

# Unit pockmarks associated with *Lophelia* coral reefs off mid-Norway: more evidence of control by ‘fertilizing’ bottom currents

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**Abstract** High-resolution topographic mapping of Norwegian deep-water *Lophelia* coral reefs and their immediate surrounding seafloor has disclosed striking associations with small (<5 m diameter) ‘unit’ pockmarks. A total of four study areas with *Lophelia* reefs and unit pockmarks are here described and discussed. At the large Fauna reef, which spans 500 m in length and 100 m in width (25 m in height), there is a field of 184 unit pockmarks occurring on its suspected upstream side. Three other, intermediate-sized Morvin reefs are associated with small fields of unit pockmarks situated upstream of live *Lophelia* colonies. For two of the latter locations, published data exist for geochemical and microbial analyses of sediment and water samples. Results indicate that these unit pockmarks are sources of light dissolved hydrocarbons for the local water mass, together with nutrient-rich pore waters. It is suggested that the ‘fertilized’ seawater flows with the prevailing bottom current and feeds directly into the live portion of the *Lophelia* reefs. With an estimated growth rate of ~1 cm per year for the Morvin *Lophelia* corals, it would take between 1,000 and 2,000 years for the reefs to colonize the closest unit pockmarks, currently occurring 10–20 m from their leading (live) edges.

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## Introduction

### Unit pockmarks

Pockmark craters in the seafloor were first discovered by Lew King and Brian MacLean in sedimentary basins off Nova Scotia (King and MacLean 1970) and, subsequently, in most seas and many lakes worldwide (e.g. van Weering et al. 1978; Newton et al. 1980; Hovland 1981; Solheim and Elverhøi 1985; Hovland and Judd 1988; Rise et al. 1999; Judd and Hovland 2007; Newman et al. 2007; Chand et al. 2008; Cathles et al. 2010; Plaza-Faverola et al. 2010). They occur in many sizes, ranging from normal (5 to 200 m in diameter, reaching 15 m deep), to giant (e.g. Ondréas et al. 2005; Sahling et al. 2008) and mega-pockmarks (Betzler et al. 2011), which are rare. The smallest ones, called ‘unit’ pockmarks, are less than 5 m in diameter and less than 1 m in depth. They were first described in the 1980s, based on seafloor surveys with towed side scan sonar systems conducted on both sides of the Atlantic Ocean (Hovland et al. 1984; Harrington 1985). They were later detected with side scan sonars and subbottom profilers mounted on remotely operated vehicles, ROVs (e.g. Hovland and Judd 1988; see overview in Judd and Hovland 2007). Today, the mapping of unit pockmarks has become easier and more accurate, with the use of ROV-mounted multi-beam echosounders. Thus, their locations and shapes can be accurately determined on digital terrain models (DTMs) having grid cell resolutions equal to or higher than 0.5×0.5 m (Hovland et al. 2010).

According to latest consensus, normal pockmarks are inferred to result from focused, continuous or sporadic gas and pore-water seepage (e.g. Sahling et al. 2008; Brothers et al. 2011) but exactly how they are formed is still a matter of debate (Betzler et al. 2011). This is mainly because only few pockmarks have been continuously monitored and observed

over prolonged periods of time, one notable example being an actively seeping pockmark in the Gulf of Patras, Greece (Marinero et al. 2006). In contrast, the smaller unit pockmarks are inferred to have been generated by pore-water seepage alone, driven by an underground ‘piston’ of a local accumulation of subsurface free gas, in the form of small bubbles which are finely disseminated in the sediments. Indeed, rapid free gas migration is hindered by capillary forces (Cathles et al. 2010; Hovland et al. 2010). The occurrence of unit pockmarks on the seafloor may thus reflect a ‘hydraulically active seafloor’ whereby small amounts of sediment pore water are tidally pumped out of the seafloor (through the small depressions) at each low tide, i.e. diurnally. According to Hovland and Judd (1988) and Hovland et al. (1999), the occurrence of normal and unit pockmarks in the seafloor manifests a hydraulically active seafloor which behaves differently to adjacent water-saturated sediments without gas. During high tide, the sediment-trapped bubbles will contract due to the increased confinement pressure. During low tide, they will expand and increase in volume. Thus, the buried local free gas accumulation acts as a ‘billows’ which induces tidal pumping of the overlying sediment pore-water system (Hovland and Judd 1988; Hovland et al. 1999). A high density of normal and/or unit pockmarks on the seafloor suggests a high hydraulic activity, whereas a low density suggests a lower hydraulic activity.

#### *Lophelia* coral reefs

Off Norway, *Lophelia* coral reefs have commonly been defined as accumulations of partly relict (dead) and partly live *Lophelia pertusa* scleractinian colonies in combination with accumulations of other live organisms, especially filter feeders, their dead remains, and sediments (e.g. Dons 1944; Wilson 1979; Hovland et al. 1994; Mortensen et al. 2001). On the mid-Norwegian continental shelf, their structures are typically over 2 m high and 10 m wide, and can be up to 45 m high and over 100 m long (Dons 1944; Freiwald et al. 1999; Fosså et al. 2000; Buhl-Mortensen et al. 2010). Here, these organo-sedimentary structures cover less than 1 % of the total seafloor (Fosså and Alvsvåg 2003) at water depths of ~50–450 m (Thiem et al. 2006), often in the vicinity of pockmarks (Hovland and Risk 2003; Hovland 2005, 2008; Hovland et al. 2010). The observed co-occurrence of *Lophelia* coral reefs with normal pockmarks, unit pockmarks and sometimes gas seepage forms the foundation of the ‘hydraulic theory’ for deep-water coral reef growth. According to Hovland and Mortensen (1999), Norwegian *Lophelia* coral reefs occur as a consequence of increased local seafloor “hydraulic activity”, as mentioned above. The hydraulic seafloor activity causes an extra input of ‘exotic’ chemical substances from the substratum to the local seawater

column. According to the hydraulic theory, substances such as H<sub>2</sub>S, NH<sub>3</sub>, CH<sub>4</sub>, fosfate (P), and CO<sub>2</sub>, and even fresh water (leaking groundwater) stimulate extra local organic production (Hovland and Mortensen 1999). More recent data have further supported this theory (see, for example, Hovland and Risk 2003; Hovland 2008).

