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1 **Spider structures: records of fluid venting from methane**
2 **hydrates on the Congo continental slope.**
3 **Les structures en araignée : enregistrement d'échappements**
4 **de fluide provenant des hydrates de méthane, sur la pente**
5 **continentale du Congo**

6

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14 Keywords: Methane seep; methane hydrates; bottom-simulating reflector (BSR); dynamic

15 seepage; methane-derived authigenic carbonates (MDAC)

16 Mots-clés : fuite de méthane, hydrates de méthane, BSR (bottom-simulating-reflector), fuite

17 dynamique, carbonates dérivés du méthane (MDAC)

18 **Abstract**

19 Fluid seepage features on the upper continental slope offshore Congo are investigated using
20 multi-disciplinary datasets acquired during several campaigns at sea carried out over the last
21 15 years. This datasets includes multibeam bathymetry, seismic data, seafloor videos,
22 seafloor samples and chemical analyses of both carbonate samples and of the water column.
23 Combined use of these datasets allows the identification of two distinctive associations of
24 pockmark-like seabed venting structures, located in water depths of 600-700 m and directly
25 above a buried structural high containing known hydrocarbon reservoirs. These two features
26 are called spiders due to the association of large sub-circular depressions (the body) with
27 smaller elongate depressions (the legs). Seismic reflection data show that these two
28 structures correspond to amplitude anomalies located ca. 60-100 ms below seabed. The
29 burial of these anomalies is consistent with the base of the methane hydrate stability
30 domain, which leads to interpret them as patches of hydrate-related bottom-simulating
31 reflection (BSR).

32 The morphology and seismic character of the two structures clearly contrasts with those of
33 the regional background (Morphotype A). The spider structures are composed of two
34 seafloor morphotypes: Morphotype B and Morphotype C. Morphotype B makes flat-
35 bottomed depressions associated with the presence of large bacterial mats without
36 evidence of carbonates. Morphotype C is made of elongated depressions associated with the
37 presence of carbonate pavements and a prolific chemosynthetic benthic life. On that basis of
38 these observations combined with geochemical analyses, the spider structures are
39 interpreted to be linked with methane leakage

40 Methane leakage within the spider structures varies from one morphotype to another, with
41 a higher activity within the seafloor of Morphotype C; and a lower activity in the seafloor of

42 Morphotype B which is interpreted to correspond to a domain of relict fluid leakage. This
43 change of the seepage activity is due to deeper changes in gas (or methane) migration
44 corresponding to the progressive upslope migration of fluids. This phenomenon is due to the
45 local formation of gas hydrates that form a barrier allowing the trapping of free gas below in
46 the particular context of the wedge of hydrates.

47 **Résumé**

48 Les caractéristiques des échappements de fluides sur la pente continentale supérieure, au
49 large des côtes du Congo, sont étudiées en utilisant des jeux de données pluridisciplinaires,
50 acquis au cours de plusieurs campagnes marines menées au cours des 15 dernières années.
51 Ces jeux de données comprennent de la bathymétrie multifaisceaux, des données sismiques,
52 des vidéos des fonds marins, des échantillons du fond marin et des analyses chimiques à la
53 fois des échantillons de carbonate et de la colonne d'eau.

54 L'utilisation combinée de ces ensembles de données a permis l'identification sur le fond de
55 l'eau, de deux associations distinctes de structures d'échappements de fluides de type
56 pockmark, localisées entre 600 et 700 m de profondeur d'eau et directement au-dessus d'un
57 haut structural enterré contenant des réservoirs d'hydrocarbures connus. Ces deux
58 structures sont appelées araignées en raison de l'association des grandes dépressions
59 subcirculaires (le corps) avec de petites dépressions allongées (les pattes). Les données de
60 sismique réflexion montrent que ces deux structures correspondent à des anomalies
61 d'amplitude localisées à 60-100 ms en-dessous des fonds marins. L'enfouissement de ces
62 anomalies est compatible avec la base de stabilité des hydrates de méthane, ce qui conduit à
63 les interpréter comme des patches de Bottom-Simulating Reflection (BSR) reliés à la
64 présence d'hydrates.

65 La morphologie et la nature des deux structures contrastent clairement avec celles de du
66 contexte régional (Morphotype A). Ces structures en araignée sont composées de deux
67 morphotype du fond marin : le Morphotype B et le Morphotype C. Le Morphotype B
68 constitue des dépressions à fond plat associées à la présence de grands tapis bactériens et
69 sans indice de présence de carbonates en fond de mer. Le Morphotype C est constitué de
70 dépressions allongées associées à la présence de croûtes carbonatées et d'une vie benthique
71 chimio-synthétique prolifique. Sur la base de ces observations, combinées à des analyses
72 géochimiques, les structures en araignée sont interprétées comme étant liées à des fuites
73 de méthane

74 Les fuites de méthane à l'intérieur de ces structures en araignée varient d'un morphotype à
75 l'autre, avec une activité plus importante dans le fond marin du Morphotype C, et une
76 activité plus faible dans le fond marin du Morphotype B, qui est interprété comme étant un
77 vestige de site d'échappement de fluides. Cette évolution de l'activité d'échappement de
78 fluides est due à des changements plus profonds dans la migration du gaz (ou du méthane),
79 correspondant à la migration progressive des fluides vers le haut de la pente. Ce phénomène
80 est dû à la formation locale d'hydrates de gaz qui forment une barrière permettant le
81 piégeage sous-jacent de gaz libre, dans le contexte particulier du biseau des hydrates.

82 **Introduction**

83 Fluid flow features represent anomalies generated during past and present subsurface flow
84 of fluids (oil, gas, brine, groundwater and magmatic fluids) from source to the seabed or land
85 surface [Cartwright *et al.*, 2007; Løseth *et al.*, 2009]. The type of structure generated
86 depends on a variety of parameters as for instance the source of fluid, the flow type, the
87 structural setting and the nature of the host sediments [Cartwright *et al.*, 2007; Huuse *et al.*,
88 2010]. Pockmarks, mud volcanoes, gas hydrates, chimneys, pipes, some sediment injections,

89 and some carbonate bodies (e.g methane-derived authigenic carbonates, MDAC), and
90 related diagenetic phenomena are examples of geologic features associated with temporally
91 varying systems of focused fluid seepage through the seabed [Cartwright *et al.*, 2007; Judd
92 &Hovland, 2007; Løseth *et al.*, 2009; Huuse *et al.*, 2010].

93 Seafloor fluid flow features, such as pockmarks, are commonly found overlying deep or
94 shallow hydrocarbon reservoirs [Hegglund, 1998], and along continental margins where they
95 are often associated with localized gas hydrate accumulations [Bünz &Mienert, 2004; Ivanov
96 *et al.*, 2007]. On 3D seismic data, these geologic features are commonly found to be
97 underlain by columnar zones of attenuated and disrupted reflections called “acoustic
98 chimneys” , or “blow-out pipes” [Løseth *et al.*, 2011] depending whether the authors just
99 describe their seismic character or consider them as genuine fluid escape conduits.

100 Fluid flow features specifically related to methane hydrates and their dynamics have
101 received specific attention over the past decade both for their potential role in climate
102 change [Maslin *et al.*, 2010] and their growing economic interest [Milkov & Sassen, 2002].

103 Accumulation of gas hydrate below the seafloor occurs either as stratiform accumulation
104 associated with a bottom simulating reflection (BSR) in the subsurface [Shipley *et al.*, 1979]
105 or as shallow gas hydrates accumulations preferentially localized along fault planes
106 [Simonetti *et al.*, 2013] and below pockmarks [Marcon *et al.*, 2014].

107 The use of high-resolution three-dimensional seismic data brings new insight to the
108 occurrence of gas hydrates, their dynamics of growth and demise, and relationship with
109 venting points and deep plumbing systems. This includes sediment collapse and pockmarks
110 formation due to hydrate dissolution forming specific features called “hydrate pockmarks”
111 [Sultan *et al.*, 2010; Imbert &Ho, 2012; Riboulot *et al.*, 2016]; local hydrate accumulations
112 below the seabed forming “hydrate pingoes” [Hovland & Svensen, 2006; Sérié *et al.*, 2012]
113 and hydrate mounds [Matsumoto *et al.*, 2009; Nakajima *et al.*, 2014].

114 The Lower Congo Basin, offshore SW Africa, is a prolific petroleum province that has been
115 extensively explored for more than 30 years, resulting in a growing quantity and quality of
116 exploration data (Séranne, 1999; Marton *et al.*, 2000; Babonneau *et al.*, 2002; Rouby *et al.*,
117 2002; Fort *et al.*, 2004; Broucke *et al.*, 2004; Gay *et al.*, 2006a; Andresen *et al.*, 2011;
118 Beglinger *et al.*, 2012). Numerous studies have recognized the widespread occurrence of
119 past and present fluid flow-related phenomena [Andresen *et al.*, 2011; Gay *et al.*, 2007],
120 including the widespread occurrence of gas hydrates [Cunningham & Lindholm, 2000],
121 pockmarks [Andresen *et al.*, 2011; Gay *et al.*, 2006a] and giant pockmarks that correspond to
122 depressions whose diameter exceeds ca. 1000 m wide, generally found in the deep part of
123 the basin [Marcon *et al.*, 2014; Ondréas *et al.*, 2005; Sahling *et al.*, 2008]. Pockmark
124 commonly seems to be closely linked to gas hydrates occurrence either for some small-scale
125 pockmarks deeply rooted with a BSR [Gay *et al.*, 2006a] or for giant pockmarks showing the
126 presence of gas hydrates in the shallow subsurface [Marcon *et al.*, 2014; Ondréas *et al.*,
127 2005; Sahling *et al.*, 2008].

128 This study presents the discovery, on the upper part of the slope, of a new type of
129 pockmark-like feature corresponding to seafloor fluid vents. These features are called
130 “spider structures” because they combine a subcircular flat-bottomed pockmark (“body” of
131 the spider) with furrows extending upslope over a distance comparable to the diameter of
132 the pockmark (“legs”). This work is based on a highly diverse array of data that allow the
133 well-constrained characterization of the newly defined spider structures. The results provide
134 a potential insight into the processes of seabed fluid venting in the particular context of the
135 pinch out of the BSR. This work aims to propose a genetic model of fluid migration from
136 depth over time in relation to inferred gas hydrate formation near seabed and ongoing
137 methane seepage. The main contribution of this work concerns how seabed vents record

138 fluid flux through time, a process of which we still have a limited understanding [*e.g.*
139 Foucher *et al.* 2009].

140 **Geological Setting**

141 The investigated area is located in the Lower Congo Basin, on the Congo slope, between
142 500 m and 1200 m water depth, north of the Congo canyon (Fig.1). The Lower Congo basin is
143 one of many sub-basins along the West African continental margin which was initiated in the
144 early Cretaceous during the opening of the South Atlantic Ocean [Brice *et al.*, 1982; Karner *et*
145 *al.*, 1997; Marton *et al.*, 2000]. Following the rifting, restricted-marine conditions allowed
146 the deposition of up to 1 km of Aptian evaporites (the Loeme Formation), that constitute the
147 decollement layer responsible for the salt tectonic that characterizes this part of the margin
148 (Fig.2) [Brice *et al.*, 1982; Duval *et al.*, 1992; Liro & Coen, 1995; Lundin, 1992; Valle *et al.*,
149 2001; Uchupi, 1992]. The gravitational sliding of the sedimentary cover above the salt layer
150 defines an upslope extensional domain characterized by rafts and grabens and a downslope
151 compressive domain characterized by salt diapirs, canopies and walls, each domain being
152 about 100 km wide within the Lower Congo Basin [Duval *et al.*, 1992; Fort *et al.*, 2004;
153 Lundin, 1992; Marton *et al.*, 2000; Rouby *et al.*, 2002]. The study area is located in the
154 extensional domain and is structured into horsts and grabens bounded by listric faults
155 (Fig.2).

156 The stratigraphy of post-rift sediments consists of two major sequences; these are separated
157 by the Oligocene Unconformity that reflects a major change in ocean circulation and climate
158 [Séranne *et al.*, 1992; Séranne, 1999]. The latter sequence corresponds to the icehouse
159 period that began in the early Oligocene. This sequence has been characterized by an overall
160 regression superimposed by alternating dry and wet climate periods and high amplitude
161 (>100m) high frequency (100 kyr) sea level oscillations [Bartek *et al.*, 1991; Miller *et al.*,

162 2005; Seranne, 1999; Zachos *et al.*, 2001]. During this period, sedimentation has been
163 dominated by the progradation of a terrigenous wedge associated with the deep incision of
164 the Congo submarine canyon [Séranne, 1999]. The large amount of terrigenous material
165 has led to the formation of the large turbidite systems of the Congo fan [Brice *et al.*, 1982;
166 Broucke *et al.*, 2004; Droz *et al.*, 1996; Uchupi, 1992]. Deep thermogenic fluids [Gay *et al.*,
167 2006a] migrating upward are preferentially trapped in sandy turbidite channel reservoirs.
168 Significant oil and gas discoveries have been made in this basin over the last two decades
169 [Beglinger *et al.*, 2012; Burwood, 1999; Cole *et al.*, 2000]. Since the early Pliocene, the shelf
170 and the slope have been bypassed because of the deep incision of the Congo canyon that
171 directly connects the Congo River with the deep basin and the abyssal plain, down to 4000 m
172 water depth [Babonneau *et al.*, 2002]. As a consequence, the slope, including the study area,
173 has only been receiving sparse amounts of fine-grained sediments along with pelagic
174 production [Jansen *et al.*, 1984; Pufahl *et al.*, 1998; Uenzelmann-Neben, 1998].

175 The Pliocene-present interval contains widespread fluid escape features, at seabed and in
176 the subsurface, indicating past and ongoing bypass of the regional seal [Andresen *et al.*,
177 2011; Cartwright, 2011; Gay *et al.*, 2006a], which corresponds to a major polygonal fault
178 system [Cartwright, 2011; Gay *et al.*, 2004].

179 **Data and Methodology**

180 The dataset (Fig.3) includes multibeam bathymetry, seismic data, seafloor videos, seafloor
181 samples geochemistry and chemistry of the water column. All these data have been acquired
182 during several marine campaigns carried out over the last 15 years (Zaiango, 1999; Zairov,
183 2000, Biozaire, 2001, Total Geohazard, 2011).

184 **Seismic data**

185 The study is based on both 3D seismic volumes and 2D, high resolution (HR) seismic profiles.
186 The seismic interpretation and attribute analyses were performed with the SISIMAGE
187 software developed by Total [Guillon & Keskes, 2004]. All data are displayed in two-way
188 travel time (TWT) and values are expressed in s (TWT) or ms TWT. The average velocity in
189 the upper section studied here is estimated at ca. 1500 m.s⁻¹ [Sultan *et al.* 2007], so that
190 100 ms TWT roughly correspond to 75 m.

191 **Exploration and High Resolution (HR) 3D seismic data**

192 Two 3D seismic volumes with a multichannel offset, acquired for hydrocarbon exploration
193 are used for this study (Fig. 3). The first dataset covers about 1900 km² with a line spacing of
194 12.5 m and a CDP distance of 12.5 m. The dominant frequency is 70 Hz in the upper 100 ms
195 TWT, with a significant frequency content up to 80-90 Hz, giving a vertical resolution of ~ 4 m
196 (at a velocity of 1700 m.s⁻¹) and a horizontal resolution of ca. 20 m; the vertical sampling is
197 4 ms TWT. The second dataset is a high-resolution 3D volume covering 120 km² with a line
198 spacing of 6.25 m in both directions (in brown on Fig.3) and a sampling rate of 3 ms TWT.
199 The dominant frequency is 70 Hz in the upper 100 ms TWT (similar to the regional survey),
200 but with a significant frequency content up to 100-110 Hz in the upper 100 ms TWT of the
201 sedimentary pile; this gives a vertical resolution of ca. 3 m for a velocity of 1700 m.s⁻¹. The
202 seabed signal is not symmetrical, which means that the data are not zero-phase [Brown,
203 2011]. This study mainly used the amplitude, “dip” and coherence [Bahorich & Farmer,
204 1995] attributes. The coherency attribute estimates over a window selected by the
205 interpreter the correlation between a seismic trace and the adjacent ones. The “dip”
206 attribute is an approximation of the local slope gradient in degrees; it was calculated here at
207 each sample over the 8 surrounding points.

