage slicks detected with the SAR system. The oil gravity, estimated
483 using the fluorescence technique, ranges from 10 to 40°API for active oil seep sites associated with sea
484 surface manifestations of oil.

485 Even though visual confirmation of asphalt inclusion remains uncommon (10 cores; black triangles in
486 Fig. 4a), 40% of drilled sites showing asphalt inclusions (4/10; green triangles in Fig. 4b) are located
487 close to a recurrent seep site at the sea surface. The geochemical analysis is available for 2 cores
488 associated with asphalt inclusions and shows that the TSF values and the concentration in C₁₅₊ reaches
489 the highest values in the core dataset (Fig. 4b).

490 We identified multiple fluid-related morphotypes on the seafloor in our study area (Fig. 5). Let us
491 examine which ones can be considered characteristic of oil-bearing seeps compared to other fluid
492 releases, by comparing geophysical features against the results of the SAR study. The number of conical
493 pockmarks, including aligned and isolated cones, represents 85% of the total fluid escape features

494 identified on the bathymetric data (1 750 individual features) (Table 3). Although these features are
495 abundant, none are presently responsible for oil seepage detected with SAR systems. Conversely,
496 clusters of heterometric pockmarks, irregular pockmarks and submarine mounds are occasional across
497 the margin. Respectively, 109, 175 and 17 were indexed from bathymetric analyses, making barely 15
498 percent of the total number of identified seafloor fluid-escape features. These 15 percent account for
499 98% of seafloor vents responsible for oil supply during the observation period (Table 3).

500 Seafloor hummocky areas are associated with oil slicks detected with SAR data for 5 out of the 10
501 seafloor hummocky areas detected on the HR dataset and 21 out of the 50 identified from the 3D
502 seismic. Both the HR survey and information deduced from 3D seismic suggest that barely half of
503 asphalt mounds fields are associated with detectable and recurrent slicks at the sea surface (21 out of
504 entire 50 hummocky areas array).

505 On the subsurface, the area imaged with the 3D seismic covers 30 individual recurrent oil seep sites,
506 28 of which are either directly related to shallow salt diapirs, or correspond to the outcropping older
507 sediment slabs uplifted by differential salt movements. The seafloor origin of recurrent oil seep sites
508 visible exclusively on SAR data (100 %) corresponds to PHAA pipes in the shallow subsurface (<100ms;
509 Fig. 9). Among the 75 individual vertical pipes identified (type 3; Fig. 8 A), about 40% of geophysical
510 anomalies (30/75) are currently associated with prolific seep sites. Conversely, none (0%) of low
511 amplitude pipes identified across the study area are associated with oil seeps visible on space-borne
512 data. Among the 75 local positive geophysical anomalies (type 3) recognised using the 3D seismic,
513 about 60 % (45/75) are associated with a BSR. Among the 30 recurrent oil seep sites imaged with 3D
514 seismic, 21 (70 %) are emplaced directly above a shallow BSR. Double BSR are unusual in the study
515 area but exclusively occur to oil seep sites detected with the SAR system (see red patches in Fig. 11 a).
516 Six of the 30 recurrent oil seep sites detected with the SAR system and imaged with 3D seismic are
517 directly emplaced above a double BSR. All the detected oil seeps belong to the areas associated with
518 the development of a HIL (Fig. 11 b). Moreover, the interpreted seafloor origin of oil seeps (irregular
519 isolated pockmarks and cluster of heterometric pockmarks; Fig. 5) corresponds to areas where the HIL

520 reach the seafloor. There is a strong geographical correlation between seafloor-reaching HIL, shallow
 521 local BSR and PHAA. At the submarine mound locations, the interface between the series affected by
 522 and unaffected by the HIL are characterised by a sharp, strong acoustic impedance contrast (Fig. 5d).
 523 The HIL crosscuts the stratigraphic series and rise towards the seafloor at the mound locations without
 524 revealing any particular internal organisation compared to stratigraphic boundaries. At the location of
 525 complex shaped pockmarks, the interface between the series affected and unaffected by the HIL is
 526 continuous and sometimes tends to align with stratigraphic boundaries (Fig. 5e).

