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# 1 Geological fluid flow in sedimentary basins

## 2 Les fluides géologiques dans les bassins sédimentaires

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9 Keywords: fluid seep; methane hydrates; bottom-simulating reflector (BSR); dynamic seepage;

10 seismic pipes, fluid migration.

11

### 12 I. Introduction (English):

13 This thematic issue on geological fluid flow in sedimentary basins is part of the Action Marges  
14 project. It is a large French coordination program that has been launched in 2008 in order to  
15 focus the continental margin research on a cross disciplinary research and develop new  
16 concepts that have an important impact for society, for resources and for risk assessment.  
17 Actions Marges (AM) is coordinated by INSU with financial contribution of TOTAL, CNRS, BRGM  
18 and IFREMER. One of the themes is dedicated to "Fluids - Organic Matter -Mineral Matter"  
19 (FO3M) and the challenge was to define fluid flow as the centerpiece of a cycle starting from the  
20 organic matter preservation at seabed, its transformation during burial forming fluids, the  
21 upward fluid migration through fine-grained sediments, the temporarily fluid storage into  
22 reservoirs such as sedimentary bodies or gas hydrates, the fluid expulsion at seafloor, to its  
23 implications on seabed stability or climate change.

24 This special issue aims at bringing together recent results from the scientific community  
25 involved in the FO3M project since 2012, with a special focus on the interplay between  
26 mineralogical, geochemical, physical and biological processes occurring during fluid  
27 remobilization and migration within the shallow interval (0-1000 m) of sedimentary basins.

### 28 II. Introduction (Français):

29 Ce numéro spécial sur les migrations de fluides dans les bassins sédimentaires fait partie intégrante  
30 du projet Action Marges. C'est un programme de recherche coordonnée, lancé en 2008, qui  
31 s'intéresse principalement aux marges continentales à travers une approche interdisciplinaire  
32 permettant d'apporter des réponses concrètes aux problèmes de société, de développer les  
33 ressources ou encore de mieux évaluer et de limiter les risques. Le projet Action Marges (AM) est  
34 piloté par l'INSU avec une contribution financière de TOTAL S.A., du CNRS, du BRGM et de l'IFREMER.  
35 Un des thèmes développé concerne les "Fluides-Matière Organique-Matières Minérales" (FO3M) et  
36 son objectif majeur était de placer les fluides au centre d'un cycle qui démarre par la préservation de

37 la matière organique sur le fond de la mer dès le dépôt des sédiments, et qui se poursuit par la  
38 préservation de la matière organique au cours de l'enfouissement l'amenant à la production de  
39 fluides, par la migration de fluides à travers la colonne sédimentaire, par le stockage temporaire de  
40 fluides dans des réservoirs comme les corps sédimentaires ou les hydrates de gaz, et jusqu'à  
41 l'expulsion des fluides sur le fond de la mer ayant une implication possible sur les changements  
42 climatiques due à la nature des fluides expulsés.

43 Ce numéro spécial réunit ainsi des synthèses des derniers travaux récents conduits par la  
44 communauté de chercheurs impliquée dans le projet Action Marges, en particulier depuis 2012. Une  
45 attention particulière a été portée sur les processus minéralogiques, géochimiques, physiques et  
46 biologiques qui entrent en jeu lors de la remobilisation et de la migration des fluides dans les  
47 premiers 1000 m de la colonne sédimentaire.

### 48 **III. Organic matter preservation and shallow fluid migration:**

49 The initial sediment lithification starts with complex interactions involving minerals,  
50 shallow interstitial water, decomposing organic matter and living organisms. This is the  
51 eogenesis domain (0-1000 m below seafloor) in which the sediments are subject to physical,  
52 chemical and mechanical transformations defining the early fabric of rocks (**Figure 1**). This  
53 interval is intensively prospected for its geological resources (hydrocarbons, metal deposits,  
54 geothermal energy). In most basins worldwide, it consists of very fine-grained sediments and it  
55 is supposed to play the role of a seal for fluids migration. Local sand-prone deposits of various  
56 origin, architecture and thickness can also be found, acting as pathways or reservoirs for fluids.

