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Potential impacts of offshore oil and gas activities on deep-sea sponges and the habitats they form

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1 **Working title of review:**

2 Potential impacts of offshore oil and gas activities on deep-sea sponges and the habitats they
3 form.

4

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7

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10

11 **Figures and tables:**

12 Figure 1: Deep-sea sponge and sponge grounds

13 Figure 2: Flow chart of oil field development divided in four phases and main activities
14 associated with each phase

15 Figure 3: Field data on the initial impact and recovery from oil drilling disturbance in deep-
16 sea sponges in the Faroe-Shetland Channel (Laggan; Jones *et al.*, 2012) and Norwegian Sea
17 (Morvin; Gates and Jones, 2012).

18 Table 1: Vulnerable marine ecosystem (VME) and ecologically and biologically significant
19 area (EBSA) criteria and their applicability to deep-sea sponge grounds

20 Table 2: Overview of major impacts of offshore oil and gas activities on deep-sea sponges
21 and deep-sea sponge grounds at community, individual, cellular and molecular levels and
22 throughout oil field development.

23 **ABSTRACT**

24 Sponges may form an important component of benthic ecosystems from shallow littoral
25 to hadal depths. In the deep ocean beyond the continental shelf, sponges can form high-density
26 fields, constituting important habitats supporting rich benthic communities. Yet these habitats
27 remain relatively unexplored. Apart from scientific exploration, the offshore oil and gas
28 industry has played a key role in advancing our knowledge of deep-sea environments. Since
29 its inception in the 1960s, offshore oil and gas industry has moved into deeper waters.
30 However, the impacts of offshore oil and gas activities on deep-sea sponges and other
31 ecosystems are only starting to become the subject of active research. Throughout the
32 development, operation and closure of an oil or gas field many activities take place, ranging
33 from the seismic exploration of sub-seafloor geological features or the installation of
34 infrastructure at the seabed to the drilling process itself. Accidental releases of hydrocarbons
35 during spills or cuttings release can significantly impact the local marine environment. Each
36 phase of a field development or an accidental oil spill will therefore have different impacts on
37 sponges at community, individual and cellular levels. Legacy issues regarding the future
38 decommissioning of infrastructure and the abandonment of wells are also important
39 environmental management considerations. This paper reviews our understanding of impacts
40 from hydrocarbon exploration and exploitation activities on deep-sea sponges and the habitats
41 they form. Effects of offshore oil and gas activities include (1) at community level, decreasing
42 of the diversity and density of benthic communities associated with deep-sea sponges owing
43 to physical disturbance of the seabed, (2) at individual level, interrupting filtration owing to
44 exposure to increased sedimentation, (3) at cellular level, decreasing in cellular membrane
45 stability owing to exposure to drill muds. However, many potential effects, not yet tested in
46 deep-sea sponges but observed in shallow-water sponges or other model organisms should also
47 be taken into account. Furthermore, to the best of our knowledge, no studies have shown impact

48 of oil or dispersed oil on deep-sea sponges. To highlight these significant knowledge gaps, a
49 summary table of potential and known impacts of hydrocarbon extraction and production
50 activities, combined with a simple “traffic light” scheme is also provided.

51

52 **INTRODUCTION**

53 Presently, offshore oil and gas production accounts for one third of worldwide
54 hydrocarbons production (Benneer 2015). Since the end of the 1960s and the beginning of
55 offshore oil and gas exploration, the oil and gas industry have developed technologies that
56 enable exploitation of deep-sea environments (Managi *et al.* 2005) and is, today, operating in
57 deeper and complex marine settings (Muehlenbachs *et al.* 2013). Hydrocarbon exploration
58 and production is taking place in areas where vulnerable benthic species such as deep-sea
59 sponges are present. For example, in the Faroe-Shetland Channel, oil production activities are
60 taking place within a Nature Conservation Marine Protected Area designated to protect the
61 local deep-sea sponge grounds (Henry and Roberts, 2014).

62 Exploration for hydrocarbon and other resources in deep waters offshore has helped
63 discover new deep-sea environments. For example, collaborative efforts between academia
64 and industry partners have been very successful in increasing our understanding of deep-sea
65 benthic ecosystems e.g. the SERPENT project (Scientific and Environmental ROV
66 Partnership using Existing iNdustry Technology) (Gates *et al.* 2016) and discovering
67 previously unknown habitats such as the Darwin Mounds in the NE Atlantic (Huvenne *et al.*
68 2016). However, industrial operations in deeper settings are strongly correlated with a
69 number of technical incidents such as blowouts, injuries or spills (Muehlenbachs *et al.* 2013)
70 as well as operational discharges and disturbances leading to the chemical contamination of
71 water and seafloor habitats as well as local scale physical impacts from amongst others
72 drilling, anchoring and pipelines (OSPAR Commission 2009a). This was most starkly

73 demonstrated by the 2010 *Deepwater Horizon* oil spill in the Gulf of Mexico, caused by a
74 well blowout at 1500 m depth (Beyer et al. 2016 and references therein). Subsea well
75 blowouts and pipeline leaks at depth have become more of a concern while the number of
76 tanker-related oil incidents at surface have decreased over time (Jernelöv 2010). In addition,
77 day to day operations can also have environmental impacts in the deep sea (Cordes *et al.*
78 2016). From the presence of man-made infrastructures on the seabed to the release of
79 produced waters or the re-sedimentation of particles close to the drilling locations, the
80 ecological footprints of the offshore oil and gas production activities are multiple (Kark *et al.*
81 2015). As it is known that recovery rates vary in the deep-sea depending on the region and
82 biological communities already living there, understanding the impact of oil and gas industry
83 related activities on deep-sea benthic ecosystems is complex (Henry *et al.* 2017).

84 Furthermore, while pressures from anthropogenic activities such as the exploitation of
85 oil and gas reserves on deep-sea ecosystems keep increasing, our understanding of deep-sea
86 organisms and the scale of human impacts on ecosystems functioning remains limited
87 (Ramirez-Llodra *et al.* 2011). Deep-sea ecosystems comprise a highly diverse set of physical
88 and biological settings, many of which are hotspots of biodiversity including hydrothermal
89 vents, abyssal plains, manganese nodule fields, cold-water coral reefs and sponge grounds
90 (Ramirez-Llodra *et al.* 2011). Although many of these ecosystems also contribute
91 significantly in global biogeochemical cycling (Ramirez-Llodra *et al.* 2011) the overall value
92 of the ecosystem services provided by deep-sea ecosystems remain poorly quantified
93 (Thurber *et al.* 2014).