Although this theory has never been proved wrong, it is contested by others stating that the main factors controlling reef occurrence are water mass characteristics, including density, and high current velocities associated with topographical seafloor highs, where eddy currents and internal waves concentrate nutrients and increase food supply (e.g. Frederiksen et al. 1992; Freiwald et al. 1999, 2002; Thiem et al. 2006). However, the notion that elevated topography plays a major role in determining specific reef locations certainly does not apply to all *Lophelia* coral reefs off mid-Norway. Here, some live reefs have been documented well below the surrounding mean seafloor elevation inside pockmark-like depressions, especially at the Kristin and Morvin hydrocarbon fields (Hovland 2005, 2008).

In the present study, the co-occurrence of *Lophelia* coral reefs with unit pockmarks has been investigated in selected sectors of the Morvin field and south of the Sula Reef Complex (Hovland et al. 1998; Hovland and Mortensen 1999; Hovland 2008), where the large ‘Fauna reef’ has recently been mapped together with unit pockmarks and a much smaller *Lophelia* coral reef. The objective was to evaluate a possible causal association between these two apparently unrelated seafloor features, based on detailed assessments of their spatial distributions combined with information on bottom currents and sediment gas characteristics.

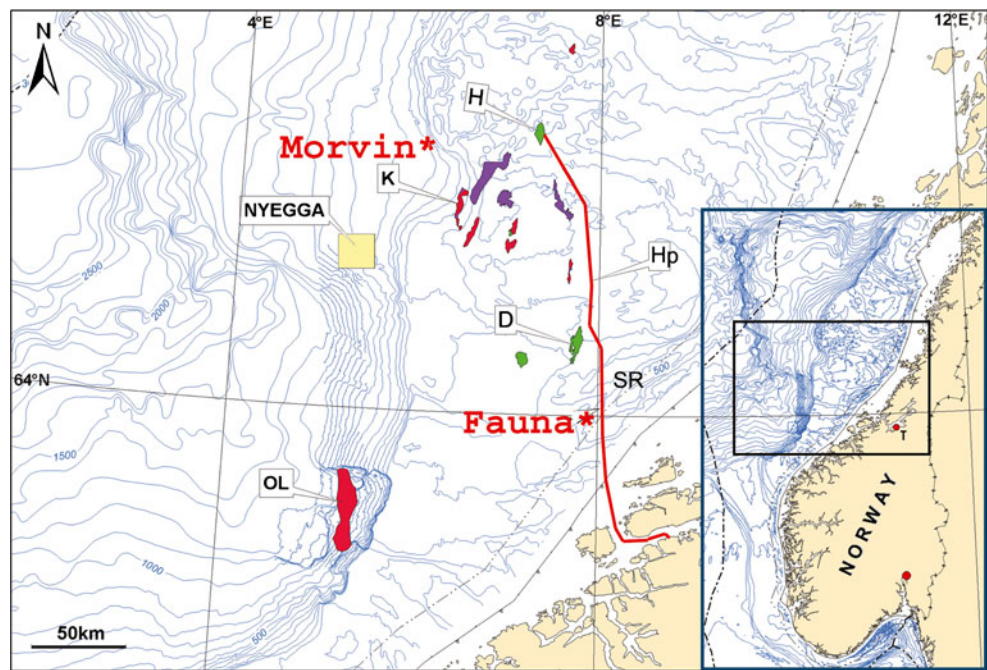
#### Study areas and previous work

Based on high-resolution seabed mapping and visual inspections conducted with ROVs during the last decade, four datasets were selected from two sectors of the mid-Norwegian continental shelf (Fig. 1):

- Areas I–III, *Lophelia* coral reefs in the Morvin hydrocarbon field (~7 km<sup>2</sup>), at water depths of 320–390 m (Hovland 2008);
- Area IV, the Fauna reef, in a newly mapped, 0.225 km<sup>2</sup> rectangular area (920×245 m) located due south of the Sula Reef Complex (Freiwald et al. 2002; Hovland et al., unpublished data).

Numerous normal pockmarks and hundreds of unit pockmarks and small *Lophelia* coral reefs occur in the study areas I–III. Over 200 unit pockmarks, the Fauna reef, and a smaller unnamed reef occur in study area IV.

**Fig. 1** Locations of oilfields (green), condensate fields (purple) and gas fields (red) off mid-Norway (Norwegian Sea): study areas I–III are in the Morvin field (asterisk), and study area IV at the Fauna reef (asterisk) close to the Sula Ridge (SR). D Draugen field, H Heidrun field, K Kristin field, OL Ormen Lange field, Hp Haltenpipe, T Trondheim (based on Hovland 2008)



The Morvin field was discovered by exploration drilling in 2003, followed by seafloor mapping, pipeline routing, steel template installation, and infrastructure field development (see [www.npd.no](http://www.npd.no) and [www.ptil.no](http://www.ptil.no)). The high density of *Lophelia* coral reefs called for particularly strong protective measures to be taken. During production drilling in 2009–2010, combined ROV-based visual monitoring and environmental studies were conducted in various sectors, including study areas I–III (unpublished proprietary Statoil ASA data). Consent to use the installed facilities at the Morvin field was granted by Ptil (the petroleum safety authority of Norway) in June 2010, and Morvin now produces through four production wells in two subsea templates (see [www.ptil.no](http://www.ptil.no)).