208 **High resolution 2D-AUV seismic data**

209 High-frequency 2D seismic data with high resolution (HR) and low penetration (2D-AUV and
210 Chirp for example) are generally used to study sub-seafloor anomalies [Orange *et al.*, 1999;
211 Savini *et al.*, 2009]. All AUV data were acquired using C&C's **C-Surveyor I™**.
212 Roughly 300 km of High Resolution (HR) 2D-AUV seismic profiles were used for the study
213 (Fig.3). The AUV was equipped with an Edge Tech Chirp Subbottom Profiler. The transmit
214 pulses are generated in the frequency band between 2 and 8 kHz. The high-resolution 2D-
215 AUV seismic profiles have a spacing of 175 m in a SW-NE direction and about 1000 m in the
216 orthogonal direction over the area of interest. The signal has a penetration of about 100 ms
217 TWT and a resolution of 6-10 cm. Due to the low penetration of the high frequency signal,
218 no reflections were identified below around 70 m below the seafloor. These 2D seismic
219 profiles were interpreted using a combination of the recorded amplitude and its "envelope",
220 a moving Root Mean Square (RMS) average.

221 **Seabed bathymetry**

222 Bathymetry data were acquired by the AUV equipped with a Simrad EM 2000 Swath
223 bathymetry system collecting soundings in a 200-meter swath underneath. Multibeam data
224 were processed at a 3-meter bin size using C&C's proprietary HydroMap software and the
225 depth values are referenced to Lowest Astronomical Tide (LAT). Bathymetry data cover an
226 area of about 400 km² (Fig. 3) with a horizontal resolution of about 3 m. The vertical
227 resolution provided by the 200 kHz source is a few cm.

228 **Side-Scan Sonar (SSS) data:**

229 Side-Scan sonar data were collected by the AUV equipped with a dual frequency chirp Edge
230 Tech Side Scan Sonar. It uses a calibrated wide band digital frequency modulated (FM) signal
231 to provide high resolution, low-noise images. This sonar simultaneously transmits linearly

232 swept FM pulses centered at two discrete frequencies: 120 kHz and 410 kHz with a
233 maximum cross-track resolution of respectively 6.25 cm and 1.8 cm. The acoustic
234 penetration can reach several meters depending on the sediments at the sea bottom. The
235 backscatter data are used for the impedance contrast detection in the seafloor sediments
236 and in the shallow sub-seafloor. High backscatter intensity is displayed in dark tones (Fig.3).

237 **Seafloor videos and sampling:**

238 Two video transects were acquired during two surveys (Fig.3). The first one (ROV track 1)
239 corresponds to the ZAIANGO IFREMER/TOTAL-FINA-ELF program (Zairov mission in 2000)
240 with the "ROV Victor" (Remote Operated Vehicle). The second one (ROV track 2)
241 corresponds to an industrial geotechnical campaign acquired by SEAROV in 2012 for Total
242 with the "ROV Seaeye Panther". The last ROV dive has allowed collecting pictures of the
243 seafloor that have never been published yet. The ROV dives were partly dedicated to the
244 sampling of massive carbonate crusts by video-controlled grab on 2 different sites (Fig.3).

245 **Isotopic analyses:**

246 Isotope values of carbon and oxygen were obtained by with the Isotope-Ratio Mass
247 Spectrometry (IRMS) method by the use of a Delta V+ spectrometer after extraction of the
248 CO₂. Analytic precision of measurements is 0.1 ‰ for both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values. The
249 isotopic ratio of carbon represents the difference between the $^{13}\text{C} / ^{12}\text{C}$ values (Table 1)
250 measured on a sample relative to the Pee Dee Belemnite (PDB) international standard. The
251 isotopic ratio of oxygen indicates the difference between the $^{18}\text{O} / ^{16}\text{O}$ ratio (Table 1)
252 measured on a sample and an international standard corresponding to the SMOW (Standard
253 Mean Ocean Water).

254 **Water column chemistry:**

255 During the Zairov mission in 2000, water was sampled in several pressurized bottles, in both
256 hydrocasts and ROV sampling, to measure the actual concentrations of dissolved methane
257 and also the concentrations of iron, manganese and silicon dissolved.

258 Hydrocasts were also carried out using a SBE 9/11+ Seabird conductivity–temperature–
259 depth (CTD) sensor with a Wet Labs nephelometer, at the BZR-01 Station (see Fig.3.B for
260 location). This CTD/rosette was also equipped with 16 pressurized bottles of 8 l capacity in
261 order to sample the water column.

262 In addition, a Victor ROV dive was carried out above the area of interest, between 550 m to
263 800 m water depth, in which 15 pressurized minibottles of water were sampled, 3 m above
264 the seabed (Fig.3.B). Aliquots of 125 ml were immediately collected in glass bulbs with
265 Teflon stopcocks and analyzed on board using a chromatographic purge/trap technique
266 [Charlou & Donval, 1993; Charlou *et al.*, 1998]. Aliquots of 60 ml were acidified for Fe and
267 Mn analysis.

268 **Geophysical characterization**

269 **Morphology and distribution of seafloor morphotypes**

270 In the Lower Congo Basin, multibeam data were combined with coherency maps derived
271 from 3D seismic data in order to better characterize the seafloor morphology. Two
272 kilometeric scale anomalies were identified at about 600-700 m water depth (Fig.4). Three
273 main seafloor morphotypes have been identified:

274 Morphotype A: The bathymetric and the slope gradient maps only show slight variations of
275 slope angles (Fig. 4A&B). The seafloor is smooth and only a few depressions and mounds are
276 visible in the north-western part. The backscatter reflectivity has an average low value

277 displayed as a light grey on Fig.4.C. The coherency is high and shows no major variations
278 over the area (Fig.4.D). This morphotype is considered as the background regional seafloor.

279 Morphotype B: The bathymetric and the gradient maps show two sub-circular flat-bottomed
280 depressions on the seafloor (Fig.4.A&B). They are 2-3 m meters deep on average and are
281 characterized by a rough bottom surrounded by continuous edges. They are both elliptical in
282 shape and their preferential elongation is close to the gradient of the regional NNW-SSE
283 slope. The northwestern depression is approximately 1.5 km long and 1 km wide,
284 representing an area of about 1.2 km². The southeastern depression is about 0.7 km long
285 and 0.6 km wide covering a surface of 0.4 km². Within the flat depressions the backscatter
286 reflectivity is low (Fig.4.C) and the coherency is generally medium (Fig.4.D). A few lower
287 coherency anomalies are also visible on the coherency map. They appear as isolated
288 irregular to crescent-shaped patches, a few tens of meters in length (Fig.4.D).

289 Morphotype C: The bathymetric map shows a set of elongated depressions, about 10-
290 m deep (Fig.4.A). They have steep edges with slope angles reaching 35° as shown by Fig.4.B.
291 Nearly 75 % of these elongated depressions trend in a NNW-SSE direction, subparallel to the
292 regional slope gradient. They are very narrow: about 50 m wide for a length ranging from 50
293 m to 1000 m. Some of the elongated depressions widen into elliptical patches, 200 m long
294 and 100 m wide (Fig.4.A). The backscatter map shows high reflectivity anomalies on the
295 seafloor (Fig.4.C), including a few thin and elongated depressions and six of the broader
296 anomalies corresponding to the elliptical patches described on the slope gradient map
297 (Fig.4.C). Within this Morphotype C, all depressions are very low in coherency (Fig.4.D).
298 Morphotypes B and C are associated in two sets, each comprised of a patch of Morphotype
299 B from whose periphery appear to emanate furrows of Morphotype C. In each set, the
300 distribution of the furrows is strongly skewed towards the SE side of Morphotype B, with the
301 orientation of individual furrows ranging from radial (with respect to Morphotype B) to

302 southeastwards trending, the latter being dominant. For each set, the network of
303 Morphotype C furrows reaches about one diameter of the patch of Morphotype B in a SE
304 direction.

305 This association of Morphotypes B and C allows defining two main objects on the seafloor:
306 the deeper one is 2.7 km long and 2 km wide and consists of a large patch of Morphotype B,
307 with peripheral furrows of Morphotype C extending southeastwards; shallower on the slope,
308 a similar feature covers 1.2 km in length and 0.7 km in width and also shows furrows
309 developing upslope from a patch of Morphotype B. They are both called "Spider Structures"
310 (SS) as they consist of a main "body" (i.e. sub-circular patch of Morphotype B) and peripheral
311 "legs" (i.e. elongated Morphotype C). The "Spider Structures" are named SS1 (larger feature)
312 and SS2 (smaller) (Fig. 5).

313 **Large amplitude anomalies on seismic sections**

314 The studied seismic interval shows several amplitude anomalies located just underneath the
315 two spider structures previously identified (Fig.6). Two strong amplitude anomalies
316 identified at 1100 ms TWT below seafloor (Fig.6.C) correspond to Miocene turbidite
317 channels that have been exploited for over a decade. They are cut by listric normal faults
318 that compartmentalize the reservoirs. Some of these faults reach the seafloor where they
319 are expressed as curved depressions (Fig.6.A).

320 Two flat high-amplitude anomalies are also identified in the shallow subsurface just below
321 the two spider structures (Fig.6). Although the used seismic dataset is not zero-phase, the
322 flat reflections can be seen to have a polarity (white/black) opposite to that of the seafloor
323 (black/white) (Fig.6.C.D). These anomalies are almost parallel to the seafloor, slightly
324 converging upslope towards it; in those respects, they fulfill the criteria of BSRs (Bottom

325 Simulating Reflections) and can thus be suspected to correspond to the Base of the Gas
326 Hydrate Stability Zone (BGHSZ) [e.g. Dillon *et al.*, 1980].

327 In order to test this interpretation, 5 couples of temperature/pressures have been estimated
328 along the amplitude anomalies on the basis of their depth of occurrence (pressure) and
329 geothermal gradient (temperature). Three gradients were used, based on the three
330 measurements reported in the vicinity [Sultan *et al.*, 2004]: 48 °C/km, 50 °C/km and
331 56 °C/km. The seabed temperature was estimated as the seabed intercept of Sultan *et al.*'s
332 dataset at about 6.5 °C. The pressure was taken as hydrostatic, in accordance to what is
333 normally observed at shallow depths with normal sedimentation rates [Osborne &
334 Swarbrick, 1997]. Time-depth conversion was carried out using a compressional acoustic
335 velocity (V_p) of 1500 m.s⁻¹ in these very shallow, uncompacted and unlithified lithologies, as
336 measured in previous studies [Sultan *et al.*, 2007]. Figure 7 shows the comparison between
337 the five (P, T°) points estimated along the suspected BSR and hydrate stability curves for
338 variable methane / ethane mixes, from 100 % to 90 % CH₄, as reported in [Sloan & Koh,
339 2007]. There is a good consistency between the burial of the observed reflection and the
340 base of the hydrate stability zone calculated using the locally measured [Sultan *et al.* 2004]
341 for a gas mixture that contains more than 99 % methane. Other combinations like a gas
342 more enriched in C₂H₆ (more stable) and a higher geotherm (pushing the stability domain
343 upward) could give the same result, but such solutions seem too speculative to be retained
344 in the absence of representative analyses of the gas at BSR level.

345 These two patches of BSRs are not strictly parallel to the seabed (Fig.6.C&D) but slightly
346 oblique to it, with a depth below the seabed decreasing from 100 to 60 ms TWT in an
347 upslope direction as the seabed shoals from 700 to 600 m water depth (Fig.6.B). Bottom-
348 simulating reflections normally wedge upslope as they approach the wedge of gas hydrates,
349 thereby reducing the thickness of the gas hydrate stability domain [Field & Kvenvolden,

1985]. The tilting of the interpreted BSRs is consistent with the fact that the upslope wedge of gas hydrates is estimated to be located at a water depth around 550 m in the study area [Sultan *et al.*, 2004]. On a map view, the high amplitude anomalies form two patches of BSRs, one covering about 2 km² and the other ca. 0.5 km² (Fig.6.B)). The wider patch of BSR is located in an area where two faults are connected (Fig.6.A). Both BSR patches are associated with an underlying high amplitude chaotic and discontinuous zone, a few ms to 150 ms TWT thick (Fig.6.c&D). Such anomalies are commonly interpreted as free gas zones below the BSR [Berndt *et al.*, 2004; Bouriak *et al.*, 2000], as the BSR commonly marks the transition between gas hydrate-bearing sediments and the underlying free gas zone [e.g. Dillon *et al.*, 1980]. The dimming of seismic reflections forms two columns of about 1500 ms TWT high and 600 m wide that extend down to the underlying hydrocarbon reservoirs.

361 **Shallow sub-seafloor amplitude anomalies**

In the study area, 2D-AUV profiles were used to highlight subsurface anomalies in the first 70 m below seafloor. The 2D-AUV seismic profile CD crosses the main body of Spider Structure 1 from NE to SW (Fig. 8.A; see Fig. 4 for location). The envelope attribute displays high-amplitude seismic anomalies as dark grey patches. Four levels of irregular high-amplitude anomalies were identified in the subsurface right below the main flat-bottom depression of Morphotype B. On both sides of the depression the envelope attribute shows low amplitude parallel and continuous reflections. They correspond to the background seismic Morphotype A in the area, as evidenced on all other 2D-AUV seismic profiles (see Fig. 3 for location).

The two deepest levels, level 1 (60 ms TWT below seafloor) and level 2 (35 ms TWT below seafloor), consist of high-amplitude reflections rather discontinuous, that concentrate under the SW part of Morphotype B (Fig. 8.A). On the contrary, the two shallowest levels, level 3

374 (25 ms TWT below seafloor) and level 4 (10 ms TWT below seafloor), are present under the
375 whole depression of Morphotype B (Fig. 8.A.B). In contrast with deeper levels, "Level 4"
376 rather appears as an interval, 8 to 12 ms TWT thick, composed of closely spaced amplitude
377 anomalies 30 to 100 m wide each (Fig.8.B).

378 Figure 8.-C illustrates on a 2D-AUV seismic profile (amplitude display) the relationships
379 between reflections outside the anomalies and inside the patch of Morphotype B.

380 Reflections visible laterally to the depression can be followed below the margin before they
381 fade out. They consistently plunge down slightly towards the center of the depression. This
382 combination of downwarping and progressive loss of amplitude may at first glance evoke
383 diffraction hyperbolae at the edge of background reflections. However, real diffraction
384 hyperbolae are clearly expressed around the main anomalies of level 4 for instance, and
385 have a much steeper slope than the gentle downwarping at issue here. This downwarping
386 can be followed at least down to below level 2 on the SW side of the seismic profile shown in
387 Fig.8.B. The shape of the crest (in particular the location of the highest point) differs from
388 one horizon to the other, as shown on Fig.8.C. This phenomenon indicates that the down-
389 bending is not a seismic artifact but corresponds to a real geological feature.

390 Figure 9 shows 2D-AUV seismic profile EF (see Fig.4 for location). This profile is parallel to
391 profile CD, and partly crosses Morphotype C. The dominant seismic facies is parallel and
392 continuous [Mitchum *et al.*, 1977]. The seafloor shows 4 depressions, 5 to 8 ms TWT deep
393 (i.e. 3 to 6 m with a water velocity of $1500 \text{ m}\cdot\text{s}^{-1}$) and 50 to 120 m wide along the section;
394 they are numbered 1 to 4 from SW to NE on Fig.9. Patches of high-amplitude anomalies
395 develop beneath the depressions. Anomalies 1, 2, 3 and 4 are buried at about 6, 20, 4 and
396 5 ms TWT respectively below the corresponding depressions. They are all associated with an
397 underlying acoustic mask that forms a very steep inverted V-shaped dimming structure. The
398 seismic reflections are disrupted on both sides of the acoustic mask or they are dimmed and

399 shifted downward suggesting a pull-down effect. The outline of the 2D-AUV profile EF is
400 shown by a dotted rectangle (Fig.9.A) on a profile extracted from the 3D cube along the
401 same line. It shows that shallow buried anomalies beneath elongated depressions
402 (Morphotype C) are all located above the BSR that lies about 90 ms TWT below seafloor
403 (Fig.6.D).

404 **Biological and geological characterization at the seafloor**

405 **Visual identification of seafloor morphotypes**

406 On the slope of the Lower Congo Basin, two ROV dives were used to investigate Spider
407 Structures 1 and 2 located between 600 m and 700 m water depth. In particular, the ROV
408 tracks crossed both the body (Morphotype B) and the legs (Morphotype C) of SS1 (see ROV
409 tracks on Fig.3 for location) without observing any gas bubbles escaping from the seafloor.
410 Three sites were selected for representative pictures within SS 1 (see Fig.3 for location): Site
411 1 in the flat-bottomed depression corresponding to Morphotype B, and sites 2 and 3 in the
412 elongated depressions corresponding to Morphotype C.