94 Sponges (Phylum Porifera) play vital roles in sustaining global deep-sea biodiversity
95 and ecosystem functioning. The diversity of sponges in the deep sea (Fig. 1A and B), the
96 rarity of some poriferan taxa (members of the class Calcarea), and the ecological uniqueness
97 of some poriferan groups such as carnivorous sponges of the family Cladorhizidae (Fig. 1C)

98 and the stalked glass sponges of the family Hyalonematidae, all add to the biological richness
99 of life in the deep ocean (Hogg *et al.* 2010). Habitats formed by dense aggregations of one or
100 several sponge taxa (sponge “grounds”, Fig. 1D) can extend over very large areas up to
101 hundreds of km² and provide three-dimensionally complex stable habitats that support
102 distinct biological communities and a biologically diverse mixture of other species
103 (Maldonado *et al.* 2016). Maldonado *et al.* (2016) provides an extensive review of sponge
104 grounds including deep-sea sponge grounds such as the hexactinellid sponge reefs in the
105 northeast Pacific Ocean off, astrophorid sponge aggregations in the north Atlantic, lithistid
106 sponge grounds or antarctic sponge grounds more than 400 species rich. Sponges themselves
107 host an array of organisms ranging from bryozoans or polychaetes to crustaceans (Wulf 2006;
108 Kazanidis *et al.* 2015) and sponge grounds act as nursery grounds and support many benthic
109 species including commercially important fish species such as rockfish, hake and blue ling
110 (Freese and Wing, 2003; Du Preez and Tunnicliffe 2011; Maldonado *et al.* 2016) (Fig. 1E to
111 H). Therefore, sponge grounds meet several criteria of Vulnerable Marine Ecosystems
112 (VMEs) as recognised by the UN Food and Agriculture Organisation (FAO). Deep-sea
113 sponge grounds also meet the criteria of Ecologically or Biologically Significant Areas
114 (EBSAs) as defined by the UN Convention on Biological Diversity (table 1) (Hogg *et al.*
115 2010).

116 Despite their ability to enhance benthic biodiversity, the biology and ecology of deep-
117 sea sponges has only started to be uncovered. What has been revealed most recently is that
118 sponges play essential roles in the biogeochemical cycling of matter in the deep oceans
119 (Cathalot *et al.* 2015). This is principally owing to sponges being very efficient at filtering
120 large volumes of water as they rely on Particulate Organic Matter (POM) as well as
121 Dissolved Organic Matter (DOM) for food (Rix *et al.* 2016). Up to 40% of the carbon and
122 nitrogen assimilated by sponges is released back into the water column in the form of

123 pumping and mesohyl cell detritus (Rix *et al.* 2016). Sponges, including deep-sea species,
124 thus recycle DOM to POM which is then available for other benthic organisms and
125 contributes to benthic-pelagic coupling in oligotrophic environments (Maldonado 2016; Rix
126 *et al.* 2016). Sponges host highly diverse microbial communities of bacteria, archaea and
127 eukaryotes, often compared for their complexity to the microbial assemblages of the
128 mammalian gut (Hentschel *et al.* 2012; Webster *et al.* 2012). Deep-sea sponges participate in
129 nitrogen cycling through these microbial symbionts capable of nitrification, denitrification
130 and ammonification reactions (Hoffman *et al.* 2009; Li *et al.* 2014). The concept of a ‘sponge loop’
131 have therefore emerged in the literature whereby sponges support oligotrophic food webs by
132 recycling organic carbon and nitrogen (De Goeij *et al.* 2013; Maldonado 2016). Furthermore,
133 sponge skeleton elements (spicules) are composed of silica assimilated from the environment
134 and sponges can play large roles in the cycling of silica. Glass sponge reefs composed of
135 hexactinellid sponges such as *Aphrocallistes vastus*, which are composed of up to 80% of
136 biogenic silica, concentrate huge amounts of Si in some areas of the seabed (Chu *et al.* 2011).

137 It is also becoming more evident that deep-sea sponges create other ecosystem
138 services: these “provisioning” services including the production of bioactive secondary
139 metabolites related to sponge-microbial associations that are of great interest to the
140 biotechnology sector. Conservation of these ancient animals (individual sponges have been
141 aged over 400 to over 2000 years old) and their habitats must therefore scale up with the rates
142 and extent of emerging anthropogenic activity, and thus the impacts that deep-water oil and
143 gas activities could have on these benthic organisms needs to be considered in management
144 plans (McMurray *et al.* 2008; Fallon *et al.* 2010).

145 The purpose of this review is to provide the first fully comprehensive review of the
146 impacts of offshore oil and gas activities on deep-sea sponges and the habitats they create.
147 Although studies on the resilience of deep-sea sponges to some oil and gas production

148 activities are starting to emerge, many knowledge gaps persist. Relevant findings from
149 shallow-water sponges or other benthic organisms has therefore also been used here to
150 highlight possible impacts on deep-sea sponges and the habitats they form. Impacts can occur
151 at all stages of offshore oil and gas activities from exploration, development and production
152 through to decommissioning and legacy effects. Furthermore, effects of these activities can
153 be detected across ecological scales from community, individual and cellular levels. This
154 review therefore adopts this multiple scale framework to assess impacts at the level of sponge
155 habitats, at the individual sponge level and at the cellular and molecular level.

156

157 **EFFECT ON SPONGE HABITATS AND COMMUNITIES**

158 During the development of an oil and gas field under development the activities can
159 broadly be broken up into four successive phases: exploration and appraisal, development,
160 production and decommissioning (DTI 2001; Fig. 2). Each phase involves a range of routine
161 activities that may have effects on deep-sea sponge habitats and the biological communities
162 they support (Fig. 2). Exceptional events such as accidental spills and chemical releases could
163 also negatively affect deep-sea sponge grounds and so should also be taken into
164 consideration. Potential impacts of accidental spills are treated separately in this section of
165 the review to help guide the development of monitoring and spill management plans.

166

167 **Impacts of routine activities on deep-sea sponge grounds and associated communities**

168 *Subsea infrastructure (wells, pipelines, manifolds and platforms)*

169 During the phases of exploration and development, offshore oil and gas activities
170 require the drilling of wells and the installations of heavy infrastructure such as manifolds
171 and pipelines that directly disturbs the seabed (Fig. 2). Physical disruption and smothering by
172 sediments is one of the main impacts linked to the early stages of oil field development

173 arising from installing pipelines, cables, bottom rigs, templates, skids, and platforms
174 including platform legs and anchoring (OSPAR commission 2010). Physical disruption and
175 increased sedimentation (Fig. 1I and J) during these phases can locally diminish benthic
176 communities by more than 90% in terms of megafaunal density within sponge grounds (Jones
177 *et al.* 2006). Long-term effects on deep-sea sponge grounds from such physical disturbance
178 are still detectable up to 10 years post-drilling and this slow, partial recovery, inversely
179 related to the distance to the well and the time after drilling, could result from the long-lived
180 nature, slow growth rates and low reproduction rates of most deep-sea organisms (Jones *et al.*
181 2012). Very limited recovery of megafauna was observed in areas where drill cuttings were
182 not eroded 10 years post drilling (Jones *et al.* 2012).

