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## Cold-water coral habitats in the Penmarc'h and Guilvinec Canyons (Bay of Biscay): Deep-water versus shallow-water settings

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### Abstract :

In 1948, Le Danois reported for the first time the occurrence of living cold-water coral reefs, the so-called “massifs coralliens”, along the European Atlantic continental margin. In 2008, a cruise with R/V Belgica was set out to re-investigate these cold-water corals in the Penmarc'h and Guilvinec Canyons along the Gascogne margin of the Bay of Biscay. During this cruise, an area of 560 km<sup>2</sup> was studied using multibeam swath bathymetry, CTD casts, ROV observations and USBL-guided boxcoring.

Based on the multibeam data and the ROV video imagery, two different cold-water coral reef settings were distinguished. In water depths ranging from 260 to 350 m, mini mounds up to 5 m high, covered by dead cold-water coral rubble, were observed. In between these mounds, soft sediment with a patchy distribution of gravel was recognised. The second setting (350–950 m) features hard substrates with cracks, spurs, cliffs and overhangs. In water depths of 700 to 950 m, both living and dead cold-water corals occur. Occasionally, they form dense coral patches with a diameter of about 10–60 m, characterised by mostly stacked dead coral rubble and a few living specimens. U/Th datings indicate a shift in cold-water coral growth after the Late Glacial Maximum (about 11.5 ka BP) from shallow to deep-water settings.

The living cold-water corals from the deeper area occur in a water density ( $\sigma\text{-t}$ ) of 27.35–27.55 kg m<sup>-3</sup>, suggested to be a prerequisite for the growth and distribution of cold-water coral reefs along the northern Atlantic margin. In contrast, the dead cold-water coral fragments in the shallow area occur in a density range of 27.15–27.20 kg m<sup>-3</sup> which is slightly outside the density range where living cold-water corals normally occur. The presented data suggest that this prerequisite is also valid for coral growth in the deeper canyons (> 350 m) in the Bay of Biscay.

**Keywords** : Bay of Biscay ; continental margin ; canyons ; cold-water corals ; *Lophelia* ; *Madrepora*

56 **1. Introduction**

57

58 Cold-water corals are widespread along the European Atlantic continental margin  
59 (Freiwald and Roberts, 2005; Freiwald et al., 2004; Roberts et al., 2006, 2009). Previous  
60 studies have already revealed a large amount of information about the distribution,  
61 significance and environmental setting of these ecosystems along the Norwegian margin  
62 (Fosså et al., 2005; Freiwald et al., 2002; Hovland et al., 1998; Lindberg and Mienert,  
63 2005; Mortensen et al., 1995), and the continental margin off Ireland and the UK (De  
64 Mol et al., 2002; Dorschel et al., 2007; Huvenne et al., 2007; Kenyon et al., 2003;  
65 Masson et al., 2003; Mienis et al., 2007; Roberts et al., 2006; Van Weering et al., 2003;  
66 Wheeler et al., 2007). Cold-water corals are able to form habitats which vary in size  
67 from small patches (few metres in size) to large reef structures covering several  
68 kilometres (Freiwald et al., 1999; Roberts et al., 2005). In the Porcupine Seabight and  
69 Rockall Trough giant cold-water mounds up to 300 m high were observed (De Mol et  
70 al., 2002; Kenyon et al., 2003; Wheeler et al., 2007; Van Weering et al., 2003). In  
71 contrast to these well studied areas, coral occurrences within the Bay of Biscay, and  
72 more specifically the Armorican margin, are less investigated (Reveillaud et al., 2008).

73

74 The occurrence of cold-water corals in the Bay of Biscay was already reported by  
75 Joubin (1922) and Le Danois (1948). The latter study mainly observed the presence of  
76 living *Madrepora oculata* and *Lophelia pertusa*, mostly occurring in a patchy  
77 distribution but at some locations able to form a dense coral field with a maximum  
78 height of 2 m. Afterwards these cold-water corals were also reported at different  
79 locations in the Bay of Biscay by Altuna (1995), Alvarez-Claudio (1994), Zibrowius

80 (1980, 1985) and Zibrowius et al. (1975). In 1997, two areas along the north Atlantic  
81 margin in the Bay of Biscay were revisited by Freiwald and Henrich (1997), namely the  
82 Penmarc'h Bank and the Banc de la Chapelle, 160 km northwest of Penmarc'h Bank.  
83 On the Banc de la Chapelle, only dead colonies of *Lophelia pertusa*, *Madrepora oculata*  
84 and *Desmophyllum dianthus* were found in water depths of 340 to 790 m. Further south,  
85 on the Penmarc'h Bank living colonies of *Dendrophyllia cornigera* were observed  
86 (Reveillaud et al., 2008). The same authors also observed *Caryophyllia smithii*  
87 specimens which yielded calibrated U/Th ages of the end of the last glacial period (11-  
88 14 ka BP) (Schröder-Ritzrau et al., 2005). In 2008, Reveillaud et al. presented an  
89 overview of the cold-water coral distribution and diversity in the Bay of Biscay based  
90 on historical reports and more recent (pre-2008) data. However, it is still not known to  
91 which extent the available information represents the actual distribution of cold-water  
92 corals in the Bay of Biscay.

93

94 Cold-water corals occur in temperatures ranging between 4° and 12°C. This temperature  
95 zone corresponds with water depths between ~50 and 1000 m at high latitudes and up to  
96 4000 m at low latitudes (Freiwald et al., 2004). Besides temperature several other  
97 environmental factors favour coral settlement and growth: hard substrates (e.g.,  
98 boulders, moraine ridges, flanks of oceanic banks, seamounts, sedimentary mounds;  
99 Dodge and Vaisnys, 1977; Rogers, 1990), strong topographically guided bottom  
100 currents (Freiwald et al., 2004), nutrient-rich waters containing labile organic matter  
101 (Kiriakoulakis et al., 2004) and zooplankton (Freiwald et al., 2004), and the depth of the  
102 aragonite saturation horizon (Davies et al., 2008). Due to the presence of these  
103 conditions along the continental slope in the Bay of Biscay, this area is a potential

104 habitat for cold-water coral ecosystems (Hall-Spencer et al., 2007; Reveillaud et al.,  
105 2008). The numerous canyons cutting the slope of the Bay of Biscay (Bourillet et al.,  
106 2003, 2006b; Le Suavé et al., 2000; Zaragosi et al., 2006) funnel sediment and labile  
107 organic matter from the continental shelf (~200 m) to the abyssal plain (~4000 m)  
108 (Freiwald et al., 2004). An additional major food source is provided by nutrient-rich  
109 waters (Freiwald et al., 2004). Recently, Dullo et al. (2008) discovered that water  
110 density also plays an important role in the distribution of cold-water corals. Along a  
111 transect stretching from 51 to 70°N (~3000 km), living cold-water corals (*Lophelia*  
112 *pertusa*) occur within a narrow density (sigma-theta) range of  $\sigma_{\theta} = 27.35$  to  $27.65$  kg m<sup>-3</sup>,  
113 independent from the surrounding water masses.

114

115 The data presented in this paper were collected during the BiSCOSYSTEMS cruise on  
116 board of the R/V Belgica from 25 May to 7 June 2008 within the framework of the EC  
117 FP6 IP HERMES and the ESF EuroDIVERSITY MiCROSYSTEMS projects. The main  
118 aim of the study was (1) to revisit one of the cold-water coral locations described by Le  
119 Danois (1948) in order to better understand their significance, distribution and  
120 environmental conditions, and (2) to test the hypothesis that cold-water corals only  
121 occur within the potential density range described by Dullo et al. (2008), also south of  
122 51°N.