527 **Table 3 : Synthesis of fluid flow manifestations as observed throughout the study area compared to**
 528 **detectable oil seeps. Pockmarks inventory are deduced from the interpretation of the 12.5m**
 529 **resolution multi-beam bathymetry. Coupling the features related to oil seep sites with non-seeping**
 530 **geophysical anomalies contributes to the understanding of the seepage potential.**

Fluid flow manifestations		Total picked-out	Oil supplying sites (SAR data)	
			Active	Percentage of correlation
Submarine mounds		17	6	30 %
Complex shaped pockmarks	Cluster of heterometric pockmarks	109	53	49 %
	Irregular isolated pockmarks	175	26	15 %
Regular shaped pockmarks	Isolated conical pockmarks	890	2	< 1%
	Aligned conical pockmarks	589	0	0 %
Total picked-up		1750	87	/
Seafloor asphalt mounds	HR bathymetry (3m)	10	5	50%
	3D bathymetry (12.5m)	50	21	42 %
Seafloor geochemical coring (<1500 m)	"Probable" and "Sure" categories	58	22	38 %
	Visual asphalt inclusion	10	4	40 %
Geophysical anomalies (n°3)	From 0 to 100 ms TWT	75	30	40 %

5.2. Significance of thermogenic seep sites geometry

5.2.1. Seafloor expressions

Defining characteristic features of thermogenic seeps on geophysical data is crucial for the understanding of petroleum system plays, to define the best seafloor coring targets and to seek and inventory extreme marine ecosystems (*Jones et al., 2014*). As demonstrated by previous studies on the LCB (*Andresen, 2012; Jatiault et al., 2019, Part I*), the location of seafloor thermogenic seeps is controlled by the shallow deformation related to the salt tectonics. Thermogenic pockmarks locate along faults associated with the underlying diapir deformation. Therefore, the location of seafloor seeps, especially clusters of heterometric pockmarks is consistently influenced by the underlying salt tectonics-related fault network. Both clustered and irregular pockmarks occur above fluid-related seismic anomalies, such as high-amplitude vertical pipes (*Løseth et al., 2011*), shallow HIL, BSR(s), or above salt. The distinction between clustered and irregular pockmarks is facilitated using the HR bathymetry, while the characteristics of the subsurface are similar. The distinction between the two is sometimes tricky and can be subject to data resolution issues or could mark a temporal evolution that depends on seepage persistence over time. The geometrical distinction could correspond to the process evolution, one being the initial stage of the other. In actively deforming areas above salt, the area affected by seepage features is likely to correspond to areas undergoing active fracturing; the pinpoint versus distributed character of seeps may reflect the localised versus distributed character of fracturing.

Previous work on the LCB reported a large number of clustered pockmarks at roughly 550 metres depth (*Gay et al., 2007*), i.e. along the feather edge of the BSR at the seabed. The presence of salt is known to deform the temperature field above and around diapirs (*Lucazeau et al., 2004*), and may affect the salinity of formation water conditions. However, the identification of BSRs above salt diapirs in this area indicates that the BGHSZ remains within the sedimentary interval at salt protrusion areas (Fig. 11). The strict association between submarine mounds and spiky diapirs suggests that the development of mounds depends on the degree of focusing of the hydrocarbon migration system.

557 Similar shaped submarine mounds (Pingoes) were described and interpreted as composed of
558 carbonate reefs interspersed with hydrates patches in the Norwegian Sea (*Hovland and Svensen,*
559 **2006**), but also in the Kwanza basin interpreted as imprinting the development of underlying hydrates
560 nodules (*Serié et al., 2012*).

561 Studies conducted at the salt front of the LCB led to differentiating active from inactive sites based on
562 seafloor reflectivity strength (*Wenau et al., 2014*), applying the general criterion defined by *Sager et*
563 *al. (2003)* who relate low backscatter area to dormant sites. In our study, we observed major recurrent
564 oil seeps on SAR data that are associated with a "moderate" seafloor response (Fig. 3 in *Wenau et al.,*
565 **2014**).

