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1 **Repeated fluid expulsions during events of rapid** 2 **sea-level rise in the Gulf of Lion, western Mediterranean** 3 **Sea.**

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18 **1. SUMMARY**

19 Based on a High-Resolution 3D seismic block acquired in the Gulf of Lion in 2004-2005
20 we investigated fluid pipes and pockmarks on the top of the interfluvial between the Hérault canyon and
21 the Bourcart canyon both created by turbidity currents and gravity flows from the shelf to the deep
22 basin in the north-western Mediterranean Sea. Combining the geometry of the potential fluid pipes
23 with the induced deformation of surrounding sediments leads then to the ability to differentiate
24 between potential fluid sources (root vs source) and to better estimate the triggering mechanisms
25 (allochthonous vs autochthonous cause). We linked together a set of derived attributes, such as Chaos
26 and RMS amplitude, to a three dimensional description of pipes along which fluids may migrate. As
27 previously shown in other basins, the induced deformation, creating cone in cone or V-shaped
28 structures, may develop in response to the fluid pipe propagation in unconsolidated sediments in the
29 near surface. The level at the top of a cone structure is diachronous. It means that stratigraphic levels
30 over this surface are deformed at the end of the migration. They collapse forming a depression called a
31 pockmark. These pipes are the result of repeated cycles of fluid expulsion that might be correlated
32 with rapid sea-level rise instead of sediment loading. The most recent event (MIS 2.2 stage) has led to
33 the formation of a pockmark on the modern seafloor. It has been used as a reference for calculating the
34 effect of a rapid sea-level rise on fluid expulsion. As all physical and geometrical parameters are

35 constrained, we were able to define that a +34 m of sea level rise may account for triggering fluid
36 expulsion from a very shallow silty-sandy layer at 9 m below seafloor since the last glacial stage. This
37 value is consistent with a sea level rise of about 102 m during this period. This study shows that the
38 episodic nature of fluid release resulted from hydromechanical processes during sea-level rise due to
39 the interactivity between high pressure regimes and principal in situ stresses.

40 2. INTRODUCTION

41 Focused fluid migration in marine sediments is a widespread phenomenon which is
42 increasingly gaining attention in the context of environmental discussions, even though it is still not
43 well understood (Berndt, 2005). However, increased data coverage and the advent of new tools in
44 oceanic exploration, such as backscatter imagery, multibeam swath bathymetry maps and 3D seismic
45 data, can provide new evidence of relatively small-scale fluid seep structures on modern continental
46 margins, and can help towards improving our understanding of the underlying processes. Fluid
47 migration in sedimentary basins is an important process because 1) they accumulate into reservoirs
48 that might be of economic interest; 2) the input of greenhouse gases into the ocean/atmosphere system
49 may be an important component of the atmospheric carbon budget (Judd et al., 2002); 3) the fluid
50 expulsion at the seafloor may play a role in potential instabilities on slopes (Prior and Coleman, 1984;
51 Evans et al., 1996; Yun et al., 1999; Cochonat et al., 2002), representing a risk for human activities
52 (Sultan et al., 2001; Elverhøi et al., 2002); and 4) fluid expulsion sites form the basis for a plethora of
53 chemosynthetic benthic ecosystems that play an important role in the deep marine communities
54 (Sibuet, 2003).

55 Since their initial identification on the Scotian Shelf by King and MacLean (King and
56 MacLean, 1970), pockmarks have been reported repeatedly during offshore hydrocarbon exploration
57 and scientific surveys in various depositional systems at water depths ranging from 30m to over 3000
58 m (for a detailed review see Josenhans et al., 1978; Werner, 1978; Hovland, 1981; Whiticar and
59 Werner, 1981; Hovland and Judd, 1988; Solheim and Elverhoi, 1993; Baraza and Ercilla, 1996; Rollet
60 et al., 2006). They generally appear in unconsolidated, fine grained sediments as cone-shaped circular
61 or elliptical depressions, ranging from a few meters to 800 m or more in diameter and from 1 m to 80
62 m in depth, and they concentrate in fields extending over several square kilometers. In some cases,
63 they have been identified along straight or circular lines correlated with glaciomarine tills (Josenhans
64 et al., 1978; Whiticar and Werner, 1981; Kelley et al., 1994) suggesting a geological control on
65 focused fluid flow (Eichhubl et al., 2000; Cifci et al., 2003; Gay et al., 2003). In particular, structural
66 surfaces along bedrock (Shaw et al., 1997), salt diapirs (Taylor et al., 2000; Satyavani et al., 2005),
67 faults and faulted anticlines (Boe et al., 1998; Soter, 1999; Vogt et al., 1999; Eichhubl et al., 2000;
68 Dimitrov and Woodside, 2003) create pathways for fluid migration (Nakajima et al., in press). These
69 observations suggest that discontinuities or unconformities are much more effective for fluid migration
70 than a simple diffusive seepage through the sedimentary column (Abrams, 1992; Brown, 2000) and

71 are responsible for focused fluid flow, fluid escape at the seafloor and pockmark development
72 (Abrams, 1992; Orange et al., 1999). The crater-like nature of pockmarks suggests an erosional power
73 of fluid venting (Hovland and Judd, 1988), commonly related to an overpressured buried reservoir of
74 biogenic gases, thermogenic gases, or oil, interstitial water, or a combination of the three. Time
75 varying fluxes may be recorded into seafloor fluid seeps. An integrated study conducted on a giant
76 pockmark of the Lower Congo Basin at 3200 m water depth has shown that the mineralogical,
77 chemical, and biological facies are clearly related to upward fluid intensity (Gay et al., 2006c).

78 On the geophysical record, either 2D or 3D seismic data, pipes (or chimneys) are usually
79 imaged as systematic disruptions and/or offset of the reflections within vertical zones, 50–1000 m
80 wide and up to 1000 m high (Løseth et al., 2011). They are augmented by observations of amplitude
81 enhancement or dimming. On seismic profiles, the pipe internal structure is characterized by
82 reflections that are bent or offset upward (pull-up effect) or downward (pull-down effect) relative to
83 the host stratigraphy by 20 to 150 ms TWT. Pipes are interpreted to represent a high-permeable
84 vertical zone called a seal bypass system (Cartwright et al., 2007) caused by high fluid overpressure
85 hydro-fracturing sediments of low permeability (Arntsen et al., 2007; Rodrigues et al., 2009). This
86 geophysical characterization seems actually well constrained in space and time. However, neither the
87 root of a pipe nor the triggering mechanisms are clearly defined. The interpretation of seismic data
88 usually leads to a gap between the final result of fluid remobilization (i.e. fluid pipe and pockmarks
89 recorded at the time of geophysical acquisition) and the physical causes that have triggered fluid
90 migration in the past.

91 In the following sections, we will investigate fluid pipes and pockmarks located in the
92 Gulf of Lion (Fig. 1). The final aim of this study is to link a set of derived attributes, such as Chaos
93 and RMS amplitude, to a three dimensional description of pipes along which fluids may migrate and
94 the induced deformation of surrounding host sediments. We will show that these pipes are the result of
95 repeated cycles of fluid expulsion. Combining the geometry of the potential fluid pipes with cone-in-
96 cone deformation structures using High-Resolution 3D seismic leads then to the ability to differentiate
97 between potential fluid sources, root vs source (Gay et al., 2012) and to better estimate the triggering
98 mechanisms (allochthonous vs autochthonous cause).

99 3. GEOLOGICAL SETTING

100 The HR 3D seismic area lies on the western flank of the Gulf of Lion (GoL) upper
101 continental slope at 250-450 m water depth (Fig. 2). The GoL forms a crescent-shaped passive margin
102 that is characterized by a 70 km wide continental shelf on the northwest part of the Mediterranean Sea.
103 The Rhone River is the modern major source of sediment to the GoL shelf while other minor fluvial
104 inputs also occur along the coastline (Pont et al., 2002). However, the buildup of the margin was
105 strongly controlled by Quaternary glacial-interglacial sea-level variations (Rabineau et al., 2006;
106 Frigola et al., 2012) and by significant subsidence at the shelf edge that has led to the deposition and

107 preservation of sedimentary bodies and to the incision of numerous canyons mainly oriented NW to
108 SE and N to S (Berné et al., 2001; Baztan et al., 2005). The study area lies between two major
109 canyons, the Bourcart Canyon and the Hérault Canyon (Fig. 2). The canyons display a marked axial
110 incision that is interpreted as the imprint of erosive turbidity current initiated at the canyon head when
111 it was connected to a river during the last sea-level low stand (Baztan et al., 2005). Actually,
112 sediments are transported through the canyons by episodic dense shelf water formation and cascading
113 events (DSWC) (Canals et al., 2006; Palanques et al., 2006; Pasqual et al., 2010; Sanchez-Vidal et al.,
114 2008, 2012; Gaudin et al., 2006).

115 In situ testing carried out at 300 m long PRGL 1 (42°41'23.30''N, 3°50'15.50''E) and
116 PRGL 2 (42°50'58.20''N, 3°39'30.85''E) boreholes (Fig. 2), have led to the identification of five
117 main sequences (S1 to S5) stacked during the sea-level lowering phases of the last five glacial-
118 interglacial 100-kyr cycles (Basetti et al., 2008). We used as a reference the commonly admitted D30-
119 45-50-55-60-64-65-70 relative high sea-levels (Fig. 3), corresponding to each Dansgaard-Oeschger
120 Greenland warm interstadial (Rabineau et al., 2006).

121 For geotechnical characterization, a continuous cone penetration test unified (CPTU) was
122 performed at sites PRGL1 and PRGL2 (Lafuerza et al., 2008) but we used here only the PRGL1 as it
123 was carried out within the area of HR 3D seismic acquisition. The test was made with a static
124 penetrometer measuring cone resistance (kPa), sleeve friction (kPa) and pore pressure acting on the
125 cone (kPa). Estimation of sediment types based on geotechnical properties was done using the method
126 of soil classification established after Ramsey (2002). All geotechnical data were combined for soil
127 characterization, considering that the pore pressure (u_2) is mainly related to the permeability of
128 sediments, whereas the resistance to cone penetration (q_t) and the lateral friction (f_s) can be directly
129 correlated to a particular lithology (Fig. 3).

