Int J Earth Sci (Geol Rundsch) (2007) 96: 201–213
DOI 10.1007/s00531-005-0495-y

ORIGINAL PAPER

Björn Lindberg · Christian Berndt · Jürgen Mienert

The Fugløy Reef at 70°N; acoustic signature, geologic, geomorphologic and oceanographic setting

Received: 15 February 2003 / Accepted: 28 February 2005 / Published online: 1 July 2005

Abstract This is the first in-depth study of a cluster of cold-water coral reefs, the Fugløy Reefs, found at 70°N on the Norwegian margin. Combining high-resolution seismic reflection data, side-scan sonar, video-images, and oceanographic measurements reveals the geologic, geomorphologic and oceanographic setting in which the reefs occur. The reefs consist mainly of the scleractinian ahermatypic *Lophelia pertusa*, and exist below the thermocline at water depths between 140 m and 190 m. The reefs appear as cone-shaped, acoustically transparent features on seismic reflection data, consistently located in places characterized by the availability of hard substrate, high relief, and periodical exposure to high tidal currents (>30 cm/s). These currents transport water of the Norwegian Atlantic Current to the reefs from an area with fluid expulsion-related pockmarks. The spatial relationship between reef, pockmark locations, and current directions suggests that seepage of biogenic gas might be a catalyst to reef growth. With a height of more than 40 m some of the Fugløy reefs are among the highest reported from the Norwegian Margin. This indicates highly favourable growth conditions, and conservative estimates indicate a *net* growth rate for the reefs of ~5 mm/year. We expect that cold-water reefs will be found further north along the Barents Sea margin as general awareness on the geophysical signature and appearance of the reefs increases, because all known factors involved in reef establishment and growth are within the required intervals also further north.

B. Lindberg · C. Berndt · J. Mienert
Department of Geology,
University of Tromsø, Tromsø,
9037 Norway

Present address: B. Lindberg (✉)
Statoil, 4035 Stavanger,
Norway
E-mail: bjlin@statoil.com
Fax: +47-51-995480

Present address: C. Berndt
European Way, Southampton Oceanography Centre,
Southampton,
SO14 3ZH, UK

Introduction

The first scientific work done on cold-water coral reefs along the coast of Norway was by Carl Dons during the 1930s and 1940s. Dons identified more than 100 reefs and compiled reef locations from fishermen reports (Dons 1944). Renewed interest in the reefs came with the introduction of submersibles in research on the continental shelf by the oil exploration industry during the 1980s and 1990s. The submersibles brought back spectacular pictures of deep-water oases, similar to well-known tropical corals with regards to colours and biologic diversity.

As industrial and scientific activity expands and moves into new offshore areas, the number of discoveries and documentation of cold-water corals along the coast of Norway increases rapidly, and a want and need for thorough understanding has developed. The reefs are already known to be important habitat for several fish species, but their importance to the ecosystem is not yet fully understood. Cold-water reefs are also a factor when it comes to underwater installations for the oil industry, as Norwegian reefs are protected by law against deliberate damage.

One of the largest and most well-known reefs along the coast of Norway is the Sula Reef discovered during a pipeline survey in 1990 (Hovland et al. 1994). The reef complex has been thoroughly studied and found to be an important habitat for marine species. The individual reefs are located on the Sula Ridge en echelon over a distance of 14 km, and 200–350 m wide. The en echelon pattern is most likely related to the orientation of iceberg plough-marks in the area, providing local highs and hard substrate for the reef larvae to settle on. The reefs are often divided into distinct zones including off-reef coral rubble, sediment-clogged coral framework, and proliferating coral framework (Mortensen et al. 1995; Hovland et al. 1998; Freiwald et al. 1999, 2002).

A recurring debate among deep-water reef scientists is on the possible role of (hydrocarbon)-seepage in relation to the nutrient supply of the reefs. Indications of linkages between the reefs and micro-seepage from the sub-seafloor include reef occurrences close to sites of increased HC-content in the sediments and signs of sub-seafloor fluid migration (Hovland 1990; Hovland and Thomsen 1997; Hovland et al. 1997, 1998; Henriet et al. 1998). Others have emphasized oceanographic factors and nutrient provision by ocean currents as the dominating factor as to where the reefs settle (Frederiksen et al. 1992; Freiwald and Henrich 1997), and anatomy and isotope studies of a reef in Stjernsund (Fig. 1) revealed the oceanographic setting as major controls reef growth (Freiwald and Henrich 1997).