566 Authigenic carbonate precipitation is presumed to consume methane in priority (Anaerobic Oxidation
567 of Methane; e.g. *Barnes and Goldberg, 1976; Ivanov et al., 1989; Boetius et al., 2000; Paull and Ussler,*
568 **2008; Knittel and Boetius, 2009; Boetius and Wenzhöfer, 2013**). The seafloor reflectivity strength used
569 in this study is rather similar between oil-supplying and non-oil-supplying seeps (Fig. 5), even if slope
570 artefacts may occur. Recent studies have shown that the type of carbonates is different between
571 systems dominated by oil and gas (e.g. *Hudson, 1997; Thomas et al., 2011; Smrza et al., 2016*), which
572 might involve a difference in precipitation rate.

573 Pockmarks associated with pore-water and biogenic methane release occur extensively in minibasins
574 in relation to local-scale features such as polygonal faults (*Andresen and Huuse, 2011; Maia et al.,*
575 **2016**) and/or tectonic faults (*Gay et al., 2006 c*). Methanogenic carbonate precipitates even in the case
576 of a "slow seep" (*Ho et al., 2012*). The absence of positive high-amplitude anomalies (*Ho et al., 2012*)
577 in association with conical pockmarks therefore suggests that the associated fluid is likely pore-water
578 dominated. We have observed that pockmarks located in minibasins are steeper (~15°) and more
579 conformable compared to those located above diapirs. Let us examine the factors that could explain
580 this difference. The mid Plio-Quaternary sedimentation in salt minibasins is dominated by fine-grained
581 sediments that act as an impermeable barrier to fluid migration (*Uenzelmann-Neben, 1998; Anka et*

582 *al., 2013*). The sediment type could have a strong influence on pockmark geometry; the recent
583 sedimentary overburden being gently eroded across the fluid ascent path could explain the
584 conformable geometry of minibasin pockmarks. The uplift of older/coarser Miocene/Mid-Pliocene
585 sediments (*Anderson et al., 2000*), combined with salt-induced faulting and seafloor
586 hydrates/carbonates distribution might be good candidates to generate multiple seafloor fluid outlets
587 (*Jatiaux et al., 2019*). In this condition, this could explain the morphological differences between
588 thermogenic seep sites above diapirs and pore-dewatering escape features in minibasin.

589 **5.2.2. Sub-seafloor expression**

590 Oil-supplying seeps correspond to small (100m diameter) sub-circular high amplitude anomalies on
591 the seafloor amplitude map (d, e and f in Fig. 5; n°3 in Fig. 8A). The presence of a BSR shows that
592 migration is focused above diapirs and that the presence of anomalies above the base of the hydrates
593 indicates that the hydrate seal is locally breached when the fluid overpressure is too high (*Cathles et*
594 *al., 2010*). The vertical successions of strong reflections are interpreted as fluid escape pipes (Fig. 8 G;
595 *Löseth et al., 2011; Karstens et al., 2015*) which can be related either to vertical stacking of authigenic
596 carbonate cementations or pavements (*Hovland et al., 1987; Hovland, 2002; Pierre and Fouquet,*
597 *2007; Römer et al., 2014*), vein-filled/ hydrate-rich sediments (*Sahling et al., 2008*) or gas-charged
598 sediments (*Schroot et al., 2003*).

599 Outcrops of Miocene-Pliocene sediments at the seabed are privileged leakage pathways due to
600 changes in lithologic properties from fine-grained/high cap-rock efficient upper Pliocene and
601 Quaternary silts and clays to coarser, more permeable Miocene series (*Anderson et al., 2000*) and
602 appear as privileged fluid outlets.