130 The lithologically homogeneous site PRGL1 is characterized by clays interbedded with
131 silty-clays and locally sand to clayey sands (Lafuerza et al., 2008). Units I, III and IV are quite similar
132 in terms of lateral friction (f_s). Subunits IIb (from 33 to 36 mbsf), IIIc (70–72 mbsf), and IVd (120 –
133 127 mbsf) comprise the reflectors corresponding to discontinuities D63, D60, and D50, which are
134 found to represent intervals of variable thickness characterized by low friction measurements due to
135 increased sand content. The lower unit V corresponds to S3. The rest of the boundaries between the
136 CPTU-based subunits correspond to specific seismic reflectors defining different seismic facies:
137 subunits IIa and IIIc correspond to low-amplitude hemistratified facies; IIIb, IVa, IVb, Va, and Vb to
138 facies of intermediate amplitude; and IIIa, IIIb, and IVc to facies of higher relative amplitude
139 (Lafuerza et al., 2008). Such changes in relative amplitude in the seismic record do correlate well with
140 the CPTU-based geotechnical-stratigraphic divisions.

141 4. DATA BASE AND PROCESSING

142 In 2004-2005 a High Resolution (HR 40-250 Hz) 3D seismic dataset was acquired in the
143 Gulf of Lion over a 8.5x1.6 km area between the Bourcart canyon and the Hérault canyon (Thomas et
144 al., 2004; Jouet, 2007) (Fig. 2).

145 The HR3D seismic source consists of small volume air guns (mini-GI gun, 110 Hz
146 dominant frequency) able to produce a repetitive signal. Two source arrays, 12.5 m apart, are fired
147 alternately in order to have the cross-line sampling interval for a given number of streamers. Two
148 streamers are deployed 25 m apart using two eight-meter long rigid bars fixed to the vessel's frame.
149 Each streamer hosts 48 channels, with a 6.25 m group interval (Thomas et al., 2012). This seismic
150 layout prevents spatial aliasing of dipping events up to 40° in the in-line direction and 20° in the cross-
151 line direction. Positioning of sources and receivers is determined using the DGPS position and
152 gyrocompass of the vessel, and magnetic compasses from 3 depth controllers along each streamer.
153 Given the accuracy of these sensors and the short length of the streamers (400 meters), receiver
154 positions are calculated within an absolute accuracy of 2 m at the head of the streamers, to 4 m at the
155 tail. Source positions are measured to an absolute accuracy of 1 m. Positioning accuracy requirement
156 to allow accurating wavefield reconstruction is $l/4$ (where l is the dominant wavelength; Gutowski et
157 al. 2008), thus 3.4 m considering the expected resolution given for the dominant wavelength (13.5 m
158 @ 110 Hz). As the achieved positioning accuracy is between 2 and 4 m, the resulting resolution is
159 slightly degraded.

160 Data editing and updating of the fold map are performed at the end of each line to assess
161 the homogeneity of the data and to adjust the acquisition program to acquire additional in-fill lines to
162 cover gaps in the fold map. Considering the relatively shallow water depth on the survey area,
163 additional 2D HR seismic data recorded using longer source-receiver offset (490 m compared to the
164 375 m maximum offset of the 3D layout) has allowed to constrain the velocity field within the upper
165 sedimentary layers of interest (Marsset et al., 2012). A two-layer velocity model, 1515 m/s for the
166 water column, and a constant gradient of 400 m/s increasing for the sediments was then applied to
167 perform 3D stacking following by constant velocity two-pass Stolt time migration. The resulting
168 seismic migrated volume should then reach a lateral resolution close to the 12.5 meters theoretical one.
169 The vertical resolution is around 2.5 meters.

170 In the following study we derived seismic attributes from the amplitude of the HR 3D
171 migrated dataset. However, free gas and/or carbonate cements have strong effects on the seismic
172 signal and on the seismic amplitude as reflections can be respectively moved down or up. This is
173 commonly attributed to a pull-down or a pull-up effect due to the migration during processing. So,
174 seismic amplitude alone can be difficult to interpret in environments dominated by lateral and vertical
175 fluid migrations through sediments. Due to the vertical pattern of seismic pipes (or chimneys) a typical
176 horizon picking is not accurate to image them in a 3D domain. New tools in the academia and

177 petroleum exploration allow individualizing these chimneys from the 3D block (Gay et al, 2006; Gay
178 et al., 2012):

179 The “RMS amplitude” (x_{rms}) provides a scaled estimate of the trace envelope. It is
180 computed in a sliding tapered window of N samples as the square root of the sum of all the trace
181 values x_n squared:

$$x_{rms} = \sqrt{\frac{1}{N} \sum_{n=1}^N w_n x_n^2}$$

182 where w_n are the window values.

183 . The “Chaos attribute” is designed to measure the “lack of organization” in the dip and
184 azimuth estimation method, based on the amplitude of reflectors and their continuity. Vertical and sub-
185 vertical seismic pipes appear as homogeneous high-amplitude anomalies, ovoid in shape.

186 High RMS amplitude associated with a high chaotic signal pattern contained within
187 seismic data can directly be related to the presence of fluids and or cements and thus can map
188 hydrocarbon indications in the data and other geologic features which are isolated from background
189 features by amplitude response (Gay et al., 2006, 2007). Alternatively, low RMS amplitude associated
190 with a high chaotic signal pattern is rarely considered in seismic data. It can be used as a good
191 indicator of the deformation of sediments induced by recent fluid motion through sediments, although
192 coherency attribute alone gives only an indication of the deformation (Gay et al. 2012).

193 5. RESULTS

194 1. Morphology and structure of seafloor pockmarks

195 We identified more than 180 pockmarks in the study area with an average density of 13,2
196 pockmarks per km² (Fig. 4). They range from 12,5 m (limit of seismic horizontal resolution) to 180 m
197 in diameter, and from 4 to 15 ms TWT in depth with respect to the surrounding seabed. Most of them
198 have a circular to sub-circular shape in plane view. The shaded relief map produced from the 3D
199 seismic data shows that pockmarks are not randomly distributed on the seafloor (Fig. 4). They are
200 mainly concentrated on the crest of a WNW-ESE striking anticline structure corresponding to the
201 interfluvies between the Bourcart and the Hérault canyons.

202 About 6 pockmarks, located in the North-East part of the 3D seismic area, are wider than
203 100 meters. They are aligned parallel to the slope break of the Hérault canyon (Fig. 4). The present
204 Hérault canyon is the last erosional episode of a series of glacial-interglacial 100-kyr cycles leading to
205 incision-infill cycles. During these successive events, the canyon moved laterally creating a large
206 valley. On the seismic section IL211, these pockmarks are aligned over a steep erosional surface of the
207 paleo-canyon that incises into the upper slope (Fig. 5). As shown in the Lower Congo Basin (Gay et
208 al.; 2007), fluids likely originate from deeper levels where they migrate laterally along dipping
209 permeable stratigraphic units and more vertically along erosional unconformities or faults.

210 In the South-West part of the 3D seismic area, only a few small pockmarks, 10 to 15
 211 meters wide, have been identified (**Fig. 4**). They lie at the border of a terrace of the Bourcart canyon.
 212 They are probably related to a similar fluid migration pathway linked to a buried erosional surface. On
 213 the almost flat part of the terrace, no pockmarks have been detected. The infilling of the terrace is
 214 made of a succession of aggrading continuous and homogenous amplitude reflections interlayered
 215 with localized chaotic facies (**Fig. 5**). This seismic pattern is typically interpreted as Mass Transport
 216 Deposits (MTD's) and they probably come from instabilities on the flank of slope slidding towards the
 217 Bourcart canyon. Due to overconsolidation during the deposition process, MTD's are usually
 218 considered as an impermeable barrier (Gay et al., 2007b and references therein). Fluids migrate
 219 laterally towards the erosional surface where they are then driven upward and may accumulate and/or
 220 be expelled at the top of the anticline structure (Gay et al., 2007a).

221 As most of pockmarks are concentrated on the top of the anticline structure, we focused
 222 on this sub-area within the 3D seismic block. Pockmarks imprint the seafloor forming sub-circular
 223 depression, and they are often correlated with underlying depressions or amplitude anomalies.

224 **2. Seismic pipes**

225 Free gas can easily be interpreted from seismic records because even small amounts of
 226 gas within pore space significantly decrease the acoustic impedance of sediments and create anomalies
 227 such as acoustic turbidity, enhanced reflections (bright spots, flags) and acoustic blanking (wipe out)
 228 (Anderson and Hampton, 1980; Judd and Hovland, 1992; Schroot et al., 2005).

229 In most basins seismic profiles through pipes show two levels of acoustic anomalies,
 230 vertically elongated under the main depression (Gay et al., 2006). The deep anomaly is an inverted
 231 cone shape in cross section and it is marked by lower amplitude reflectors and acoustic turbidity. On
 232 both sides of this region the bright reflectors shift upward. This pull-up may be due to fluid movement
 233 (structural) or to velocity effects caused by hydrate/carbonate cementing within the overlying pipe
 234 corresponding to the shallow anomaly. The pipe is ovoid in shape with depressed high-amplitude
 235 reflectors considered as a reduction of the seismic velocities (pull-down effects), even if this could be
 236 real depressions due to fluid expulsion (ancient pockmarks?). Such acoustic anomalies are also called
 237 seismic chimneys and could be indicative of fluid flow from deeper levels (Hovland and Judd, 1988;
 238 Judd et al., 1992; Hempel et al., 1994; Heggland, 1997; Tingdahl et al., 2001; Ligtenberg, 2005).