123

## 124 **2. Regional setting**

125

126 The continental margin in the Bay of Biscay can be subdivided in five main geographic  
127 areas (Fig.1A): the Celtic margin and Armorican margin in the north, and the Aquitaine

128 margin, Cantabrian margin and Galician margin in the south. The Armorican margin  
129 has an orientation of  $140^\circ$  with a relatively broad continental shelf, up to 200 km wide,  
130 and a steep slope, with an average gradient between  $2.86^\circ$  and  $5.15^\circ$  (Lallemand and  
131 Sibuet, 1986; Le Suavé et al., 2000). The slope extends from a water depth of 200 m  
132 down to 4000 m. The morphology of the continental slope is characterised by spurs and  
133 canyons, organised in submarine drainage basins (Bourillet and Lericolais, 2003).

134

135 The water column stratification in the Bay of Biscay predominantly shows that water  
136 masses are of North Atlantic origin (Pollard et al., 1996). The uppermost water mass is  
137 the Eastern North Atlantic Central Water (ENACW) which extends down to water  
138 depths of 600 m. The ENACW is characterised by a cyclonic gyre with an average  
139 velocity of  $4 \text{ cm.s}^{-1}$  (Pingree and Le Cann, 1989). Below a minimal density layer,  
140 probably due to the influence of the Sub Antarctic Intermediate Water (SAIW), the  
141 Mediterranean Outflow Water (MOW) is observed down to 1500 m water depth. Its  
142 circulation as a contour current is conditioned by seafloor irregularities and the Coriolis  
143 effect. MOW velocities have been measured in the Bay of Biscay at  $8^\circ\text{W}$  and  $6^\circ\text{W}$  with  
144 average values of  $2\text{-}3 \text{ cm.s}^{-1}$  (Pingree and Le Cann, 1989). Between 1500 and 3000 m  
145 water depth, the North Atlantic Deep Water (NADW) is observed. It includes a core of  
146 Labrador Sea Water (LSW), recognised by a salinity minimum at 1800 to 2000 m, and  
147 the Iceland-Scotland Overflow Water (ISOW) which is identified by a small salinity  
148 maximum around 2600 m (González-Pola, 2006; McCartney, 1992; McCave et al.,  
149 2001; Pingree, 1973). Below the NADW, the Lower Deep Water (LDW) is identified  
150 (McCartney, 1992). A cyclonic recirculation cell over the Biscay Abyssal Plain is

151 recognised with a characteristic poleward velocity near the continental margin of  $1.2 (\pm$   
152  $1.0) \text{ cm.s}^{-1}$  (Dickson et al., 1985; Paillet and Mercier, 1997).

153

154 Along the slopes of the Bay of Biscay strong, localised internal tides are reported, due  
155 to a combination of favourable water mass stratification, steep topography and strong  
156 barotropic tidal currents (Huthnance, 1995; Pingree and Le Cann, 1989, 1990). These  
157 may be channelled and result in regions of locally increased flow and local circulations  
158 (Pingree and Le Cann, 1990). Internal tides are proposed to explain the enhanced levels  
159 of surface phytoplankton abundance (Holligan et al., 1985; Pingree and Griffiths, 1982).

160

### 161 **3. Materials and methods**

162

#### 163 *3.1. Multibeam echosounding*

164

165 The multibeam echosounder used during the BiSCOSYSTEMS cruise is a Kongsberg  
166 Simrad EM1002 system, installed permanently on the R/V Belgica. The EM1002 has up  
167 to 111 receiver beams of  $2^\circ$  (across track) x  $3.3^\circ$  (along track) width. The high-  
168 resolution depth data was obtained with a nominal frequency of 95 kHz and a ping-rate  
169 of 4 to 6 Hz. Survey speed was between 4 and 6 knots depending on water depth and  
170 wave conditions. In total, an area of  $560 \text{ km}^2$  along the Armorican margin was mapped  
171 in water depths between 160 m and 1000 m (Fig.1B).

172

173 The bathymetric information of the recorded files was extracted as xyz-data with the

174 open source MB-Systems software (Caress and Chayes, 1995). Next, data editing

175 occurred in the IVS Fledermaus software package resulting in a digital terrain model  
176 (DTM) with a 5-m grid resolution.

177

### 178 *3.2. CTD measurements*

179

180 Two CTD casts (CTD 03: 46°51.990'N/5°31.768'W at 1450 m water depth and CTD  
181 04: 46°54.536'N/5°21.262'W at 1250 m water depth) were obtained in the Guilvinec  
182 Canyon using a SBE Seacat 19 in order to gain insight into the local water mass  
183 stratification and to calibrate the EM1002 echosounder for sound velocity. The raw data  
184 were binned at 1 m using the SBE Data Processing software (version 7.18c).

185

### 186 *3.3. ROV observations*

187

188 The Remotely Operated Vehicle (ROV) 'Genesis' from Ghent University is a Sub-  
189 Atlantic Cherokee-type ROV with an operational survey depth down to 1600 m.  
190 Imagery was obtained from one forward-looking colour camera, recorded with and  
191 without a navigational overlay. High-resolution still images were obtained from a  
192 Canon Powershot camera. Two parallel laser beams with a distance of 10 cm were used  
193 as a scale during seabed observations. The ROV positioning was obtained using the  
194 USBL (Ultra Short Base Line) IXSEA GAPS positioning system. This allowed  
195 subsurface positioning with an accuracy of about 2-3 m. The processing and  
196 interpretation of the dives was performed using OFOP (Ocean Floor Observation  
197 Protocol) version 3.2.0c (Huetten and Greinert, 2008). Based on the observations, a

198 number of facies characteristic for the study area were identified. Each facies was given  
199 a colour-code and integrated into ArcGIS 9.1, resulting in a facies interpretation map.

200

#### 201 *3.4. Sedimentological analyses of boxcore samples*

202

203 Boxcores were taken at different locations within the Guilvinec Canyon. For each  
204 boxcore, subsamples from different depths (mostly one sample from the surface and one  
205 from the bottom) and/or subcores (if possible) were taken for sedimentological analysis.  
206 Each subcore was sampled every 5 cm. The location of boxcores B08-1305-bc and B08-  
207 1306-bc was accurately determined by using the GAPS USBL system.

208

209 Subsamples were analysed for grain-size distribution with a Malvern Mastersizer 2000  
210 (Marine Biology Section, Ghent University). First, the sediment was dried in a furnace  
211 at 60° for about 48h. After subsampling 1 cm<sup>3</sup> of sediment, the carbonate fraction was  
212 removed by adding 75 ml of 10% acetic acid (CH<sub>3</sub>COOH). This process was performed  
213 twice in order to remove all carbonate fragments. Afterwards, the sample was rinsed  
214 twice with distilled water, each time followed by a 24 h settling period. Finally, the  
215 sediment was transferred in a 15 ml centrifuge tube together with 0.2% calgon (sodium  
216 hexametaphosphate, (NaPO<sub>3</sub>)<sub>6</sub>). Prior to analysis, the samples were rotated (20 rpm) for  
217 24h. Afterwards, the results were processed with GRADISTAT (Blott and Pye, 2001)  
218 and the mean grain-sizes were calculated using the Folk and Ward (1957) method.

219

220 Six cold-water coral specimens (*Lophelia pertusa*) from the surface of different

221 boxcores (B08-1301-bc, B08-1305-bc and B08-1306-bc) were sampled for U/Th dating.