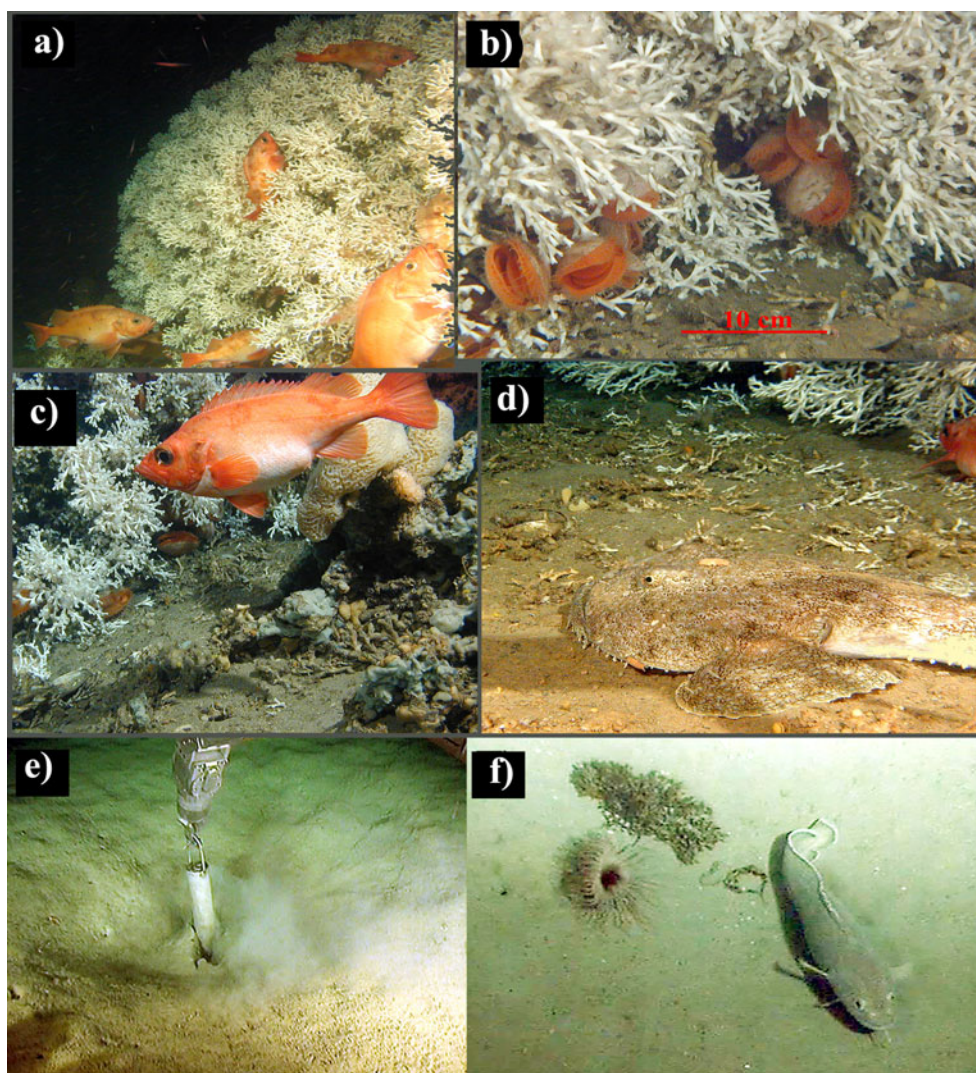
Nearly 1 year of close inspection of live *Lophelia* branches and even individual polyps (mainly from study area I) has revealed that the Morvin corals grow at a relatively high rate of close to 1 cm per year, slightly faster than the 0.7 cm per year recorded elsewhere in the region (Mortensen 2000; Buhl-Mortensen et al. 2010). One of the larger coral reefs studied to date is the MRR08 reef (Morvin Reference Reef 2008; Hovland et al. 2010), located 1–2 km west of the current study areas I–III. The MRR08 reef is about 80 m long and 25 m wide. It occurs inside a normal pockmark (130×80×10 m) and occupies about one third of the depression. The reef is growing from the maximum depth of 370 m, up along the northern side, to the rim of the pockmark at 360 m water depth (Fig. 2). Solitary and clustered unit pockmarks occur near this reef (Hovland et al. 2010).

Geochemical analyses at Morvin have demonstrated the natural occurrence of light hydrocarbons (methane, ethane,

propane and butane) at varying concentrations in shallow sediments (0–40 cm), which would imply natural seepage of light hydrocarbons from below via molecular and fluid migration, so-called micro-seepage (Judd and Hovland 2007; Etiope et al. 2009). At and near the MRR08 reef, eight sediment core samples were acquired from the seafloor (Hovland 2008), with one core (S8) from the centre of a unit pockmark (Fig. 2), others from normal pockmarks, and one background core (S6; Table 1). Compared to this regional reference core (S6), the total hydrocarbon concentrations were 2–5 times higher in the other cores, which are interpreted to represent micro-seep locations. A continuous, general and partly focused flux of light hydrocarbons through the seafloor is indicated also by the documented occurrence of potentially hazardous (for drilling) ‘shallow gas’ accumulations (see, for example, Judd and Hovland 2007) above the Morvin hydrocarbon reservoir at about 2 km depth below seafloor (unpublished proprietary Statoil ASA data).