413 Morphotype B: Within the flat-bottomed depression, pictures obtained during ROV dives on
414 site 1 (see Fig.3 for location) revealed the presence of white bacterial mats overlying blackish
415 reduced sediments (Fig.10.A). Bacterial mats are discontinuous and consist of several closely
416 spaced patches ranging in size from tens of square centimeters to tens of square meters
417 (Fig.10.A). Bacterial mats are associated with the presence of mostly empty shells of bivalves
418 belonging to the thiotrophic family Vesicomidae [Ondréas *et al.*, 2005] scattered all over
419 the seafloor (Fig.10.A). Bivalve shells are sometimes grouped together in the periphery of
420 the bacterial mats forming accumulations of empty shells (Fig.10.B) and sometimes
421 associated with living bivalves.

422 Morphotype C: Within elongated depressions, ROV dives on sites 2 and 3 (see Fig.3 for
423 location) revealed the occurrence of outcropping carbonates, with a variable degree of
424 cementation (Fig.10.C, D, E and F). Carbonate outcrops can form tubular and/or nodular
425 rocks partially or totally buried in the sediment which sparingly outcrop on the seafloor
426 forming domes (Fig.10.C). Carbonate can also outcrop as thicker tabular carbonate
427 pavements with a flat top (Fig.10.D&E). These carbonate crusts form massive slabs that are
428 often tilted (Fig.10.E) and even fractured (Fig.10.D). The tilted crusts are a few cm to a few m
429 in thickness. They cover an area of about a few hundred square meters. The white bacterial
430 mats grew up directly on the carbonate pavements forming small and discontinuous patches
431 (Fig.10.D, E, F), and they can be associated with black reduced sediments at the toe of
432 carbonate pavements (Fig.10.F). An abundant benthic life, such as tubeworms, anemones,
433 Galathea and bivalves, has been identified on and around carbonate crusts as these provide
434 a solid substrate to which sessile organisms can fix (Fig.10.E). Living bivalves and empty
435 shells are scattered all over the seafloor of this area.

436 **Morphology of seafloor carbonates**

437 During the ROV dives, two main types of carbonate were sampled at sites 2 and 3 (see Fig. 3
438 for location): 1) Carbonate pavements, associated with bivalve shells, are the most common
439 (Fig.11.D&E). They consist of very poorly sorted shell fragments that are slightly cemented
440 together. These carbonate rocks have a high porosity and are quite brittle due to the low
441 amount of cement (Fig.11.A&C); 2) Nodular or tubular carbonates, which are less observed
442 as they are often found buried within the sediment (Fig.10.C). The only tube-shaped
443 carbonate recovered has a central conduit about 1 cm in diameter (Fig.11.B) connected to
444 smaller secondary conduits of variable diameter which appear as small holes along the main
445 tube (Fig.11.D). Nodules and pipes are much indurated and form hard carbonates.

446 **Chemical analyses of carbonates and water samples**

447 **Seafloor carbonates isotopic compositions**

448 The isotopic composition of carbon and oxygen were analyzed on four samples taken from
449 seafloor sites 2 and 3 in patches of Morphotype C (see Fig.3 for location). Delta ^{18}O and $\delta^{13}\text{C}$
450 measurements for both sites are displayed on Table 1. The analyses on site 2 were made
451 separately on the cement part and the shell part of the carbonate samples visible on
452 Fig.11.A, and on a bivalve shell taken from the seafloor. The measurement on site 3 was
453 carried out on a carbonate sample visible on Fig.11.C. With negative values of $\delta^{13}\text{C}$
454 (-35.5 ‰ on Site 2 and -34.3 ‰ on Site 3 (Table 1), the carbon isotopic compositions on the
455 carbonate cement fraction are nearly the same at both sites. However, the carbon isotopic
456 compositions for the shell fraction of the carbonate sample (Fig.11.A) and for the isolated
457 shell (both at site 2) show a major change, -3.1 ‰ and 2.1 ‰ respectively (Table 1). The $\delta^{18}\text{O}$
458 values for bulk carbonate fractions are in the range of +3.6‰ to +4.1 ‰ for sites 2 and 3
459 (Table 1).

460 **Near-bottom water chemical analysis**

461 During the ROV dive near-bottom waters were regularly collected 1-2 m above the seafloor
462 from the northwest corner to the southeast corner of the studied area (Fig.12.A). The water
463 samples were then analyzed for dissolved methane (CH_4), iron (Fe), manganese (Mn) and
464 silicon (Si). Measurements 1-2 (about 820 m water depth) and 13-15 (about 550 m water
465 depth) were made 2 km away from the seafloor anomalies. They were sampled over
466 Morphotype A corresponding to the normal background seafloor. Except for point 2,
467 measurements 1, 13, 14 and 15 range from 3 to 6 nmol/l for CH_4 , 153,7 to 308,7 nmol/l for
468 Fe, 9 to 16,9 nmol/l for Mn and 22,3 to 31,7 $\mu\text{mol/l}$ for Si (Fig. 12.A and refer to Table 2-B
469 for exact values).

470 The only measurement made over Morphotype Bat point 3 (Table 2-B) yielded a CH₄
471 concentration of 16 nmol/l. Over Morphotype C, CH₄ concentration is higher with an
472 average of 38 nmol/l and reached four times higher values at points 5 and 6 (Table 2-B).
473 Dissolved methane concentrations measured over the Morphotype C of the deeper Spider
474 Structure 1 (samples 4, 5, 6, 7 and 8) are higher than those measured over the Morphotype
475 C of the shallower spider structure 2 (samples 10, 11 and 12) (Fig.12.A, Table 2-B).
476 Fe and Mn values measured over both Morphotype B and C are comparable to those over
477 Morphotype A (Table 2-B), with the exception of a single sample (point 8).
478 Calibration values are given by silica due to its low solubility in water. With values ranging
479 from 22,3 to 39,1 µmol/l and a slight decrease with water depth, silica concentrations are
480 consistent with dissolved ratios in seawater [Cheong *et al.*, 2014].

481 **Water column chemical analysis**

482 Complementary analyses have been conducted during the cruise. A vertical CTD/rosette was
483 operated in the water column over the seafloor anomaly (See Fig.3.B for location). The
484 deepest measurement is very close to point 5 measured over the seafloor during the ROV
485 dive. The dissolved methane concentration decreases downward reaching a minimum value
486 of 0.7 nmol/l at 540 m water depth (100 m above the seafloor). From this depth and
487 downward the dissolved CH₄ shows a regular increase reaching its highest value of 4.1
488 nmol/l at 646 m water depth, close to the seafloor (Fig.12.C and Table 2-A).
489 The Fe and Mn vertical profiles show a slight increase down to about 540 m water depth
490 (Fig.12.B and Table 2-A). From this depth downward the Fe and Mn concentrations increase
491 more rapidly reaching the values of 75,1 nmol/l and 6,4 nmol/l respectively at 653 m water
492 depth, close to the seafloor (Fig.12.B).

493 **Discussion**

494 Spider structures are made of a central depression forming a giant pockmark (Morphotype
495 B) bordered by elongated depressions (Morphotype C) extending dominantly upslope. Flat-
496 bottomed giant pockmarks reminiscent of Morphotype B have been reported in literature
497 from the deeper parts of the Lower Congo Basin [e.g. Ondréas *et al.* 2005] and the Western
498 Mediterranean Sea [Ingrassia *et al.*, 2015]. The set of hydrate pockmarks reported by Sultan
499 *et al.*, 2014 in the deep Niger Delta are also flat-bottomed and exceed 500 m in diameter,
500 making them quite similar to the other examples, although they were not formally referred
501 to as “giant” by the authors. These pockmarks appear as isolated fluid flow features in
502 associations of giant pockmarks with peripheral elongated depressions and have not been
503 described yet. However a close look at Figure 1 of Marcon *et al.* (2014) shows 3 or 4 short
504 (ca. 100-m-long) high-reflectivity furrows extending upslope of the giant Regab pockmark,
505 but these are quite inconspicuous and have not been described as such by the authors. They
506 might be seen as “short-legged spider structures” by reference to the example shown here.

507 In addition, the Spider Structures develop right above the structural culmination of a proven
508 hydrocarbon reservoir, and are underlain by a seismic reflection that has all the
509 characteristics of a hydrate BSR. Those three factors: 1) surface geometry analogue to that
510 of hydrate pockmarks; 2) presence of a BSR underneath and 3) structural setting over a
511 hydrocarbon field strongly suggest that the two observed Spider Structures could result from
512 dysmigration of hydrocarbons from the underlying reservoir. The following discussion will
513 challenge this hypothesis, starting from water column and seabed data and moving
514 progressively down. The following issues will be addressed: do spiders reflect present
515 seepage? The provenance of the fluids and the migration pathways will be discussed as well
516 as the temporal variability and the origin of the pockmark depression. Finally, the resulting

517 interpretation will be developed into a full genetic and evolutionary model of the Spider
518 Structures.

519 **Are Spider Structures seafloor seeps?**

520 **Fluid venting activity within the spider structures**

521 Background dissolved methane concentrations in the deep ocean are normally below 0.9
522 nmol/l [Scranton & Brewer, 1978]. Significantly higher values just above seafloor or in the
523 water column are considered indicative of significant fluid expulsion [Gay *et al.*, 2006b;
524 Sassen *et al.*, 1994, 2001; Suess *et al.*, 1999].

525 In the study area, three values of methane concentrations were measured away from the
526 two venting sites, two at 3 nmol/l and one at 6 nmol/l. This is higher than values normally
527 found as ocean background [Scranton & Brewer, 1978]. This could be due to the proximity of
528 active sites of gas release and the presence of an active hydrocarbon generating system in
529 the area.

530 The values observed above Spider Structure 1 (SS 1) and 2 (SS2) are comprised between 16
531 and 70 nmol/l. This is about 10 to 80 times the upper limit of normal marine background
532 values, and still 4 to 18 times the average value of the local background; however, these
533 values remain about 3 orders of magnitude below the saturation value for the local
534 thermodynamic conditions (ca. 60,000 nmol/l, <http://models.kl-edi.ac.cn/models/ch4-sea>,
535 from [Duan & Mao, 2006], accessed 2016/06/21). These values indicate an actual anomaly of
536 methane on both spider structures, albeit with a moderate flux, which is consistent with the
537 fact that no gas bubbles release was observed at the seafloor. Such methane concentrations
538 are not as large as those typically found in sites of gas venting, in particular in other parts of
539 the Lower Congo basin [e.g. Ondréas *et al.*, 2005]. These relatively low methane
540 concentrations measured over Morphotype B and C could be due to a progressive release of

541 methane by steady dissolution of BSR hydrates, which are known to act as dynamic systems
542 [Sultan *et al.*, 2014].

543 Let us now examine the differences between the two spider structures: eight values of CH₄
544 concentration were recorded for Morphotype C, five of them over Spider Structure 1 (SS1)
545 and three over SS2. The two sets are well contrasted, with an average of 50 nmol/l for SS1
546 and 20 nmol/l for SS2, in each case with pretty well clustered values. This strongly suggests
547 that SS1 is currently more active than SS2.

548 It is then possible to examine the variability between the two Morphotypes: as mentioned
549 above, only one single value was obtained for Morphotype B, in SS1, at 16 nmol/l. This single
550 value is three times smaller than the average recorded over Morphotype C in the same SS1.
551 In order to better assess the significance of this contrast, we compared the ROV
552 observations made on Morphotypes B and C. Measurements of CH₄ concentrations capture
553 one moment in time, and it is known that venting is an episodic phenomenon [Tryon *et al.*,
554 1999]. On the contrary, sustaining benthic life requires steady supply of nutrients (methane
555 for chemosynthetic communities). The observation at the seafloor of bacterial mats in
556 Morphotype B, and an active benthic life combined with carbonate pavements in
557 Morphotype C indicates sustained gas venting at both sites.

558 One hydrocast collected water samples above Morphotype C at various water depths
559 (Fig.12). Dissolved methane decreases regularly upward from the lowest measurement up to
560 ca. 550 m, which is interpreted to reflect the presence of a methane plume undergoing
561 progressive dilution upwards. The lower 2 measurements have CH₄ concentrations of ca. 4
562 nmol/l, about 9 times what is considered as the upper limit normal oceanic background
563 [Scranton & Brewer, 1978]. Above 550 m, the values steadily increase upwards, a classical
564 behavior in surface waters as methane is a product of metabolism in the intestinal tract of

565 zooplankton and fish [Dafner *et al.*, 1998 ; Lamontagne *et al.*, 1973 ; Oremland, 1979]. The
566 hydrocast also recorded iron and manganese concentrations, which are well correlated with
567 CH₄ in the lower part influenced by the plume. On board ROV measurements, 1-2 m above
568 the seafloor, showed localized peaks of dissolved methane concentrations above both
569 Morphotype B and C; this indicates that localized points of emission may be active
570 simultaneously in both morphotypes; however methane venting is much more active over
571 Morphotype C rather than over Morphotype B. The seepage sites have thus fed distinct
572 methane plumes all contributing to a much larger plume identified in the water column
573 using the hydrocast.

574 Although Fe and Mn concentrations seem to be correlated with methane venting in the
575 hydrocast record, they do not show significant correlation with the dissolved methane
576 concentration at the seafloor over Morphotypes B and C. The rapid oxidation of iron in the
577 water column can explain the fact that iron concentrations at dissolved methane emission
578 points are sometimes close to the ocean background, suggesting that such gas vents have a
579 variable and maybe a lower activity. On the contrary, the high iron concentrations could
580 correspond to an active gas plume with a steady flow. The in situ production/oxidation of
581 methane can be coupled to the cycling of Mn [Sujith *et al.*, 2014]. The high concentration of
582 Mn in pore water probably suggests the participation of subsurface microorganisms in the
583 geochemical cycling of diverse substrates and their active involvement in the release of Mn
584 [Lovley, 1991]. It could also be attributed to the slower rate of oxidation compared to that of
585 reduction in anoxic sediments [Yadav, 1996]. Dissolved CH₄-Fe-Mn anomalies are the result
586 of fluid seepage into the water column forming a 110-m plume (Fig.12.B.C).

587 Based on the chemical analyses in bottom seawater and in the water column (hydrocasts),
588 Spider Structures 1 and 2 can be considered as large seafloor seeps resulting from the
589 clustering of u numerous smaller seepage sites, as shown for the Haakon Mosby Mud

590 Volcano [Milkov *et al.*, 2004; Vogt *et al.*, 1997], in the Barents Sea [Lammers *et al.*, 1995], on
591 the Cascadia Margin [Suess *et al.*, 1999] and in the Lower Congo Basin [Charlou *et al.*, 2003;
592 Gay *et al.*, 2006b].

593 **Flux vs. carbonate development**

594 Having established that the Spider Structures are sites of methane seepage, we will now
595 address the issue of the spatial variability of methane flux, based both on the measured
596 concentrations that reflect instantaneous flux and on the absence / presence / type of
597 benthic communities of seep carbonates, which both inform on the mid-term flux.

598 First and foremost, in what conditions can methane seep up to the seabed? In normal
599 subseafloor conditions without external input of dissolved methane, the sediment pile
600 shows a bacterial zonation in which bacteria live on less and less energetically efficient redox
601 pairs with increasing depth below seabed. The deepest zone corresponds to
602 methanogenesis, while the one just above is the sulfate reduction zone. Dissolved methane
603 generated by microbial activity is typically consumed within sediment by anaerobic oxidation
604 coupled with reduction of sulfate diffusing from sea water at the interface between these
605 two zones, known as the Sulfate-Methane Transition Zone (SMTZ). The SMTZ typically lies a
606 few meters to a few tens of meters below seabed in normal conditions. The reaction is
607 mediated by a Bacteria / Archaea consortium that produces hydrogen sulfide and HCO_3^-
608 [Boetius *et al.*, 2000; Orphan *et al.*, 2001; Reeburgh, 1976; Valentine & Reeburgh, 2000].

609 When dissolved methane is actively supplied from deeper zones, its flux can result in the
610 consumption of the entire sulfate available in the shallow section, so that the SMTZ may be
611 pushed up to the seabed by dissolved methane in excess. In that case, dissolved methane
612 can feed benthic life and escape into the water column [Gay *et al.*, 2006a], as observed in
613 the Spider Structures.