183 Physical disruption and increased sedimentation are also associated with the
184 installation of pipelines, which export produced hydrocarbons onshore. Power transmission
185 cable installations significantly impact local benthic communities inflicting a 100% mortality
186 rates to glass sponges below the cables and a 15% mortality rate within 1.5 m of the cables all
187 along its footpath (Dunham *et al.* 2015) with potentially similar effects expected from
188 pipeline deployments (OSPAR commission 2010).

189

190 *Discharges of drill cuttings and drill muds*

191 In the early stages of drilling a well drill cuttings and muds, comprising residual rock
192 fragment from the well and drilling fluid chemicals, are released directly into the
193 environment at depth (Ellis *et al.* 2012). For the remainder of the drilling process, treated
194 cuttings are typically discharged at the surface, where they sink to the seafloor under the rig.
195 Unless dispersed by active near-bed currents, drill cuttings can accumulate on the seabed and
196 over time may release contaminants, especially if disturbed (OSPAR commission 2010). The
197 usually customised drill muds can be classified into three types: oil-based, synthetic and

198 water-based fluids all of which may contain toxic chemicals, including polyaromatic
199 hydrocarbons and heavy metals. Only two studies have shown the impact of drilling mud and
200 cuttings on megafaunal communities with abundant sponges, both in the north east Atlantic
201 (Gate and Jones, 2012; Jones *et al.* 2012). Both studies indicate major reductions in sponge
202 densities and reduced diversity close (100-200 m) to drilling activity that persist for several
203 years (Fig. 3). The gravity of the impact of drill muds and cuttings has been better studied on
204 other benthic communities where the impacts have been shown to depend largely on abiotic
205 conditions such as depth and currents as well as the concentration of chemicals associated
206 with the muds (Ellis *et al.* 2012, Henry *et al.* 2017). For synthetic and water-based muds, a
207 decrease in community diversity and abundance have been measured up to 1,000 m away
208 from the release location (Ellis *et al.* 2012). Functional changes in benthic communities,
209 associated with a loss of suspension-feeding species and an increase in deposit feeders have
210 also been detected at release sites (Trannum *et al.* 2010; Ellis *et al.* 2012). The spatial impact
211 footprint is largest during the first one to two years after drilling and reduces in extent and
212 contaminant concentration afterwards due to leaching into the water column (OSPAR
213 Commission 2016). Today the production and release of oil-based drill muds have been
214 widely reduced in the North East Atlantic by the oil and gas industry (OSPAR
215 Recommendations R2001/1, 2006/5 and 2010/18) but use of oil-based drill muds in the past
216 has been shown to have a local but strong and lasting impact on benthic communities
217 (OSPAR Commission 2010; Henry *et al.* 2017). Potential impacts of past releases of oil-
218 based drill muds on sponge grounds and associated benthic communities therefore still need
219 to be understood.

220

221 *Decommissioning*

222 As offshore infrastructures age, decommissioning options for the physical removal of

223 oil and gas infrastructure including pipelines, platforms, drill cuttings and the capping of
224 wells needs to be considered (Fig. 2). Worldwide, there are over 7,500 oil and gas structures
225 offshore and about 85% of them will need to be decommissioned by 2025 (Fowler *et al.*
226 2014). In the North East Atlantic, the dumping, and leaving wholly or partly in place, of
227 disused offshore installations has been prohibited within certain sea areas, under OSPAR
228 Decision 98/3 on the Disposal of Disused Offshore Installations since 1998. Based on a pre-
229 defined assessment demonstrating that there are significant reasons why an alternative
230 disposal is preferable to reuse or recycling or final disposal on land, the competent authority
231 of the relevant Contracting Party may authorise companies to leave some parts of the
232 installations in place after consultation with the other Contracting Parties. Such derogations
233 concern very heavy concrete and steel installations which might provide a suitable settlement
234 ground also for deepwater sponges. Until 2009, 122 offshore installations have been brought
235 ashore for disposal and only five permits have been issued for structures to be left in place
236 (OSPAR Commission 2009a). However, with more and more installations approaching their
237 end of life, the industry has started to lobby for a modification of the Decision itself instead
238 of using the derogation options provided by OSPAR Decision 98/3. The argument is that the
239 physical impact on the seabed as well as the economic costs of such operations are
240 substantial.

241 Environmental impacts caused by a complete removal of offshore infrastructure that
242 could negatively affect deep-sea sponge grounds and associated communities may include:
243 contamination of the water column by hydrocarbons and other chemicals, direct damage to
244 the seabed and smothering by increase sedimentation (Fowler *et al.* 2014). Decommissioning
245 of oil and gas industry infrastructure has not yet taken place within known deep-sea sponge
246 grounds and so potential impacts of decommissioning at community level is for the moment
247 unknown. Under UK regulation, decommissioning impacts on the environment must be

248 considered in the Environmental Impact Assessment (EIA) produced in the beginning of any
249 new oil and gas field development (DECC, 2011).

250 **Accidental spills and releases**

251 The *Deepwater Horizon* oil spill was one of the largest and deepest offshore oil spills to
252 date, with approximately 3.19 million barrels of oil released into the water at a depth of 1500
253 m (Beyer *et al.* 2016 and reference therein). It was also the first time dispersants were used to
254 such an extent at depth to mitigate the formation of a surface oil slick that would have
255 impacted upon sensitive coastal ecosystems (White *et al.* 2014). Almost 3 million litres of
256 dispersant Corexit™ 95000 were released near the well head (White *et al.* 2014). A large
257 amount of the oil released into the water column formed several subsurface oil plumes
258 (Diercks *et al.* 2010). The most significant sub-surface plume extended for 35 km at
259 approximately 1100 m depth (Camilli *et al.* 2010). The *DeepWater Horizon* incident thus
260 created a new kind of oil spill where deep water ecosystems and habitats were exposed to
261 high concentrations of dispersed crude oil and dispersants (Peterson *et al.* 2012).

262 Impact of accidental oil releases are better understood in shallow water than in deep
263 ecosystems. In shallow water coastal environments, oil spills have shown both lethal (high
264 mortality rate) and sub-lethal effects (carcinogenic and cytotoxic impacts) on benthic species
265 leading to changes in community diversity, age structure and trophic interactions (Suchanek
266 1993). Impact of oil spills on deep-sea benthic ecosystems are far less understood. After the
267 *Deepwater Horizon* incident, significant decreases in macro- and meio-fauna diversity were
268 detected after the blowout up to 17 km away from the well (Montagna *et al.* 2013). Other
269 studies have shown high mortality rate of deep-water corals, colonial and pelagic tunicates,
270 sea pens as well as glass sponges within a 2 km radius of the well but no further result on
271 deep-sea sponges is given (White *et al.* 2012; Valentine and Benfield 2013).