Previous coral and geochemical studies in the vicinity of the Fauna reef include work on the Haltenpipe Reef Cluster (HRC) about 1.5 km NE of study area IV (Hovland et al. 1998; Hovland and Mortensen 1999; Hovland 2008), where nine gravity cores were acquired from the base of the large coral reefs. Compared to the regional background value, the total hydrocarbon concentrations of two samples (G1 and G2) collected near clusters of unit pockmarks were 2–3 times higher (Hovland et al. 2010). Furthermore, dating of oldest relict *Lophelia* fragments documented that the HRC had been growing continuously at the same location for over 8,000 calendar years (Hovland and Mortensen 1999; Hovland 2008).

**Fig. 2** Prolific marine life at *Lophelia* coral reefs off mid-Norway. a, c *Sebastes* (redfish) congregating for spawning on a 1.5-m-tall *Lophelia* colony in study area I (Morvin field). b *Lophelia* colony with *Acesta excavata* bivalves attached to its lower portion (study area I). d Monk fish resting on the sea-floor next to a *Lophelia* colony in the Morvin field. In b and d, the long white coral branches suggest relatively rapid growth rates (see main text). e Geochemical sampling inside a unit pockmark at Morvin, site MRR08 (see Table 1, and also Hovland et al. 2010). f *Brosme* sp., a *Flustra* sp. colony, and a sea anemone inside a unit pockmark (~80 m west of the Fauna reef)



## Materials and methods

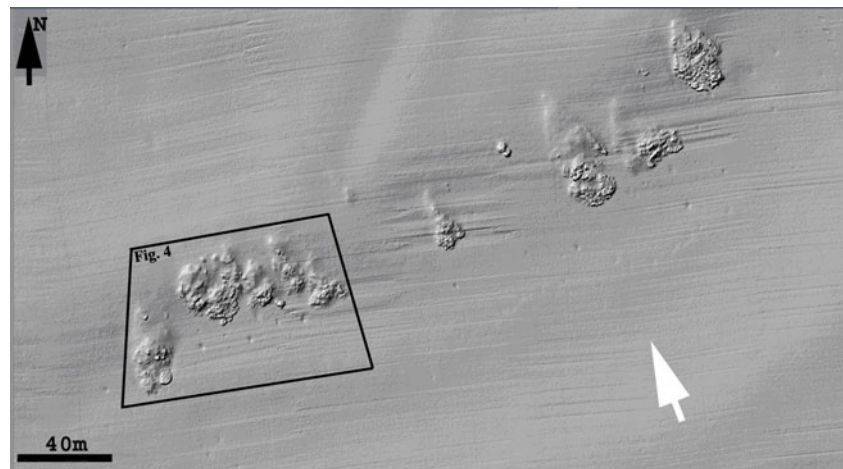
Each of the four study areas has been mapped by means of (1) high-resolution ROV-mounted multi-beam echosounders, to a resolution better than  $0.5 \times 0.5$  m grid size, and (2) visual transects with ROV-based continuous video recording. The resulting DTMs have at least one depth sounding per  $0.5 \text{ m}^2$ . At such high resolution, it is possible to discern between living and relict *Lophelia* colonies, and to detect and visualize unit pockmarks. Each selected study area has been analysed by the following steps:

1. Review of available video material and still photographs acquired with ROV; assessment and analysis of mapped geomorphological elements, using high-resolution shaded relief DTMs;
2. Assessment of *Lophelia* coral reefs and their live portions, based mainly on slope angles and video documentation;
3. Determination of the prevailing bottom current direction, based on current measurements, visual ROV observations, surface sediment structure (drifts), and the orientation of *Paragorgia* corals (Mortensen 2000);
4. Identification of unit pockmarks: assessment of their distribution and density (number of pockmarks per

**Table 1** Hydrocarbons in sediments of the Morvin field ( $\mu\text{l}$  gas per litre sediment; extracted from Hovland 2008). Samples S1 and S4 were acquired near the centre of a *Lophelia* coral reef, S8 within a unit pockmark adjacent to another *Lophelia* reef MRR08, and S6 about 30 m from any *Lophelia* reefs and unit pockmarks

ID	Methane	Ethane	Propane	n-Butane	Sum
S1	472.7	79.8	43.8	18.7	615.1
S4	371.1	61.8	36.1	16.6	485.5
S6	103.1	16.9	9.5	4.4	134.0
S8	250.0	36.2	19.8	8.8	314.8

**Fig. 3** Artificially shaded relief DTM in study area I (Morvin field; illumination from NW) revealing *Lophelia* coral reefs aligned along a slight SW-NE-trending depression, whereas each individual reef tends to align along the prevailing current direction (white arrow). Despite some instrumental noise (parallel striping caused by swath acoustic beams), fine details such as individual live *Lophelia* colonies and unit pockmarks are visible



- 1,000 m<sup>2</sup>) relative to the adjacent *Lophelia* coral reefs and prevailing bottom current direction;
5. Assessment of faunal observations, as well as geochemical and microbial data (Jensen et al., unpublished data; Hovland 2008).

This integrated analysis of geomorphology and biology together with unpublished (proprietary) data provides the main basis for the current study.

## Results

### Study areas I–III, Morvin field

Numerous *Lophelia* coral reefs have been mapped at the Morvin field (65 °09'N, 6 °28'E) in the Norwegian Sea (Fig. 1). Many of the reefs cluster at the base of slight ridges, in local depressions, and along iceberg plough marks (Hovland 2008; Hovland et al. 2010).