603 The negative impedance contrast resulting in the BSR is known to primarily reflect the presence of free
604 gas beneath the base of the hydrates stability zone, rather than the increase of impedance due to the
605 presence of hydrates above (*Holbrook, 2001*). The identification of a second BSR was reported in a few
606 case studies (*Andreassen et al., 2000; Foucher et al., 2002; Popescu et al., 2006; Posewang and*
607 *Mienert, 1999; Zander et al., 2017*) with various interpretations (changes in environmental conditions,

608 paleo BSR relics, and heavier gas components). In the LCB, the observations of a second cross-cutting
609 and negative polarity reflections exclusively occur; (1) at the crest of salt diapirs and (2) in the
610 conditions of proven thermogenic fluid seepage from the identification of recurrent slicks. The second
611 BSR could be associated with heavier gas components in conditions of abundant thermogenic
612 dysmigration (*Jatiaux et al., 2019, Part I*). Stacked BSR 1 and 2 would then involve distinct hydrocarbon
613 compositions between the two layers, which excludes the hypothesis of a mix of hydrocarbon
614 components from BSR1 and BSR2, and therefore suggests distinct migration pathways. In that case,
615 the 100% methane-related BSR would probably follow a lateral path along minibasin stratigraphic
616 interfaces towards the crest of the diapir. Knowing that structure II and H hydrates are stable at
617 greater depths (*Sloan, 1990*) and considering the limited extent of BSR2, the thermogenic BSRs would
618 follow more vertical advection paths along salt flanks.

619 **5.3. Relevance of multi-scale integrated evaluation of the thermogenic** 620 **seepage potential**

621 **5.3.1. Pre-existing methodology**

622 The combination of different geophysical observations provides key features to better understand
623 hydrocarbon seep systems and fluid flow phenomena (*Serié et al., 2017*). The integration of multi-
624 proxy tools is relevant for confirming source rock maturation and for studying fluid migration across
625 sedimentary series. The technique used in pre-existing methodology has its own advantages and
626 limitations that are listed and explained below:

627 - For underexplored areas, remote sensing analysis provides a first-order approach for
628 evaluating the seepage potential (*Williams and Lawrence, 2002*). The main SAR system limitations are
629 its limited spatial resolution (Table 1) and dependency on weather conditions (1.5 to 5.5 m.s⁻¹; *Jatiaux*
630 *et al., 2017*). On SAR images, low backscatter areas can also be look-alikes (such as algae blooms,
631 surface micro-layer; *Mityagina et al., 2007*) and the natural origin of low radiometric features without
632 a seafloor validation therefore remains questionable, even when recurrent (*Ryan et al., 2010*). The

633 SAR detectability thickness threshold may prevent the recognition of active oil seeps when the oil flow
634 is low.

635 - Even low-intensity oil seep sites are detectable with seabed geochemistry using fluorescence
636 analysis (**Abrams, 2005**). The recognition of asphalt inclusions in cores demonstrates the thermogenic
637 origin of fluid migrations. However, the pinpoint nature of geochemical coring means that even with a
638 dense set of cores, the technique potentially misses a large array of active seep sites.

639 - The seafloor seismic amplitude provides information on lithological modifications, especially
640 above salt diapir where the outcropping Pliocene/Miocene series constitutes privileged pathways for
641 migrating fluids.

642 - The identification of a negative polarity BSR also helped us locate focused hydrocarbon fluid
643 migration above salt diapirs (**Taylor et al., 2000; Lucazeau et al., 2004; Serié et al., 2017**). In the
644 context of a shallow underlying diapir, the associated thermal anomaly creates an upward
645 displacement of the BSR that is suitable for the formation of a hydrate-related trap for hydrocarbon
646 migration. However, the survival period of a BSR following the cessation of fluid migration remains
647 under-documented, limiting the appraisal of seepage activity.