272 Long-term impacts of oil spills in shallow water ecosystems often take the form of

273 community structure anomalies (absence of organisms of a specific age class) owing to the
274 longevity and slow growth rate of some species (Kingston 2002). Long-term impacts of deep-
275 sea oil spill such as the *DeepWater Horizon* oil spill remains unknown. Deep-sea sponges
276 display relatively slow and strongly seasonal growth rates varying from a few millimetres to
277 a couple of centimetres per year (Fallon *et al.* 2010; Dayton *et al.* 2013; Dunham *et al.* 2015),
278 suggesting that deep-sea spills in the vicinity of deep-sea sponge grounds could have a strong
279 long-term community effect on these habitats.

280

281 **PHYSIOLOGICAL AND ECOTOXICOLOGICAL EFFECTS ON INDIVIDUAL** 282 **SPONGES**

283 **Main impacts of routine offshore oil and gas activities on deep-sea sponges**

284 *Seismic surveying during hydrocarbon exploration and appraisal phases*

285 During the initial phases of exploration and appraisal, seismic surveys are conducted
286 to assess sub-seafloor structures and determine drilling location (DTI 2001). Impact of
287 seismic surveys on marine invertebrates and larval development and survival has been
288 investigated in several studies (Aguilar de Soto *et al.* 2013; Nedelec *et al.* 2014).
289 Developmental delays and malformations in scallops have been identified as potential effects
290 of seismic surveys on benthic organisms (Aguilar de Soto *et al.* 2013). In gastropods, seismic
291 pulses decrease larval development and increased mortality by over 20% (Nedelec *et al.*
292 2014). However, no studies have yet investigated the effect of seismic surveys on sponges or
293 their larval stages.

294

295 *Sedimentation from seabed disturbance*

296 The phases of offshore exploration and development are characterised by drilling and
297 the installation of heavy infrastructure, which are associated with re-suspension of sediments

298 that can affect local benthic organisms including deep-sea sponges (OSPAR Commission
299 2010) (Fig. 2). Bell *et al.* (2015) summarized the often species-specific effects of
300 sedimentation on marine sponges, focussing mainly on shallow-water species. Increased
301 sedimentation impacts sponge filtration and feeding (Reiswig 1971; Bannister *et al.* 2012
302 amongst others), respiration (Lohrer *et al.* 2006; Bannister *et al.* 2012 amongst others),
303 reproduction (Roberts *et al.* 2006 amongst others) and growth (Wilkinson and Vacelet, 1979;
304 Roberts *et al.* 2006 amongst others). Additionally, evidence of tissues sloughing in shallow-
305 water sponge *Halichondria panicea* was found after exposure to increased sedimentation
306 (Barthel and Wolfrath 1989). Studies on deep-water sponges have confirmed some of the
307 findings made on shallow-water sponges. Heavy sedimentation on deep-water sponge *Geodia*
308 *barretti* led to a 50% to 86% reduced respiration rate depending on sediment concentration
309 tested but was associated with a fast recovery after exposure to sediments (Tjensvoll *et al.*
310 2013; Kutti *et al.* 2015). Furthermore, sedimentation caused a rapid arrest in feeding
311 behaviour and chamber clogging in the two deep-sea glass sponges *Rhabdocalyptus dawsoni*
312 and *Aphrocallites vastus*. However, some aspects in the response of the two glass sponge
313 species differed: feeding was resumed earlier in *A. vastus* and sediment level required to halt
314 feeding was lower for *R. dawsoni* (Tompkins-Macdonald and Leys, 2008). This shows that
315 increase in sedimentation have an overall negative impact on deep-sea sponges, with some
316 species more resilient than others.

317

318 *Release of contaminants in the environment during routine operations*

319 Routine operations during the production phase of an oil field development include the
320 discharge to the sea of produced water that contains small amounts of hydrocarbons such as
321 polyaromatic hydrocarbons (PAHs), dissolved metals and naturally occurring radioactive
322 elements such as radium-226 and radium-228 (Fig. 2) (Neff *et al.* 2011).

323 Although the volume of oil released into the sea in the NE Atlantic through produced
324 water discharges has overall been reduced following industry effort through decision such as
325 OSPAR recommendation 2001/1, produced water still remains the main source of
326 hydrocarbons in the environment from oil and gas industry linked activities (OSPAR
327 Commission 2010; Neff *et al.* 2011). Upon release, produced water is believed to be diluted
328 very rapidly into the ambient seawater (Neff *et al.* 2011). Therefore, although some PAHs are
329 persistent compounds in the environment and can be toxic at higher concentration as
330 discussed in the next section (for accidental releases of hydrocarbons), produced water is
331 expected to have a very low impact on marine organisms (Neff *et al.* 2011). However, PAHs
332 from produced water could have sub-lethal effects on deep-sea sponges. Benthic suspension
333 feeders such as mussels have been shown to accumulate PAHs when exposed to produced
334 water (Sundt *et al.* 2011). Moreover, low concentration of PAHs can be bioaccumulated in
335 sponges at higher levels than mussels (Negri *et al.* 2006; Batista *et al.* 2013; Mahaut *et al.*
336 2013; Gentric *et al.* 2016). Changes in fatty acid content in sponges exposed to PAHs has
337 also been observed. It has therefore been suggested to use sponges as environmental
338 bioindicators for PAHs concentration monitoring (Batista *et al.* 2013).

339 Dissolved metals can also be present in produced water including barium, iron,
340 manganese, mercury and zinc. Shallow-water sponges are known to bioaccumulate zinc
341 (Gentric *et al.* 2016). It is consequently possible that deep-sea sponges could also
342 bioaccumulate metals in their tissue from produced water exposition but no study has been
343 conducted so far on this subject. Notably, zinc naturally present in the environment has been
344 shown to be incorporated into sponge spicules (Hendry and Andersen 2013). However, no
345 studies looking at the impact of metal concentration from anthropogenic sources in sponge
346 spicules have been conducted so far.

347

348 *Decommissioning*

349 Removal of aging offshore infrastructures during decommissioning could lead to an
350 increase in sedimentation and a release of hydrocarbons and other chemicals into the marine
351 environment (Fig. 2) (Fowler *et al.* 2014). Yet targeted disturbance experiments of the drill
352 cuttings accumulated on the seafloor demonstrate no major effect on the spatial distribution
353 of cuttings contamination or the biological communities present in the seabed located greater
354 than 100 m from the original location of the installation (OSPAR Commission 2009b). It has
355 to be born in mind, however, that the removal of large anchors or installations on the seafloor
356 will likely cause resuspension of a much larger extent. Intensive water column and sediment
357 monitoring will be required to assess the effects of the removal of individual or multiple
358 installations.

359 As previously stated, no infrastructure decommissioning project has yet taken place
360 within deep-sea sponge grounds and so potential impacts of decommissioning at individual
361 level is for the moment unknown. It can only be hypothesized that impacts on deep-sea
362 sponges associated with high sedimentation rate and hydrocarbon pollution described during
363 the exploration, development and production phases could also occur during the
364 decommissioning phase.