222 The U-series measurements and age determination were carried out in the Laboratoire  
223 des Sciences du Climat et de l'Environnement (LSCE) in Gif-sur-Yvette using  
224 inductively coupled plasma source mass spectrometry (Thermo-Fisher X-Series).  
225 Preparation of corals, analytical procedures and physical measurement routines  
226 followed the detailed description by Frank et al. (2004, 2005) and Douville et al. (in  
227 press).

228

## 229 **4. Results**

230

### 231 *4.1. Environmental setting of the canyons and spurs*

232

#### 233 *4.1.1. Geomorphology*

234

235 The morphology of the canyon head and SE flank of the Penmarc'h Canyon, the  
236 Guilvinec Canyon and the NW flank and canyon head of the Odet Canyon was studied  
237 in detail using multibeam mapping (Fig.1B). These canyons are orientated in a NE-SW  
238 direction and are separated by two spurs: the Penmarc'h Bank and the Odet Spur.

239

240 The Penmarc'h Canyon is a slightly asymmetric V-shaped canyon with a maximum  
241 width of 10 km. The SE flank has an average slope of 10° and is incised by WNW-ESE  
242 orientated gullies with average slopes varying between 9-14° (Fig. 1B).

243

244 The Guilvinec Canyon is an asymmetric V-shaped canyon with a maximum width of 16  
245 km. The NW slope has an average slope of  $8^\circ$  whereas the SE slope is characterised by

246 an average slope of 6°. The total length of the canyon from the canyon head until the  
247 abyssal plain is about 33 km and the maximum incision depth is 2 km. The slopes  
248 flanking the canyons show ENE-WSW orientated gullies on the SE flanks with an  
249 average slope of 8-11° and NW-SE orientated gullies on the NW flanks with an average  
250 slope of 10°. The width of the gullies varies between 600 and 1000 m.

251

252 The Odet Canyon is also an asymmetric V-shaped canyon with a maximum width of 9  
253 km. The NW flank of the Odet Canyon has a constant average slope of about 11°,  
254 compared to the SE flank where an abrupt change in slope occurs around 1000 m water  
255 depth. The NW slope of the Odet Canyon shows NW-SE orientated gullies with an  
256 average slope of 8-12°.

257

258 The Penmarc'h Bank is a narrow spur with a minimum width of 4 km which goes up to  
259 10 km close to the canyon heads. In contrast the Odet Spur has a maximum width of 14  
260 km. Along both spurs, NE-SW orientated gullies occur with an average slope of 8-13°.  
261 In the shallow area on the western part of the Odet Spur between 200 and 300 m water  
262 depth, small mounds were observed with a diameter of approximately 100 m and a  
263 height of 5 to 10 m.

264

#### 265 4.1.2. Hydrography

266

267 The stratification of the water masses does not change significantly over the study area  
268 (Fig. 2). The CTD casts show the presence of a seasonal thermocline down to 50 m

269 water depth. A salinity minimum (35.58 psu) is observed at 550 m, separating the

270 overlying ENACW from the MOW, which has its salinity maximum (35.76 psu) at  
271 about 1000 m. Below, the T/S (temperature versus salinity) profile gradually follows the  
272 27.75 kg.m<sup>-3</sup> potential density gradient towards the LSW and NADW, as shown in  
273 González-Pola (2006) and Van Rooij et al. (submitted-b).

274

#### 275 4.2. *Shallow-water coral rubble fields on Odet Spur*

276

277 Mini mounds were observed on the multibeam echosounder data on Odet Spur in water  
278 depths of 260 to 350 m. The gentle slope features an average gradient of 3-4° (Fig. 1B).  
279 ROV observations allowed to distinguish four different facies: (1) rippled soft sediment  
280 with a patchy distribution of dead cold-water corals (Fig. 3A), (2) rippled seabed with  
281 biogenic debris and a patchy distribution of dead cold-water corals, (3) rippled soft  
282 sediment covered with gravel or small pebbles (Fig. 3B), and (4) a dense cold-water  
283 coral rubble coverage, dominated by *Lophelia pertusa* and/or *Madrepora oculata* (Fig.  
284 3C and Fig. 3D).

285

286 Figure 4A shows that the small mounds are covered by dead cold-water coral rubble. At  
287 the base of the mounds and in between them, an alternation of rippled soft sediment  
288 with a patchy distribution of dead cold-water corals and/or biogenic debris, and rippled  
289 soft sediment with gravel-sized particles was observed (Fig. 3A and Fig. 3B). The coral  
290 rubble consists of crushed coral fragments (Fig. 3C and Fig. 3D) and nearly no visible  
291 living fauna. The size of the coral rubble fields varies between 20 to 80 m. The  
292 undulatory N-S to NNW-SSE orientated sand ripples appear with wavelengths between  
293 5 and 10 cm and have heights of about 3-5 cm.

294

295 Boxcore samples were taken along the track of ROV dive B08-03 resulting in two  
296 different lithofacies (Fig. 4B). Lithofacies 1 is characterised by olive brown to olive  
297 grey poorly-sorted, fine to medium sand with mean grain-sizes varying between 215  $\mu\text{m}$   
298 and 305  $\mu\text{m}$ . Within this facies in boxcore B08-1302-bc fine laminations are observed  
299 between olive brown and olive grey sand. In contrast, a clear colour change is observed  
300 in boxcore B08-1305-bc at a depth of 5 cm. In boxcore B08-1303-bc, on top of a mini  
301 mound (Fig. 4A), only a very thin layer of lithofacies 1 is observed. The surface of all  
302 boxcores is covered with coarse biogenic debris and several *Lophelia pertusa* fragments  
303 (1-4 cm), up to 5 cm depth. At the surface of boxcore B08-1303 also large gravel  
304 fragments (up to 7 cm) were observed. Lithofacies 2 is characterised by olive grey very  
305 poorly to poorly-sorted, medium silt with grain-sizes varying between 8.9  $\mu\text{m}$  and 12.6  
306  $\mu\text{m}$ . Within this unit black sediment spots, supposedly caused by reducing geochemical  
307 conditions, were observed. In boxcore B08-1303-bc a few sand lenses occur between 5  
308 and 10 cm depth.

309

310 Boxcore B08-1304-bc had a penetration of only 5 cm (no subcoring). It consists of olive  
311 grey, well sorted sand (lithofacies 1) with coarse biogenic debris and robust coral  
312 fragments of *Lophelia pertusa* (several cm).

313

314 In addition, several coral fragments were dated using U-series: two coral fragments  
315 (*Lophelia pertusa*) were collected during ROV dive B08-03, one coral fragment  
316 (*Lophelia pertusa*) in boxcore B08-1301-bc and two coral fragments in B08-1305-bc.