239 On the seismic section IL211 a 250 ms TWT thick sub-vertical anomaly has been
 240 identified (**Fig. 5**). The pipe is the result of vertically stacked pull-down reflections, from 40 to 200 m
 241 in diameter. The main vertical axis of the pipe (i.e. the lowest part of each downbending reflection) is
 242 generally marked by higher amplitudes than the average amplitude along the reflections. The base of
 243 the pipe, or the root, seems to be at the D50 stratigraphic reflection. However, a single seismic section
 244 gives a partial view of the pipe. On a set of 9 seismic sections crosscutting the pipe (**Fig. 6**), the IL239
 245 clearly shows that the anomaly starts about 15 ms TWT above the D45 stratigraphic reflection. The
 246 base of the pipe is visible on IL239 to IL231 and stops at the D50 stratigraphic reflection. On IL227 to

247 IL219, there is no anomaly detected above or beneath the D50 stratigraphic reflection. On IL215 to
248 IL207, the pipe starts from the D50 stratigraphic reflection and propagates upward. High amplitude
249 anomalies within the pipe affect the D60 stratigraphic reflection on IL211 and 215 at about 560 ms
250 TWT. On IL215, from 475 to 525 ms TWT, downbending reflections are not continuous and they are
251 crosscut by a vertical anomaly characterized by polarity inversions at some points. This typical pattern
252 of a gas charged pipe propagates upward on IL 219 where it reaches the seafloor and connect to the
253 modern pockmark. The bottom of the main depression (i.e. the deepest point of the pockmark
254 compared to the regional seafloor) is located on IL219. However, high amplitude reflections forming a
255 vertically elongated anomaly are still visible on the south flank of the pockmark from IL227 to IL239.

256 This basic description of seismic anomalies clearly illustrates that a fluid pipe is not only
257 a vertical to sub-vertical conduit. Although seismic sections are commonly used for interpreting fluid
258 pipes, this method cannot be used to characterize all pipes present in a seismic block. A derived
259 attribute, the Chaos attribute, has been calculated and time slices are extracted every 50 ms from 400
260 ms to 750 ms TWT (**Fig. 7**). The Chaos attribute calculation is based on the amplitude variation and
261 the continuity of reflections. At 400 ms TWT, the dipping flanks of the major pockmarks, 40 to 200 m
262 wide, appear with a medium to high amplitude of Chaos. The bottom of the depression is low in
263 amplitude of Chaos, which is more consistent with surrounding regional sediments. The small
264 pockmarks, 20 to 40 m wide, are close to the detection limit and they appear as spots of medium to
265 high amplitude of Chaos. At 450 ms TWT, the time slice crosscut underlying pipes. They are
266 characterized by a ring of medium amplitude of Chaos that does correspond to the area where the
267 reflection starts to bend. The flanks are low in amplitude of Chaos and the axis of the pipe,
268 corresponding to the bottom of the depression, is medium to high in amplitude of Chaos. This pattern
269 would allow discrimination of pipes and ring and of pockmarks and paleo-pockmarks on a vertical
270 section. However, a paleo-pockmark and its associated underlying pipe can be re-used or reactivated
271 by later fluid migration and the geophysical signal might be modified, sometimes even shaded. This is
272 the case from 500 to 750 ms TWT where rings of medium to high amplitude of Chaos are vertically
273 correlated with spots or pipes of high amplitude of Chaos that appear over these features. This vertical
274 succession of amplitude anomalies shows that pockmarks can be reactivated, leading to the
275 development of a new pipe capped by a new pockmark until the fluid expulsion episode stops.

276 The large pockmark identified on seismic sections IL207 to IL239 (**see Fig. 5**) illustrates
277 the vertical succession of amplitude anomalies (**Fig. 7**). It is marked by flanks of high amplitude of
278 chaos down to 450 ms TWT. From 500 to 550 ms TWT the pipe is characterized by a ring of medium
279 amplitude of Chaos. At 600 ms TWT it transforms into a spot of high amplitude of Chaos. Below 650
280 ms TWT, no anomaly has been detected, which is consistent with the interpretation of a vertical
281 section showing that the base of the pockmark takes root right beneath the D45 stratigraphic level.

282 In such an approach, either characterizing a pipe on a vertical section or in time slices
283 using seismic amplitude and Chaos attribute, it is particularly difficult to define the root of each event

284 corresponding to the reactivation. For example, the root accounting for one event can be situated
285 beneath the paleo-pockmark or within the pipe corresponding to the previous event.

286 **3. Constraining pipe geometry using horizontal dissection**

287 A new method for characterizing fluid pipes has been recently developed using sandbox
288 models coupled to geophysical analysis (Mourgues et al., 2011, 2012; Gay et al., 2012). Based on the
289 RMS amplitude, 7 levels of the fluid pipe have been identified from the D45 stratigraphic reflection to
290 the seafloor (Fig. 8). About 200 time slices have been extracted. 19 time slices display the same
291 pattern in which the base of a level is marked by a tiny spot of very low RMS amplitude. A ring of low
292 RMS amplitude develops from the base and becomes greater to the top of the interval with an average
293 diameter of 50 to 70 m for small depressions and an average diameter of 150-250 m for large
294 depressions.

295 In a 3D view, the vertical succession of spots defines a stem and the flanks of the cone
296 refer to as a corolla in a flower structure (Gay et al., 2012). It is interesting to note that the corolla on
297 RMS amplitude is about 20% larger than the depression identified both on seismic amplitude and
298 Chaos attribute.

299 **6. DISCUSSION**

300 In the Gulf of Lion (GoL) margin, western Mediterranean Sea, deltaic forced Regressive
301 Progradational Units (RPU) stacked on the outer-shelf and upper slope during relative sea-level falls
302 led some authors to describe this margin as a forced regressive system (Posamentier et al., 1992;
303 Tesson et al., 1990, 2000). The significant subsidence rate of the margin, 250 m.Myr⁻¹ at the shelf edge
304 (Rabineau, 2001), eased the preservation of RPU in the upper slope, as it was continuously
305 submerged even during pronounced lowstands. These significant subsidence rate allowed preserving
306 the majority of the regressive/transgressive depositional sequences across the outer shelf (former
307 coastal deposits from old lowstand coast lines) and the upper slope accumulation where dating is
308 easier, thus, resulting in an ideal area for the study of the late Quaternary sedimentary succession
309 (Rabineau, 2001).

310 In this context, numerous fluid escape features, fluid pipes in the sedimentary column and
311 related pockmarks at the seabed, provide evidence for a focused fluid flow system in the Gulf of Lion
312 (Riboulot, 2011). The detailed observation of the pockmark geometry, obtained from High Resolution
313 3D seismic volume, contributed to identify the evolution through time of the fluid pipes, which are
314 interpreted as stacked pockmarks linked to the 100-kyr cyclicity within the hosting sedimentary
315 sequences (lowstand periods). However, the mechanism by which focused fluids move up the
316 sedimentary column to the surface is not well constrained. During burial, the sediment porosity
317 decreases due to loading of overlying sediments. A set of processes, such as particle re-orientation and
318 fluid expulsion, leads to the decrease of void spaces between particles (Maltman 1994; Vasseur et al.
319 1995). Vertical migration of fluids through thick (up to 600 m), low permeability fine-grained

320 sediments cannot occur at a rate sufficient to explain the observed seafloor seeping structures in a
321 context known to not be actually overpressured in shallow sediments (Lafuerza et al., 2008).

322 ***Cone propagation and pockmark formation***

323

324 Several authors have used physical experiments to study the formation of piercement
325 structures in various cases: kimberlite pipes (Walters et al., 2006), hydrothermal vents (Nermoen et al.,
326 2010), mud volcanoes (Mazzini et al., 2009), or gas seeps (Varas et al., 2009, 2011). All these
327 experiments involved non-cohesive materials such as glass microballs and sand which were fluidized
328 by injecting locally a fluid (air or water). They obtained similar fluidization morphologies involving a
329 large diverging cone-like structure of remobilized material just above the fluid injection. Nermoen et
330 al. (2010) derived analytical solutions and concluded that fluidization occurs when the seepage forces
331 integrated over the conical fluidized area balance the weight of the granular material (Mourgues and
332 Cobbold, 2003). Furthermore, the role of fluid pressure in the re-opening of pre-existing fractures has
333 long been emphasized (Grauls et al., 1994 and references therein). An increase in fluid pressure can lead
334 to shearing (the minimum stress field is positive and the stress deviators are high) and the tensile
335 failure (the minimum stress field is negative and the stress deviators are small). A context where the
336 fluid pressure (P) is almost equivalent to the minimum principal stress (σ_3) will lead to the opening of
337 fractures perpendicular to σ_3 . So, such conditions favoring vertical fluid transfers are preferentially
338 filled during periods of horizontal stress relaxation, once the minimum in situ stress field is less than
339 the previously induced pressure regime ($P > \sigma_3$). The consequence is a reduction of the stress deviator
340 that will initiate a negative minimum effective stress field.

341 The pipe identified on the North-East corner of the 3D block in the Gulf of Lion may be
342 characterized using RMS amplitude (Fig. 8). We identified 7 well individualized intervals of low RMS
343 amplitudes. Each interval starts with a tiny point of low RMS amplitude which evolves upward as a
344 ring and then suddenly disappears. In a 3D view, this corresponds to vertically stacked cone structures
345 (Fig. 9). In general, the size of the ring is wider than the depression identified on seismic sections and
346 on the Chaos attribute.

347 The seismic data suggest that the most accurate interpretation for a pipe boundary is at the
348 transition from continuous layer reflections outside and the disturbed seismic pattern inside the pipe.
349 The pipe-fill in the pipes may therefore be structureless as observed in outcrop (Løseth et al., 2011).
350 This would imply that layered reflections inside the pipe are geophysical artifacts. However, laterally
351 abrupt changes in impedance values may be due to enhanced density and/or velocity contrasts, which
352 may be related to small-scale gas accumulations associated with fluid expulsion (Taylor et al., 2000).

353 As previously shown in the Gjallar Ridge (Gay et al., 2012), in the North-Sea (Mourgues
354 et al., 2011) or in the Lower Congo Basin (Monnier et al., 2013), these cone structures identified using
355 attributes derived from 3D seismic are due to the deformation of surrounding host sediments during
356 upward fluid propagation. The flanks of a cone appear as discrete normal faults in sandbox models due

357 to the collapse after major fluid flow (Mourgues et al., 2012; Gay et al., 2012). However, the throw is
 358 smaller than can be resolved and the faults are not clearly seen in seismic profiles with the
 359 conventional amplitude attribute. The low RMS amplitude marking the flanks may be due to the shear
 360 effect along the fault plane, locally reorienting particles and dispersing energy of the seismic signal.