648 ***5.3.2. Improvements of the methods***

649 In addition to pre-existing methodology, the following additional data analysis can help to refine the
650 fluid flow phenomena in sedimentary basin (Fig. 12). Let us examine what are the improvements
651 performed by the integration of additional data:

652 - A detailed analysis of surface slicks better constrains oil seep sites locations and address the
653 present-day seepage expelled volumes. In this study, recurrent surface slicks were successfully linked
654 with seafloor features 98% of the time. This confirms the relevance of combining the SAR system with
655 marine geophysical surface data to constrain hydrocarbon plumbing system during the exploration
656 workflow. The occurrence rates defined as the ratio between the amount of detected slicks and SAR
657 data coverage range from 5 to 80% (**Jatiaux et al., 2017**). Considering that the SAR system efficiency

658 depends on weather conditions and that active seep sites are mostly intermittent, exhaustive
 659 inventory of oil seep sites relies on a high multi-temporal satellite data coverage with at least fifty
 660 overlapping SAR scenes in our study area. The amount of oil that naturally enters the marine
 661 environment is roughly split into two equal parts between natural seepage and human activity (*Prince*
 662 *et al., 2003*). For quantitative geological studies, it is necessary to discriminate natural seepage to
 663 unnatural oil (*Macdonald et al., 2015*). Considering average displacement values at the sea surface in
 664 the LCB of 17 cm.s^{-1} due to surface currents and winds (*Jatiaux et al., 2017*) and assuming that slicks
 665 thinner than $0.1 \mu\text{m}$ thick are not detectable (*de Beukelear et al., 2003*), the estimated minimum
 666 detectable oil flow varies between 0.76 to 9.2 l.h^{-1} depending on the spatial resolution of SAR systems
 667 (Table 4). Considering that 4380m^3 are expelled annually from one hundred seep sites (*Jatiaux et al.,*
 668 *2017*), the average expelled volume of a random oil seep is estimated at 5 l.h^{-1} in the study area. This
 669 demonstrates that the expelled volume is within the order of the detectability threshold. The SAR
 670 detectability thickness threshold might therefore be too high to detect the activity of a subset of
 671 potential seep sites interpreted from seismic data.

672 **Table 4 : Minimum oil output estimation depending on the spatial resolution of different SAR**
 673 **systems.**

Satellite/ Sensor	Envisat /WSM	ERS/IMP	Cosmo-SkyMed	TerraSAR – X	RADARSAT-2
Pixel Spacing (m)	75	12.5	3-15	20	25-50
Minimum volume output (l.h^{-1})	9.2	0.76	0.18 – 0.92	1.22	3.06 – 6.13

674 - The integration of current profilers (or the use of regional metocean models when the former
 675 are not available) helps constrain probable oil migration routes through the water column and quantify
 676 the probable lateral deflection (*Jatiaux et al., 2018*).

677 - The detection of asphalt mounds on HR survey confirms that oil is migrating towards the
 678 seafloor and constitutes another proof of an active oil-seep sites (*Jones et al., 2014*). The presence of
 679 asphalt mounds implies that hydrocarbon dysmigration is sufficiently slow for the oil to be heavily
 680 degraded and stored on the seafloor (*Head et al., 2003; Larter et al., 2003; Jones et al., 2008; Larter*

681 *et al., 2006; Peters et al., 2005; Peters et al., 2007; Jones et al., 2008*). In the present case, using
682 specific seismic attributes such as curvature identified a high proportion of the mounds and may be
683 used at least for a first screening.