317 The resulting ages after correction are shown in Table 3.

318

319 4.3. Deep-water corals in the Penmarc'h and Guilvinec Canyons

320

321 The second setting features cold-water corals observed in the Penmarc'h and Guilvinec  
322 Canyons in water depths of 700 to 900 m. Both living and dead coral specimens occur,  
323 predominantly *Madrepora oculata*. In total, eleven different facies were defined during  
324 four ROV dives (Table 1). Facies 1 and 2 correspond to respectively even (Fig. 5A) and  
325 rippled soft sediment with at some locations intense bioturbation. Facies 3 and 4  
326 correspond to respectively even and rippled soft sediment covered with a patchy  
327 distribution of cold-water corals (mostly *Madrepora oculata*) (Fig. 5B). Living as well  
328 as dead species occur. Soft sediment with a cover of biogenic debris was defined as  
329 facies 5 (Fig. 5C). No ripple marks were observed. Facies 6 and 7 are characterised by  
330 respectively even and rippled soft sediment covered with biogenic debris and a patchy  
331 distribution of cold-water corals (dead and living *Madrepora oculata*). Next, facies 8  
332 consists of soft sediment with gravel (Fig. 5D). The gravel fragments reach sizes up to  
333 10 cm. Facies 9 corresponds with outcropping hard substratum (Fig. 5E and Fig. 5F),  
334 colonised by living cold-water corals (*Madrepora oculata*) and sponges. At some  
335 locations, cracks filled with soft sediment were observed (Fig. 5G and Fig. 5H). Finally,  
336 facies 10 and 11 relate to the cold-water coral coverage. Facies 10 is characterised by a  
337 dense coverage of coral rubble (Fig. 6A) whereas facies 11 also features living species  
338 of *Madrepora oculata* and *Lophelia pertusa* on top of the coral rubble, creating dense  
339 coral fields (Fig. 6B, Fig. 6C and Fig. 6D). Facies 11 often coincides with a very rough  
340 seafloor and big boulders (20 cm up to 1 m). Boxcore B08-1306-bc was taken within

341 this facies which delivered three coral pieces for U-series dating (Table 3). Grain-size  
342 analysis reveals very poorly sorted fine sand with a mean grain-size of 81  $\mu\text{m}$ .

343

344 Four ROV dives were undertaken. Dive B08-01 is located on the SE flank of the  
345 Penmarc'h Canyon in water depths of 385 to 750 m. During this dive, an E-W  
346 downslope transect was made with an average slope gradient of 8-10°. A large part of  
347 the track consists of soft sediment with gravel (facies 8). At a water depth of 530 m the  
348 gravel disappears and strongly bioturbated soft sediment (facies 1) remains until a water  
349 depth of 720 m (Fig. 5A). Below 720 m, the first cold-water corals (facies 3) (*Lophelia*  
350 *pertusa* and *Madrepora oculata*), with a size of 10-20 cm width and about 15 cm high,  
351 appear on boulders with a diameter of 25 cm. Except for one living *Madrepora oculata*,  
352 all corals are dead.

353

354 Dive B08-02 on the NW flank of the Guilvinec Canyon has a U-shaped track starting  
355 with a first transect southwards from the NE flank of a gully at 712 m water depth and  
356 ending with a second transect on the SW flank of that gully. The slope of this part  
357 features an average gradient of 11°. During this dive many different facies were  
358 observed (Fig. 7). In the uppermost part of the slope, between 700 and 900 m, soft  
359 sediment alternates with coral fields which vary in diameter between 10 and 60 m (Fig.  
360 6B). The soft sediment is sometimes covered with biogenic debris (Fig. 5C), gravel  
361 (Fig. 5D) and/or a patchy distribution of cold-water corals, mostly *Madrepora oculata*.  
362 Also big boulders with a diameter up to 1 m were observed, colonised with living cold-  
363 water corals (*Madrepora oculata*) and *Hexadella sp.* sponges (Fig. 6E and Fig. 6F).  
364 Between 800 and 900 m, asymmetric N-S orientated sand ripples appear with

365 wavelengths between 10 and 20 cm and with heights of about 5 cm. Below 900 m water  
366 depth, mostly hard substratum (Fig. 5E and Fig. 5F) occurs with a patchy distribution of  
367 living cold-water corals (*Madrepora oculata*). NW-SE orientated cracks of 5 cm up to  
368 40 cm occur in this area, and are filled with (rippled) soft sediment (Fig. 5G and Fig.  
369 5H). At several locations, the rather smoothly sloping seabed is interrupted by the  
370 presence of small banks (Fig. 6G) or cliffs (Fig. 6H). Between 700 and 750 m water  
371 depth, these escarpments have an E-W orientation, while the deeper ones reveal a S-N  
372 or SSW-NNE orientation. The banks are generally few decimetres in height and thus  
373 much smaller than the cliffs, which vary in height between 2 and 4 m. At three  
374 locations, the escarpments are colonised by *Madrepora oculata* corals and  
375 *Neopycnodonte zibrowii* oysters, which are discussed in more detail in Van Rooij et al.  
376 (submitted-a).

377

378 Dive B08-04 is located on a small spur with dimensions of 200 by 400 m on the SE  
379 flank of the Guilvinec Canyon in water depths of 675 to 700 m. Only one facies was  
380 recognised: a dense cold-water coral coverage with dead and living species,  
381 predominantly *Madrepora oculata* (Fig. 6C and Fig. 6D). The living species grow on  
382 the dead coral rubble, which is built up by chunky coral fragments up to 40 cm.

383

384 Finally, dive B08-05 investigated the southern shoulder of a gully south of the spur that  
385 separates the Penmarc'h Canyon from the Guilvinec Canyon. The track follows a  
386 southern to western course between 300 and 750 m water depth with an overall slope  
387 gradient of 8-10°. This track does not show many different facies. Between 300 and 450  
388 m a rippled seafloor with regionally some biogenic debris and/or gravel was observed.

389 The straight to gently undulatory SSE-NNW orientated sand ripples have a wavelength  
390 between 10 and 15 cm. The area between 450 and 730 m is characterised by soft  
391 sediment with bioturbations and a zone of low-relief rippled seabed. Close to a water  
392 depth of 480 m, some small escarpments are present. At 735 m, the gently dipping  
393 seafloor is interrupted by a 4 m high WSW-ENE escarpment, colonised by *Madrepora*  
394 *oculata* cold-water corals and *Neopycnodonte zibrowii* oysters (Van Rooij et al.,  
395 submitted-a).

396

## 397 **5. Discussion**

398

### 399 *5.1. Canyons as cold-water coral habitats*

400

401 For the first time a cold-water coral habitat is mapped in detail within a canyon setting  
402 in the Bay of Biscay. Although deep-sea canyons may provide suitable environmental  
403 conditions for cold-water corals to grow, resulting deep-water habitats have not yet been  
404 described in detail. Canyons are transport ways of organic matter from the continental  
405 shelf down to the abyssal plain (Canals et al., 2006; Freiwald et al., 2004). During most  
406 of the ROV dives described here, an intense marine snow was observed, composed of  
407 suspended particulate material, ideal nutrients for scleractinians. In addition, the cold-  
408 water corals occur just above, in case of the shallow water setting, and just beneath, in  
409 case of the deep-water setting, the physical boundary between the Eastern North  
410 Atlantic Central Water (ENACW) and the Mediterranean Outflow Water (MOW) (Fig.  
411 2). As De Stigter et al. (2007) already demonstrated, the mixing of both water masses  
412 results in enhanced suspended material thus favouring the feeding of scleractinians.

413 Moreover, the observations of ripple marks on the seabed, within the upper zone of the  
414 MOW, indicate the presence of an E-W bottom current with a speed around 10 to 40  
415  $\text{cm.s}^{-1}$  (Stow et al., 2009). This elevated bottom current is beneficial for coral growth as  
416 it delivers nutrients to the polyps. Additionally, the asymmetry of the sand ripples  
417 shows a sediment transport direction away from the shelf edge into the canyon axis.  
418 Similar observations were made by Cunningham et al. (2005) in the canyons on the  
419 Celtic Margin between Goban Spur and Brenot Spur. Apart from the flow velocity of  
420 the MOW, the bottom currents may be enhanced by strong internal tides (White, 2007).  
421 Next to a favourable oceanographic environment, the sedimentological environment of  
422 deep-sea canyons provides hard substrates for living cold-water corals to settle on.  
423 Indeed, during the ROV dives, corals were observed on cliffs, outcropping hard  
424 substratum and on the numerous boulders which are scattered on the seabed. The dives  
425 also revealed a preferential erosion of the western flank of the canyons while the eastern  
426 flank is draped with soft sediment. This is attributed to the strong E-W bottom currents.  
427 The western slope will act as an obstacle for these enhanced currents intensifying the  
428 easterly bottom currents through isopycnal doming, which results in erosion  
429 (Hernandez-Molina et al., 2003; Iorga and Lozier, 1999; Van Rooij et al., submitted-a).  
430 Hence, the constant reworking by downslope (turbiditic) and alongslope (contouritic)  
431 current processes (Arzola et al., 2008; Bourillet et al., 2006b; Cunningham et al., 2005;  
432 Pingree and Le Cann, 1989; Toucanne et al., 2009) which occur along this slope will  
433 play an important role in the shaping of habitats suitable for coral settlement. This study  
434 indicates that canyons are perfectly suited for coral growth due to the food availability,  
435 strong bottom currents and the presence of hard substratum. More coral habitats might  
436 be discovered in a similar setting in the future.