57 For the first time, the solid phase BrOrg has been evidenced as a conservative tracer of  
58 the debromination of sedimentary organic matter in a shallow core (<50 m) taken on the Nile  
59 deep-sea fan ([Murat et al., this issue](#)). The rate of debromination illustrates the complex  
60 interplay between organic matter, microbes and inorganic compounds in unconsolidated  
61 sediments. It obviously depends on the TOC, meaning that it increases with TOC up to 3% due to  
62 the availability of the bacterial population. However, the debromination process decreases for  
63 TOC higher than 4%. This is of high interest for organic-matter transformation as the BrOrg  
64 tracer determines how fine-grained organic-rich intervals become potential source rocks at  
65 depth and how bacterial populations modify fluids and organic matter characteristics during  
66 early stages of burial (**Figure 1**). In addition, the BrOrg can be used as a tool for defining  
67 intervals that were "fluid engineers" in the eogenesis domain once the organic matter has been  
68 transformed at depths where diagenesis is the most active process for lithification (>1000 m  
69 below seafloor).

70 However, the eogenesis domain is commonly affected by polygonal faulting due to a volume loss  
71 by contraction of smectite-prone clay sediments during burial ([Andresen et al., 2011](#);

72 Cartwright, 2011; Gay *et al.*, 2007). This process is of high interest to constrain fluids circulation  
73 within fractured reservoirs and/or preservation of the sediment-cover integrity but it is still not  
74 well constrained as this interval can either promote the migration of fluids from underlying  
75 reservoirs (Gay *et al.*, 2004; Lonergan *et al.*, 1998). In addition, mineralized fluids intensify  
76 diagenesis in the fracture planes, rendering this interval all the more impermeable (Laurent *et*  
77 *al.*, 2012). The detailed analysis of the geometric relationships between high-impedance seismic  
78 anomalies and polygonal fault pairs reveals that they can act as a seal during early stages of  
79 burial (Ho *et al.*, 2016). In the Congo Basin, The Pliocene-present interval contains widespread  
80 fluid escape features, at seabed and in the subsurface, indicating past and ongoing bypass of the  
81 regional seal which is intensely affected by a major polygonal fault system (Gay *et al.*, 2004).  
82 Casenave *et al.* (this issue) have shown that this polygonal fault interval might also have sealing  
83 properties. In this case, fluids are mainly driven along major faults to reach the seabed, leading  
84 to more focused and localized fluid seeps (Figure 1). The next challenge will be then to define  
85 where, when and how does this polygonal fault interval occur. This can only be done by  
86 understanding the behavior of clay grains and fluids during early burial stages.

87 In the Sobrarbe Delta (Eocene Ainsa Basin), diagenetic conditions were limited to low  
88 temperatures (up to 75°C), meaning that sediments have been buried to a maximum of 2 km  
89 (Odonne *et al.*, this issue). Both some sliding surfaces and their surrounding deposits were  
90 investigated. Results reveal higher smectite ratio close to the sliding surfaces and smectites were  
91 found at the wall of dissolution voids of K-feldspars (Figure 1). This indicates that fluids  
92 preferentially circulated following the sliding surfaces that acted as major heterogeneity within  
93 the sediment pile. In these conditions, clay minerals such as smectite appear as a robust marker  
94 of shallow fluid circulation as the kaolinite requires a temperature of 130-140°C to change into  
95 illite.

#### 96 IV. Seafloor fluid seepage

97 Once fluids (water, gas, oil or a mix) reach the seafloor, they are expelled in the water column  
98 forming sub-circular depressions called pockmarks (Hovland and Judd, 1988). Pockmarks have  
99 been reported in various depositional systems at water depths ranging from 30 m to over 3000  
100 m (for a detailed review see (Rollet *et al.*, 2006 ; Gay *et al.*, 2007). They generally form in  
101 unconsolidated, fine-grained deposits. They are cone-shaped circular or elliptical depressions,  
102 ranging from a few meters to 800 m or more in diameter and from 1 m to 80 m in depth. They  
103 concentrate in fields extending over several square kilometers. For the last decade, discoveries  
104 of new fluid seep structures were not reported although both academic and industrial surveys  
105 intensified.