365

366 **Impacts of accidental hydrocarbon release and dispersants use on deep-sea sponges**

367 During accidental spills, large amounts of hydrocarbons are released directly into the
368 marine environment. During oil spills, PAHs are of particular concern when considering
369 ecotoxicological impacts on organisms present in the vicinity of the spill location (Blackburn
370 *et al.* 2014 and references therein). In shallow-water sponges, high concentrations of PAHs
371 have been shown to disturb sponge larval settlement and development (Cebrian and Uriz
372 2007; Negri *et al.* 2016). Effects of dispersants and dispersed oil on larval stages of various

373 other marine organisms have been investigated but results of higher toxicity associated with
374 the use of dispersant seem to depend on the organisms considered and the duration of
375 exposition (Singer *et al.* 1998; Epstein *et al.* 2000, Stefansson *et al.* 2016). In tropical corals,
376 exposure to dispersed crude oil resulted in increased mortality in larvae of the coral
377 *Stylophora pistillata* and a stronger decrease in larvae settlement rate compared to exposure
378 to crude oil alone (Epstein *et al.* 2000). Furthermore, exposure to dispersed oil and
379 dispersants alone has led to a strong health decline (defined by percentage of live polyps and
380 tissue coverage) in three deep-water coral species from the Gulf of Mexico (DeLeo *et al.*
381 2016). To the authors' knowledge no studies have yet tested the effects of dispersed oil or
382 dispersants on marine sponges and sponge larvae.

383 Long-term impacts of a deep-sea oil spill could be derived from sediment associated
384 hydrocarbons. It is estimated that 35% of the oil released into the marine environment during
385 the *Braer* oil spilled off the Shetland Islands in the northeast Atlantic subsequently ended up
386 in subtidal sediments (Davies *et al.* 1997). PAHs and hydrocarbon breakdown is slowed
387 down in sediments owing to overall anoxic conditions within the sediments (Atlas and Hazen
388 2011 and references therein). However, benthic organisms can be exposed to sediment
389 associated PAHs or hydrocarbon via sediment resuspension. Bivalves are able to accumulate
390 PAHs from the sediment during resuspension episodes (Nandini Menon and Menon 1999). It
391 has been suggested that deep-sea sponges can derive part of their nutrition from re-suspended
392 matter (Hogg *et al.* 2010) and therefore could be impacted by PAH contaminated sediments.
393 Furthermore, Culbertson and collaborators (2008) showed that short-term and long-term
394 exposure to 38-year-old residual petroleum associated with sediments led to a decrease in
395 growth rate, lower health condition and decreased filtration rate in mussels. Dispersants have
396 also been shown to persist in deep-sea sediments as dispersants were quantified in sediments
397 collected within deep-sea coral communities 6 months after the *Deepwater Horizon* spill

398 (White *et al.* 2014). This suggests that oil spill can have long term impacts on deep-sea
399 benthic organisms when hydrocarbon and dispersants enter the sediments, which is of
400 concern for deep-sea sponges.

401

402 **EFFECT ON DEEP-SEA SPONGES AT CELLULAR AND MOLECULAR SCALES**

403 **Impacts of offshore oil and gas production activities on deep-sea sponges at a cellular** 404 **level**

405 During the production phase of offshore oil field development, the release of drill
406 muds has been shown to impact deep-sea sponges at a cellular level (Edge *et al.* 2016).

407 Barite, one of the major solid components of these drill muds has been shown to decrease
408 lysosomal membrane stability in the deep-sea sponge *G. barretti* (Edge *et al.* 2016).

409 Hydrocarbon contamination including PAH pollution is also a main concern when
410 considering cellular impacts of offshore oil and gas activities on sponges. Water
411 accommodated oil fraction (solution of soluble hydrocarbons in seawater) activates the
412 Mitogen-Activated Protein Kinase (MAPK) and apoptosis pathways in the sponge *Suberites*
413 *domuncula* (Châtel *et al.* 2011). The MAPK pathway plays an important role in cellular
414 response to environmental and oxidative stress (Regoli and Giuliani 2014). Increased DNA
415 damage was also detected in *S. domuncula* (Châtel *et al.* 2011), confirming previous work
416 conducted by Zahn *et al.* (1981, 1983) showing exposure to PAH induced DNA damage in
417 the shallow-water sponge *Tethya lyncurium*.

418 Furthermore, the cytochrome P450-dependent monooxygenase system has also been
419 shown to be involved in the detoxification of PAH benzo-a-pyrene, in two marine sponge
420 species (Solé and Livingstone 2005). Lower yields of cytochrome P450 protein were
421 detected in sponges compared with other phyla (Cnidaria, Mollusca, Annelida, Arthropoda,
422 Echinodermata and Chordata) but this could result from overall lower metabolic rates (Solé

423 and Livingstone 2005). Under PAHs contaminated conditions produced in the laboratory,
424 PAH molecules interact with the aryl hydrocarbon receptor and induce the cytochrome P450
425 pathway (Regoli and Giuliani 2014). The cytochrome P450 pathway is known to play an
426 important role in oxidative stress responses (Solé and Livingston 2005), which are induced in
427 many organisms after exposure to PAHs (Nebert *et al.* 2000; Puga *et al.* 2002; Regoli and
428 Giuliani 2014 amongst others). Oxidative stress is a consequence of an imbalance in the
429 antioxidant system in an organism. Normal aerobic metabolism produces reactive oxygen
430 species (ROS), which are neutralised by the antioxidant system. Exposure to xenobiotic
431 compounds can increase the formation of ROS and decrease the antioxidant system's
432 functioning. Formation of ROS in turn, downregulates the cytochrome P450, which limits the
433 organism's capacity to deal with contaminants such as PAHs (Regoli and Giuliani 2014). The
434 role of the aryl hydrocarbon receptor in organisms impacted by oil spills was recently
435 confirmed in a transcriptomic study showing an induction of a large amount of stress
436 response genes such as the aryl hydrocarbon receptor and the glutathione-S-transferase in
437 oysters deployed during the *Deepwater Horizon* oil spill (Jenny *et al.* 2016). However, to the
438 authors knowledge, no studies have reported the activation of the aryl hydrocarbon receptor
439 and cytochrome P450 pathway in deep-sea sponges.

440 Dispersants themselves have been shown to trigger cellular stress responses in
441 different organisms. In the commonly used model organism *Caenorhabditis elegans*
442 (Nematoda), exposure to dispersant Corexit™ 9500A caused the abnormal expression of
443 twelve genes, involved in a wide range of biological processes ranging from egg-laying to
444 neurological functions and oxidative stress (Zhang *et al.* 2013). However, in the tropical coral
445 *Montastraea franksi*, Corexit™ 9527 exposure led to increased expression of genes coding
446 for P-glycoprotein, heat shock protein 70 and heat shock protein 90 and, to a lesser extent,
447 proteins involved in other cellular stress responses (Venn *et al.* 2009). Furthermore, exposure

448 to dispersants alone as well as dispersants and crude oil lead to an increase in cell membrane
449 damages in diatoms, which was not observable in diatoms exposed to oil alone (Hook and
450 Osborn 2012). No studies so far have investigated the impact of dispersants on marine
451 sponges.