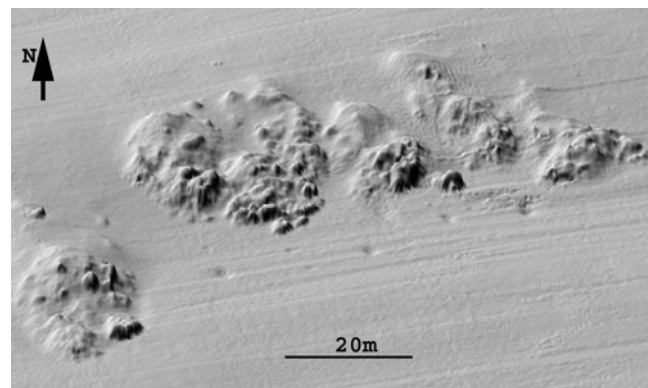
### Area I, *Lophelia* reefs and unit pockmarks

On artificially shaded relief maps (DTMs) for study area I in the Morvin field (e.g. Figs. 3 and 4), live *Lophelia* colonies appear as steep, rounded structures up to 3 m in height. They generally face into the prevailing current (Hovland 2008)—here, more or less unidirectional from the SSE (Fig. 3). Moreover, the reefs tend to align SSE–NNW, sometimes comprising long chains of smaller reefs. Visual inspection has shown that the Morvin colonies are unusually asymmetric in their growth. On the DTMs, the live portions of the reefs are generally characterized by steep slope angles of >20 ° (Fig. 4), whereas their lee-side dead portions are significantly less steep.

Several *Lophelia* coral reefs and steep-sided live colonies, as well as unit pockmarks are evident on the oblique view DTM of Fig. 4. The vertical scale has been exaggerated (×2) in the image so that, compared to Fig. 3, an improved 3D depiction has been achieved. Whereas the

steep, live portions of the *Lophelia* colonies are seen facing southwards, their lee side is less steep and contains dead and partly buried corals and organic debris. From Figs. 3 and 4, it is tentatively suggested that live *Lophelia* colonies tend to occur adjacent to and downstream of unit pockmarks in study area I, generally at a distance of less than 30 m.

On Fig. 5, a relatively large colony is seen to be alive only at the outer tips of branches facing into the prevailing current. The image also suggests that there is a relatively high degree of sedimentation (silting) on the lee side of the living coral branches. The newly formed colonies (branches) may become stressed by this before succumbing to lee-side burial. Whereas *Lophelia* colonies near the Sula Ridge (Fig. 1), for example, tend to grow in the expected spherical fashion (Wilson 1979; Hovland and Mortensen 1999), the ones at Morvin tend to form steep facades which only seem to cover a sector up to ~120 ° (Fig. 5). A plausible reason for this strong asymmetry in colony growth is the near-unidirectional nature of the bottom current, as has been documented by near-bottom measurements and ROV observations over a



**Fig. 4** Obliquely viewed artificially shaded relief DTM in study area I (for location, see Fig. 3) showing unit pockmarks generally occurring immediately upstream of live *Lophelia* colonies. The 4–5 unit pockmarks seen here are all within about 10 m of the live colonies

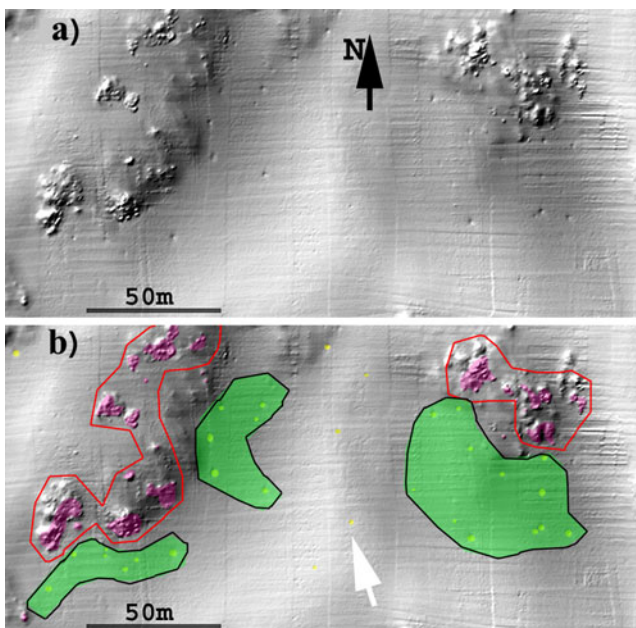


**Fig. 5** Video-grabbed image of a typical *Lophelia* coral reef in the Morvin field, showing the live, outer few cm of the colony (white rinds, downstream view). The rest of the colony is gradually silted up and colonized by other organisms, and eventually buried in sediments (based on Hovland 2008)

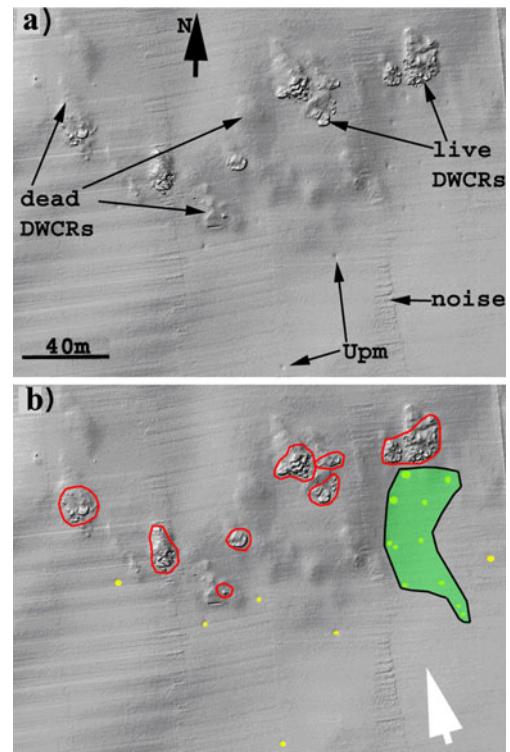
continuous period of about 8 months during 2009–2010 (unpublished proprietary Statoil ASA data).