106 However, the use of high-resolution geophysical imagery systems leads to the identification of  
107 unknown high-density field of pockmarks (about 3500 sub-circular pockmarks per square km)

108 in unsuspected shallow marine environment (about 35 m water depth) like the Bay of  
109 Concarneau (France) (Baltzer et al., this issue). The pockmarks appears to be active as the fields  
110 limits coincide with the settlements of *Haploops* tube mats covering muddy deposits. To date,  
111 this is the highest density of pockmarks ever found in marine environment (Figure 1). The  
112 acquisition of bathymetry and other geophysical tools in the same area in 2011 and 2014 was  
113 essential in order to determine lasting of *Haploops* communities related to fluid seeps within  
114 pockmarks.

115 In the Lower Congo Basin (LCB), the combined use of various datasets acquired during the last  
116 15 years and including multibeam bathymetry, seismic data, seafloor videos, seafloor samples  
117 and chemical analyses of both carbonate samples and of the water column allowed the  
118 identification of two distinctive associations of pockmark-like seabed venting structures, located  
119 in water depths of 600-700 m (Casenave et al., this issue). These two features are called "spiders  
120 structures" because of their morphology consisting of a large and flat sub-circular depression  
121 (the body) surrounded by elongated depressions (the legs). The body consists of muddy low-  
122 reflective hemipelagic sediments, covered by patches of bacterial mats and empty shells, and  
123 seems dormant while the legs appear to be the present-day active seep location (Figure 1). This  
124 observation is similar to what was already described for more conventional pockmark  
125 structures on the Nile margin (Bayon et al., ; Dupré et al., ; Migeon et al., 2014) but it is the first  
126 time that such a specific sea-bed planform morphology associated with such a fluid-circulation  
127 activity is reported.

128 Pockmarks and gas seeps can also be detected on acoustic records as long as they are active  
129 (Dupré et al., 2015). This is the case in the Bay of Concarneau where acoustic flares were  
130 identified on Chirp profiles (Baltzer et al., this issue). This is also the case on the Romanian  
131 sector of the Black Sea where widespread gas flares were evidenced in the water column related  
132 to high fluid fluxes escaping from the seabed (Riboulot et al., this issue). Gas flares are a useful  
133 tool to easily identify active pockmarks during multibeam and 2D high-resolution seismic  
134 surveys (Figure 1). Should we add a sentence explaining that active pockmarks might be related  
135 to presence of a gas-hydrate stability zone, so that identification of gas flares could also be a  
136 good tool to recognize hydrate areas?

## 137 V. From the source to the seafloor

138 On the geophysical record , either 2D or 3D seismic data, vertical fluid pathways called pipes (or  
139 chimneys) are usually imaged as systematic disruptions and/or offset of the reflections within  
140 sub-vertical zones, 50–1000 m wide and up to 1000 m high (Løseth et al., 2011). This  
141 interpretation is also supported by observation of amplitude enhancement or dimming. On  
142 seismic profiles, the internal structure of pipes is characterized by bent reflections with offset  
143 upward (pull-up effect) or downward (pull-down effect) relative to the host stratigraphy by 20

144 to 150 ms TWT. Pipes are interpreted to represent a high-permeable vertical zone called a seal  
145 bypass system (Cartwright et al., 2007). They are thought to be caused by high fluid  
146 overpressure hydro-fracturing sediments of low permeability (Arntsen et al., 2007; Rodrigues et  
147 al., 2009). This geophysical characterization seems actually well constrained in space and time.  
148 However, using a set of derived seismic attributes, it is now possible to identify the root of a pipe  
149 (i.e. the depth at which fluids are originating from) and the paleo-pockmark surface (i.e. the level  
150 representing the paleo-seafloor at the time the fluid expulsion started? Was active?). In the Gulf  
151 of Lion, the fluid pipe induces a deformation of surrounding unconsolidated sediments during  
152 upward migration, leading to the formation of a cone in conical or V-shaped structures (Gay et  
153 al., this issue). A multi-attribute calculation made on 3D seismic data allows the precise 3D  
154 mapping of the points of fluid injection while the top of the cone structure marks the top of the  
155 focused migration (**Figure 1**).

156 It is classically invoked that most of the fluids reaching the seabed are originating from shallow  
157 buried levels (**Figure 1**) although when carbonate crusts build at the seafloor there is  
158 undoubtedly a contribution of deeper fluids allowing oil or thermogenic gas to be expelled (Leon  
159 et al., 2010; Leon et al., 2014). This is the case in the Gulf of Lion (Gay et al., this issue), on the  
160 Romanian shelf (Riboulot et al., this issue) or in the Bay of Concarneau (Baltzer et al., this issue)  
161 where fluid releasing is attested. These vertical chimneys or pipes are among other acoustic  
162 anomalies usually present in the shallow sub-surface due to gas accumulations or carbonate  
163 precipitation (**Figure 1**). In the Lower Congo Basin, such anomalies were identified on either 3D  
164 seismic data, HR 3D seismic data or 2D-AUV data (Casenave et al., this issue) corresponding to  
165 bright spots, elongated acoustic anomalies or black patches.