452

453 **Impacts of offshore oil and gas production activities on deep-sea sponge associated** 454 **micro-organisms**

455 Sponges host highly diverse microbial communities often compared for its
456 complexity to the bacterial community of the human gut (Hentschel *et al.* 2012). Although
457 bacteria generally dominate deep-sea sponge microbial communities, eukaryotic and archaeal
458 symbionts have also been described. Mainly found in the mesohyl of the sponges these
459 microbes are metabolically very active and are believed to play important roles in the
460 nitrogen and carbon metabolism (Li *et al.* 2014). Deep-sea sponges are a rich source of
461 secondary metabolites of great interest as new therapeutic compounds and it is often the
462 associated microbial communities that synthesises these compounds. Sponges' secondary
463 metabolites show properties that include antifouling, antifungal, antibacterial or antiviral
464 properties and are believed to play a major role in sponge defence against diseases or against
465 other benthic organisms competing for the same substrata (Sipkema *et al.* 2005).

466 The impact of environmental pollution and specifically exposure to hydrocarbons or other
467 offshore oil and gas extraction activities on the sponge-associated microbial communities are
468 currently unknown. Studies have investigated the stability of the shallow-water sponge
469 associated microbial community when exposed to thermal stress, changes in seawater pH or
470 to high metal concentrations (Webster and Hill. 2001; Webster *et al.* 2008; Selvin *et al.* 2009;
471 Fan *et al.* 2013; Fang *et al.* 2013; Tian *et al.* 2014). However, only a few of these studies

472 found, under stressed conditions, a shift in the associated microbial community composition
473 (Webster and Hill. 2001; Webster *et al.* 2008; Fan *et al.* 2013; Tian *et al.* 2014). A change in
474 associated microbes was also correlated with a decline in overall sponge host health status
475 characterised by an increase in sponge tissue necrosis and increased expression of genes
476 linked to cellular oxidative stress (Webster and Hill. 2001; Webster *et al.* 2008; Fan *et al.*
477 2013; Tian *et al.* 2014). An oil degrading surfactant biosynthesis gene has been isolated from
478 bacteria associated with the shallow-water sponge *Acanthella sp* (Anburajan *et al.* 2015).
479 However, the capacity of the bacteria to synthesize the surfactant when associated with the
480 marine sponge and when exposed to crude oil was not investigated (Anburajan *et al.* 2015).
481 In the Gulf of Mexico, the deep-sea sponge *Myxilla methanophila* growing on tubeworms
482 near cold-seeps was described to be associated with putative oil degrading bacteria after
483 deep-sequencing of its associated microbial community (Arellano *et al.* 2013). In this case, it
484 was hypothesized that the sponge had acquired the symbiont from its environment naturally
485 rich in hydrocarbons (Arellano *et al.* 2013). Whether the bacteria played a role in
486 hydrocarbon detoxification or in sponge nutrition was not be investigated (Arellano *et al.*
487 2013). The capacity of deep-sea marine sponges to acquire oil-degrading bacteria after an oil
488 spill event has not yet been investigated.

489

490 **CONCLUSIONS**

491 Oil and gas activities are today taking place in deeper settings and will impact deep-
492 sea ecosystems. Oil and gas production activities impact deep-sea sponges and the habitats
493 they form at all stages of field development and at community, individual and cellular levels
494 as summarised in table 2. At community level, physical disturbance and discharge of drill
495 muds have been shown to decrease diversity and density of organisms associated with deep-
496 sea sponge grounds. At individual level, physical disturbance and increased sedimentation

497 inhibit the filtration systems of deep-sea sponges, while the discharge of produced water and
498 drill cuttings could lead to bioaccumulation of hydrocarbons and metals (as shown in
499 shallow-water sponges). At cellular and molecular levels, discharge of drill muds and
500 produced water could trigger cellular stress responses as has been shown for shallow-water
501 sponges exposed to PAH and metal contaminated seawater. Accidental releases of
502 hydrocarbons and the use of dispersants during oil spill could result in benthic diversity
503 decrease, individual sponge mortality and larval settlement disruption as well as trigger
504 oxidative stress. However, most of the possible impacts described in this review have not yet
505 been studied in deep-sea sponges.

506 Offshore oil and gas activities are managed by national legislations within the
507 exclusive economic zones and under United Nations legislations in the high seas. In most
508 countries, oil companies are required to complete EIAs before starting any new operation
509 (Budd 1999). EIAs have become a major component of oil and gas industry regulation as
510 their aim is to identify and manage adverse environmental impacts before they occur by: (1)
511 screening for possible impacts (2) completing baseline surveys (3) producing Environmental
512 Statements and (4) leading the decision-making process. The major benefits of EIAs are that
513 the environment is considered in an early stage of the project and that scientific data are
514 acquired during the EIA process (Budd 1999). However, despite its widespread use in
515 offshore activity regulation, EIAs' project specific approach means that cumulative
516 environmental impacts owing to the development of several oil fields in the same area cannot
517 be taken into account (Baker and Jones 2013) and by their nature EIAs have to rely on
518 existing scientific understanding of ecosystems function. Despite promising advances in
519 recent years the latter remains poorly developed in deep-water settings including those that
520 support deep-sea sponge grounds. Strategic Environmental Assessments are therefore now
521 starting to be adopted by the oil & gas industry (Fidler and Noble 2012). National

522 jurisdictions apply only to waters within the 200 nm EEZ of coastal states. However, deep-
523 sea sponge grounds occur beyond the EEZ of coastal states. The United Nations Convention
524 on the Law of the Sea (UNCLOS) signed in 1972 first enabled the deep-sea floor and High
525 Seas to be exploited for biological and geological resources and technological improvements
526 over time have made the deep-sea accessible (Ramirez-Llodra *et al.* 2011). In 2008
527 Ecologically or Biologically Significant Areas (EBSAs) were defined by the United Nations
528 Convention on Biological Diversity to help international organisations protect key marine
529 environments. Following this, 8 EBSAs were proposed in September 2011 in the northeast
530 Atlantic to protect cold-water corals and sponge grounds (Weaver and Johnson 2012) but
531 have not been subsequently developed. Since 2009, deep-sea sponge grounds are considered
532 by the UN Food & Agriculture Organisation as Vulnerable Marine Ecosystems, as defined by
533 the General Assembly resolution 61/105, calling states to restrict destructive fishing
534 practices. Although VME designations are used to control the adverse effect of fishing on
535 marine species, it brings organisms with specific conservation needs to light and is therefore
536 also useful in the context of offshore oil and gas industry activities. In addition to EBSA and
537 VME designations, the development of Marine Protected Areas (MPAs) and design of
538 connected networks have gained momentum during the early 2000 under the OSPAR
539 convention (Howell 2010; O’Leary *et al.* 2012). Indeed, deep-sea sponges entered the
540 OSPAR Threatened and/or Declining Species and Habitat list in 2008. Criteria for the
541 designation of MPAs were determined by the World Conservation Union (IUCN) in 1994
542 and include ecological, scientific and economic importance (Howell 2010).