361 The top of a cone structure does correspond to the end of pipe propagation. Sandbox
 362 models have shown that the pipe propagation induces a seafloor uplift caused by inflation of fluid-
 363 charged sediments (Gay et al., 2012). The next step in the evolution of the structure would be a
 364 collapse creating sub-circular depressions, so-called pockmarks (Mourgues et al., 2011), i.e. structures
 365 defined by a basal unconformity is seismic stratigraphy (Andresen et al., 2011). In addition, buried
 366 depressions or pockmarks mark the end of the propagation process. The levels hosting pockmarks do
 367 not correspond to the time at which fluid migration started (Gay et al., 2012).

368 ***Triggering mechanisms***

369 Thanks to the combination of three CPTU measurements (cone resistance, lateral friction,
 370 pore pressure (Ramsey, 2002) it is possible to define the soil type based on a soil classification chart
 371 (Lafuerza et al., 2008). There is an apparent correlation between the soil type or the nature of
 372 sediments and fluid remobilization periods evidenced in the area. For example, the levels at which
 373 fluids are remobilized correspond to major lithological change, from sand or sandy-silty intervals to
 374 clayey to muddy intervals (Bassetti et al., 2007).

375 The conventional interpretation of seismic pipes leads to the conclusion that 7 repeated
 376 events of fluid expulsion occurred for the fluid pipe located at IL211. The strong deformation of
 377 surrounding sediments is interpreted as the result of fluid pipe propagation and in some extent, the
 378 basal unconformity outlining the depression marks the end of the fluid expulsion process. More
 379 precisely, the first continuous reflection sealing the depression and the faults signs the end the upward
 380 cone propagation and related fluid pipe activity. In consequence, the base of the V-shaped structure
 381 (the cone of deformation) represents the point of fluid injection (i.e. the top of reservoir) and clearly
 382 marks the base of chimneys or pipes. The top of the V-shaped structure marks the level attained by the
 383 fluid pipe. It doesn't mean that this surface is consistent with the seafloor. Sandbox models have
 384 shown that focused migration through vertical pipes may transform into a more distributed or diffuse
 385 migration a few meters beneath the seafloor (Gay et al., 2012). This is mainly due to less cohesive
 386 sediments and higher porosity and permeability in the sub-surface. It makes difficult to identify the
 387 level (i.e. the time) at which fluid migration was initiated, although our study shows that the base of
 388 the pipes can be interpreted using a set of attributes derived from the seismic data. Seismic
 389 interpretation of amplitude–time data may lead to misinterpretation of the base of pipes and thus leads
 390 to a wrong location of fluid pressure build-ups within the sedimentary basin.

391 In the absence of any calibration method, it is particularly difficult to estimate the
 392 sediment thickness above the point of injection that would help in determining the head pressure (Δh).

393 However, the level at which fluids started to migrate upward is located between the top of the cone
394 structure and the base of the next overlying point of injection.

395 In the Gulf of Lion, core analysis in PRGL1 has shown that sediments are quite
396 homogeneous but they are mainly composed of fine sands – silty sands - interbedded with more shaly
397 intervals, playing the role of potential reservoirs and seal respectively. Fluids can migrate along both
398 erosional surfaces (see Fig. 5) delineating the Hérault canyon and the Bourcart canyon and they may
399 accumulate preferentially in the sandy-silty layers forming an anticline structure at the interfluvium.

400 However, due to the non-cohesive nature of sediments and high porosities and
401 permeabilities in the shallow sub-surface (Lafuerza et al., 2008), the dissipation of excess pore-
402 pressure is a very fast process. In order to create a focused fluid migration, an overpressure must be
403 generated at the point of injection:

404 **1) Effect of sediment loading:**

405 The vertical stress due to an additional load is:

$$406 \quad \sigma_v = \rho_{\text{sat}} \cdot d \quad (\text{Equation 1})$$

407 where ρ_{sat} is the bulk density (in $\text{kN}\cdot\text{m}^{-3}$) and d is the thickness of the new deposit (in m). The average
408 bulk density in the core PRGL1 is about $11,230 \text{ kN}\cdot\text{m}^{-3}$ with a vertical stress of about $707 \text{ kN}\cdot\text{m}^{-2}$
409 (Lafuerza et al., 2008) Equation (1) gives a value of d equal or superior to about 63 m. The thickness
410 (d) needed to create overpressure is about 63 m of sediments that must be deposited almost instantly
411 (at a geological time scale). In the area, the maximum thickness can be evaluated from event 7,
412 corresponding to the present day last event of fluid expulsion, and the effect of compaction is
413 minimized. The point of initiation, or the point of injection determined on RMS amplitude time-slices
414 (Fig. 8), is located at 434 ms TWT, corresponding to 9 m below seafloor. It means that the interval is
415 not thick enough to generate the required overpressure for focused pipe creation. Furthermore,
416 sedimentological core description does not evidence any catastrophic turbiditic events on the
417 interfluvium between the Hérault canyon and the Bourcart canyon and the average sedimentation rate is
418 only $1 \text{ m}\cdot 10^3 \text{ yr}^{-1}$ (Bassetti et al., 2007; Dennielou et al., 2009).

419 The dissipation time of overpressured fluids (t_0) depends on the hydraulic diffusivity D_z
420 ($1\cdot 10^{-8} \text{ m}^2\cdot\text{s}^{-1}$ in the study area, calculated from PRGL1), on the maximum vertical distance of
421 dissipation z (the dissipation can be performed upward or downward, so $z = 9 / 2 = 4,5 \text{ m}$) and on a
422 time factor T_v (in %):

$$423 \quad t_0 = \frac{T_v \cdot (z)^2}{D_z} \quad (\text{Equation 2})$$

424 T_v is related to the consolidation rate U (in %). The process of consolidation is directly
425 linked to the rate of excess pore pressure dissipation. The one dimensional consolidation theory is
426 governed by the following differential equation (Terzaghi, 1943):

$$427 \quad D_z \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \quad (\text{Equation 3})$$

428 where u is the pore water pressure, Dz is the hydraulic diffusivity, t is time and z denotes the position
 429 where u is determined. The Terzaghi's consolidation equation can be solved using analytical or
 430 numerical techniques. The solution obtained depends on the boundary conditions. For our case, with a
 431 soil layer of height, $2H$, the boundary conditions are:

432 (a) complete drainage at top and bottom of the layer; $u = 0$ at $z = 0$ and $z = 2H$;

433 (b) the initial excess pore water pressure $\Delta u = u_i$ is equal to the applied stress increment $\Delta \sigma$.

434 The solution is obtained as a Fourier series, which can be expressed in the following form:

$$435 \quad U_z = 1 - \sum_{n=0}^{\infty} f_1\left(\frac{z}{H}\right) f_2(Tv) \quad (\text{Equation 4})$$

436 where U_z is the degree of consolidation at time t , at depth z , and Tv is a non-dimensional time factor.

437 U_z and T are given by:

$$438 \quad Tv = Dz \frac{t}{H^2 ar} \quad (\text{Equation 5})$$

$$439 \quad U_z = -\frac{u}{u_i} \quad (\text{Equation 6})$$

440 where H_{dr} is the length of the longest drainage path. Based on the numerical solution of equation (4),
 441 and in order to define the time factor T_v as a function of the degree of consolidation U_z , [Casagrande](#)
 442 [\(1936\)](#) and [Taylor \(1948\)](#) determined a 'pre-calibrated' curve concerning the Time factor Tv which is
 443 given by the following equations:

444 $U_z > 60\%$

$$445 \quad Tv = 1.78 - 0.933 \log(100 - U_z(\%)) \quad (\text{Equation 7})$$

$$446 \quad U_z > 60\% \quad Tv = \frac{\pi}{4} \left(\frac{U_z(\%)}{100}\right)^2 \quad (\text{Equation 8})$$

447 From equations (5), (7) and (8) and for a given hydraulic diffusivity Dz and a given
 448 drainage path H_{dr} , it is possible to evaluate the time (t) needed to get a specified degree of
 449 consolidation U_z .

450 For a consolidation rate of 50%, $Tv_{50\%}=0.197$ and Equation (2) gives a time dissipation of
 451 about 4 years. For a consolidation rate of 99%, $Tv_{99\%}=2$, the time dissipation is about 37 years. It
 452 means that for an average sedimentation rate of $1 \text{ m} \cdot 10^3 \text{ yr}^{-1}$, 9 m of sediments are deposited in 9000
 453 years and the potential excess pore pressure is dissipated in 37 years for the best case of consolidation.
 454 So, the effect of sediment loading alone cannot be taken into account for fluid expulsion in shallow
 455 sediments of the Gulf of Lion.

456 **2) Effect of sea level variation**

457 In a sedimentary column, an elementary volume ΔV is subjected to three forces:

458 (1) its own weight, F_g , due to gravity:

$$459 \quad F_g = \rho_{sat} \cdot \Delta V \quad (\text{Equation 9})$$

460 where ρ_{sat} is the specific gravity (in $\text{kN} \cdot \text{m}^{-3}$);

461 (2) forces of buoyancy, F_b , due to immersion in water:

$$462 \quad F_b = \rho_f \cdot \Delta V \quad (\text{Equation 10})$$

463 where ρ_f is the specific gravity of fluid (generally 10 kN.m^{-3});

464 (3) seepage forces, F_s , due to fluid flow:

$$465 \quad F_s = i \cdot \rho_f \cdot \Delta V \quad (\text{Equation 11})$$

466 where ρ_f is the specific gravity of fluid and i is the hydraulic gradient, with $i = -\text{Grad } h$,
467 where h represents the head pressure.