437

438 *5.2. Mini mounds on Odet Spur*

439

440 The shallow area, located in water depths between 278 and 289 m, revealed a dense  
441 coverage of dead cold-water coral fragments on top of mini mounds and small ridges  
442 (Fig. 4A). Within the boxcores, cold-water coral fragments were only found in the  
443 uppermost 5 cm which suggests that these mini mounds were present before the settling  
444 of the cold-water corals. The fact that the boxcores only show a thin sand cover (1.5 cm)  
445 on top of the mini mound while at the base of the mound the sand cover increases to 11  
446 cm, these mini mounds and ridges are probably the result of selective erosion of the  
447 clayey substrate due to strong bottom currents during interglacials and interstadials, as  
448 observed by Øvrebø et al. (2006) offshore Ireland. This observation highlights the  
449 importance of an elevated topography which acts as a template for coral settlement  
450 (Freiwald et al., 2004; Roberts et al., 2006). The lack of coral fragments deeper in the  
451 sediment of the mini mounds is a fundamental difference with the giant coral mounds  
452 observed along the Irish margin which are completely constructed by corals (Kano et  
453 al., 2007). In that aspect, the mini mounds on Odet Spur reveal strong similarities with  
454 the Darwin mounds in the northern Rockall Trough. The size of the coral topped  
455 Darwin mounds is similar (height: 5 m / diameter: 75 m) but they are located in a deeper  
456 water depth (1000 m). Coring revealed that corals are not a major contributor to mound  
457 building (Masson et al., 2003). The Moira mounds in the Porcupine Seabight which are  
458 characterised by diameters of 30-50 m and heights up to 5 m (Foubert et al., 2005;  
459 Wheeler et al., 2005) might also serve as an analogue for the mounds observed on Odet  
460 Spur.

461

462 *5.3. Time and distribution of coral growth*

463

464 The dating of the cold-water corals using U-series reveals that coral growth in the study  
465 area started at the beginning of the Holocene. The older age of the corals in the shallow  
466 (7.4-9.1 ka) compared to the deeper setting (1.2-2.3 ka) indicates a migration of the  
467 coral habitats towards greater water depths. Moreover, the fact that the corals observed  
468 in the shallow water setting are heavily bio-eroded and disintegrated, demonstrates that  
469 they are already exposed on the seabed for a significant amount of time. In contrast, the  
470 corals in the deeper setting are much better preserved suggesting a younger age for these  
471 species. The cause of the downslope migration of the corals is still uncertain. However,  
472 the changing sea level, influencing labile organic matter fluxes (Hall and McCave,  
473 1998), and the rising temperatures, might have forced corals to deeper water depths,  
474 where they found better live conditions. A more dramatic hypothesis is that the shallow  
475 coral reefs were destroyed by bottom trawling since the shallower area is subject to  
476 intense fishing activity (Bourillet et al., 2006a). According to Hily et al. (2008), a great  
477 change has been observed in the benthic communities in the northern part of the Bay of  
478 Biscay since the 1960s due to bottom trawling. Bottom trawling could also explain the  
479 age difference between sample B08-03 C, with an age of  $1.41 \pm 0.17$  ka, and the other  
480 samples with ages over 7 ka (Table 3). Due to the reworking effect of trawling, most of  
481 the coral reefs are turned upside down. However, no trawl marks were observed within  
482 the shallow water area during the ROV dive.

483

484 On a more regional scale, the U-series datings of the corals confirm a climate-driven  
485 influence. Since the Late Glacial Maximum (about 11.5 ka BP), extended living cold-  
486 water coral reefs appear along the European margin between 50° and 70° N (Frank et  
487 al., 2009). In contrast, during glacial times, the cold-water corals were only able to  
488 survive in the relatively more temperate Atlantic below 50° N (Frank et al., submitted).  
489 At present, only scarce coral occurrences are observed south of 50°N (Reveillaud et al.,  
490 2008; Wienberg et al., 2009), which is also confirmed by the results presented in this  
491 paper. The northern part of the Bay of Biscay, and more specifically the Armorican  
492 margin, can be seen as a transition zone between the eastern temperate Atlantic and the  
493 eastern North Atlantic between 50° and 70° N. This might explain why no successive  
494 mound growth occurred in the Bay of Biscay, resulting in the build up of giant coral  
495 mounds as discovered in the Porcupine Seabight (De Mol et al., 2002; Dorschel et al.,  
496 2007; Henriët et al., 1998; Huvenne et al., 2007, 2009; Wheeler et al., 2005) and the  
497 Rockall Trough (De Haas et al., 2009; Kenyon et al., 2003; Mienis et al., 2006; Van  
498 Weering et al., 2003).

499

#### 500 5.4. Relation between potential density and cold-water coral occurrence

501

502 The results of the present study may add to the theory of Dullo et al. (2008) who  
503 concluded that the potential density ( $\sigma_{\theta}$  = sigma-theta), where cold-water corals are  
504 able to live and migrate along the Norwegian margin and in the Porcupine Seabight,  
505 needs to be between 27.35 and 27.65 kg.m<sup>-3</sup>. The deeper canyon setting, where living  
506 cold-water corals have been observed, is located in this density range (27.35 and 27.55  
507 kg.m<sup>-3</sup>) (Fig.2) and thus supports the results of Dullo et al. (2008). In contrast, the dead

508 shallow water corals fall within a density range of 27.15-27.20 kg.m<sup>-3</sup> which is slightly  
509 outside the density range where living cold-water corals normally occur. This finding  
510 demonstrates that the density range of 27.35 and 27.65 kg.m<sup>-3</sup> is also valid for the living  
511 cold-water corals in the Bay of Biscay. In addition, our results confirm that this density  
512 range is not only applicable for dense living *Lophelia pertusa* reefs but also accounts in  
513 this setting for living *Madrepora oculata* species.

514

## 515 **6. Conclusions**

516

517 Cold-water coral habitats along the Gascogne margin in the Bay of Biscay, earlier  
518 reported by Le Danois in 1948, were investigated. The R/V Belgica BiSCOSYSTEMS  
519 cruise was set out to better understand the significance and distribution of these cold-  
520 water coral ecosystems and the environmental controls on their living habitat.

521

522 The main conclusions are:

- 523 • Deep-sea canyons such as the Penmarc'h and Guilvinec Canyons are suitable  
524 habitats for the settlement of cold-water corals (*Madrepora oculata* and  
525 *Lophelia pertusa*).
- 526 • Two cold-water coral settings were distinguished within the canyons: a shallow  
527 setting in water depths of 280-290 m with only dead coral rubble (mostly  
528 *Lophelia pertusa*) and a deep-water setting (700-920 m) with mostly living  
529 *Madrepora oculata* species on top of coral rubble. The occurrence of the mini  
530 mounds at ~280 m water depth is an unusually shallow water depth compared to  
531 most other cold-water coral (reef) occurrences along the NE Atlantic margin.