543 Lack of scientific data on the effects of deep-sea hydrocarbon exploitation activities
544 on deep-sea benthic organisms such as sponges is limiting the efficiency of national and
545 international management and monitoring regulations. Collaborative initiatives between
546 academic and industry partners provide a constructive way to close the current knowledge

547 gaps. The access to and sharing of environmental data between industry and academia should
548 also be encouraged (Murray et al. IN PREP). Furthermore, the increasing use of new
549 technologies and methodologies such as Autonomous Underwater Vehicles and predictive
550 habitat modelling to survey and map large areas of the seabed will offer new opportunities to
551 increase our understanding deep-sea benthic environments. As oil and gas production
552 activities already occur within deep-sea sponge grounds, further collaboration between
553 industry and research partners to better monitor the effect of oil and gas activities on deep-sea
554 sponge and deep-sea sponge grounds are urgently needed.

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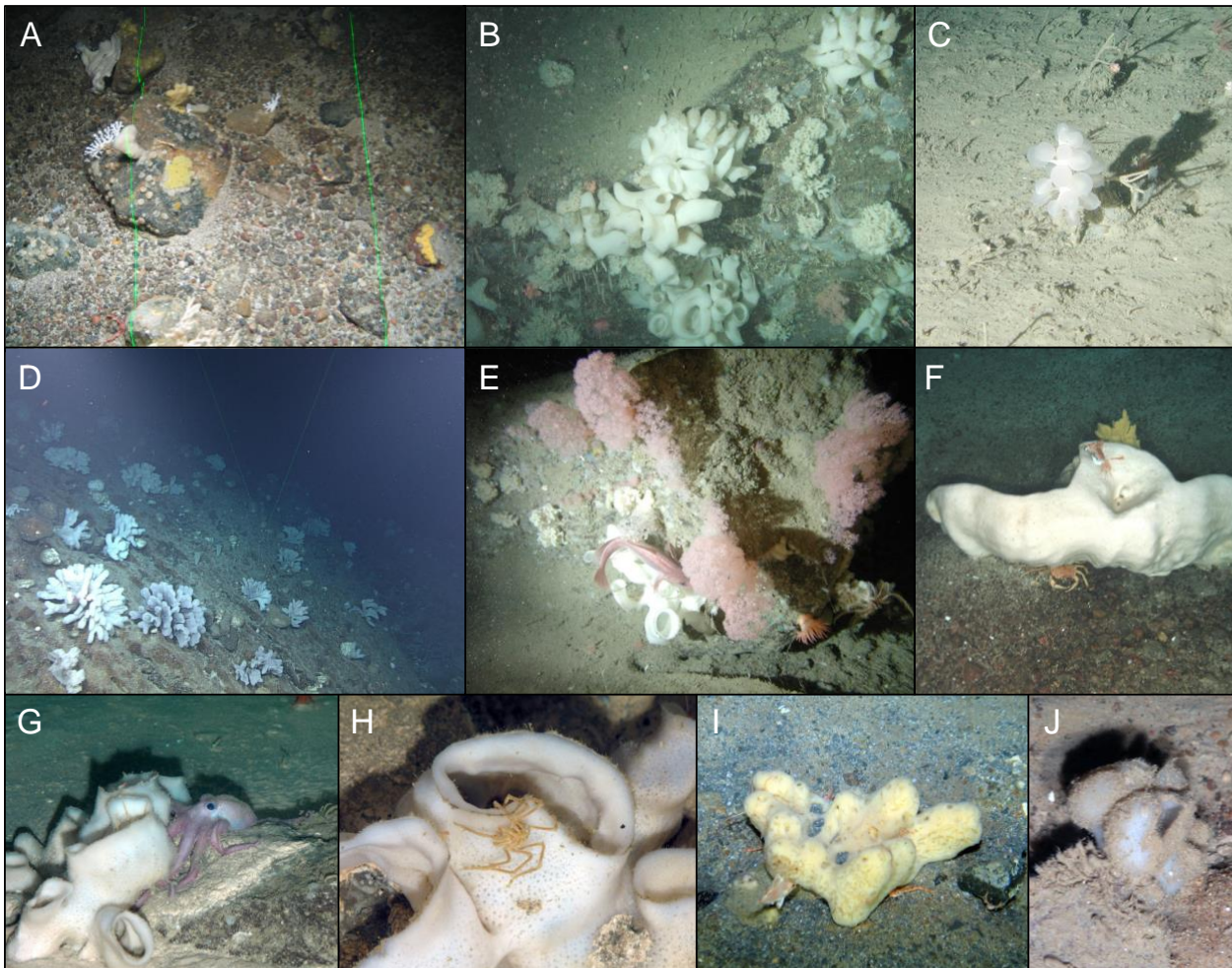
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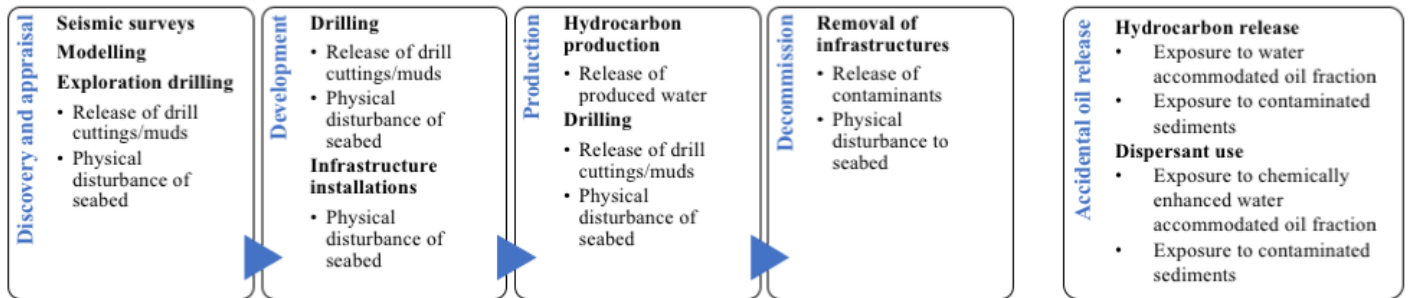
868 **Figure 1: Example of deep-sea sponges and of the habitats they form.** (A, B) Example of
869 deep-sea sponge morphotypes from the Faroe-Shetland Channel. (C) Carnivorous sponges of
870 the family Cladhorizidae constitute a deep-sea ecological oddity. (D) Present in high
871 abundance, deep-sea sponges can form sponge grounds as seen here at 1890m depth from
872 Orphan Knoll, NW Atlantic. (E to H) Deep-sea sponges and sponge grounds provide habitats
873 for various benthic organisms (I and J) Sponges are impacted by offshore oil and gas
874 activities amongst other through increased sedimentation. Photo credits: (D) Fisheries &
875 Oceans, Canada (DFO). (G to I) SERPENT Project, National Oceanography Centre,
876 Southampton UK.