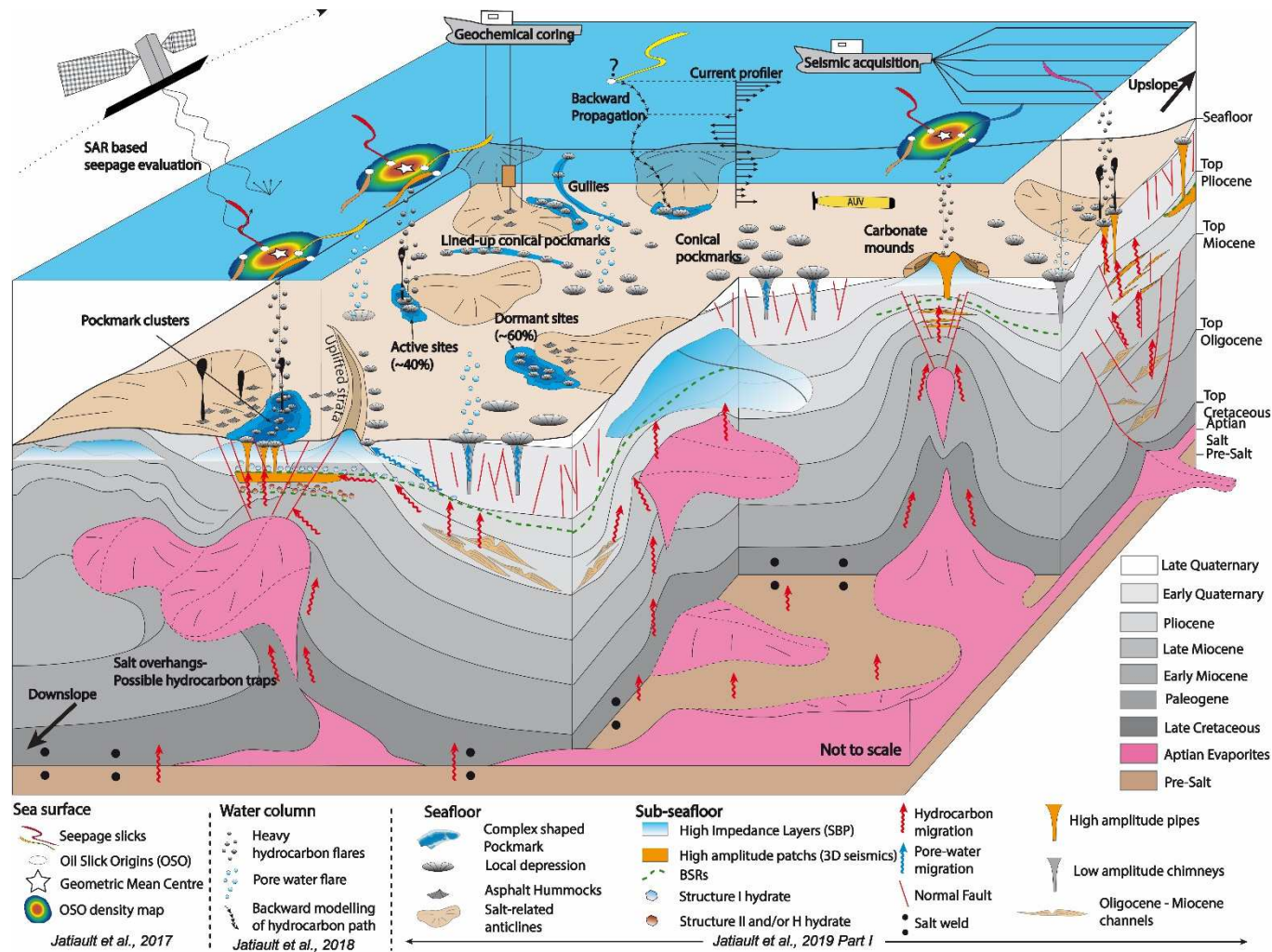
684 - The computation of an RMS amplitude map of shallow subsurface (first 100 ms in this study)
685 quickly pinpointing isolated sub-circular high-amplitude anomalies likely to sign the presence of fluid
686 migration, while reducing the amplitude anomaly associated with the slope inflection. Vertical stacking
687 of anomalies, if observed on cross-sections, is a strong additional indication of hydrocarbon leakage.
688 However, the technique is irrelevant for assessing the fluid type.

689 - We observed double BSRs only at the location of oil seeps proven by SAR analysis. Double
690 BSR could mark the basal level of stability of a mix of heavier gas. Additional studies would be needed
691 to know if this is related to compositional or concentration effects.