- 532 • The Bay of Biscay can be considered as a transition zone between the temperate  
533 Atlantic (below 50°N) and the cold north-eastern Atlantic between 50° and  
534 70°N. After the Late Glacial Maximum, cold-water corals started to grow along  
535 the Armorican margin but migrated likely during the mid Holocene to deeper  
536 water depths.
- 537 • The density range of 27.35 to 27.65 kg.m<sup>-3</sup> (Dullo et al., 2008) is also valid for  
538 the living cold-water corals (mostly *Madrepora oculata*) in the Bay of Biscay,  
539 which makes it a good prerequisite for the distribution and growth of living  
540 cold-water corals along the northeast Atlantic margin. It can be used as a  
541 predictive tool in order to discover more cold-water coral habitats along the  
542 European continental margin.

543

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545

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560

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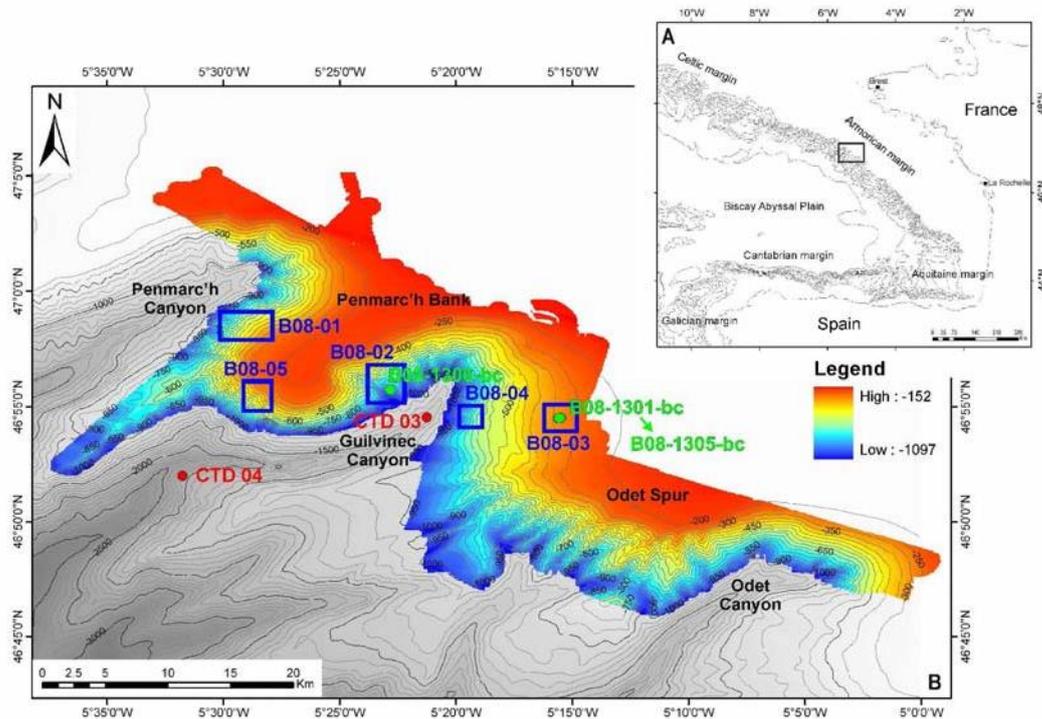
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843 **Figures**

844

845 Figure 1.



846

847 (A) Location of the study area along the French Atlantic continental margin (GEMCO

848 bathymetry, contour lines every 500 m), (B) Detail of the study area with EM1002

849 bathymetry (contour lines every 50 m) and the location of the CTD casts (red), ROV

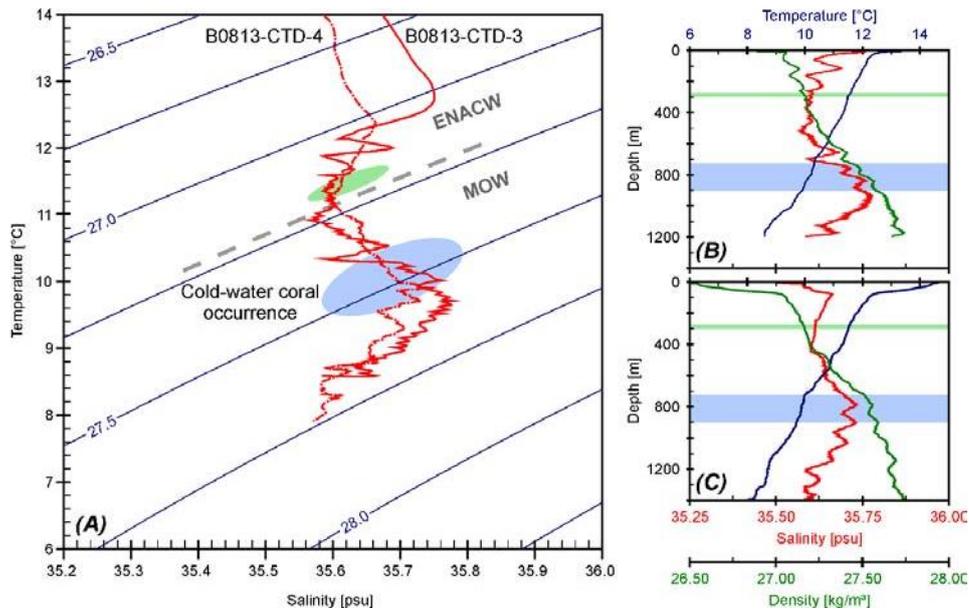
850 dives (blue) and boxcores (green), collected during the R/V Belgica BiSCOSYSTEMS

851 cruise (2008). As background a bathymetric map of IFREMER (Normand and Mazé,

852 2000) is used (contour lines every 100 m).