In this first thorough study of the Fugløy Reefs, we map and examine the area (Fig. 1) by acoustic methods and hydrographical measurements as part of the EU-funded fifth framework program Environmental Control on Mound Formation along the European Margin (ECOMOUND). High-resolution acoustic data (side-scan sonar imagery and seismic reflection data) allow detailed mapping and study of the individual reefs, thereby giving good control on their extent, size, shape, acoustic signature and geomorphologic setting. Underwater video provides ground-truthing and information on the meso-scale structure of the reefs, allowing identification of various reef-zones. The CTD and current-meters were deployed to investigate current speed and direction, temperature, and salinity in the area.

We present a synthesis of these data to evaluate the importance of geological and oceanographic controls on cold-water coral reef growth. To facilitate the identification of reefs, we provide the typical traits of the reefs and their appearance on seismic reflection data. In particular we analyse the abundance, size and distribution of the reefs and compare the findings with spatial variations in the geological and oceanographic environmental variations in order to delimit the importance of such variations for reef growth.

Setting

The Fugløy Reef area, located about 300 km north of the Arctic Circle at 70°N (Fig. 1) is the northernmost published location of cold-water reefs (Hovland and Mortensen 1999; Fosså et al. 2000). During a pipe-line survey conducted by Statoil, acoustic and photographic data were acquired, but the area was not subjected to detailed study. The study area measures 13×20 km and is found at the outlet of a fjord system incising the Norwegian mainland. The basement in the area consists of fyllites, mica-schists, micaceous gneiss and mud-schists of Cambro-Silurian age, metamorphically overprinted during the Caledonian orogenesis (Sigmond 1992). Non-metamorphic Mesozoic rocks are found less than 20 km to the north, and the hydrocarbon reservoirs Snøhvit and Goliat are located some 130 km north in sandstones of Jurassic age, 1800 and 2300 m below sea floor (Sigmond 1992; Linjordet and Grung Olsen 1992).

Several phases of erosion have occurred offshore northern Norway during the last 600 ka due to the Scandinavian ice-sheet, which advanced all the way to the shelf-edge at full glaciations (Henrich and Baumann 1994). The latest deglaciation was characterized by several still-stands during the ice-retreat, which left three

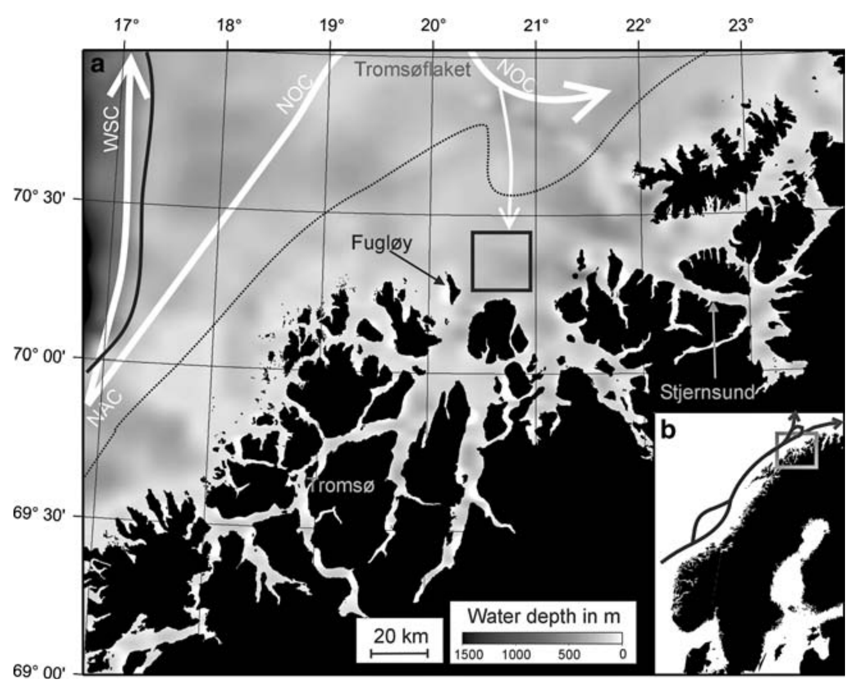

Fig. 1 **a** Map showing the large-scale bathymetry off northern Norway and location of the study area (*black square*). The *dotted line* marks the boundary between metamorphic and sedimentary bedrock, and the *bold line* marks the maximum ice extent during the last glacial (shelf edge). The *white arrows* show the dominating direction of the Norwegian Atlantic Current (*NAC*) splitting into the West Spitsbergen Current (*WSC*) and the North Cape Current (*NOC*), see text for further explanation. **b** Location of map (**a**) relative to Scandinavia, also showing the NAC (*bold line*) (modified from Poulain et al. 1996; Loeng 1991)

prominent moraine ridges on the continental shelf in the southwestern Barents Sea (Rokoengen et al. 1979). The bathymetric highs in the study area consist of diamictons but it would require additional regional mapping to attempt a correlation with known moraine ridges in the area. Vorren and Kristoffersen (1986) speculate that the southwestern part of the Barents Sea was deglaciated before 13.5 ka. The study-area lies well outside the Younger Dryas moraine (10–11 ka) and the glacial features must therefore be older. In local basins post-glacial sediments are found on top of the moraine (Rokoengen et al. 1979; Vorren and Kristoffersen 1986).