614 As shown by Figures 4.C and 8.B, the regional background (Morphotype A) shows neither
615 seabed reflectivity nor amplitude anomalies in the subbottom, indicating that the limited
616 methane flux observed there is insufficient to promote any significant carbonate
617 development.

618 The more moderate CH₄ concentrations associated with bacterial mats observed over
619 Morphotype B indicate moderate and possibly episodic fluxes of dissolved methane there.
620 This ongoing venting of gas can only sustain the growth of microbial mats and locally of
621 bivalve communities; conversely, the higher concentrations observed above Morphotype C
622 attest to a higher and likely more permanent flux there, resulting in the development of
623 thriving biological communities [Gay *et al.*, 2006b]. The presence of carbonates over
624 Morphotype C implies that even if the measured methane concentrations are quite low,
625 compared for instance to what has been observed on the Regab pockmark (10 to 100 times
626 higher) in the same basin [Ondréas *et al.*, 2005], methane fluxes must have been high and
627 sustained enough over a long time to allow the formation of the massive carbonates
628 observed on Morphotype C for instance (Fig. 10D, 10E, 10F). On the contrary, the low
629 concentrations of dissolved methane recorded above Morphotype A are clearly insufficient
630 to promote the development of carbonate precipitation at the seabed. Overall, the
631 comparison between CH₄ concentrations and the presence or absence of carbonates on
632 Morphotypes A, B and C is interpreted to indicate that significant carbonate bodies can only
633 develop at the seabed in conditions of high and steady enough methane supply.

634

635 **Origin of fluids**

636 The next issue is the provenance of the seeping methane; it will be addressed using the
637 isotope analyses of the carbon and oxygen of the carbonates. First, the carbon isotopic

638 composition of authigenic carbonates serves as an indicator for the origin of carbon
639 incorporated during carbonate precipitation [Anderson & Arthur, 1983; Reeburgh, 1980;
640 Ritger *et al.*, 1987].

641 The carbon isotope composition ($\delta^{13}\text{C}$) of shell fractions collected at sites 2 and 3 on
642 Morphotype C (see Fig.3 for location) are -3.1 ‰ and 2.1 ‰ (Fig.13). These values are very
643 close to the shell group defined by [Campbell, 2006], indicating that the carbon corresponds
644 to dissolved inorganic carbon from seawater [Campbell, 2006; Judd & Hovland, 2007]. The
645 two cement fractions of carbonate samples collected on Morphotype C have a very similar
646 carbon isotopic composition with negative values of $\delta^{13}\text{C}$: -35.5 ‰ at site 2 and -34.3 ‰ at
647 site 3 (Fig.13).

648 According to Aharon *et al.*, 1997 and Whiticar, 1999, sources of carbon to the pore fluids
649 include (1) biogenic methane ($\delta^{13}\text{C} < -65$ ‰ PDB) or thermogenic methane ($\delta^{13}\text{C}$ from -30 ‰
650 to -50 ‰); (2) sedimentary organic carbon ($\delta^{13}\text{C} \sim -25$ ‰); and (3) marine biogenic
651 carbonate or seawater CO_3^{2-} with a $\delta^{13}\text{C}$ value close to 0 ‰. The amount of mixing between
652 these different sources will determine the $\delta^{13}\text{C}$ value of any authigenic carbonate [Paull *et*
653 *al.*, 1992]. According to [Campbell, 2006], the $\delta^{13}\text{C}$ value close to -35 ‰ measured on studied
654 samples is located at the junction of three possible carbon sources (1) sedimentary organic
655 diagenesis (-15 ‰ $< \delta^{13}\text{C} < -35$ ‰), (2) oil fractions (-20 ‰ $< \delta^{13}\text{C} < -35$ ‰) and (3) thermogenic
656 methane (-40 ‰ $< \delta^{13}\text{C} < -50$ ‰) (Fig.13). Although the measured values of $\delta^{13}\text{C}$ are not
657 conclusive by themselves here: they are compatible with an origin from thermogenic
658 hydrocarbons, but also from a combination of biogenic methane and normal marine
659 carbonates.

660 The stable oxygen isotopic composition of authigenic carbonates provides further
661 information about environmental conditions such as the fluid source and temperature

662 during precipitation [Han *et al.*, 2004; Kim *et al.* 2007]. Carbonate precipitation is
663 accompanied by a temperature-dependent oxygen isotope fractionation relative to the
664 water from which the carbonates precipitate. The $\delta^{18}\text{O}$ carbonate isotope analyses of the
665 four samples show homogeneous values close to 4 ‰ V-SMOW (from 3.6 to 4.3 ‰, Fig.13,
666 Table 1), with no significant variations at sites 2 and 3 indicating uniform conditions during
667 carbonate growth at the seafloor. According to Rohling, 2013, the values of $\delta^{18}\text{O}$ in surface
668 water range worldwide between -7 ‰ in polar waters and +2 ‰ in tropical waters, and the
669 values along the west coast of Africa lie between + 0.5 and +1 ‰. In that respect, the
670 observed values around +4 ‰ are anomalous. Such anomalously positive $\delta^{18}\text{O}$ value of 4 ‰
671 V-SMOW have commonly been observed in seep carbonates resulting from gas hydrate
672 dissociation [Bohrmann *et al.*, 1998; Feng *et al.*, 2010 ; Greinert *et al.*, 2001; Haas *et al.*,
673 2010]. This is due to the fact that the water in the gas hydrate cages is enriched in ^{18}O by
674 2 ‰ to 3 ‰ relative to the primary pore-waters [Davidson *et al.*, 1983; Ussler & Paull, 1995].
675 The positive anomaly of $\delta^{18}\text{O}$ measured at both sites can thus be related to gas hydrate
676 dissolution in underlying sediments.

677 Isotopic analyses are therefore not conclusive as regards the origin of the seeping methane;
678 in other terms, both thermogenic hydrocarbons coming from the deep and biogenic gas
679 generated in the shallow section could fuel the Spider Structures. The main indication for the
680 distribution of dissolved methane in the area is provided by the two patches of BSR
681 underneath the two Spider Structures (Fig.6). They are located right above two underlying
682 vertical zones of reduced amplitude connecting at depth with Miocene turbidite channels
683 (Fig.6). Hydrates are stable only in dissolved methane-saturated water [Lapham *et al.*, 2010],
684 i.e. in the presence of a continuous flux of gas (dissolved at saturation level or in gaseous
685 state). Local generation of biogenic gas in the shallow section is not supported by any
686 seismic observation, and it seems difficult to envision the presence of localized patches of

687 organic matter in the hemipelagic context of the Pliocene of the area [Uenzelmann-Neben,
688 1998]. The most likely source for the seeping methane is thus the underlying Miocene
689 reservoir. The next section will discuss the possible migration pathway for the methane from
690 the reservoir up to the Spider Structures.

691 **Fluid pathways**

692 The presence of gas hydrates (whose formation requires active methane supply) just above
693 the local culmination of the underlying hydrocarbon reservoir, and there only, strongly
694 suggests that methane is actively migrating vertically up from the Miocene reservoirs to the
695 BSR (but not necessarily as free gas). There are two main pathways for fluids through a
696 sedimentary column, along fault planes and within fluid pipes [Gay et al., 2007].

697 In the study area, major normal faults are associated with slight linear depressions on the
698 seafloor (Fig.3&6). However, they are not directly related to gas venting sites, except where
699 they cross Miocene turbidite channels at depth. Here, deep-rooted faults individualized
700 several half-grabens (Fig.6). The two patches of BSR and the two related seafloor seep sites
701 are located over the crest of a horst block forming local culminations of the Miocene
702 reservoirs. This suggests that the structural tops of the Miocene reservoirs act as leakage
703 points for upward hydrocarbon migration. Some high-amplitude anomalies have been
704 identified at variable levels at depth along major fault planes with variable polarities and
705 may represent seep carbonates indicating past occurrence of gas seepage along some of the
706 faults (positive amplitudes) or minor gas accumulations trapped in local reservoirs (negative
707 patches).

708 The Pliocene to Present interval is highly affected by polygonal faulting [Gay *et al.*, 2004].
709 Polygonal faults may act as migration conduits for driving up fluids entrapped within
710 underlying sandy reservoirs [Gay *et al.*, 2004; Lonergan *et al.*, 2000], it has recently been

711 argued that they could also seal early after burial in the same Lower Congo Basin, on the
712 basis of a detailed analysis of the geometric relationships between high impedance seismic
713 anomalies and polygonal fault pairs [Ho et *al.*, 2016]. There is no clear evidence on our
714 dataset that these faults played any role in the formation of the Spider Structures in the
715 area.

716 Both patches of BSR are partly underlain by columns of low-amplitude, commonly fuzzy
717 reflections down to the top of the Miocene reservoirs; locally, these columns slightly widen
718 downward (Fig.6.B). They could correspond either to an acoustic masking effect by the
719 shallow free gas trapped under the BSR, or real evidence for the presence of free gas
720 bubbles attenuating the signal. The only difference between these two hypotheses is the
721 thickness of free-gas-bearing sediment: a few meters or tens of meters in the former, or the
722 full column from reservoir to BSR in the latter. The seismic cube was processed for
723 amplitude vs. offset studies (AVO), and both short and long offset cubes are available.
724 Undershooting by far seismic offsets should narrow down the masking window at depth,
725 while a continuous gas column down to the reservoir should have the same geometry on
726 short and long offset data. A comparison of short and long offset cubes was undertaken, but
727 did not prove conclusive due to the differences in frequency content between the two
728 cubes.

729 Whatever the case, the patches of BSR match the local culminations of the underlying
730 reservoirs. If the gas migrated along the normal faults that affect the series, i.e. along
731 oblique surfaces with a dip of ca. 45°, the BSR should be offset in the upslope direction of
732 the faults. This is not the case, so that fault control on gas migration is negligible. As
733 mentioned in the previous section, independent in situ generation of biogenic gas in the
734 section overlying the reservoirs would imply that patches of source rock were deposited
735 right above the culmination of the underlying reservoirs, which does not seem to make

736 sense. We therefore conclude that gas migrated vertically upward through the seal, without
737 being affected by faults.

738

739 **Methane seepage evolution over geological time**

740 **Buried carbonates and seabed fluid fluxes in Morphotype B**

741 The envelope display of a 2D-AUV profile across Morphotype B shows closely spaced patches
742 of high amplitude buried within the first 60 ms TWT below the main seafloor depression of
743 Morphotype B (Fig.8.A&B). In fluid venting zones, on siliciclastic mud-dominated slopes,
744 positive high amplitude patches on seismic data are generally interpreted as the response of
745 buried carbonate concretions [Bayon *et al.*, 2009; Ho *et al.*, 2012; Römer *et al.*, 2014; Savini
746 *et al.*, 2009]. These patches thus seem to correspond to buried seep carbonates that mainly
747 concentrate along four laterally discontinuous levels under the depression of Morphotype B
748 (Fig.8). The distribution of amplitude anomalies into four levels suggests that fluid venting
749 activity has been recently higher than at the present day [Stakes *et al.*, 1999], with periods of
750 massive dissolved gas release alternating with periods of low to very low seafloor fluid
751 venting, possibly representing self-sealing of the seeps [Gay *et al.*, 2006b; Hovland, 2002].
752 The four levels of amplitude patches are not present on each high-resolution 2D seismic
753 profile, and each level has a different lateral extension. The two deepest levels concentrate
754 in the western part of the main depression (Fig.8), meaning that fluid venting was initially
755 more active in this area. The two shallowest levels are more heterogeneous with high to
756 very high amplitude patches (Fig.8). This could indicate zones where gas venting activity was
757 locally higher. This has also been observed in the elongated depressions of Morphotype C,
758 where sites of massive dissolved gas release (Fig.12) were correlated with high amplitude
759 seafloor anomalies on seismic data (Fig.9). The shallowest level, 10 ms TWT thick, is made of

760 densely distributed high amplitude patches. This interval is buried at about 10 ms TWT
761 below seafloor and it was identified on all high resolution 2D seismic profiles crossing
762 Morphotype B. This suggests that the episode of massive dissolved gas release responsible
763 for the formation of this uppermost concretion-bearing interval affected the entire
764 depression of Morphotype B. Morphotype B consists of two ellipsoidal flat-bottomed and 1-
765 3 meters deep depressions with smooth edges (Fig.4.A&B). They are characterized by
766 medium coherency values, indicating a rough bottom or subbottom due to the
767 heterogeneous distribution of the sub-seafloor anomalies. They are also characterized by a
768 very low backscatter reflectivity (Fig.4.C), similar to the regional slope reflectivity. The
769 vertical resolution of the latter tool being a few cm, this means that there is no buried hard
770 structures are present in the first few cm below seafloor in Morphotype B. The bottom of
771 Morphotype B only revealed the presence of wide white patches of bacterial mat settled on
772 black reduced sediments, but neither associated with benthic life, nor with carbonate slabs
773 (Fig.10.A-B). The low concentrations of dissolved methane with relatively low concentrations
774 of dissolved Mn and Fe suggest a rather diffuse and low fluid venting activity. The patch of
775 Morphotype B can thus be considered as a dying site, which is being draped by hemipelagic
776 sediments and currently undergoing a low gas venting activity with low and probably
777 discontinuous release of dissolved methane in the water column.

778 **Seabed carbonates and fluid fluxes in Morphotype C**

779 Where 2D-AUV profiles cross elongated depressions of Morphotype C, the seismic profiles
780 show high amplitude patches located in the immediate sub-seafloor section (Fig.9). The size
781 of these high-amplitude patches mostly depends on the width of the associated seafloor
782 elongated depressions. The high amplitude patches visible on seismic data, are usually
783 associated with an underlying acoustic blanking effect (Fig.9), which is quite commonplace
784 on high-resolution shallow seismic profiles in areas where gas is present [Judd & Hovland,

785 2007]. At the seafloor, Morphotype C is characterized by low values of coherency (Fig.4.-D),
786 and high values of backscatter reflectivity, more particularly in the broadest depressions
787 (Fig.4.C). This means that there is a significant contrast in lithology between the regional
788 slope made of hemipelagic sediments and the bottom of elongated depressions. The in-situ
789 seafloor observations obtained during ROV dives confirmed that the depressions of
790 Morphotype C correspond to carbonates as massive slabs, nodules and tubes with a central
791 conduit (Fig.10.C to 10.F, Fig.11); the distribution of carbonates matches the extent of the
792 high-coherency and high-reflectivity depressions. The authigenic carbonates of
793 Morphotype C are associated with the extensive occurrence of microbial mats on blackish
794 reduced, flat sediments outcropping between carbonate concretions (Fig.10.F), indicating
795 widespread intense hydrocarbon seepage and active microbial dissolved methane
796 conversion via anaerobic oxidation of methane [Römer *et al.*, 2014]. Carbonate slabs can
797 form massive and large slabs many of which are tilted; this leads to the exhumation of a part
798 of the slab while the other part is buried in the surrounding hemipelagic sediments (Fig.10.D-
799 E). Most of these slabs, besides being tilted, are fractured and form several fragments, some
800 of which collapsed onto the mud-covered floor of the adjacent furrow (Fig.10.D). The
801 nodular and tubular carbonates with central conduits are partly buried although they
802 generally form within the sediments suggesting a later erosion of covering hemipelagic
803 sediments (Fig.10.C). The presence of authigenic carbonate slabs associated with an
804 abundant benthic life as tubeworms and bivalves (Fig.10.E) is an indicator for sustained seep
805 activity [Gay *et al.*, 2006b; Macelloni *et al.*, 2013; Olu *et al.*, 2009].

806 **Temporal evolution**

807 The vertical evolution of seismic reflectivity observed in subseafloor from level 1 to level 4
808 and at the seabed thus indicates that the high flux of dissolved methane seepage was
809 initially concentrated in the western part of Morphotype B and progressively migrated

810 eastwards. It is presently concentrated in Morphotype C, which is located E-SE of
811 Morphotype B. This means that the lateral migration of the fluid seepage, since the
812 emplacement of the deepest anomaly identified at 60 ms TWT below seafloor, has been
813 following the same direction over time corresponding to an E-SE (i.e. upslope) migration of
814 the fluid seepage.