692 - The HIL is presumably related to limited-size carbonate slabs with shallow asphalt and
693 potentially with hydrates (*Jatiaux et al., 2019, Part I*) also helps locate active hydrocarbon seepage.
694 HIL patches are typically wide, but reach the seabed in a very limited area; consequently, the
695 identification of the point where the HIL reaches the seabed reduces the uncertainty on the
696 identification of the point of seepage. The SBP dataset provide information on sub-seafloor hardness
697 and possibly a discrimination between similar shaped features, i.e. soft mud volcanoes (*Serié et al.,*
698 **2017**) compared to harder carbonate and/or hydrate mounds/pingoes (this study; *Hovland and*
699 **Svensen, 2006**). The proximity of HIL features with the seafloor also constrains seep outlets location
700 and improve the targeting of cores locations. However, the deployment of such toolsets in a given area
701 implies that the given area has already been extensively explored.

702 The combination of different observations and techniques provides an integrated vision of the
703 hydrocarbon fluid seepage phenomena in the Lower Congo Basin and helped refining the methodology
704 of studying the fluid flow phenomena (Fig. 12).

705



706

707 Fig. 12: Synthetic block diagram illustrating the methodology and the main results concerning the characterization of the heavy hydrocarbon fluid flow in

708 the Lower Congo Basin.

709 The inventory of geophysical features associated with the oil seeps sites in this study would benefit
710 from comparative studies conducted in different geological contexts.

711 **5.4. Spatio-temporal variability of oil seepage activity**

712 The combined manifestation of recurrent sea-surface slicks and seafloor evidence of active fluid flow
713 demonstrates that liquid hydrocarbons are currently being expelled from the seafloor in the study
714 area. The combination of seismic data together with SAR imagery and geochemical features validated
715 the natural origin of the seepage (*Serié et al., 2017*). We highlighted a series of geophysical features
716 (seafloor and subsurface) associated with oil-seep systems that were extrapolated towards similar fluid
717 flow features that could also be responsible for thermogenic escapes, namely potential oil-seep sites.
718 Both geochemical and geophysical evidence demonstrate that many potential seep sites were not
719 associated with recurrent sea-surface slicks. The present-day seepage activity observed on SAR data
720 corresponds to 40 % of the total array of potential oil seep sites detected on the seafloor and sub-
721 surface (Table 3). The remaining 60 % of geophysical anomalies n°3 present the same characteristics
722 as active oil seep sites and most of them (75 %) are overlain by a seafloor fluid-flow feature, which
723 shows that most are active at seismic resolution scale and suggest much longer emission frequencies.
724 The active array proportion is concordant with results published in the Gulf of Mexico, where 50% of
725 geophysical anomalies identified on seismic datasets correspond to an active oil seep site at the sea
726 surface (*Garcia-Pineda et al., 2010*). Oil seep sites are mostly transient with a widespread range of
727 periods of recurrence (*Garcia-Pineda et al., 2010; Garcia-Pineda et al., 2015; Jatiault et al., 2017*).
728 The SAR data collection dates from 1994 to 2016, which is very brief in comparison to geological time
729 scales. The remaining 60% of geophysical anomalies could also be associated with dormant seep sites
730 whose inactive stages: (1) exceed the SAR monitoring period (22 years), or (2) are shorter than SAR
731 acquisition intervals (varying from few hours to few months).
732 Barely half of seafloor areas characterised by seafloor asphalt presence (seafloor mounds and oil-
733 impregnated cores) are currently supplying oil. Using fluorescence as a proxy for oil gravity (*Abrams,*

734 **2005**), seafloor samples in our study area range from 10 to 40°API. High biodegradation leads to an
735 increase in the density of the oil in the reservoirs (*Head et al., 2003; Peters et al., 2007*) but also in the
736 shallow sub-surface (e.g. *Zengler et al., 1999; Wilkes et al., 2001*), so that biodegraded oils can reach
737 density values greater than that of ocean water (*Larter et al., 2003*). For oil when the °API gravity is
738 below that of ocean water (10), asphalts remain stored on the seafloor (*Macdonald et al., 2004; Jones*
739 *et al., 2014*). Bathymetric hummocky features, reportedly composed of a large volume of stored
740 asphalt on the seafloor, have already been observed in other provinces without sea surface
741 manifestations (*Keller et al., 2007; Valentine et al., 2010*).