468 Without any specific pathways where fluid may circulate and/or accumulate, pore fluids
469 can escape up to the seafloor if sediments are fluidized: grains become suspended in fluid, which can
470 migrate upward. Therefore, the balance between ascending forces (F_s and F_b) and descending forces
471 (F_g) must be equal and the hydraulic gradient, i , must reach the critical gradient, i_c . For a vertical
472 seepage, i_c is given by the following equations:

$$473 \quad \rho_{sat} \cdot dV = \rho_f \cdot dV + i_c \cdot \rho_f \cdot dv \quad (\text{Equation 12})$$

474 and

$$475 \quad \rho' = \rho_{sat} - \rho_f \quad (\text{Equation 13})$$

476 where ρ' corresponds to the submerged density. The equation (12) becomes:

$$477 \quad i_c = \frac{\rho'}{\rho_f} \quad (\text{Equation 14})$$

478 For fluid migration up to the seafloor, a vertical critical gradient must be taken into
479 account from the point of initiation to the seafloor:

$$480 \quad i = \frac{\Delta H}{L} = i_c = \frac{\rho'}{\rho_f} \quad (\text{Equation 15})$$

481 where ΔH is the variation of head pressures between the point of initiation and the
482 seafloor and L represents the thickness between these two points.

483 For an average specific gravity, ρ_{sat} , of $3,9 \text{ kN.m}^{-3}$ in the first 100 m of the sedimentary
484 column calculated from PRGL1 site (Lafuerza et al. 2008), a specific gravity of seawater, ρ_f , of $1,03$
485 kN.m^{-3} , and 9 m for L corresponding to the burial depth of the event 7 initiation point (9 m below
486 seafloor), the variation of head pressure is 34,2 m, representing an excess pore pressure of 334 kPa
487 (considering g equal to $9,81 \text{ m.s}^{-1}$).

488 An excess pore pressure of 334 kPa can be created by a sea level rise, increasing pore
489 water pressure at depth only in drained conditions. The needed sea level rise ($H_1 - H_0$) for such an
490 excess pore pressure able to create fluidization and expulsion can be calculated:

$$491 \quad \Delta P = (H_1 - H_0) \cdot \text{gradPs} \quad (\text{Equation 16})$$

492 Where ΔP represents an excess pore pressure of 334 kPa at 9 m below seafloor, H_1 is the
493 actual bathymetry of 300 m, H_0 is the initial bathymetry, and gradPs is about $10,07 \text{ kPa.m}^{-1}$ in
494 seawater. The calculated bathymetry, H_0 , is about 266 m, giving a sea level rise of about +34 m.

495 The measurement of Relative Sea Level (RSL) can be done relative to present day Sea
496 Level ($t=0$). Paleobathymetry is usually estimated from cores with a description and evolution of
497 sedimentary facies with microfossil assemblages (Ferland et al., 1995; Yokoyama et al., 2000;
498 Hanebuth et al., 2000) and must be corrected from the subsidence effect. The most accurate study has

499 directly estimated the RSL in the western part of the Gulf of Lion from seismic data (Rabineau et al.,
500 2006). They provided the position of the delta front at the last glacial maximum MIS2 giving an
501 estimated value of 102 ± 6 m at MIS 2.2 stage. This value is consistent with previous estimates in the
502 region based on molluscs ages (Aloisi et al., 1975; Labeyrie et al., 1976; Aloisi et al., 1993) and also
503 based on glacio-hydro isostatic modeling. More recent studies suggested a RSL of at least -115 m but
504 this value is not corrected from subsidence of the shelf (Jouet et al., 2006).

505 A sea level rise of about $+34$ m triggering fluid expulsion during event 7 is consistent
506 with a global sea level rise of about 102 to 115 m since the last glacial maximum MIS 2.2 stage. A
507 quick look at all other pipes present in 3D seismic area shows that the last event of fluid expulsion
508 (event 7) is marked by cones of deformation accompanying the upward fluid pipe propagation. As the
509 initiation point is situated at the same stratigraphic level, it means that most of the modern pockmarks
510 were generated during the last sea level rise. Further investigations are required in order to check out
511 whether the Gulf of Lion experienced a major fluid release since the last glacial stage as shown in
512 other basins (Plaza-Faverola et al., 2011). For instance, in the Ceuta Drift and the Gulf of Cadiz, high
513 resolution images have revealed that the pockmarks are connected to shallow subsurface reservoirs
514 (Leon et al., 2010; Leon et al., 2014). In such environment, coarser-grained sediments can act as
515 reservoirs for fluid accumulation and overlying fine-grained sediments may act as effective seals
516 (Somoza et al., 2012; Leon et al., 2014). In this area, pockmarks are associated with the first
517 subsurface erosion surface which is overlain by a transparent layer representing the final transgressive
518 Holocene deposit (Leon et al., 2014). The decrease in hydrostatic pressure during the sea-level
519 lowstand resulted in the expansion of sediment-trapped bubbles within the shallow subsurface
520 reservoirs. At the same time, rhythmic tidal water level changes and large internal waves acted as
521 "hydraulic pumps" of the shallow subsurface free gas accumulations (Leon et al., 2014). At the
522 beginning of the transgressive period, seawater coming from the Atlantic Ocean started to overflow
523 into the Mediterranean Sea creating internal waves (Leon et al., 2014). This event can be recorded at
524 shallower depths (<100 m) where the internal waves interacted with the sea bottom to form giant sand
525 waves, like in the Gulf of Valencia (Albarracin et al., 2014). The propagation of internal waves
526 alongshore may act together with the general sea-level rise at the beginning of the transgressive period
527 as a hydraulic pump for fluids trapped at shallow depths, resulting in the formation of pockmarks
528 (Leon et al., 2014). It means that, for each start of transgression, large amount of methane-rich fluids
529 were possibly released into the ocean and atmosphere, possibly increasing the greenhouse effect
530 (Dunkley Jones et al., 2010).

531 ***A model for cyclic fluid expulsions***

532 A recent geotechnical survey, conducted northwest and southeast of the study area
533 (Sultan et al., 2007) has shown only one active gas emission within a pockmark. Based on in situ pore
534 pressure measurements, they considered that the excess pore pressures and pockmark activities
535 observed were most likely associated with the presence of free gas that partially saturated underlying

536 sedimentary layers. Furthermore, deep sea benthic analyses have shown that sediments within the
537 active pockmark fields had lower meiofaunal abundance and biomass when compared with the
538 surrounding sediments that were not influenced by the gas seepage (Zeppilli et al., 2012). All other
539 investigated pockmarks in the area are inactive at the present day (Sultan et al., 2007; Zeppilli et al.,
540 2012). This clearly indicates that 1) fluids are actively migrating from deeper levels. Given the
541 geological context of the interfluvium, they are possibly driven through erosional surfaces or
542 discontinuities; 2) fluids are accumulating in silt to sand-rich shallow buried levels leading to an actual
543 increase in pore pressure; and 3) fluids are trapped under a low-permeability seal; and 4) fluids can
544 escape at the seafloor in only a few places, the fluid escape is in a quiescence mode. This period is
545 illustrated on Fig. 10 as stages A or E where there is a pressure build-up within a shallow buried silt-
546 rich layer overlain by a mud-rich interval.

547

548 The pressure build-up is generated due to the fluid accumulation, leading to the
549 development of a cone of deformation in overlying sediments and a bulge (or doming) at the seafloor
550 (stage B, Fig. 10), as shown in other basins (Mourgues et al., 2012).

551 The possibility of dilatancy can be considered here due to erosion of the structure at the
552 seafloor. The fluid pipe can vertically propagate along pre-formed cracks at stage B. Most of the fluids
553 are released at this stage, leading to a collapse of the structure creating the seafloor depression (Gay et
554 al., 2012; Dumke et al., 2014), or pockmark (stage C, Fig. 10). During stage B, the anticline structure
555 developing between both turbiditic canyons is in a compressive regime bringing about a significant
556 increase in fluid pressure although relaxation period alone will allow fluid to migrate upward at stage
557 C. Then, during sea level highstand or continuing sea-level rise, the seafloor structures are smoothly
558 draped by clayey hemipelagic sediments interlayered with thin beds of sand or silty sands (Bassetti et
559 al., 2007) (Stage D, Fig. 10). This stage of draping is then accompanied or followed by a new period
560 of fluid accumulation in more porous silty-sandy to sandy intervals, It can be called the recharge
561 period (Stage E, Fig. 10). The next step is a new period of release unless the amplitude of sea level, or
562 the depth of the reservoir, does not allow an excess pore pressure sufficient for triggering fluid
563 expulsion.

564 7. Conclusion

565 3D seismic data provide new insights on the Gulf of Lion fluid migration history. It
566 substantially improves the understanding of post-depositional processes that affect the sedimentary
567 column in shallow subsurface. Analysis of such data makes it possible to understand the link between
568 fluid pipes propagation and associated V-shaped structures. As previously shown in other basins, these
569 cone structures may develop in response to the deformation of surrounding sediments during fluid
570 migration in the near surface. They cannot be evidenced in a traditional way using seismic amplitude
571 only and a set of derived attributes, such as RMS amplitude coupled to Chaos, must be calculated.

572 They allow the precise 3D mapping of the point of fluid injections in overlying sediments and the top
573 of the cone structure marks the top of the focused migration. Based on these observations we focused
574 on one example of fluid pipe characterized by repeated cycles of fluid expulsion. We have shown that
575 these expulsion events might be correlated with sea level rise instead of sediment loading. The most
576 recent event (event 7 corresponding to MIS 2.2 stage) has led to the formation of a pockmark on the
577 modern seafloor. It has been used as a reference for calculating the effect of sea level rise on fluid
578 expulsion. As all physical and geometrical parameters are constrained, we were able to define that a
579 +34 m of sea level rise may account for triggering fluid expulsion since the last glacial stage. This
580 value is consistent with a sea level rise of about 102 m during this period.

581 We propose a model that integrates with previous hypotheses. However, interpreting
582 seismic facies alone doesn't provide the key for having the full picture of fluid migration processes in
583 the shallow sub-surface. The assumption that the sea level rise, or the speed at which sea level is rising
584 up, may be responsible for triggering fluid escape is highly relevant for predictive models describing
585 the occurrence of pockmarks on slopes (implications for human activities such as cable, pipelines or
586 platform anchors) and may account for large greenhouse gas release into the ocean and atmosphere
587 (implication for climate change). The processes of fractures opening and fluid build-up in shallow
588 reservoirs of lower pressure regimes preferentially occur during the relaxation phases of lateral
589 tectonic stresses and as soon as the effective minimum stress become negative. Such conditions can be
590 reached during sea-level rise in the Gulf of Lion.

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595 involved in this project.