853

854 Figure 2.

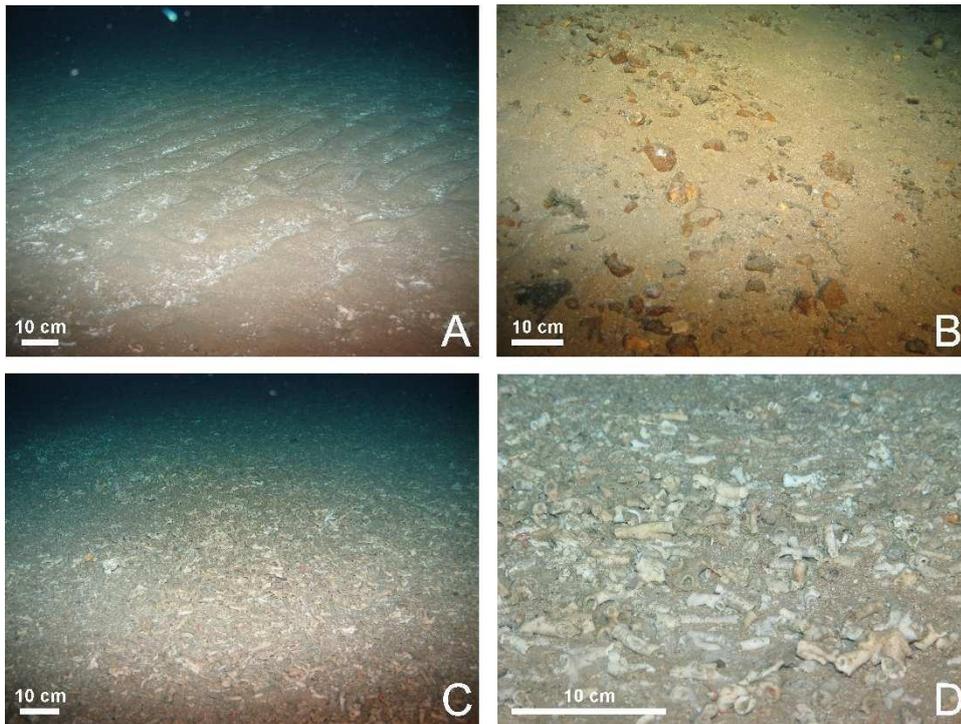


855

856 Hydrographic data of the Guilvinec Canyon. (A) Temperature/salinity plot for both  
857 CTD casts, with indication of the boundary (dashed grey line) between the Eastern  
858 North Atlantic Central Water (ENACW) and the Mediterranean Outflow Water  
859 (MOW). The estimated occurrence envelope of the shallow-water (green) and deep-  
860 water (blue) cold-water corals in the Penmarc'h and Guilvinec Canyons is based on the  
861 ROV observations, plotted on the CTD data of respectively (B) cast B0813-CTD-3 and  
862 (C) cast B0813-CTD-4.

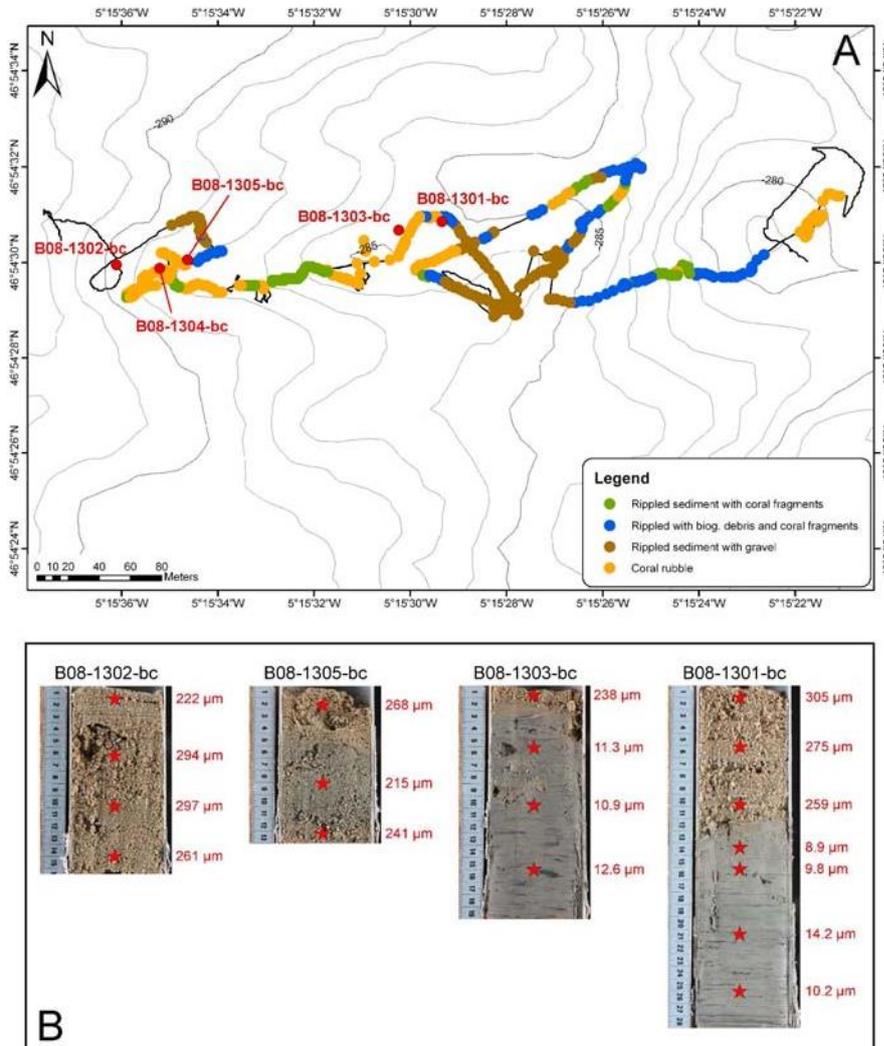
863

864 Figure 3.



865  
866 ROV images from the shallow-water setting (ROV dive B08-03): (A) rippled seabed  
867 with a patchy distribution of cold-water corals, (B) coarse sand with a high amount of  
868 gravel, (C) the dense cold-water coral rubble coverage on top of the small mounds, and  
869 (D) zoom in this coral rubble facies with predominantly *Lophelia pertusa*.  
870

871 Figure 4.

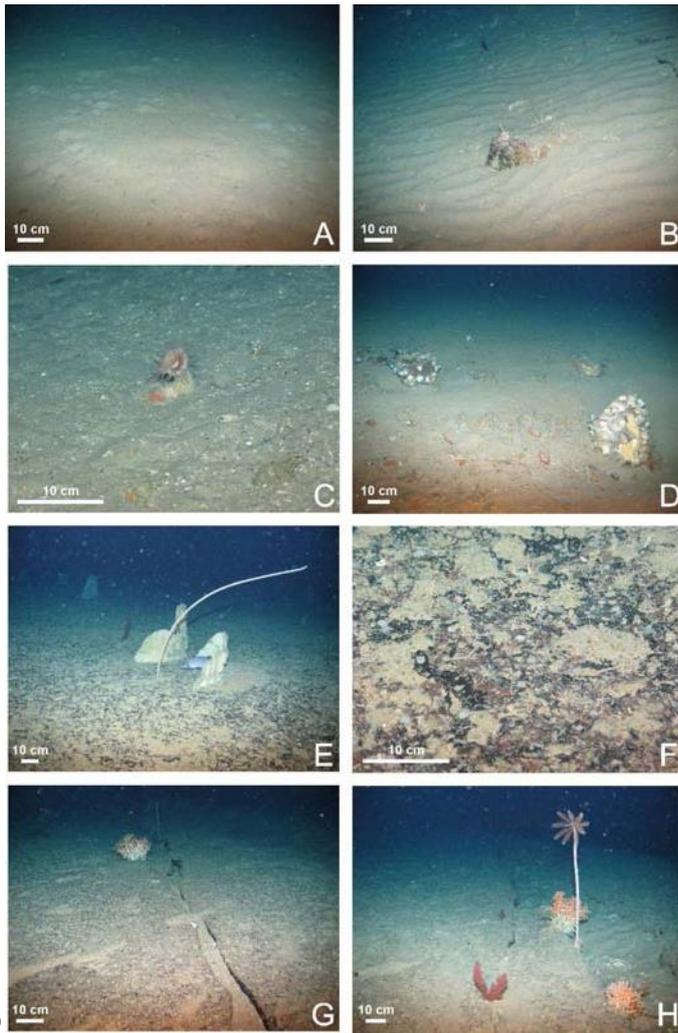


872

873 (A) Facies interpretation map of the shallow-water dive B08-03 on the southeastern  
874 flank of the Guilvinec Canyon in water depths between 278 and 289 m. (B) Photographs  
875 of the obtained boxcores in the shallow water area with the locations and mean grain-  
876 size values.