The Norwegian Atlantic Current (NAC), and the Norwegian Coastal Current (NCC) both flow northwards parallel to the coast of Norway (Fig. 1b) and dominate the large-scale surface water oceanography in the area. The warm and saline (typically T: 6–9°C and $S > 35$) NAC water-mass enters the Norwegian Sea from the south reaching velocities in excess of 40 cm/s. Towards the north, the NAC branches eastwards into the Barents Sea North Cape Current (NOC) and north along the shelf break West Spitsbergen Current (WSC) (Blindheim 1990; Poulain et al. 1996). Where the NAC reaches Tromsøflaket (71°30′N, 17°18′E) north of the study area, it is topographically influenced and deflected south towards the coast where it turns east along the shore (Loeng 1991). The NCC is a surface current, primarily fed from the Baltic Sea and run-off from the Norwegian main-land and thus less saline and colder ($T > 2$°C, $S < 34.7$) than the NAC (Loeng 1991). The NCC stretches as a westward thinning wedge above the water mass of the NAC due to salinity differences, and mixing increases towards the north (Vorren et al. 1984).

Data and methods

Three cruises were carried out with R/V Jan Mayen (University of Tromsø), acquiring geological and geophysical data during 2000–2002. The database for the study-area consists of ~350 km single-channel seismic profiles, 35 km^2 of high-resolution side-scan sonar data, as well as video-transects, current measurements, and CTD-measurements (Fig. 2).

We used an EG&G DF-1000 digital side-scan sonar recording backscatter data at 100 kHz. The tow-fish was