596 **9. List of Figures**

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 619 structure defines a cone in 3D, or a V-shaped anomaly on 2D sections. They are associated with cones
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622 **Figure 9:** Correlation between the 7 cycles of pipe propagation and associated cone of deformation
 623 and the sea level variation deduced from de $\delta^{18}\text{O}$ curve. These expulsion events might be correlated
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 628 fluid expulsion, D) end of expulsion and drapping, E) accumulation stage.

629

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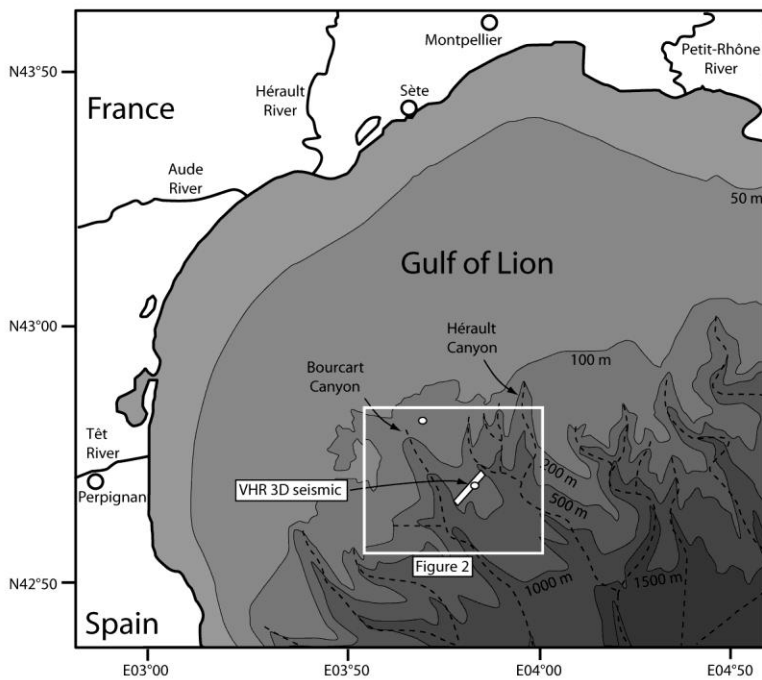
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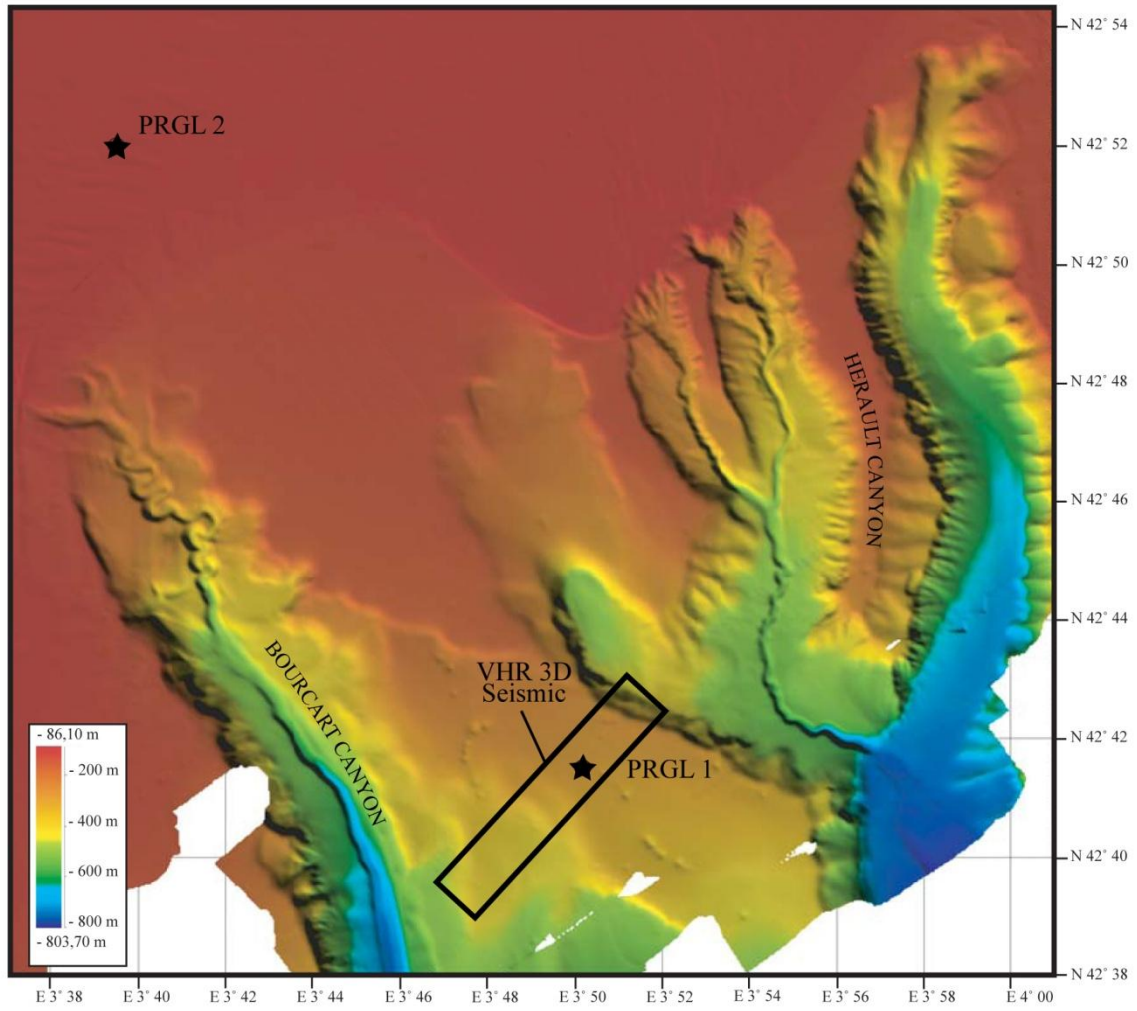
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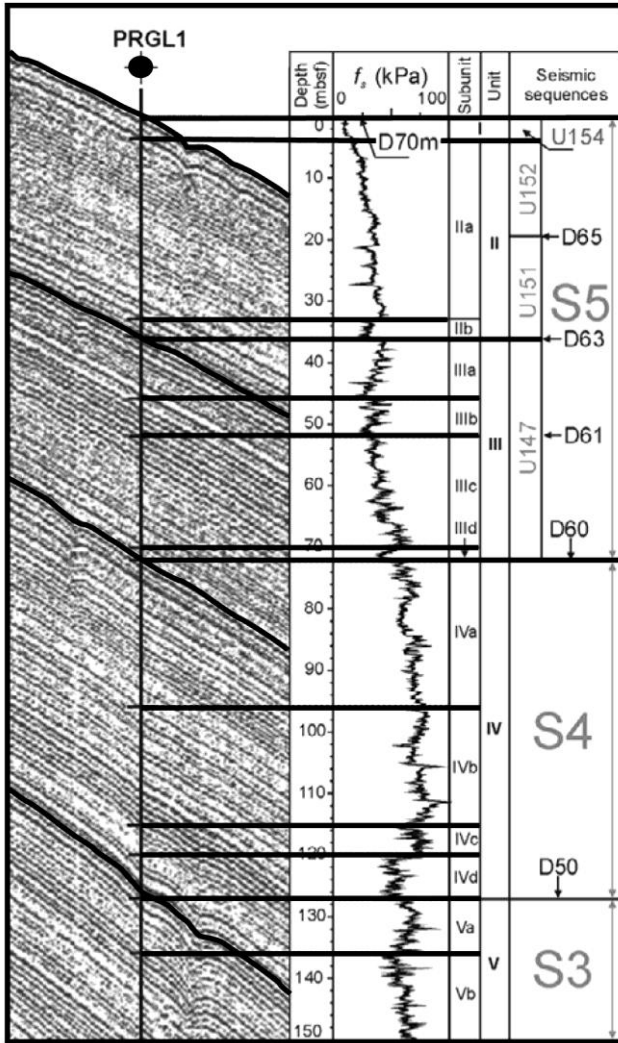
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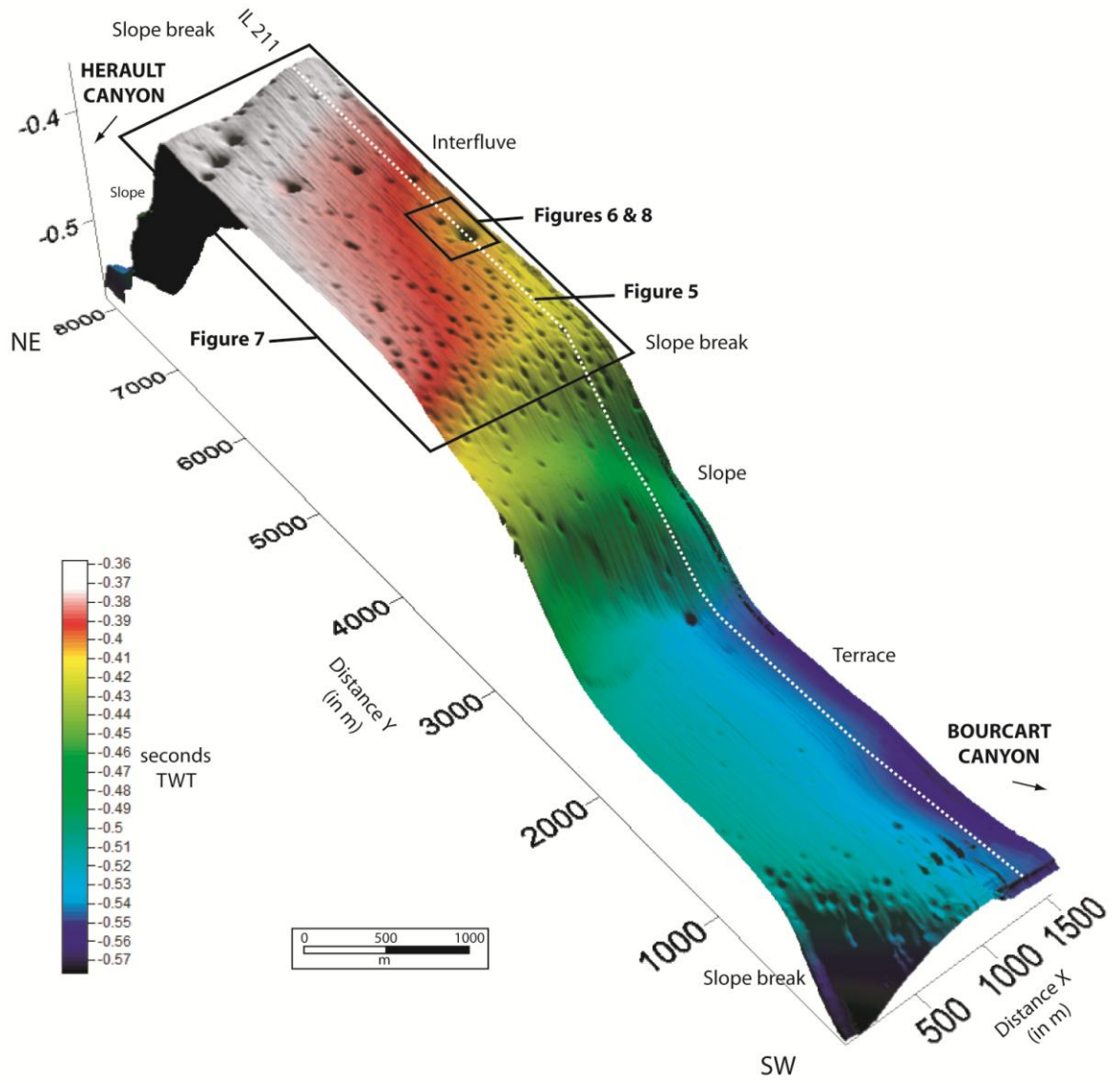
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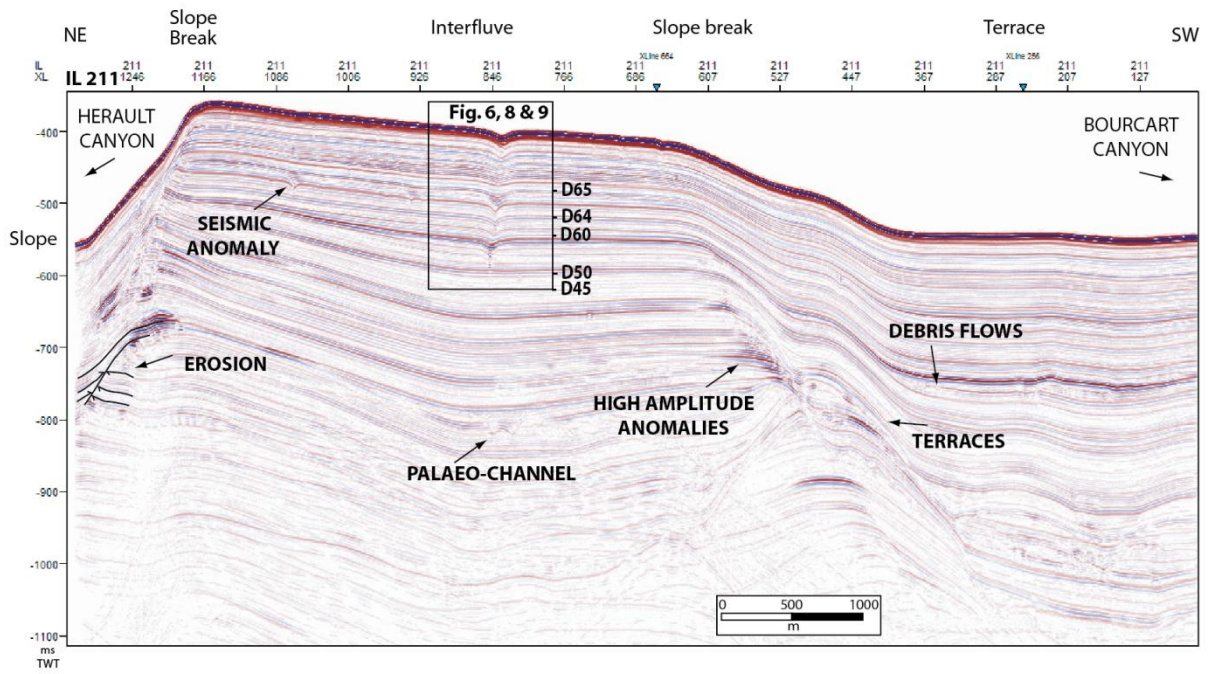