#### Area II, *Lophelia* reefs and unit pockmarks

A shaded relief DTM for study area II in the Morvin field reveals that the coral reefs are growing at the northern rims



**Fig. 6** a Artificially shaded relief DTM in study area II (Morvin field; illumination from NW), with prevailing current direction indicated in b (white arrow): despite some instrumental noise (parallel striping caused by swath acoustic beams), there is distinct evidence of unit pockmarks (green) generally occurring immediately upstream of live *Lophelia* colonies (red outlines)



**Fig. 7** a Artificially shaded relief DTM in study area III (Morvin field; illumination from NW): despite some instrumental noise, there is distinct evidence of deep-water coral reefs (DWCRs, both live and dead) as well as unit pockmarks (Upm). Each individual *Lophelia* reef tends to align along the prevailing current direction (white arrow in b). b Distinct group of unit pockmarks (green) immediately upstream of live *Lophelia* colonies (red outlines)

of two slight seafloor depressions, or basins (Fig. 6). The study area can be subdivided into a western and an eastern group of reefs, the inferred live portions of each reef being coloured red in Fig. 6b.

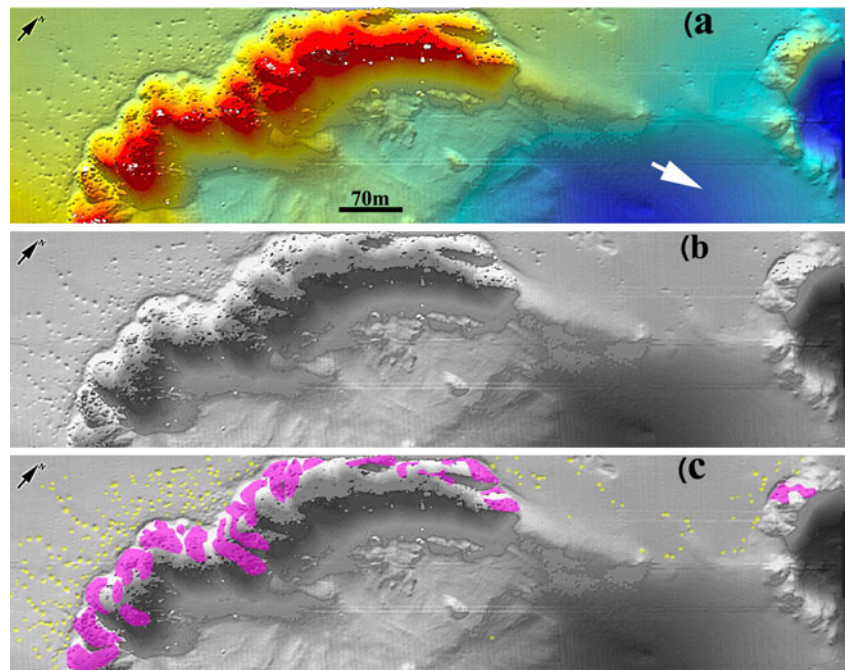
In Fig. 6a, it is possible to distinguish several individual unit pockmarks, comprising 13–14 unit pockmarks in the western part of area II and 7–8 in the eastern part. Grouping of unit pockmarks occurring within 25 m of each other reveals that they are concentrated immediately upstream of the *Lophelia* coral reefs (Fig. 6b).

#### Area III, *Lophelia* reefs and unit pockmarks

Figure 7 shows a shaded relief DTM for study area III in the Morvin field. The geomorphological features strongly resemble the eastern part of study area I (Fig. 3), although study area III is located about 3 km further to the west (note the stretch of pipeline in the NE corner of Fig. 7). This clearly illustrates how uniform the terrain and many of the reefs appear in the Morvin field (see also Fig. 4.32 in Hovland 2008).

Some main features have been highlighted in Fig. 7a, which can serve as guide for analysing the other images

**Fig. 8** Artificially shaded relief DTM of the rectangular high-resolution mapped area which includes study area IV (see Fig. 9; illumination from NW): the large Fauna reef is clearly seen as an elevated elongated structure. a, b Unit pockmarks at various water depths (blue+violet 300–295, green 295–292, yellow 290–285, orange+red 285–273 m). The prevailing bottom current flow direction (white arrow) is inferred to be from west to east, particularly evidenced by the linear sedimentation features (drifts) seen here. c Unit pockmarks (yellow) and inferred live *Lophelia* colonies (purple)



shown for the Morvin field. There are relatively few unit pockmarks visible in study area III—15 in all, of which only about half can be grouped in terms of nearest neighbour at max. 25 m spacing. Nevertheless, the live *Lophelia* coral reefs (Fig. 7b) generally occur to the north and northwest of nearby unit pockmarks, at maximum distances of 40–50 m. Interestingly, wide patches of seafloor mapped in Figs. 3, 4, 6 and 7 contain neither any unit pockmarks, nor any live reefs, consistent with an interrelationship between the two elements.