742 Extreme marine ecosystems are highly reactive to hydrocarbon flow fluctuations with a survival period
743 following seepage extinction of about one year (*Hessler et al., 1988; Shanks, 1995; Shank et al., 1998;*
744 *Mullineaux et al., 2000*). In-situ records of photo/video from ROV dives would greatly help ascertain
745 the presence of modern chemosynthetic communities and therefore address the seeping mechanism
746 and activity of the remaining 60% dormant geophysical anomalies (*Charlou et al., 2004, Gay et al.,*
747 *2006a, Marcon et al., 2014*).

748 Comparable studies conducted in similar geological context, yet revealed a much tenuous oil seepage
749 manifestations (*Serié et al., 2017*). Recent sedimentation stage of the LCB were particularly high due
750 to the establishment of the Congo DSF during Neogene and upwelling system during Early Quaternary
751 (*Savoye et al., 2000; Ferry et al., 2004; Seranne and Anka, 2005; Marciano et al., 2013*), which lead to
752 salt-related deformation enhancement. The tectonic regime of seeping provinces, mostly transitional
753 in Kwanza basin and compressive in LCB could play a significant role on expelled volumes.

754 **6. Summary and Conclusions**

755 We used several tools to assess the seepage potential in the distal salt province of the Lower Congo
756 Basin. The analysis of sea-surface oil manifestations imaged with satellite imagery, coupled with a
757 dense geochemical core-set and seafloor/ sub-seafloor manifestations of oil presence provides an
758 integrated approach of the present-day seepage efficiency.

- 759 • The geophysical features of thermogenic seeps sites previously recognised at local scale
760 (*Jatiaux et al., 2019, Part I*) are validated at the full scale of the study area. Thermogenic seeps
761 sites (1) consist of complex-shaped features (clusters of irregular pockmarks and seafloor
762 mounds), (2) are associated with shallow high-impedance layers on the sub-bottom profiler
763 and (3) are underlain by BSR that (4) are underlain by consistent amplitude and (5) are overlain
764 by clusters of pipe-like features (PHAA).
- 765 • The knowledge of the fluid flow phenomena is improved from the integration of detailed slicks
766 map that provide a means to quantify seepage activity. The SBP data that provides a
767 discrimination technique between hydrocarbons and pore dewatering features and also
768 reveals the seafloor distribution of asphalt storage areas.
- 769 • About 40% of geophysical anomalies are associated with recurrent oil slicks at the sea surface
770 while the remaining 60% are most likely related to dormant seep sites whose periodicity
771 exceeds the 22-year SAR monitoring or are shorter than SAR scene acquisition intervals.
- 772 • A large number of low-amplitude pipes (582) were identified in salt minibasins from the 12.5m
773 seismic resolution that are linked with conical-shaped seafloor pockmarks, interpreted as
774 related to pore-water expulsion.
- 775 • Extensive high amplitudes related to the uplift of older/coarser/ more permeable sediments
776 due to the salt tectonics and characterised by extensive near-surface positive amplitude
777 geophysical anomalies appear to correspond to preferential seafloor thermogenic migration
778 outlets.
- 779 • Only 20% of BSRs are double, and these occur exclusively in association with thermogenic
780 hydrocarbons seeps.

781 **Acknowledgements**

782 The authors express their grateful thanks to Total SA, Total Angola (TEPA) and partners for the data
783 disclosure approval of the industrial seismic and sub-bottom profiler data. The authors thank Total

784 team DSO for the geochemical analysis. This work was performed in the frame of a PhD project (CIFRE
785 convention) granted by the ANRT (Agence Nationale de la Recherche et de la Technologie, No.
786 2014/0308), funded by Total SA in collaboration with University of Perpignan, France. The authors
787 thank the European Space Agency (Envisat WSM, IMP) for the delivering of free-access data. Seismic
788 interpretation was carried out using Total's proprietary software Sismage. We kindly thank Christophe
789 Serié and an additional reviewer who provided critical suggestions in order to improve the impact and
790 benefits of the paper.

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