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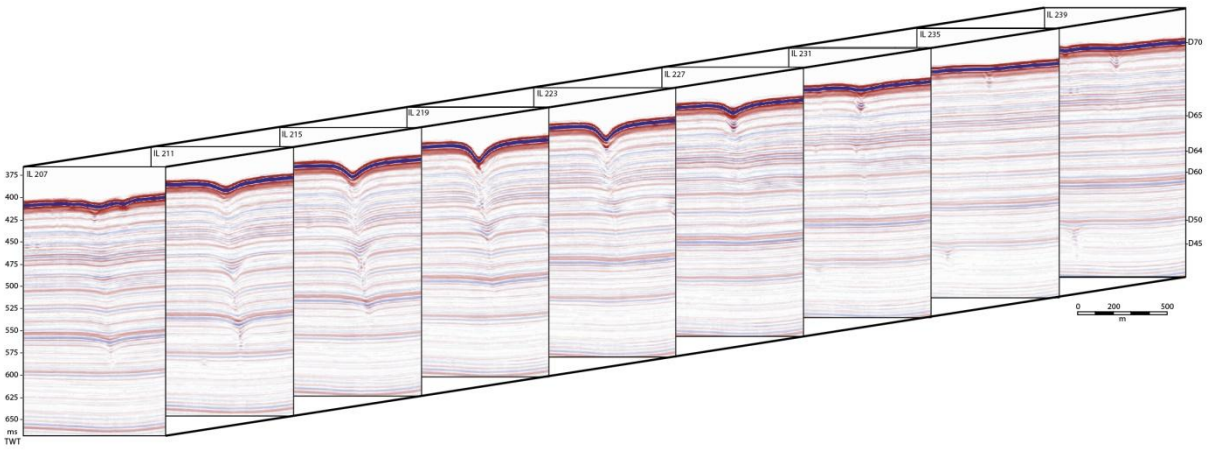
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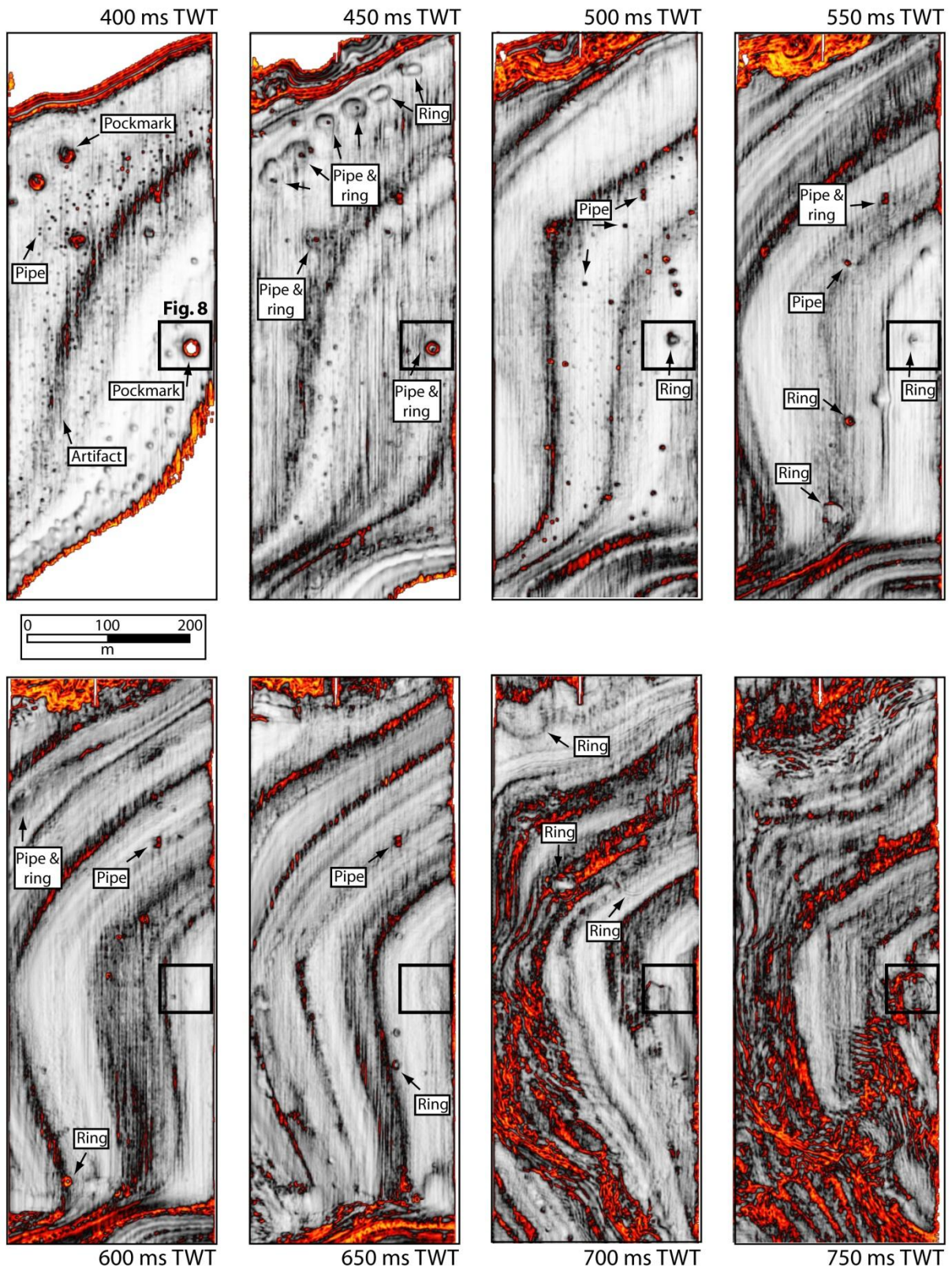
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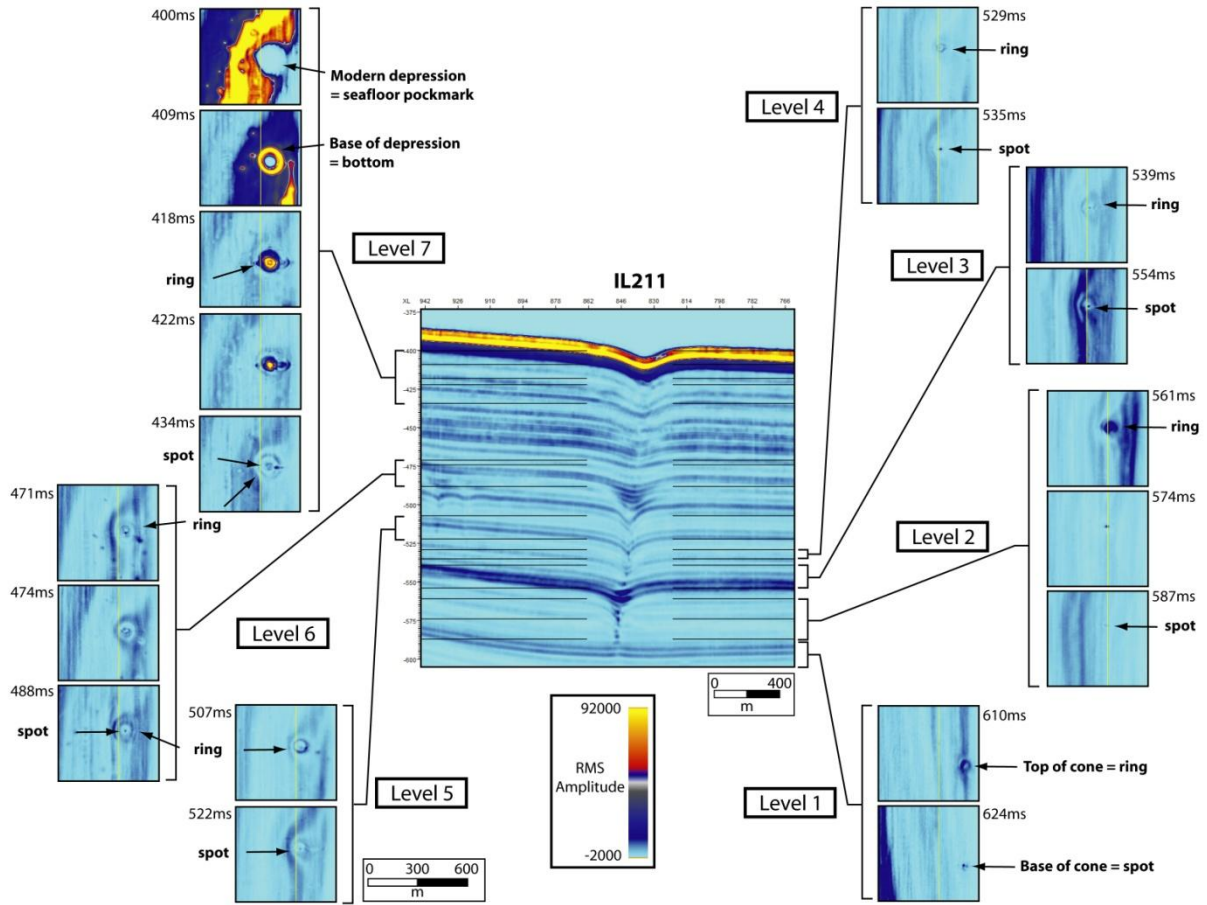
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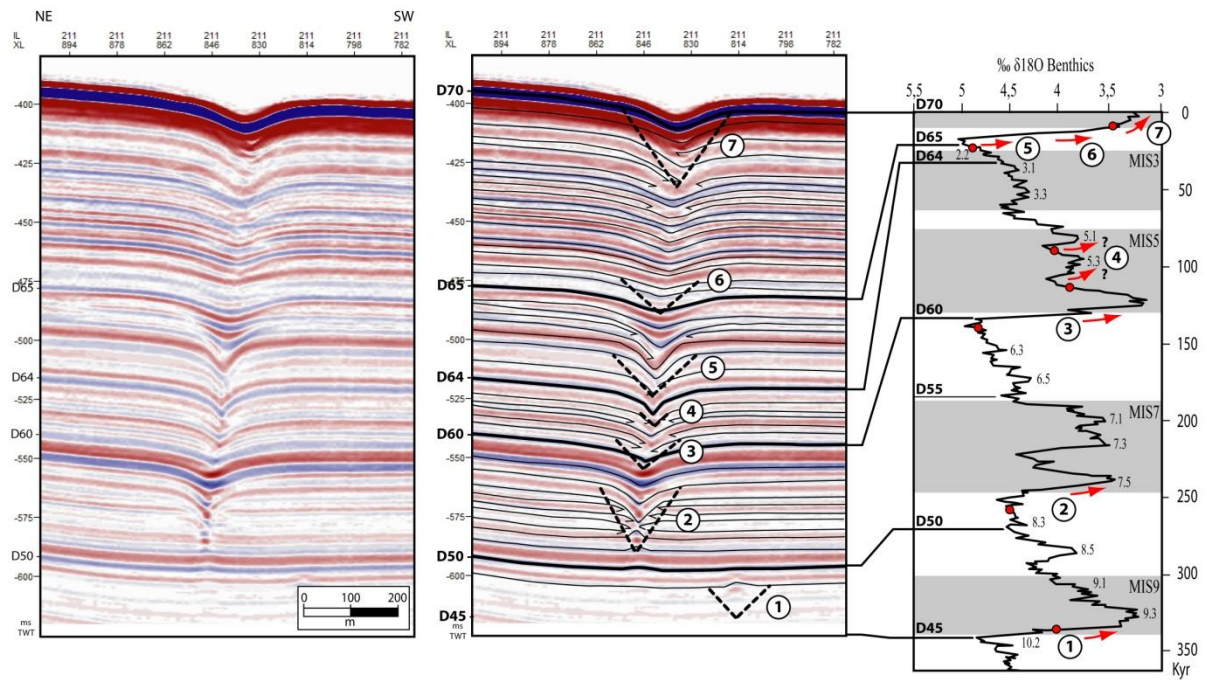
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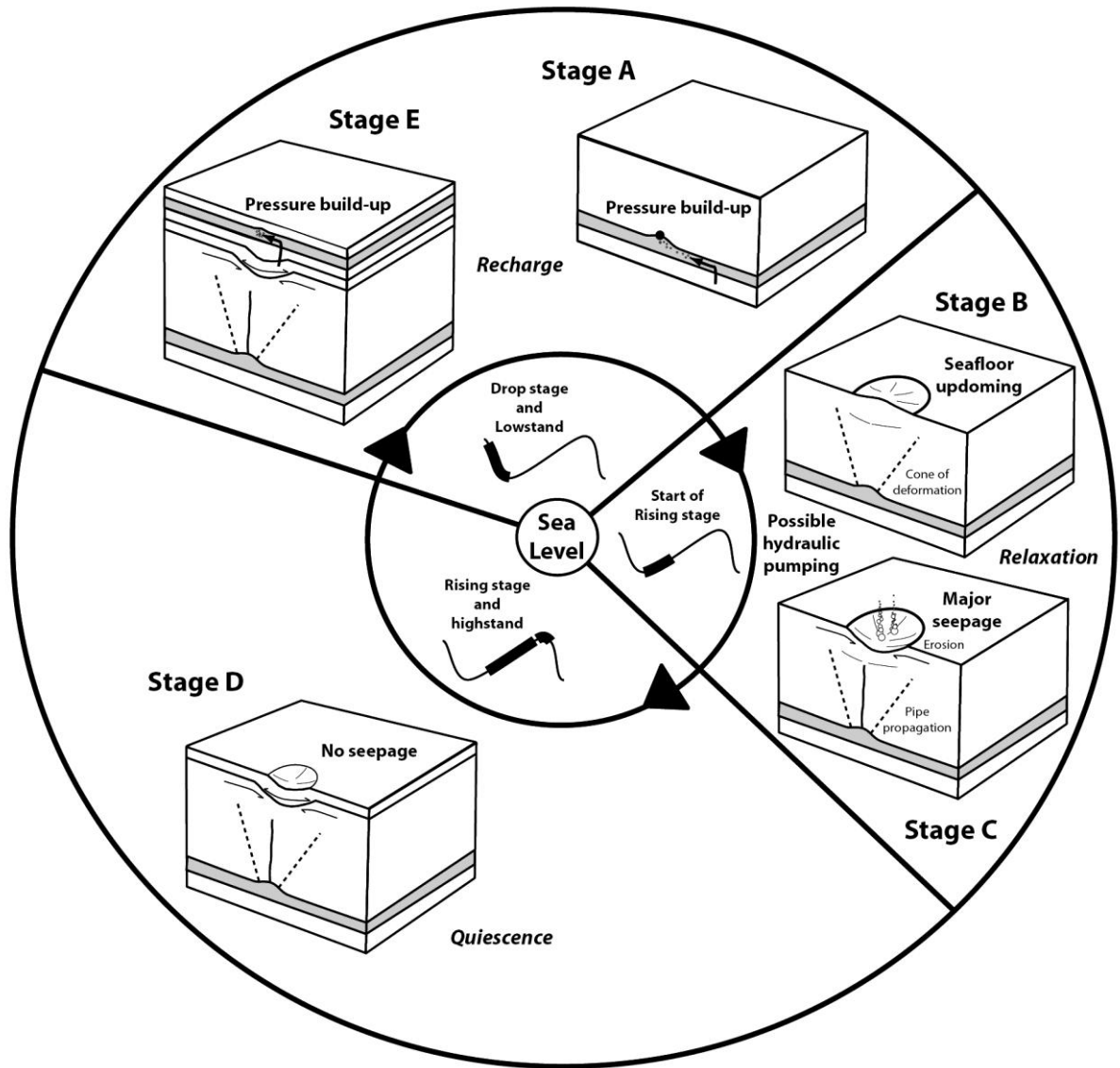
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