Study area IV, Fauna reef

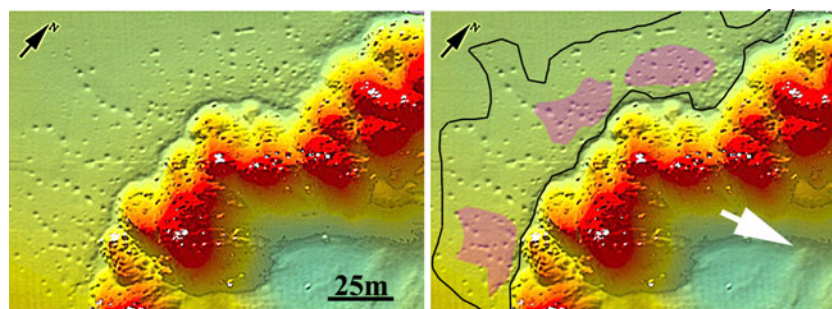
The Fauna reef was named after the multipurpose vessel *Edda Fauna*, which was used to investigate the reef in 2010. The reef is about 500 m long, 100 m wide and 25 m high (Fig. 8). The high-resolution mapping was conducted in a rectangular

area of 920×245 m (centred at 07 °53'E, 63 °54'N) about 15 km SSW of the well-known Sula Reef Complex (Fig. 1).

Area IV, *Lophelia* reefs and unit pockmarks

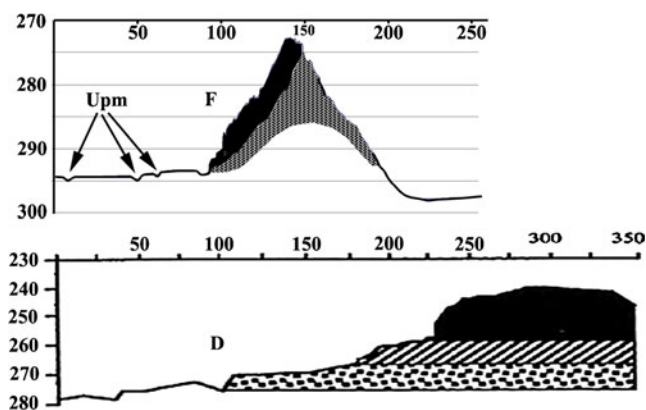
In all, 233 unit pockmarks were identified in study area IV, distributed in three groups (Fig. 8). The largest, SW group consists of 184 unit pockmarks immediately to the west of the Fauna reef. There is another group directly north of the Fauna reef. The NW group is situated to the west of a much smaller *Lophelia* coral reef, which is ca. 50 m long, 30 m wide and 7 m high (see far right side of Fig. 8).

Pockmark density is highest in the SW group, varying between 3 and 16 per 1,000 m<sup>2</sup>. Whereas 79 % of the unit pockmarks are evenly scattered within this group (Fig. 9) upstream of the prevailing current at the Fauna reef, the rest are scattered upstream of the much smaller *Lophelia* coral reef.



**Fig. 9** Artificially shaded relief DTM at the Fauna reef, study area IV. Left Un-interpreted, with evidence of numerous unit pockmarks on the west side of the reef, and individual *Lophelia* colonies on the reef (small dark shadows). Note also the lobate shape of the reef, bounded

towards the ‘undisturbed’ seafloor (to the west) by a ca. 3-m-wide trough or ‘moat’. Right Unit pockmarks (black outlines) and the moat along the reef. Violet Areas of highest densities of unit pockmarks (up to 16 per 1,000 m<sup>2</sup>)



**Fig. 10** Two interpreted profiles across two different *Lophelia* coral reefs. *Top* W–E depth profile across the Fauna reef (F, study area IV) showing three of the unit pockmarks (Upm) occurring to the west of the live *Lophelia* colonies. *Bottom* Modified version of a depth profile extracted from Mortensen et al. (1995) across *Lophelia* reef D in the Haltenpipe Reef Cluster about 2 km north of the Fauna reef. *Black filling* Live *Lophelia* colonies, *other fillings* dead *Lophelia* colonies and *Lophelia* rubble (remains)

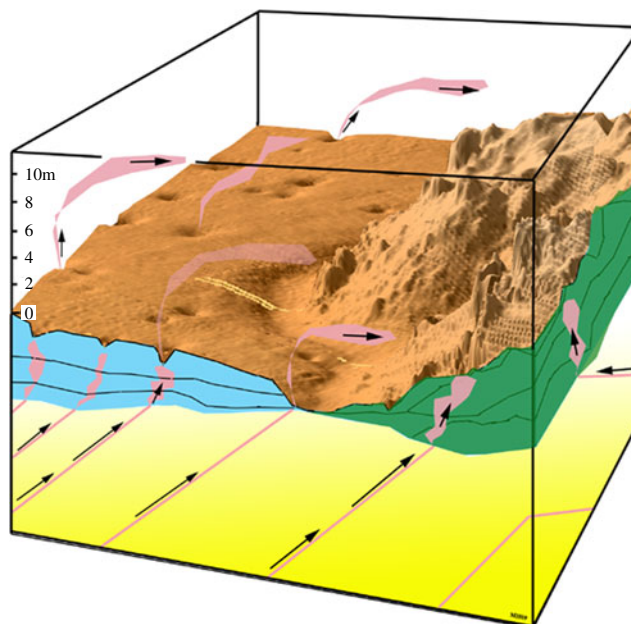
In Fig. 10, an interpreted W–E vertical depth profile through the Fauna reef (study area IV) is compared with a previously published profile for reef D in the HRC (Mortensen et al. 1995), both based on ROV video transects revealing the distributions of live and dead *Lophelia* colonies (in the figure, shown as black and patterned respectively), as well as relict *Lophelia* (rubble). Whereas the distance between the live *Lophelia* colonies and the unit pockmarked (normal) seafloor sediments is less than ~50 m in area IV of the Fauna reef, it is more than 100 m at reef D in the HRC. Furthermore, colonization of dead *Lophelia* by live *Lophelia* colonies is less pronounced in area IV.