815 We tried to assess the temporal variation of the fluid venting activity within the
816 spider structure by estimating the sedimentation rate and then the ages of the buried levels
817 of high amplitude under Morphotype B. The Pliocene interval of the study area is
818 approximately 1 s twt thick. We used this assessment to estimate the sedimentation rate
819 during the Pliocene interval, assuming an average velocity of 1800 m/s for the interval. The
820 sedimentation rate with these parameters is estimated at around 20 cm/ky. This value is
821 consistent with the sedimentation rates obtained in the shallower 80 m on ODP (Ocean
822 Drilling Program) well 1076, which is 30 cm/ky. The deepest seismically visible level under
823 Morphotype B (level 1) is located at around 60 ms twt below seafloor, corresponding to
824 around 45 m with a velocity of 1500 m/s in the shallow subsurface [Sultan *et al.* 2007]. Using
825 the locally estimated sedimentation rate, Level 1 is dated at ca. 0.2 Ma, which would
826 indicate that spider structure 1 has been active since the Ionian stage of the Pleistocene.

827 The shallowest anomaly (level 4) ca. 10 m below seabed could be dated around 50 ka
828 with this estimate. Keeping in mind that the upper 10 m are significantly less compacted
829 than deeper level, this value is likely to be a maximum.

830

831 **Origin of the depression**

832 Careful picking of the high-resolution 2D-AUV seismic profile crossing Morphotype B has
833 shown that background horizons could be followed into the domain covered by Morphotype

834 B (the seafloor depression) and that they show some downward bending below the edge of
835 that domain. Figure 8.C indicates that horizons are affected down to below Level 1,
836 suggesting local removal of material over the area of Morphotype B, below the deepest seep
837 carbonate interval (Level 1). Along with the presence of hydrates interpreted from the BSR
838 underneath, this sagging is interpreted to reflect hydrate dissociation and removal like in
839 hydrate pockmarks observed in Nigeria [George & Cauquil, 2007] and documented by
840 [Sultan *et al.*, 2010]. The dimming of the reflections below Morphotype B makes it difficult
841 to see whether sagging occurred in one episode or progressively over time.

842 **Genetic model of the Spider Structure**

843 **1. Present-day situation**

844 At present, both Spider Structures exhibit a similar style of venting, with lower activity in
845 Morphotype B and higher activity in Morphotype C. The former is just sufficient to feed
846 microbial mats at the seafloor and give a CH₄ concentration in surface sediments that
847 exceeds the local background by a factor 3 or 4. In Morphotype C, CH₄ concentration is
848 about 3 times higher than in Morphotype B of the same Spider.

849 The morphology of the two morphotypes are very contrasted, B being smooth and very
850 uniform whereas Morphotype C shows long furrows separated by plateaus of smooth
851 seabed. Carbonates are widespread at the floor of the furrows and in their banks.

852 As regards hydrates, Morphotype B is underlain by a continuous patch of BSR, while the BSR
853 is much more subdued and discontinuous below Morphotype C. No BSR can be seen in areas
854 of background Morphotype A.

855 Morphotype A corresponds to very limited CH₄ supply if any, Morphotype B to areas of
856 uniform low flux and Morphotype C to a clustering of linear domains of flux high enough to
857 sustain abundant chemosynthetic life.

858 Let us now examine the recent evolution of the flux, integrating the shallow subsurface
859 information below Morphotype B.

860 **2. Evolution since the most recent carbonate (from level 4 to present)**

861 Combining now subsurface observations with seafloor observations and analyses, it is
862 possible to propose an evolutionary model depicting the two morphotypes as successive
863 stages of evolution of the leakage system, as follows:

864 ***a) Active gas venting activity at the giant pockmark (MB)***

865 In an early phase, methane migrating from the Miocene reached the seabed with fluxes high
866 enough to promote the development of seep carbonates below what is currently
867 Morphotype B (level 4 on Fig.8). Methane hydrates may have started to form during this
868 phase or not; in any case, enough gas was supplied / the BSR was discontinuous enough to
869 let abundant methane pass upwards through it and reach the seabed. Figure 14.A depicts
870 the situation at that time, showing the situation where the hydrate BSR was beginning to
871 form in the area. No venting activity could be recorded below the “legs” of the spiders at
872 that time

873 ***b) Upslope shifting of the gas venting activity, from the giant 874 pockmark (MB) to elongated pockmarks (MC)***

875 At a certain point in time, the development of porosity-clogging hydrates was such that
876 upwards migration of methane significantly decreased at Morphotype B, as shown on Fig.
877 14.B. Methane went on diffusing from the hydrates above the BSR upwards to the seafloor
878 through diffusion, with possibly some additional advective flux along fractures or other
879 preferential pathways. This residual flux is able to sustain the growth of microbial mats, with
880 the local development of small communities of pelecypods, but not to promote the
881 development of widespread full communities as observed on Morphotype C. From this point

882 on, the former seep carbonates were progressively buried by hemipelagic drape that
883 smoothed the seabed over Morphotype B.

884 The dissolution of hydrates in the lower part of the hydrate stability zone (above the
885 impervious BSR) results in progressive subsidence of the overlying series, forming the
886 seafloor depression. The body of the spider can thus be viewed as a progressively collapsing
887 hydrate pockmark, as described by [Wei *et al.*, 2015] for an active example or [Imbert & Ho,
888 2012] for a cluster of fossil equivalents

889 *c) Setting of the current gas venting activity in elongated*
890 *pockmarks (MC)*

891 When there were enough hydrates to significantly decrease methane flux at Morphotype B,
892 incoming methane was redirected below the BSR overall acting as seal and shifted upslope
893 to the area of Morphotype C (Fig. 14.C). Methane venting is currently ongoing there, as
894 evidenced by the thriving biological communities present in and around the furrows, and it
895 has been active long enough for thick carbonate crusts to develop. The furrows are
896 interpreted as the linear equivalent of pockmarks, where leakage is responsible for removal
897 of fine-grained material and excavation of the furrows. The reason of this focusing of
898 dissolved gas along linear features is not clear yet: some furrows appear to follow very
899 shallow faults (less than 100 ms twt deep) while others develop without seismic evidence for
900 a fault, at least with the resolution of the seismic data.

901 **3. Speculative evolution of the fluid venting activity below the giant**
902 **pockmark (MB), over four carbonate levels**

903 How did the Spider Structures form in the first place? This section will propose a few
904 elements that could guide further reflection about the issue, based on the previous

905 discussed points, the presence of 4 stacked interpreted carbonate levels below Morphotype
906 B and the estimated timing.

907 The estimate we could make for the full duration of the 4 successive stacked levels of
908 interpreted carbonates underneath Morphotype B is ca. 200 ky. This is clearly to take as an
909 order of magnitude, regarding the uncertainties on the precise rate of sedimentation in the
910 area and its possible fluctuations through time. Using the same estimate, the emplacement
911 of the upper level 4 could be dated around 50 ka. One possibility would be to have the 4
912 carbonate levels associated with the last 4 major low sea-level stands of the Quaternary ca.
913 350 ka (MIS 9), ca. 250 ka, ca. 150 ka and ca. 20 ka. [Lobo & Ridente]. We speculate that
914 these may correspond to times when the wedge of hydrates was displaced seaward of the
915 Spider Structures, so that the full methane supply could reach the seabed directly.

916 **Conclusion**

917 Our multidisciplinary study of a site of dissolved methane leakage above a hydrocarbon-
918 bearing reservoir has evidenced a specific type of gas escape feature, undocumented so far.
919 This type of seabed anomaly, here called the “Spider Structure” has the following
920 characteristics:

- 921 • A Spider Structure is comprised of a sub-circular, depression (“body” of the spider)
922 from which a set of multi-m-deep furrows (“legs”) protrude, dominantly upslope
- 923 • In our study area, both the “body” and “legs” leak dissolved methane into the water
924 column, but the “body” shows limited activity while the “legs” are very active.
- 925 • The two “spiders” we observed lie above the structural crest of an oil and gas
926 reservoir, some 900 m below; patches of hydrate BSR are visible just below the body
927 of each spider, about 100 m below seabed.

- 928 • Visual observation and sampling show carbonates at or just below the seabed in the
929 “legs” of the spiders. Isotopic analysis indicates that these carbonates result from
930 anaerobic oxidation of thermogenic methane.
- 931 • The “body” is underlain by at least 4 seismic horizons rich in patches of high-
932 impedance material (interpreted as seep carbonates) in the uppermost 100 m of the
933 sedimentary column.
- 934 • These seep carbonate levels are 10 to 20 m apart vertically, the shallowest being ca.
935 10 m below present-day seabed. The vertical stack is interpreted to reflect temporal
936 variations in the emitted flux of dissolved methane.
- 937 • The activity of the seeps has been shifting upslope over time, with early stages
938 essentially developed in the most downslope part of the “body”, subsequent ones
939 filling the whole body, while at present the body is moribund and most of the
940 dissolved gas currently leaks from the “legs”.
- 941 • The shift from “body” to “legs” is interpreted to reflect self-sealing of the hydrate
942 BSR over time, as more dissolved gas is supplied since the base hydrate stability zone
943 (GHSZ) reached its present position at the end of the Holocene transgression. The
944 body still records episodic leakage of low fluxes, reflecting progressive dissolution of
945 the starving upper part of the GHSZ.

946 This model makes the “Spider Structure” one highly dynamic end-member of the spectrum
947 of hydrate-related leakage features, like hydrate pingoes, mounds and pockmarks. The body
948 is comparable in many respects to hydrate pockmarks described in literature, with a
949 dissociating body at depth leading to some collapse upon hydrate dissolution. The legs could
950 be seen as a precursor stage of the leakage, before hydrate growth makes a continuous layer
951 and clogs the leakage points. A “spider structure” would then be a snapshot of the shift from

952 a dying early activity distributed over a subcircular patch and a later, more juvenile activity
953 restricted to a network of furrows located upslope of the subcircular patch.

954 The present study has deciphered the recent evolution of the two “Spider Structures” of the
955 area. The study of deeper anomalies on the available 3D seismic surveys should lead to a
956 better understanding of the long-term evolution of the leakage system.

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1334 **Fig.1:** Bathymetric map of the Lower Congo Basin from EM12 multibeam acquisition
1335 (Zaïango project, 1998-2000) showing the location of the study area, on the upper part of
1336 the slope.

1337 **Fig. 2:** Regional geoseismic section across the West African Margin illustrating the general
1338 stratigraphic architecture and salt tectonics (location on Fig. 1), modified from Babonneau *et*
1339 *al.*, 2002.

1340 **Fig.3:** A. Two-way time map of the seafloor with dip overlain showing the 2D and 3D seismic
1341 coverage and the area covered by side-scan sonar (red rectangle). B. Bathymetric map of the
1342 area of interest with the two ROV tracks (orange and purple) and the two sites where
1343 carbonates were sampled.

1344 **Fig.4: A.** Bathymetric map of the seafloor showing Morphotype A which is characterized by a
1345 smooth and regular morphology; Morphotype B, which is rougher and slightly depressed and
1346 Morphotype C, which consists of elongate depressions. B. Color-coded dip of the seabed
1347 calculated from the 3D two-way time map of the seafloor. Both Morphotype A and
1348 Morphotype B just show the regional dip, while Morphotype C is marked by high dips that
1349 correspond to the margins of the elongated depressions. C. Seabed reflectivity from the side
1350 scan sonar data showing Morphotype A and B with a low reflectivity, whereas Morphotype C
1351 is strongly reflective, indicating a higher acoustic impedance. Reflectivity highlights a series
1352 of elliptical patches that develop along the depressions of Morphotype C. D. Coherency map
1353 of the seabed from 3D seismic data highlighting the difference between Morphotype A
1354 (highest coherency), Morphotype B with an intermediate coherency (especially in the NW
1355 patch) and Morphotype C, with a very low coherency.

1356 **Fig.5:** Morphotypes distribution from the compilation of the maps of Fig. 5. This composite
1357 map highlights the presence of two similar structures, each composed of a subcircular patch

1358 of Morphotype B with a set of peripheral elongated depressions (Morphotype C) dominantly
1359 extending to the SE of the patch.

1360 **Fig.6: A.** Map of the seabed reflectivity showing the two spiders structures (SS1 and SS2),
1361 the major normal faults and the location of the 2 seismic lines AB and CD. **B.** Isopach map of
1362 the interval between the seafloor and the BSR, showing that the BSR is distributed in two
1363 patches and that it is shallower in the SE than in the NE. **C.** Seismic section AB (see Fig.3 for
1364 location) from the HR 3D volume, showing the two tilted BSRs associated with a strong
1365 amplitude decrease and a distortion of reflections underneath. The seabed shows an
1366 asymmetrical “red over black” signal, meaning that the seismic is not zero-phase [Brown,
1367 2011]; conversely, the BSRs appear as “black over red”, i.e. with the opposite polarity. The
1368 set of high amplitudes at depth is known to correspond to hydrocarbon-bearing reservoirs.
1369 **D.** Seismic section CD (see Fig.5.A for location) showing the tilted BSR and its
1370 correspondence with each morphotypes A, B and C at the seafloor.

1371 **Fig.7:** Gas hydrates stability diagram for both pure methane and different proportions of
1372 methane (methane + ethane mixture) [from Sloan and Koh, 2007] on which are plotted
1373 several couples of temperature/pressure points corresponding to the observed patches of
1374 BSR. Calculation of the temperature at the BSR was made with 3 geothermal gradients
1375 obtained close to the structure of interest [Sultan *et al.*, 2004].

1376 **Fig.8:** Seismic sections (location shown on figure 5) across the main patch of Morphotype B.
1377 **A.** Insert from 3D seismic data to show the context above the BSR. **B.** Close-up of the zone
1378 shown on A with a white rectangle on 2D-AUV data (envelope display, see text). This high-
1379 resolution display highlights the gentle depression associated with Morphotype B, and
1380 shows 4 levels of discontinuous sets of aligned reflections underneath, vertically spaced by
1381 10 to 20 ms. The signal labeled “direct arrival” at the top is a seismic acquisition artifact and

1382 not a geological reflection. **C.** Amplitude display of the same seismic profile as B over the SW
1383 margin of the depression showing reflection geometry down to below level 1. Seven
1384 horizons have been picked and show downwarping below the margin of the depression. The
1385 two vertical seismic profiles show the exact location of the rim of the depression (left) and
1386 its lowest point (right). The highest point of the picked horizons is not perfectly aligned with
1387 the rim, showing that these horizons are not multiples. A number of diffraction hyperbolae
1388 can be seen (white circles) where the aligned reflections were observed on 7B. They all show
1389 the same curvature, idealized in the box labeled "DH". The curvature of the NE edges of the
1390 picked horizons is much gentler, indicating that the reflections correspond to the presence
1391 and morphology of real reflectors in subsurface. Vertical scale is in seconds TWT.

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1393 **Fig.9: A.** Seismic section from 3D seismic data for the context (location shown on Fig.5)
1394 across the elongated depressions of Morphotype C, shown in a white rectangle. **B.** Section
1395 from 2D-AUV seismic data (envelope display). The seismic profile shows high-amplitude
1396 anomalies below each of the depressions, with the deepest anomaly below the gentlest
1397 surface depression.

1398 **Fig.10:** Seafloor pictures from submersible dives, taken on three sites of Morphotypes B and
1399 C (locations shown on Fig.3). **A.** Bacterial mats (white patches) associated with black reduced
1400 sediments and empty shells of bivalves. **B.** Accumulation of empty bivalve shells scattered on
1401 hemipelagic sediments. **C.** Small mound formed by carbonate tubes popping through soft
1402 mud. **D.** Flat-topped carbonate crust with a conical shape emerging from the mud, which is
1403 highly broken, and crabs walking over. **E.** Flat-topped 'tabular carbonate crust', showing a
1404 high porosity with living tubeworms and crabs. **F.** Scrappy carbonate crust with white
1405 bacterial mats associated with black reduced sediments in between.

1406 **Fig. 11:** Carbonate samples recovered from sites 2 (A, B, D) and 3 (C). **A.** Shell fragments,
1407 very heterogeneous in size, poorly cemented and showing a very high porosity. **B.** Section
1408 through a tubular carbonate showing the presence of a central conduit connected to
1409 peripheral conduits of smaller diameter. **C.** Crumbly carbonate made of cemented shell
1410 fragments with a high porosity. **D.** Well indurated tubular carbonate.

1411 **Fig.12:** Geochemical data. **A.** Concentrations of dissolved methane, iron and manganese
1412 measure: very close to the seabed, along the ROV track over Morphotypes A, B and C.
1413 Bathymetry in background. **B.** Vertical evolution of iron and manganese concentrations in
1414 the water column above station BZR01 (location on Fig. 3). **C.** Same as B for methane.