166 However, even with 3D seismic imagery, the full architectural pattern of the fluid network  
167 remains very complex to determine. Only a few examples of modern fluid-related systems have  
168 been studied in details at sea, probably because of the limited number of areas where VHR  
169 investigations of the seafloor/sub-surface together with 3D seismic data exists. It is then  
170 possible to better understand these features on field analogues, once the stratigraphic intervals  
171 hosting them have been uplifted due to tectonic activity and brought above the sea-level (**Figure**  
172 **1**). For instance, in the uplifted accretionary prism of Hikurangi Margin (New-Zealand), tubular  
173 concretions are outcropping in several Miocene mudrocks intervals (Malié et al., this issue).  
174 Most of the pipes are subvertical with their length-axis perpendicular or sub-perpendicular to  
175 the bedding plane. They are 10 to 40 cm in diameter and 50 cm to 10 m in length. In some cases,  
176 they are inter-connected, forming a real plumbing system. A direct comparison with seismic-  
177 scale features is still not realistic to manage because their dimensions are far below the seismic  
178 resolution. Anyway, this suggests that a fluid pipe few hundred-meters wide identified on the  
179 seismic record is most probably a set of several small-scale pipes together propagating in a large

180 area of sediment impregnated with fluids (**Figure 1**). This should be the target for the  
181 development of future research fields.

## 182 **VI. The dual role of hydrates in cover integrity**

183 The sub-vertical fluid pipes (or chimneys) are often disrupted at depth by a high-amplitude  
184 reflection parallel to the seafloor. This reflection is interpreted as a bottom-simulating reflector  
185 (BSR) corresponding to the lower thermodynamic limit of the gas-hydrate stability zone  
186 (Shipley et al., 1979; Kvenvolden 1988; Hyndman and Spence, 1992). This can be also  
187 considered as the top of the free-gas zone beneath the hydrates (MacKay et al., 1994). BSRs are  
188 characterized by a reverse polarity reflection compared to the seafloor. This is due to a decrease  
189 in seismic impedance and, therefore, of seismic velocity. The main restriction for the occurrence  
190 of hydrates is the presence/supply of sufficient amounts of stabilizing gas molecules (Rempel  
191 and Buffet, 1997). As outlined by Egorov et al. (1999), the steady-state model for gas hydrates  
192 requires a methane flux from below to compensate for its diffusive dissipation into the pore  
193 water (Sultan et al. 2014). This statement is confirmed on the Romanian shelf where BSRs are  
194 deflected upward ([Riboulot et al., this issue](#)), suggesting a localized positive heat flow anomaly  
195 probably due to an ascending movement of fluids through the sedimentary column (De Batist et  
196 al., 2002; Gay et al., 2006). It means that gas hydrates are locally not impermeable, allowing  
197 fluids to migrate upward along any major discontinuity such as faults, and then to form  
198 pockmarks at the seabed (**Figure 1**). So, there is a close association between BSRs at depth,  
199 indicating an active fluid flux, and seafloor pockmarks. This is also the case in the Lower Congo  
200 Basin where the new "spider structures" are located above patches of BSR ([Casenave et al. this](#)  
201 [issue](#)).

202 As gas hydrates are usually considered impermeable, additional free gas may migrate laterally  
203 right beneath the hydrates. Once they find a way up, they can escape to the seabed. On the  
204 seismic record, this kind of seepage is often evidenced by hyperbolae located at the landward  
205 termination of the BSR and overlaid with seafloor gas escape structures (**Figure 1**) ([Riboulot et](#)  
206 [al. this issue](#); [Casenave et al., this issue](#)).

207 Gas hydrates have a dual role in sedimentary basins as 1) they temporarily store fluids  
208 migrating from deeper geological horizons to their stability zone or as free gas beneath them  
209 and 2) they avoid fluids to reach the seabed with properties similar to a barrier. In consequence,  
210 they can be considered as both a reservoir and a cover in the shallow subsurface (**Figure 1**).