## Discussion and conclusions

In general, pockmarks occur only in areas of the seafloor which have been or are hydraulically active (e.g. Judd and Hovland 2007; Hovland et al. 2010), and unit pockmarks are suspected to form by tidally induced pore-water escape through the seafloor (see Introduction). Both dissolved and particulate organic and inorganic substances, including nutrients, are entrained in the flow, thereby forming a pool of locally enriched water. Although the sampled unit pockmarks have higher than background concentrations of light hydrocarbons in the present study areas, analyses of other chemical compounds remain to be performed. Nevertheless, it is well known that pore water is enriched in numerous components vital for marine life sustenance, such as phosphorous, sulphur and nitrogen (see overviews by Reeburgh 2007, and Jørgensen and Boetius 2007). For example, methane and sulphide are beneficial for invertebrates in many reduced environments (Dubilier et al. 2008). A group of

sulphur-oxidising *Gammaproteobacteria* related to endosymbionts of deep-sea mussels colonizing hydrothermal vents and cold seeps has been found associated with *Lophelia* (Neulinger et al. 2008; Kellogg et al. 2009). In *Lophelia* reef seawater from the Kristin field adjacent to the Morvin field *Lophelia* reefs, bacterial analyses revealed a high number (8 %) of clones related to sulphide-, nitrite-, and iodide-oxidising bacteria. The finding suggests chemosynthesis to be involved with the maintenance of the local deep-water coral reef ecosystem (Jensen et al. 2008). Furthermore, the discovery, in gills of the bivalve *Acesta excavata*, of a novel gammaproteobacterium related to host associates of coral and sponges (Jensen et al. 2010) strikingly reflects the high diversity of nutritional adaptations harboured by organisms in these coral reefs.

The results of the present study convincingly demonstrate a very close relationship between the occurrences of unit pockmarks and colonies of live *Lophelia* coral reefs off mid-Norway. Because the reefs and unit pockmarks are relatively rare, their co-occurrence at four different and independent locations (study areas I–IV) is highly unlikely to be by pure chance. Rather, the data are consistent with a causal, non-random relationship. According to the hydraulic theory, the unit pockmarks involve tidally mediated nutrient flow, representing a very reliable source



**Fig. 11** Conceptual illustration of the intimate relationship between unit pockmarks and nearby *Lophelia* reefs off mid-Norway. Free gas and pore water (subsurface arrows) migrate upwards along sedimentary bedding planes. Small pockets of subsurface free gas cause the formation of unit pockmarks, where gas and nutrient-charged pore water are ‘pumped’ upwards into the water column as a result of tidal forces. This forms elongated ‘plumes’ of ‘fertilized’ seawater emanating from the unit pockmarks, and subsequently swept horizontally towards the downstream coral reef



which would feed more or less continuously into the nearby corals independently of season, summer as well as winter.

Because of the unique situation at the Morvin field, where there is an overall steady unidirectional bottom current which waxes and wanes in velocity during the tidal cycle, the *Lophelia* reefs tend to develop in an elongated pattern. The finding that the coral branches grow into the current at an estimated rate of about 1 cm per year implies that the colonies would shift by about 10 m per  $10^3$  years. Considering that the oldest *L. pertusa* dating of buried material is ~8,600 calendar years (Hovland and Mortensen 1999), this suggests that the reefs at Morvin could have travelled about 86 m since reefs were established off mid-Norway.

If the distance to a unit pockmark is 20 m, it may take 2,000 years for the corals to reach and fill the pockmark. In the meantime, it would act as a reliable source of nutrient-containing fluids. Because the preliminary results on seafloor geomorphology reported for the present study areas suggest that the reefs can grow within a downstream distance of over 30 m from unit pockmarks, it is likely that numerous unit pockmarks have been buried underneath *Lophelia* coral reef debris over the last 10,000 years. Thus, the low-relief mounds (about 0.5 m high) could represent sediment-buried organic material (debris) which could have occupied previous unit pockmarks here. As a corollary it is suggested that, because unit pockmarks are such small features, they are liable to be rapidly colonized and subsequently obliterated and sealed off by organic growth and sedimentation (Hovland 2002), a situation apparent not only in study area IV near the Fauna reef but also at several reefs at the Morvin field, including reef MRR08 (Hovland et al. 2010).

#### Conceptual unit pockmark/*Lophelia* reef model

The present findings can be integrated into the following conceptual model (Fig. 11):

1. Unit pockmarks manifest the most recent and probably still continuously active seepage locations (Hovland et al. 2010);
2. Seepage adds nutrients to the water column which fuel primary and secondary production;
3. The prevailing near-bottom current transports this 'fresh' food (nutrients) directly to the coral polyps and associated organisms;
4. Once the reef has managed to grow into and colonize a unit pockmark, the nutrients feed directly into the reef and the topographic feature is obliterated;
5. Eventually, the small vent (unit pockmark) is occupied by organisms such as sponges, and becomes clogged and sealed by living and dead organic materials.

Future work on *Lophelia* reefs should also include systematic stable isotope analyses, combined with more geochemical sediment analyses and microbial studies. In conclusion, it is postulated that unit pockmarks provide the necessary seep-related nutrients to stimulate year-round healthy coral growth and reef development, even in the dark winter season of limited or no surface primary production. A possible test of this interpretation, which supports the 'hydraulic theory', would be to detect stable carbon isotope variations in DWCR skeletons as a function of season. The idea is that the coral would proportionally digest more seep-related nutrients during the winter/spring than during the suspected 'main' growth season, the summer/autumn months.

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