1415 **Fig.13:** Distribution of carbonate samples, recovered over Morphotype C (on sites 2 and 3),
1416 in a $\delta^{13}\text{C}$ vs. $\delta^{18}\text{O}$ diagram showing the possible sources of carbon [modified from Campbell,
1417 200].)

1418 **Fig.14:** Schematic evolution of the Spider Structures in relationship with a cycle of methane
1419 input linked with the dynamic of the gas hydrate formation. **A. (above):** Incipient methane
1420 supply, the gas starts feeding the BSR but high fluxes reach the seabed and feed an active
1421 fluid vent associated with well-developed seep carbonates. **B. (centre):** The BSR is fully
1422 developed and plugs the porosity, so that continuously incoming methane cannot reach the
1423 seafloor as before, but it is diverted upslope and starts spilling over to the east. **C. (below):**
1424 As methane spills over upslope, it allows the gradual growth of the BSR upslope. Methane
1425 starts escaping to the surface making the elongated depressions of Morphotype C that
1426 correspond to the active methane venting sites.

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1429 **Table 1:** Isotopic analysis (^{13}C and ^{18}O) made on carbonates samples recovered over
1430 Morphotype C on site 2 and 3. Samples analyzed on site 2 correspond to the cement fraction
1431 (C-c2) and the shell fraction (C-Sh2) of a carbonate sample of Fig.10.A, and an empty shell of
1432 bivalve (Sh2). The sample analyzed on site 3 corresponds to a carbonate (Carb3) of Fig.10.C.

1433 **Table 2:** Concentrations of dissolved methane, iron, manganese and silica measured 1 to 2 m
1434 above the seabed along the ROV track. These concentrations have been measured at 15
1435 points in Morphotypes A, B and C, and evidence high lateral variability.

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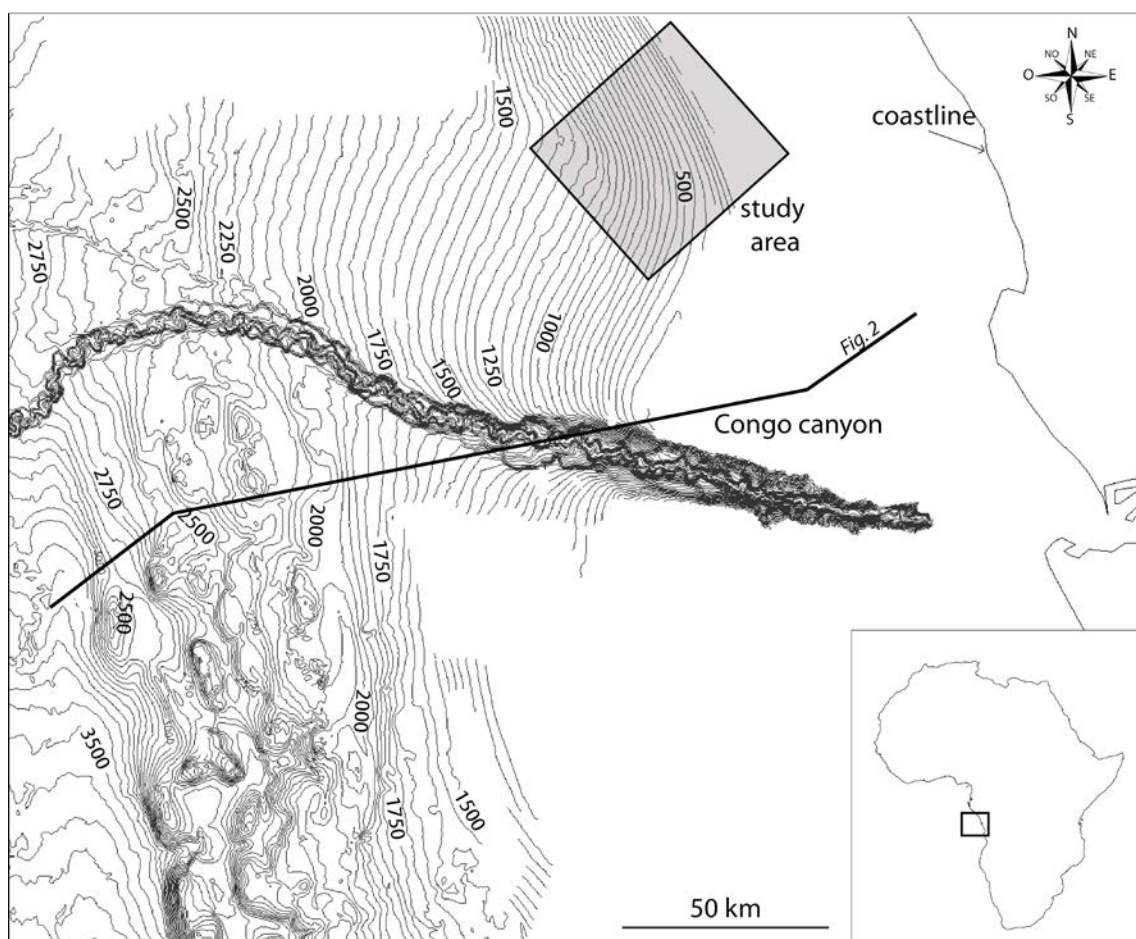
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1449 Fig.1 :



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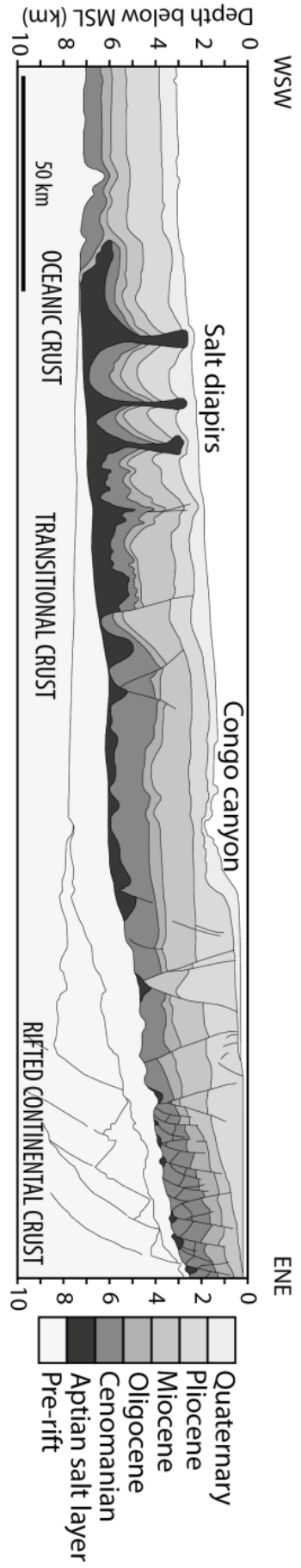
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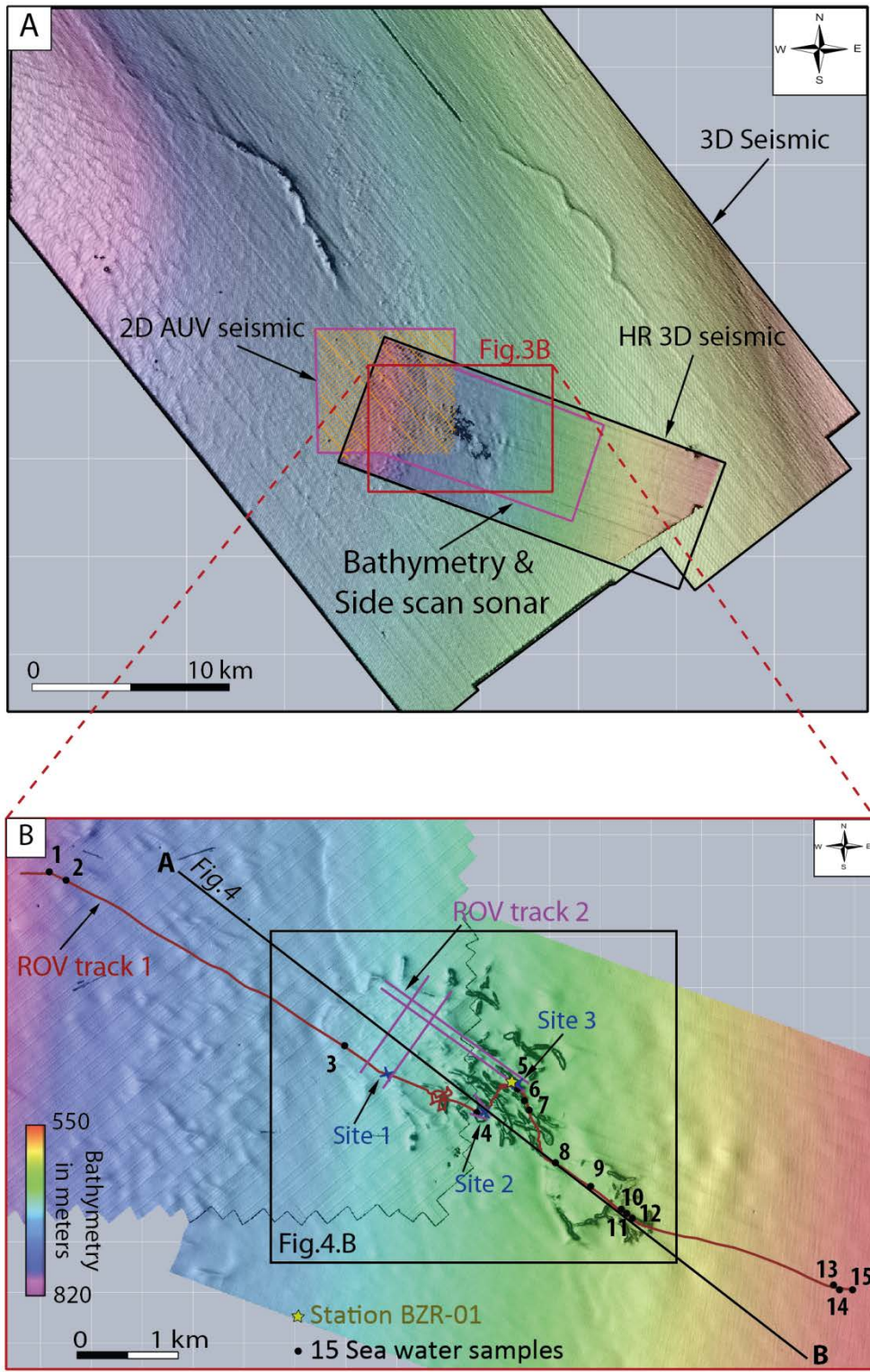
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1461 Fig.3:

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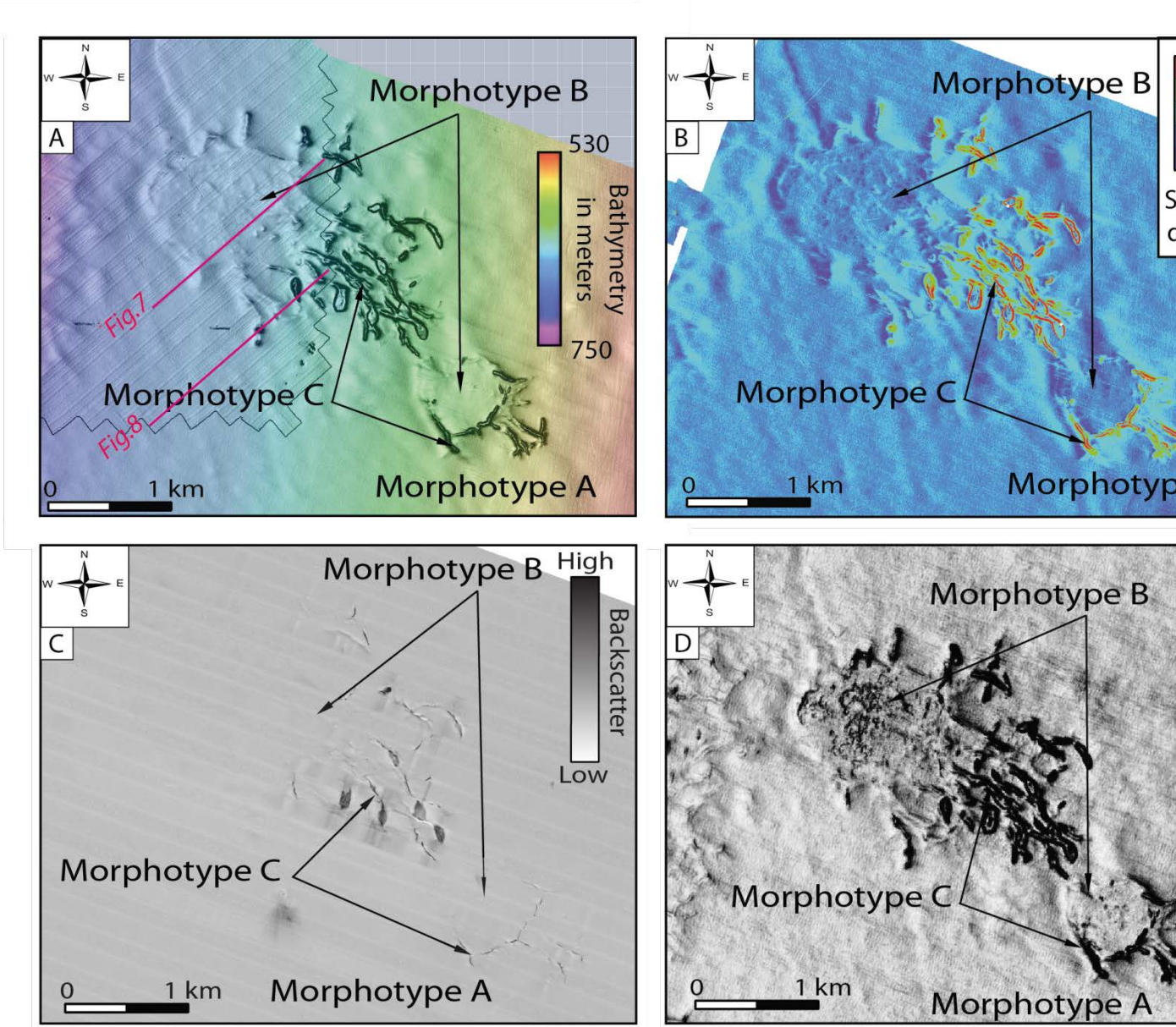
1466 Fig.4:

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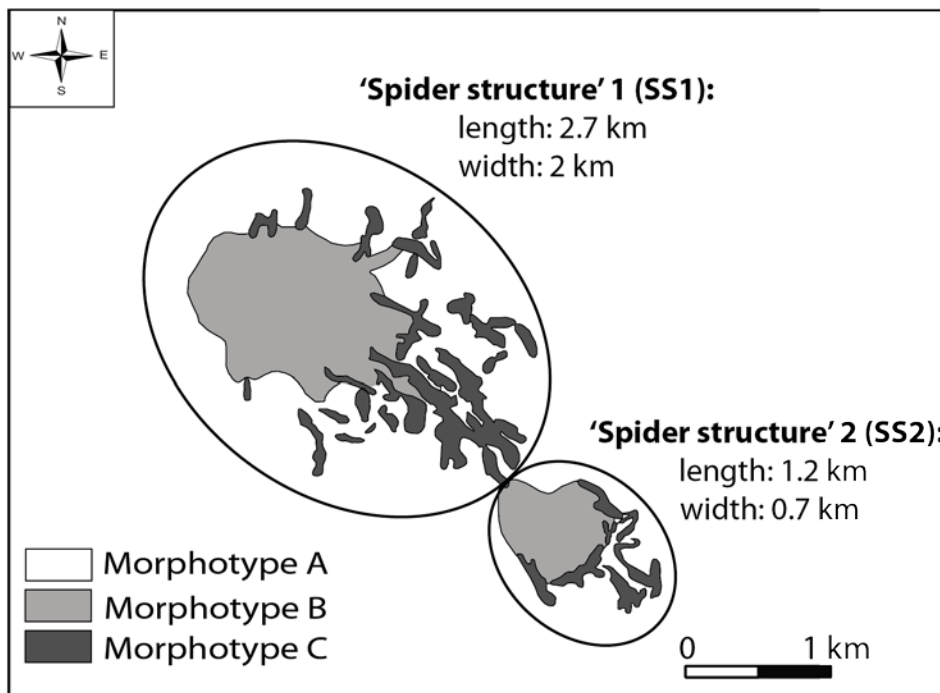
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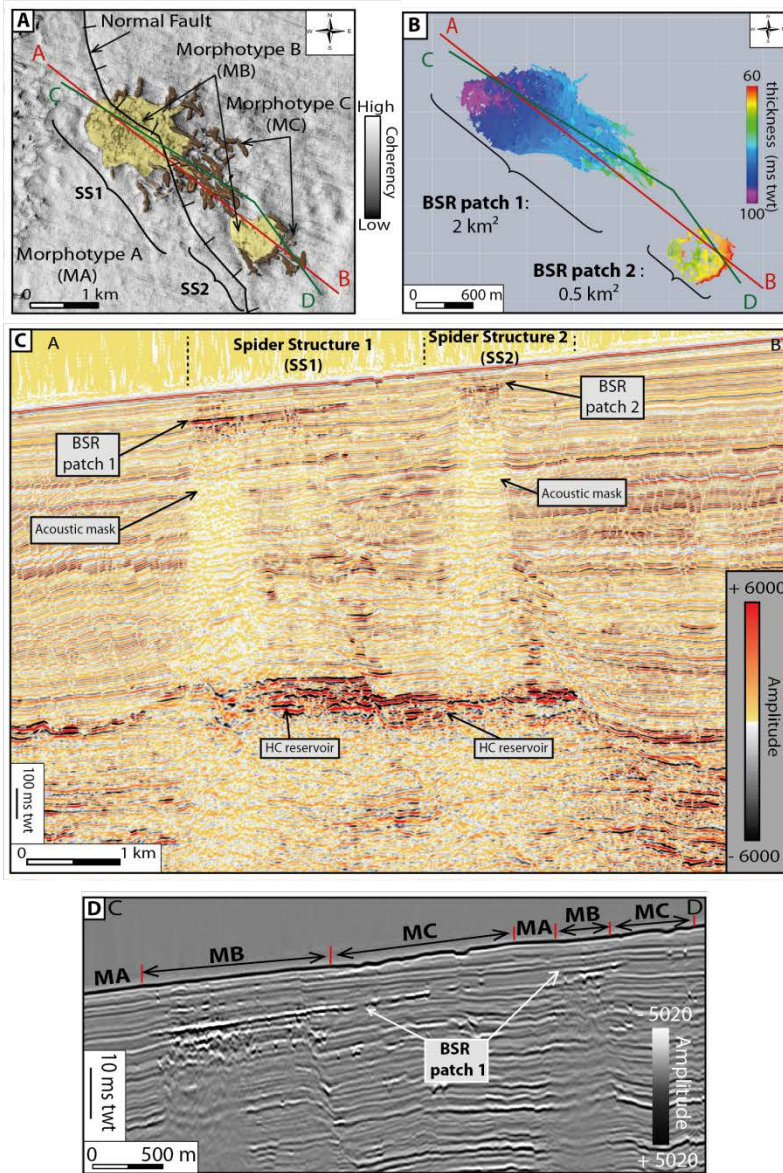


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1484 Fig.6:



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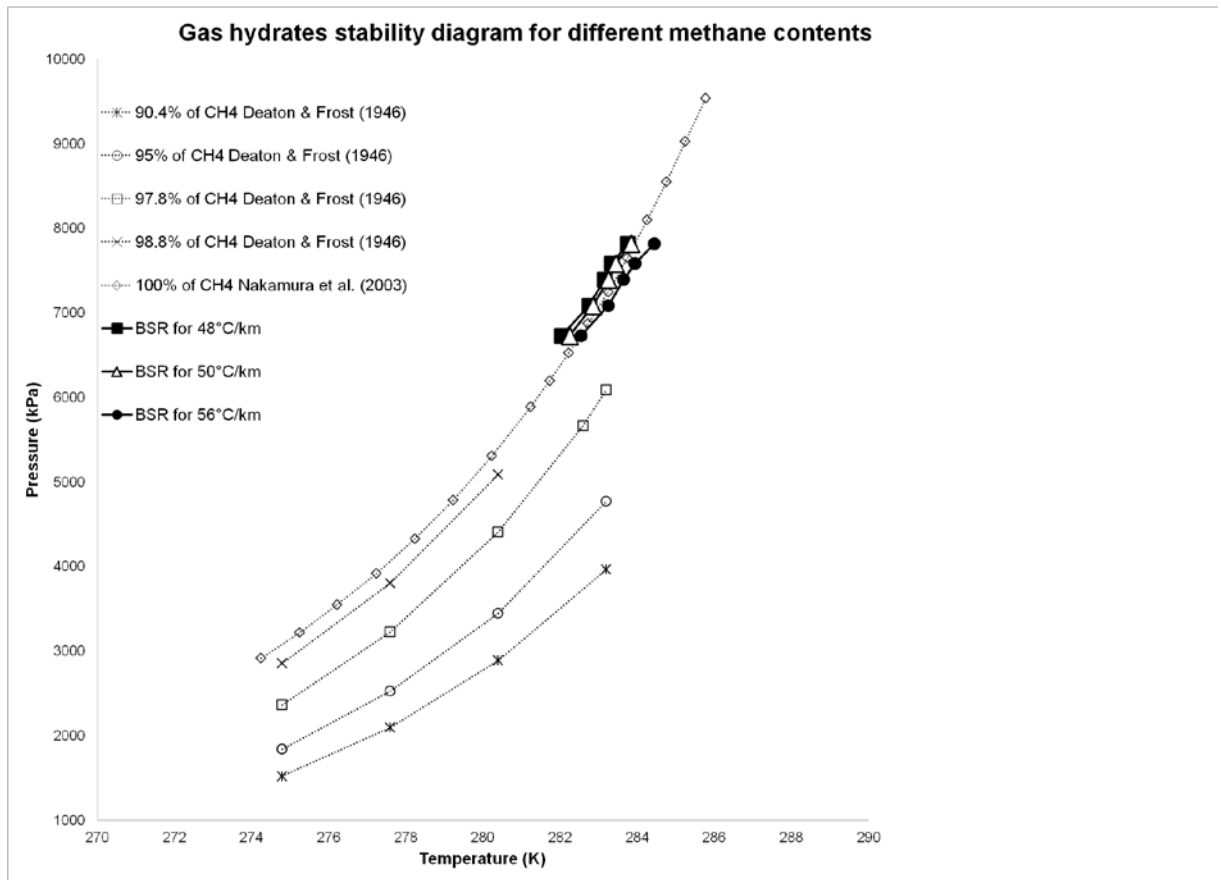
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Fig.7:



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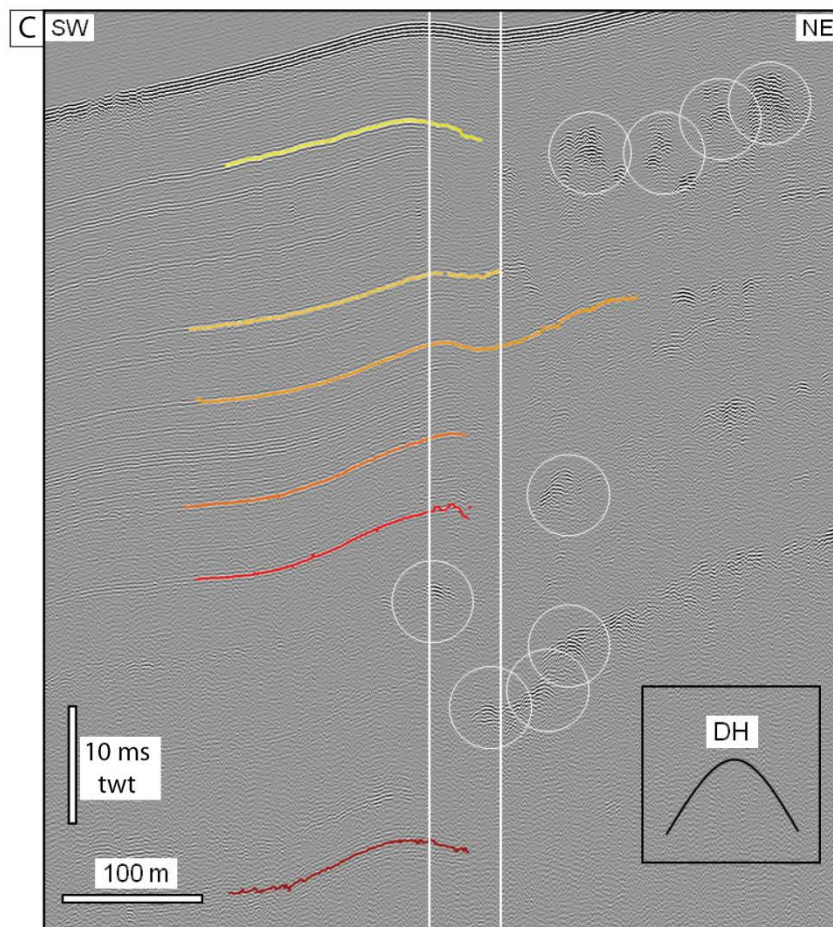
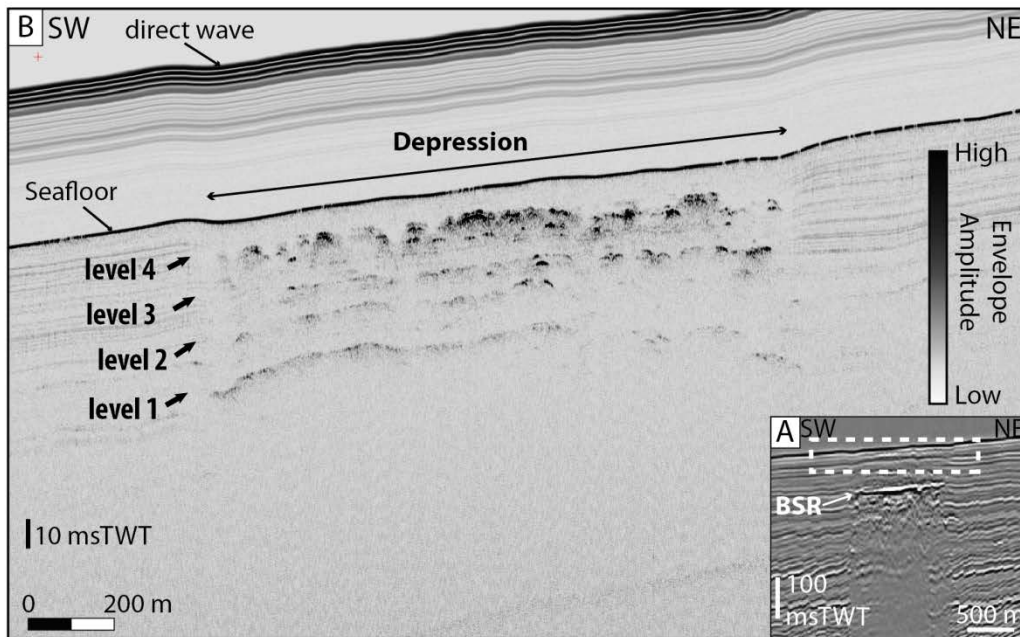
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Fig.8:

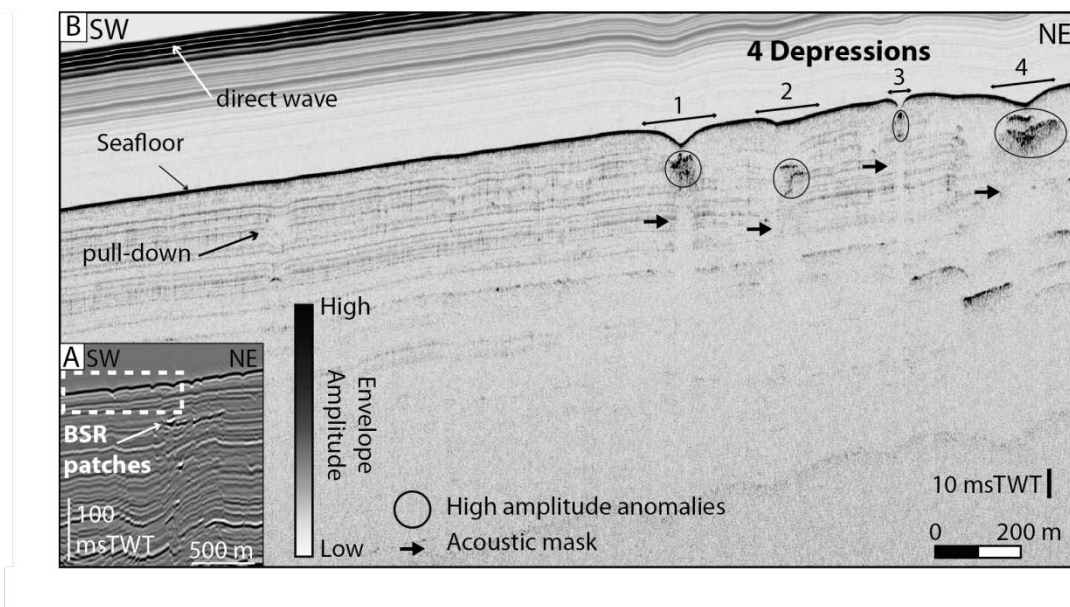


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1505 Fig.9:



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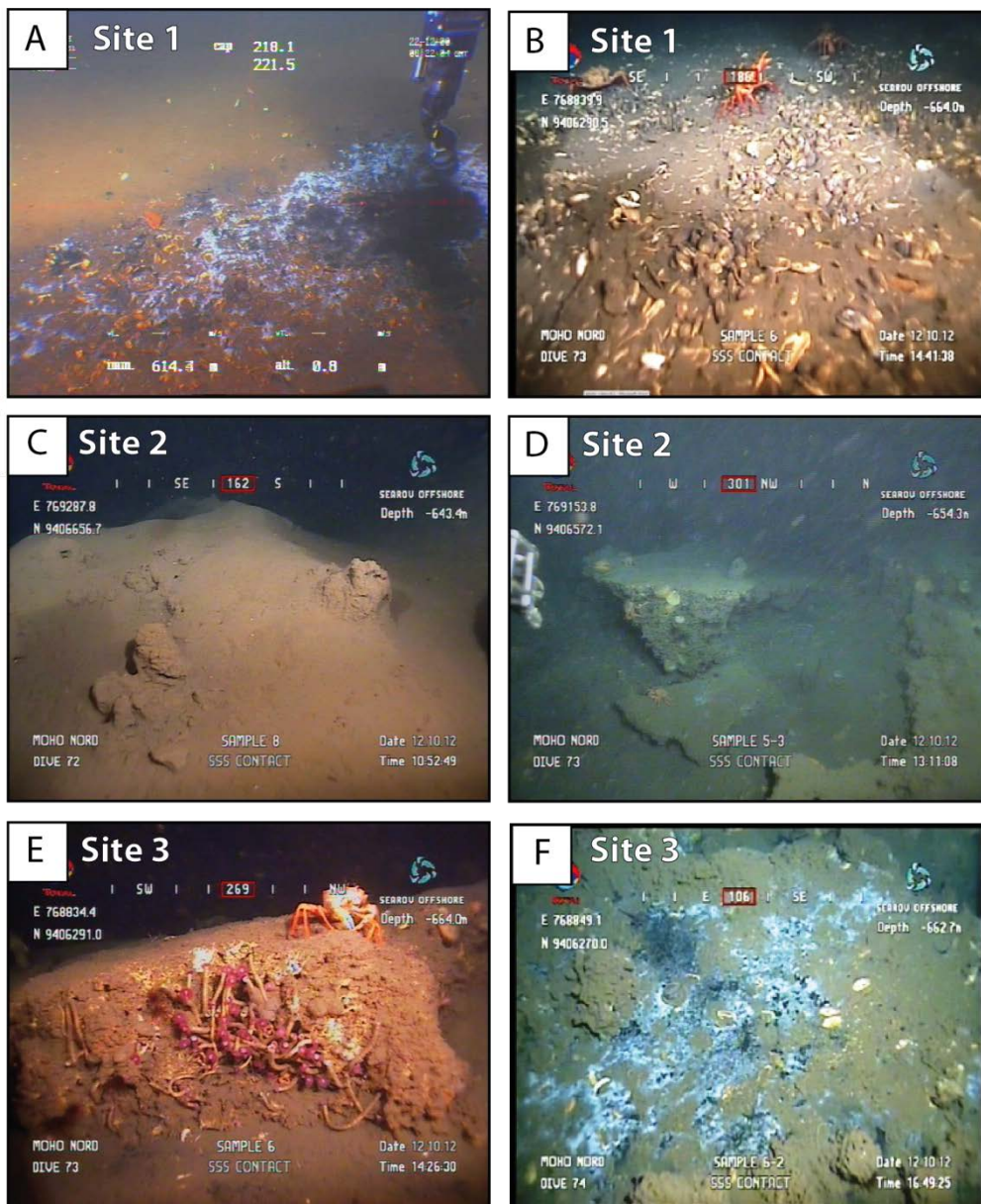
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1516 Fig.10:



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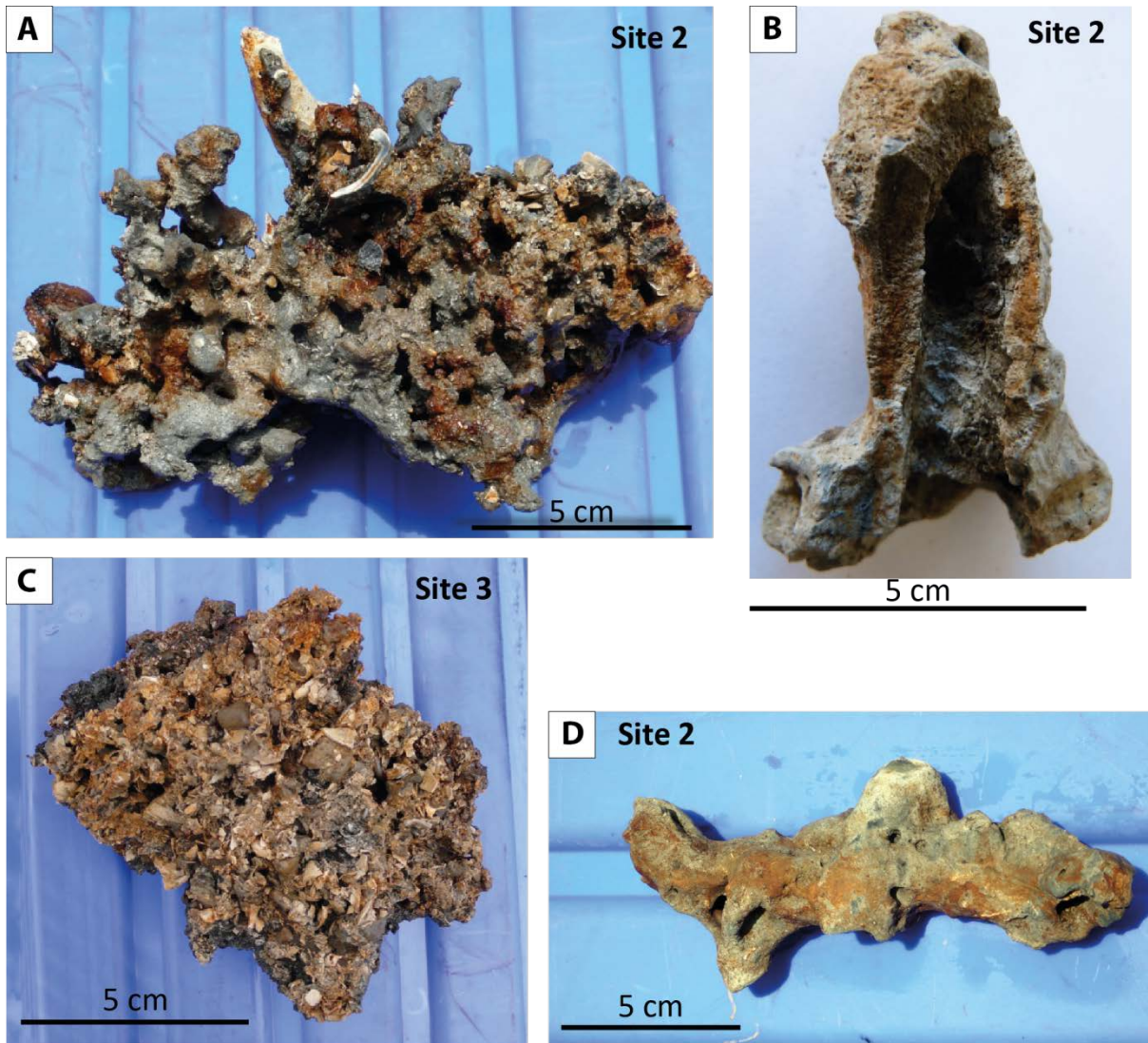
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1523 Fig.11:



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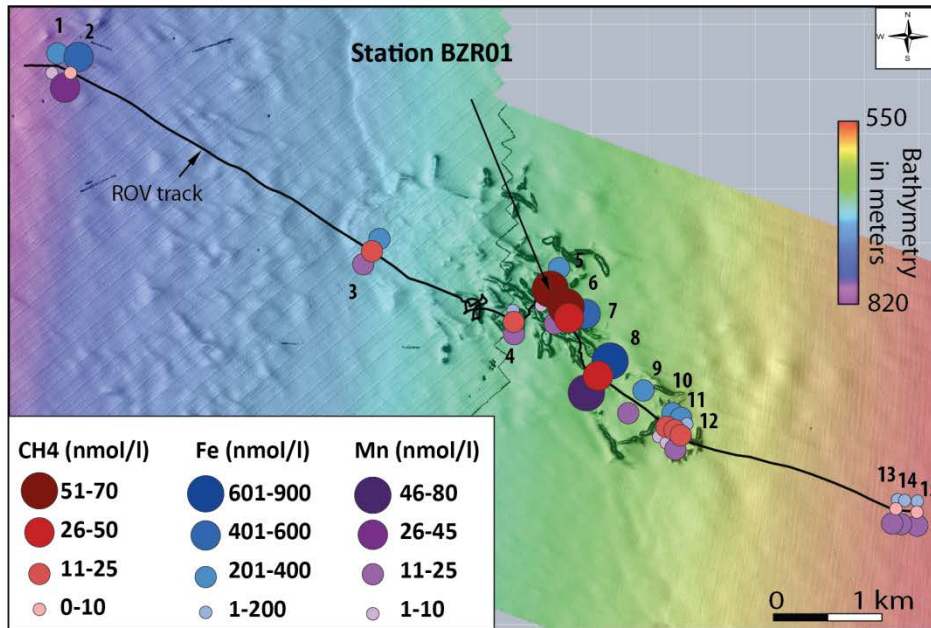
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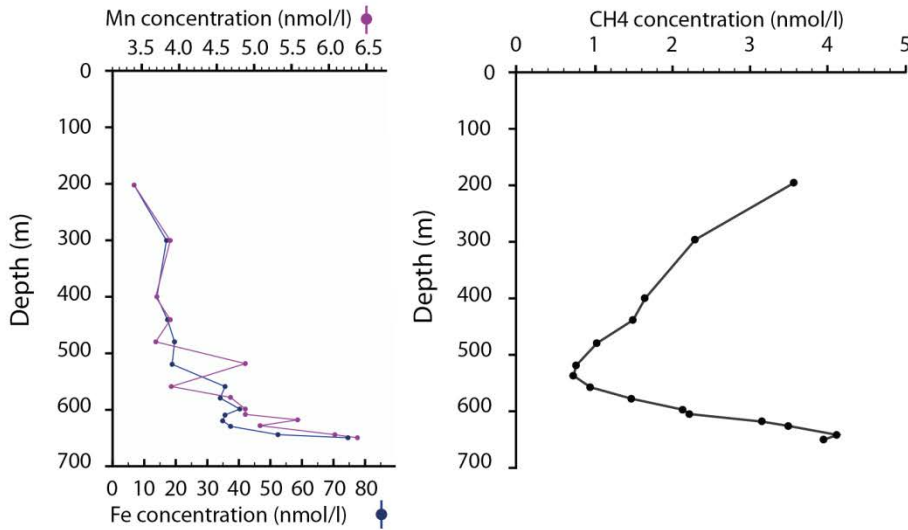
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1531 Fig.12:

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Station BZR01



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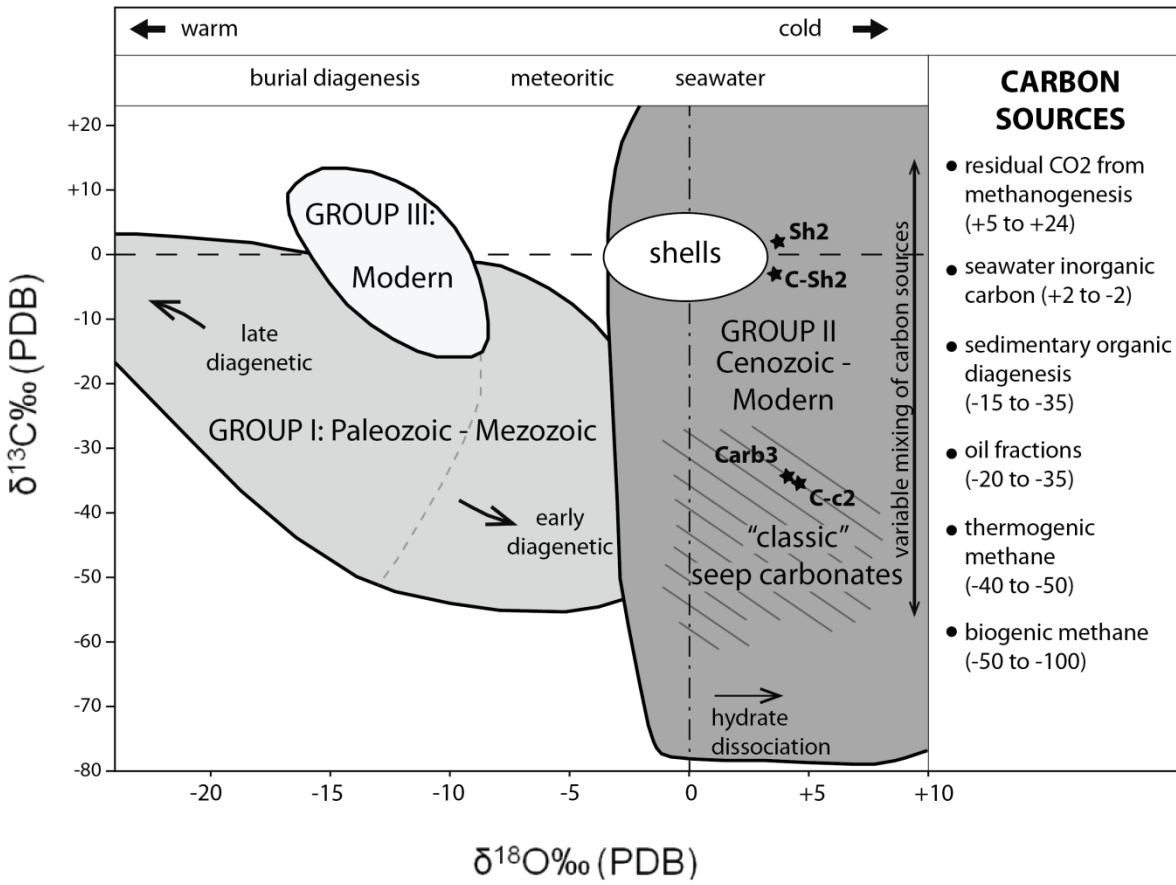
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1541 Fig.13:



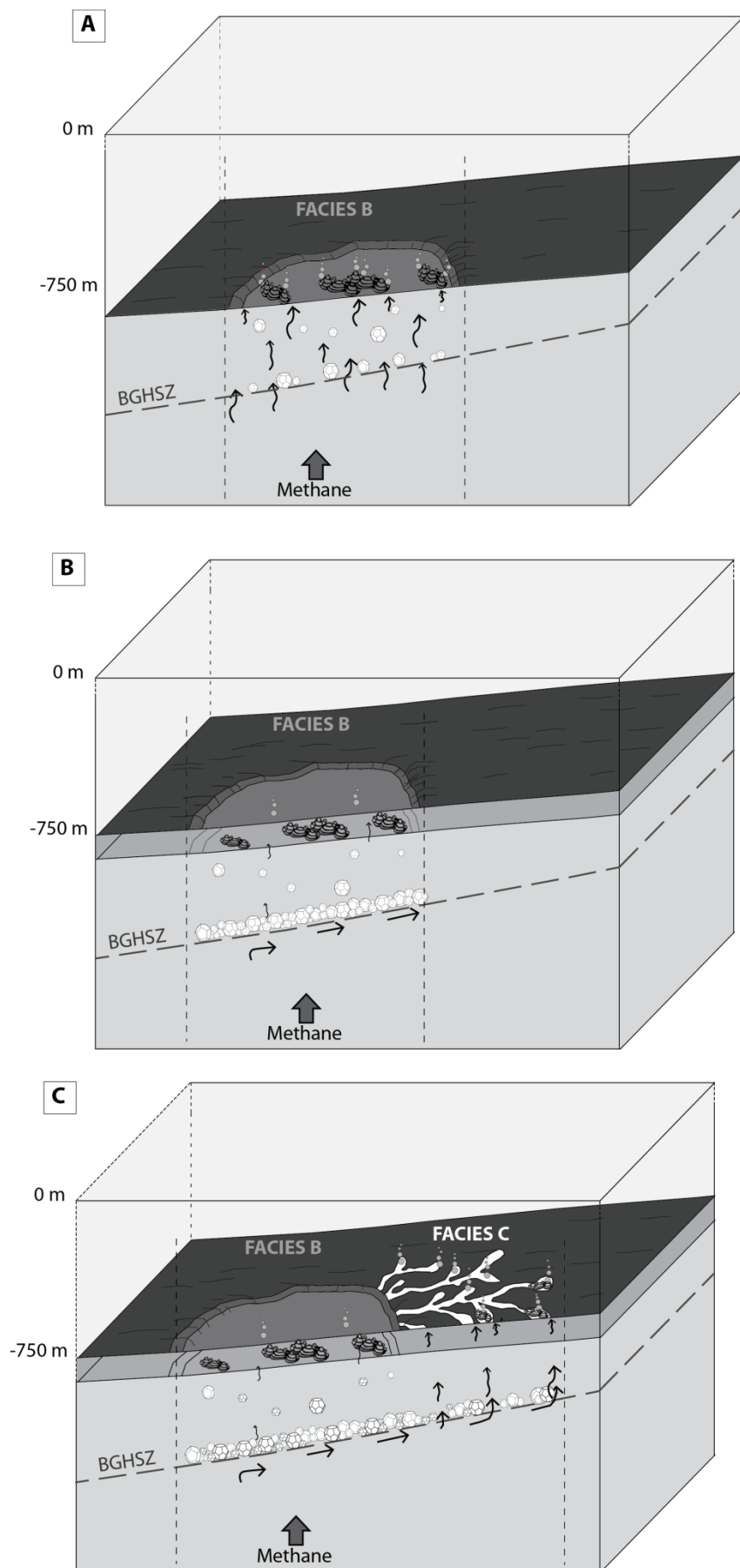
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1546 Fig.14:



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1548 Table 1:

	Samples	$\delta^{13}\text{C}$ (PDB)	$\delta^{18}\text{O}$ (PDB)	CaCO ₃ (%)
Site 2	Carbonate Cement fraction (C-c2)	-35,5	4,3	75,3
	Carbonate Shell fraction (C-Sh2)	-3,1	3,6	89,3
	Bivalve Shell (Sh2)	2,1	3,7	94,5
Site 3	Carbonate sample (Carb3)	-34,3	4,1	74,4

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1566 Table 2:

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A. Hydrocats BZR01 samples:

Depth (m)	653	646	630	620	610	600	580	560	540	520	480	440	400	300	200	
CH4 (nmol/l)	3,9	4,1	3,4	3,1	2,2	2,1	1,4	0,9	0,7	0,8	1	1,5	1,6	2,3	3,5	
Fe (nmol/l)	75,1	52,8	37,7	35,3	36,1	40,9	34,5	36,1		19,3	20,1	17,8	14,6	17,8	7,4	
Mn (nmol/l)	6,4	6,1	5,1	5,6	4,9	4,9	4,7	3,9		4,9	3,7	3,9	3,7	3,9	3,4	

B. ROV water samples :

Num d'ech (Zäirov)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Seismic morphotypes	MA	MA	MB	MC	MC	MC	MC	MC	MB	MC	MC	MC	MA	MA	MA
CH4 (nmol/l)		3	16	23	70	68	42	43		18	20	24	6		3
Fe(nmol/l)	309	597	278	185	287		436	867	222	265	234	188	185	188	154
Mn (nmol/l)	9	45	17	13	3		21	74	13	9	6	14	17	11	11
Si (µmol/l)	22	39	40	35	35	36	36	36	33	33	32	33	32	31	31

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