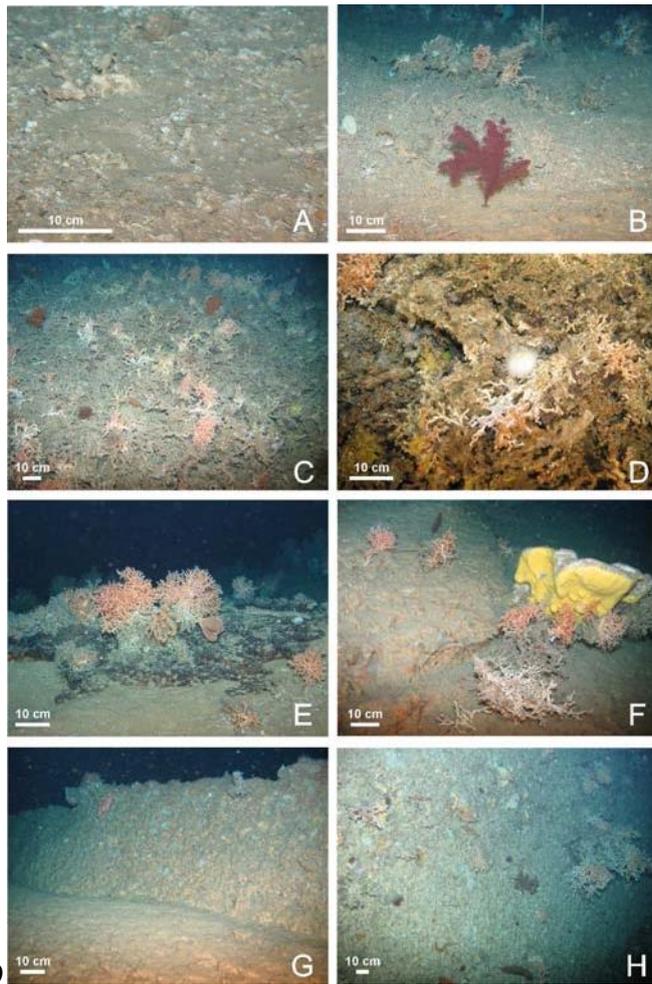
877

878 Figure 5.



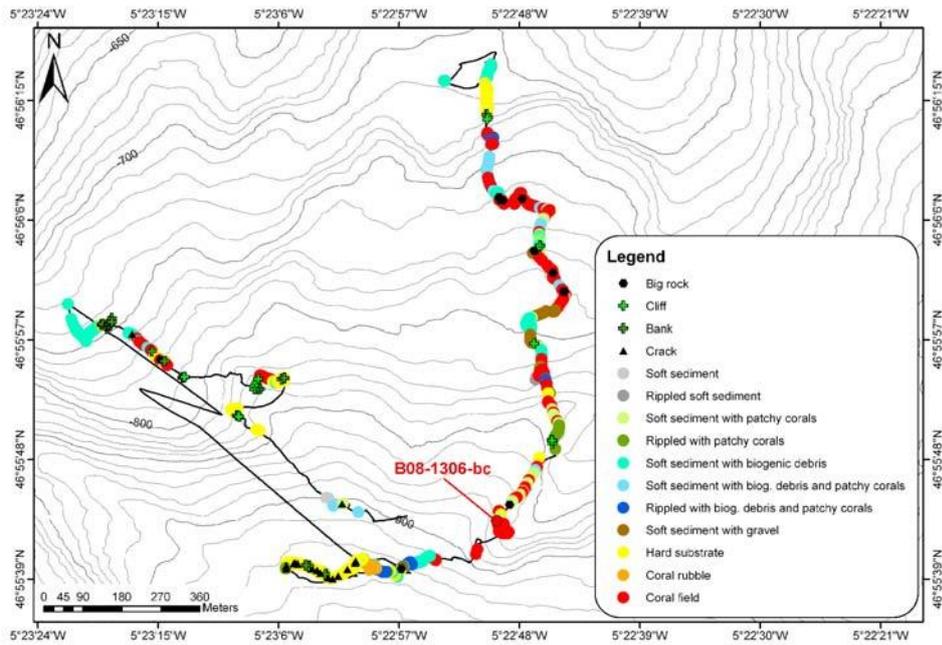
879  
880 ROV stills imagery highlighting the most important facies and associated fauna in the  
881 deep-water setting: (A) soft sediment with bioturbations; (B) rippled soft sediment with  
882 gravel; (C) a seabed covered with biogenic debris; (D) soft sediment with a patchy  
883 distribution of gravel; (E) hard substrate with a patchy distribution of cold-water corals,  
884 sponges and a sea urchin; (F) zoom on the hard substrate; (G) hard substrate with a  
885 large crack and one *Madrepora oculata* species; (H) hard substrate with a crack filled  
886 up with rippled soft sediment, colonised by a crinoid and a few living *Madrepora*  
887 *oculata* corals.

888 Figure 6.



889  
890 ROV stills imagery highlighting the different types of cold-water coral occurrences in  
891 the deep-water coral setting: (A) rippled seabed with coral rubble and biogenic debris;  
892 (B) example of a coral field with living and dead coral species; (C) a dense cold-water  
893 coral coverage with both living and dead species; (D) detailed zoom on the facies  
894 mentioned in A; (E) outcropping hard substratum with a few living coral species  
895 (*Madrepora oculata*) and Gorgonians; (F) outcropping hard substratum with the  
896 sponges *Geodia sp.* and *Topsentia sp.*, and again living and dead *Madrepora oculata*  
897 specimens; (G) a small bank with a height of 50 cm colonised by oysters and a few  
898 living coral species; (H) a vertical cliff colonised with oysters and living *Madrepora*  
899 *oculata*.

900 Figure 7.



901

902 Facies interpretation map of ROV dive B08-02 on the northwestern flank of the

903 Guilvinec Canyon in water depths of 712 to 900 m.

904

905 **Tables**

906

907 Table 1. Names, locations and operational data of the ROV Genesis dives. Time in

908 UTC.

Name	Area	Start track		End track	
		Time	Depth	Time	Depth
B08-01	South flank of Penmarc'h canyon	13:16:02	385 m	16:47:44	699 m
B08-02	North flank of Guilvinec canyon	11:24:46	712 m	15:46:00	900 m
B08-03	South flank of Guilvinec canyon: small mounds/ridges on the top	12:29:41	278 m	14:05:25	289 m
B08-04	Spur, south flank of Guilvinec canyon	15:51:10	676 m	16:38:51	691 m
B08-05	North flank of Guilvinec canyon	11:17:00	305 m	14:27:53	529 m

909

910

911 Table 2. Location, water depth and recovery length of the studied boxcores.

Core number	Latitude	Longitude	Water Depth	Recovery
B08-1301-bc	46°54.514' N	5°15.489' W	285 m	31 cm
B08-1302-bc	46°54.499' N	5°15.602' W	290 m	17 cm
B08-1303-bc	46°54.511' N	5°15.504' W	285 m	20 cm
B08-1304-bc	46°54.498' N	5°15.587' W	288 m	5 cm
B08-1305-bc	46°54.501' N	5°15.577' W	288 m	14 cm
B08-1306-bc	46°55.723' N	5°22.828' W	866 m	10-15 cm

912

913 Table 3. Overview of the U-series datings in the shallow water setting (left) and the  
 914 deep-water setting (right).

Shallow water setting			Deep-water setting		
Sample name	Age (ka)	Error (ka)	Sample name	Age (ka)	Error (ka)
B08-1301-bc	7.35	0.45	B08-1306-bc A	1.32	0.52
B08-1305-bc A	7.78	0.71	B08-1306-bc B	1.21	0.13
B08-1305-bc A	9.07	0.25	B08-1306-bc C	2.27	0.30
B08-03 B	8.89	0.31			
B08-03 C	1.41	0.17			

915