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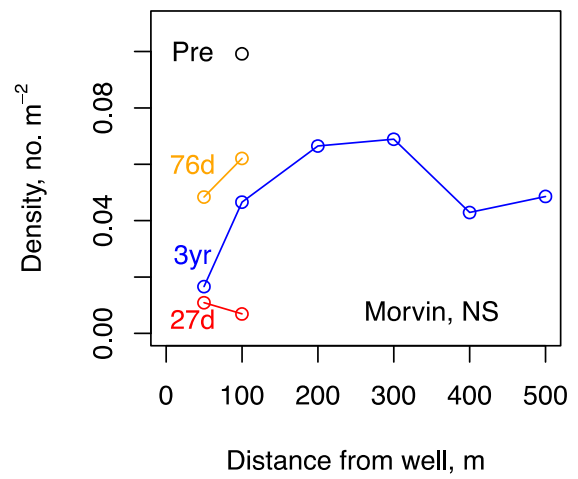
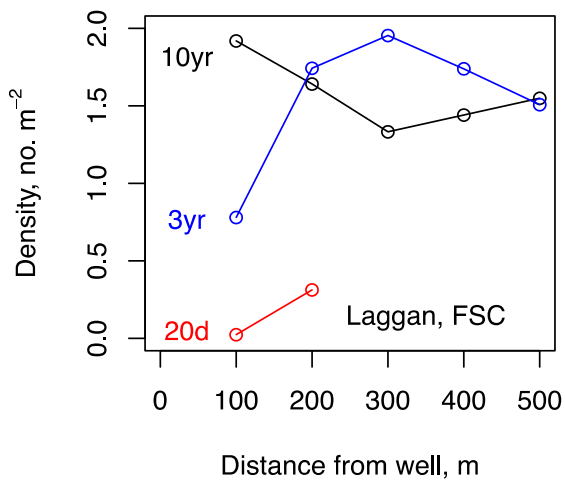
878 **Figure 2: Flow chart of oil fields development process divided into 4 phases and main**

879 **activities associated with each phase.**



880 **Figure 3: Field data on the initial impact and recovery from oil drilling disturbance in**
881 **deep-sea sponges in the Faroe-Shetland Channel (FSC), at the Laggan site (Jones *et al.***
882 **2012), and Norwegian Sea (NS), at the Morvin site (Gates and Jones 2012).**

883 The density of all megafaunal sponges is shown with distance from drilling activity at
884 different time points (colours) after drilling (units years [yr] and days [d]). Pre indicates
885 densities prior to drilling activity.



886 **Table 1: VME and EBSA criteria and their applicability to sponge grounds as**
887 **respectively defined by the UN FAO and the UN CBD.**

Designation	Criteria	Characteristics of deep-sea sponges and/or sponge grounds fulfilling criteria
VME	Uniqueness or rarity	Deep-sea sponge grounds are not rare but occur in specific and limited areas where favourable abiotic conditions are present
	Functional significance of habitats	Deep-sea sponges increase physical heterogeneity of benthic ecosystems
	Fragility	Deep-sea sponges are extremely vulnerable to physical damage by trawling or other anthropogenic activities
	Life history traits making recovery difficult	Deep-sea sponges are considered as slow-growing, long lived organisms and their reproduction cycles are largely unknown
	Structural complexity	Deep-sea sponge grounds give three-dimensionality to seabed increasing the number of available microhabitats
EBSA	Uniqueness or rarity	Deep-sea sponge grounds are not rare but occur in specific and limited areas where favourable abiotic conditions are present
	Special importance for like history stages of species	Deep-sea sponge grounds constitute nursery grounds for fish and invertebrate species
	Importance for threatened, endangered or declining species and/or habitats	Deep-sea sponge grounds constitute nursery grounds for threaten species such economically important fishes
	Vulnerability, fragility, sensitivity or slow recovery	Deep-sea sponges are considered as slow-growing, long lived organisms, making them both vulnerable to anthropogenic activities and slow to recover
	Biological productivity	Deep-sea sponges play important roles in the biogeochemical cycling and the habitat they create support diverse benthic ecosystems
	Biological diversity	Deep-sea sponge grounds provide a habitat to diverse benthic vertebrate and invertebrate species
	Naturalness	Anthropogenic activities such as oil and gas exploitation and mining are impacting deep-sea sponge grounds

889 **Table 2: Overview of major impacts of offshore oil and gas activities on deep-sea sponges and deep-sea sponge grounds at community,**
890 **individual, cellular and molecular levels and throughout oil field development.** Impacts described in deep-sea sponge species are highlighted
891 in green. Impacts described in shallow-water sponge species but not yet confirmed for deeper species are highlighted in orange. Impacts
892 described in other benthic organisms but not yet investigated in any sponge species are highlighted in red to emphasize current knowledge gaps.

		Exploration and appraisal	Field Development	Production	Decommissioning	Deep-sea oil spill
Community level	Main concern	<i>Physical disturbance of seabed and increase sedimentation</i>		<i>Discharge of drill muds and cuttings</i>	<i>Removal of structure</i>	<i>Exposure to high hydrocarbons and dispersant concentrations</i>
	Impacts				Benthic habitat destruction.	Changes in benthic community abundance, age structure and trophic interactions.
		Diminished benthic community.		Benthic community diversity/abundance decrease.		
Individual Level	Main concern	<i>Seismic survey and increase sedimentation</i>	<i>Increase sedimentation</i>	<i>Discharge of produced water</i>	<i>Release of chemical contaminants</i>	<i>Exposure to high hydrocarbons and dispersant concentrations</i>
	Impacts	Larval development delay and malformations.				Health decline, hydrocarbon bioaccumulation.
		Changed respiration rate and reproduction capacities. Decreased growth rate.		Bioaccumulation of PAH and heavy metals.		Larval settlement disturbance. Hydrocarbon bioaccumulation.
		Paused filtration.				
Cellular & Molecular levels	Main concern	<i>Discharge of drill muds and exposure to chemicals via release of produced water</i>				<i>Exposure to high hydrocarbons and dispersant concentrations</i>
	Impacts	Decrease immune system function.				Decreased immune system function.
		Activation of MAPKs and cytochrome P450 pathways. Oxidative stress.				Activation of MAPKs and cytochrome P450 pathways. Oxidative stress.
		Decrease of lysosomal membrane stability.				