## 211 **VII. Triggering and control mechanisms:**

212 In the uplifted accretionary prism of Hikurangi Margin (New-Zealand), trending of fossil tubular  
213 carbonate concretions coincides with tectonic lineament suggesting that the main factor

214 controlling the fluid expulsion and location is the tectonic activity ([Malié et al., this issue](#)). It is  
215 suggested that the tectonic uplift together with fault activity can shift the depth of the Hydrate  
216 Stability Zone (HSZ), leading to dissociation of pre-existing hydrates and releasing of methane.

217 Gas hydrates are also "climate sensitive" as they form or dissolve in response to sea-level  
218 variations controlling bottom seawater temperatures. In the Lower Congo Basin, the various  
219 stratigraphic levels hosting fluid escape structures have been correlated to sea-level rises  
220 following the latest Holocene lowstands ([Casenave et al., this issue](#)). This is due to free gas  
221 naturally migrating landward due to the pronounced tilting of the base of the gas hydrate  
222 stability zone at 600-700 m water depths (close to theoretical pinch-out of the BSR).

223 This relation with sealevel variations has also been evidenced in the Gulf of Lion where most of  
224 the modern pockmarks were formed during the last sea-level rise ([Gay et al., this issue](#)). Leon et  
225 al. (2014) have shown that in the western Mediterranean Sea, the propagation of internal waves  
226 alongshore may act together with the general sea-level rise at the beginning of the transgressive  
227 period as a hydraulic pump for fluids trapped at shallow depths, resulting in the formation of  
228 pockmarks (**Figure 1**). It suggests that, at the beginning of each transgression, large amount of  
229 methane-rich fluids might be released into the ocean and atmosphere, possibly increasing the  
230 greenhouse effect (Dunkley Jones et al., 2010).

231 The effect of hydraulic pumping can be responsible for the formation of the large fields of  
232 pockmarks in the Bay of Concarneau ([Baltzer et al., this issue](#)). At a shorter time-scale, the high-  
233 frequency expulsion activity may be related to the action of spring tides (**Figure 1**). Although the  
234 initial pockmark craters is thought to be formed during seismic events ([Baltzer et al., this issue](#)),  
235 pockmarks could be activated when the tidal pressure would be high enough during spring tides,  
236 leading to the formation of plumes in the water column.

237 As previously proposed by Hasiotis et al., (1996), these observations imply that gas supply  
238 towards pockmarks is a continuous process during the life-span of the seep structure (**Figure 1**).  
239 It also means that the sediments within the migration pathways are loaded with gas, which is of  
240 high interest for seafloor hazards.

## 241 **VIII. Conclusion**

242 Recent studies of fluid migrations in sedimentary basins have shown that these phenomena are  
243 ubiquitous and interact with the surrounding sedimentary rocks over the basin's history, from  
244 its early opening stages, to the mature infilling, or even the ultimate exhumation stages. Finally,  
245 these fluids act as major markers for the geodynamic events that structure the basins.

246 In order to understand the role of fluids in sedimentary basins, several challenges must be met.  
247 We must, in particular, determine the source of the fluids, their pathways and the timing of these  
248 migrations and releasing at the seafloor. Thus, depending on the geodynamic context of a given

249 basin and on its evolution over time, several fluid migration histories may overlap, though these  
250 fluid events are all preserved in the sedimentary record. The goal is thus to identify a number of  
251 geophysical, mineralogical and geochemical markers of fluid migration and expulsion. They are  
252 closely controlled 1) by early sediment deformations and fracturing and 2) by the location of  
253 bodies and sedimentary sequences likely to temporarily store and/or conduct fluids laterally all  
254 along the margin and 3) by allocyclic phenomena such as sealevel variations.

255 In this special issue, the methods have combined complementary approaches to analyse fluid  
256 migrations in sedimentary basins: 1) geophysical characterisation based on 2D, 3D and 2D-AUV  
257 seismic data, core and exploratory well data, 2) sedimentological and mineralogical  
258 characterisation based on petrophysical data and crystallographic and texture analyses, 3)  
259 identification of geochemical markers on samples collected at various depths of the sedimentary  
260 column up to the surface and 4) definition of the mechanical parameters triggering and  
261 controlling fluid re-mobilisation.

262 The final goal of this research field will be to generate a concept of "fluid sequences" that, in a  
263 similar fashion to sequence stratigraphy, will be used as a direct approach to determine the  
264 migration pathways and potential traps, and to quantify the volume and nature of expelled  
265 fluids. This is of major importance as it will help determining the timing and activity of seafloor  
266 fluid expulsion leading to geohazard assessment (catastrophic fluid blow-out, landslide  
267 triggering etc...). As a reverse approach, it will make possible to define the evolutionary status of  
268 a sedimentary basin and to infer its geodynamic context at any given period of its history. The  
269 aim is thus to significantly improve fluid expulsion models in sedimentary basins, which is a  
270 challenge for basin exploration (open window over the petroleum system, seafloor stability and  
271 fluid accumulation).

## 272 **IX. Acknowledgements**

273

## 274 **X. References**

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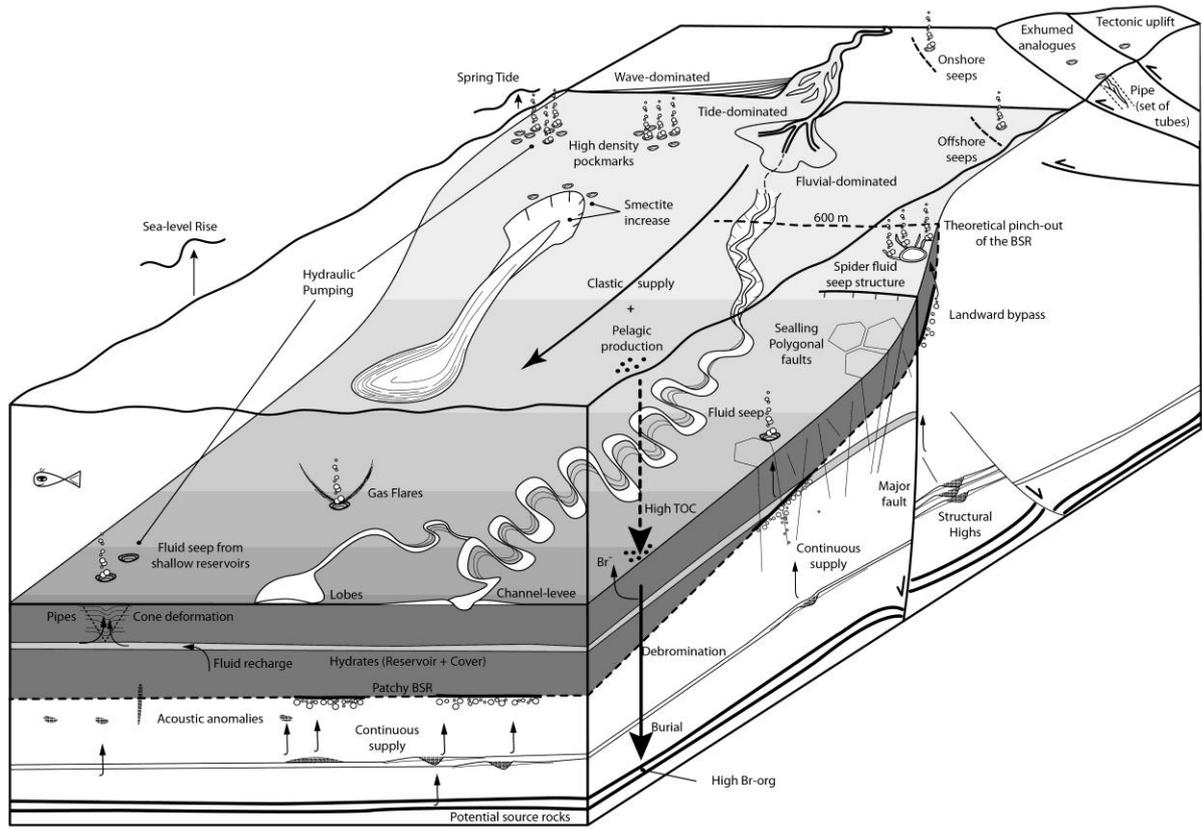
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376 Figure 1: Schematic block illustrating new developments since 2012 in geological fluid  
377 production, migration and expulsion in sedimentary basins, based on studies conducted through  
378 the FO3M thematic action in the Action Marges project.



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