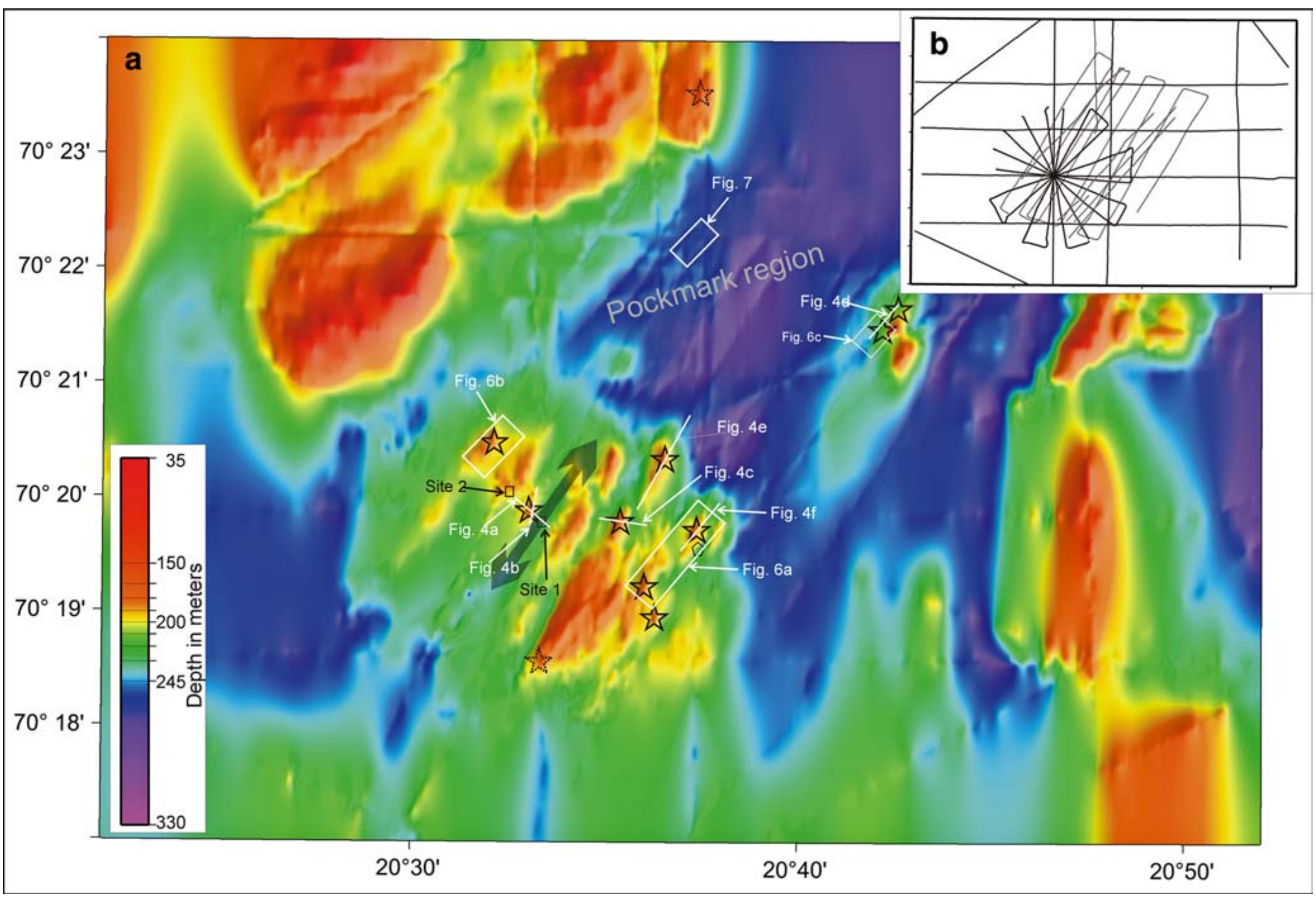

Fig. 2 **a** Bathymetric map of the study area with reefs (*stars*), current metres (*squares*, sites 1 and 2) and CTD locations (*pentagon*). The *large arrow* indicates dominating current directions. Most identified reefs are found on a hummocky central high, whereas the basin in the northeastern part mostly displays low relief and pockmarks (see text for discussion). Seismic examples and side scan sonar examples shown in the paper are marked in *white*. The location of the seismic database is shown in the inset map (**b**). *Bold line* sleeve-gun and 3.5 kHz, *dotted black line* 3.5 kHz data, *dotted grey line* side-scan sonar and 3.5 kHz

kept at ~30 m above the seafloor, and the swath of the system reaches approximately 250 m to each side, with a horizontal resolution on the order of 0.5 m. The sources for the seismic reflection data were two 40 cubic inch sleeve-guns giving a vertical resolution of ~0.5 m. The seismic data were digitally recorded (Elics-Delph) and subsequent processing included bandpass frequency filtering, trace mixing, and AGC-scaling. Shooting interval varied between 5 s and 10 s, and vessel speed was generally 3–5 km. The 3.5 kHz-data was acquired with a keel-mounted GeoPulse 137 sediment profiler consisting of 12 piezo-electric transceivers emitting a pulse of 1–2 ms, giving a maximum resolution of 0.2 m. The central frequency of the system is 3.5 kHz, and the data were printed out on paper as well as digitally recorded for processing. The processing performed was frequency filtering, AGC-scaling, and smoothing to remove heave. Shooting intervals varied from 1 s to 5 s, and the vessel speed was from 2 km to 5 km. An underwater video-camera mounted on a sledge, collected black/white photography from the seafloor while drifting over the areas of interest.

Three current metres (RCM9 Aanderaa Instruments) were deployed for measuring current (velocity and direction), temperature, salinity, and water depth. The CTD data were collected using a SEABIRD-sounder.

Observations

Oceanography

Based on continuous logging of depth during the three cruises, we compiled a bathymetric map (Fig. 2). The data were gridded using near neighbour algorithm, and some track-parallel noise is visible. The compiled bathymetry of the study-area ranges from ~50 m to 330 m, with highs in the central, north-western, and eastern areas (Fig. 2). A basin is located in the central-northern part of the study-area, with water depths in excess of 330 m, deepening towards the north-east (Fig. 2). The central high with water depths from 120 m to 160 m has prominent incised channels in a NNE–SSW orientation, cutting down to >200 m.

Three current metres were deployed for a >12 h period in early March 2002. Two current metres were deployed in one of the NNE–SSW trending channels (site 1) at heights of 1 and ~15 m above seafloor (192 and 178 m water depth, respectively), and the third one (site 2) was placed on the topographic high on which the reefs are located (Figs. 2, 3). The three current metres all display a pronounced tidal signal (although slightly out-of-phase for salinity and temperature), with flow velocity apparently reaching minima at low tide and high tide. This was anticipated as the tidal range in the area is 1.5 m. The current directions are parallel to the incised channels (NNE–SSW). The water coming in during high tide flows southwards in accordance with the gyre around Tromsøflaket described above. The inflow has higher velocities and is also warmer and more saline than the water flowing out, with a certain delay before the cool and less saline water flows out. The sites close to the seabed display very low (generally <10 cm/s) velocities during low tide compared to higher up in the water column. The temperature and salinity values ($5.6 < T < 6.4$ and $34.2 < S < 35.3$) are clear indications that Atlantic water (NAC) is flowing into the area.

The CTD-profile (Fig. 3) was recorded close to the largest reef in the area, and these measurements were performed at the end of November of 2000, thereby deviating in temperature from the current metre measurements deployed in March 2002. The salinity curve of the CTD increases steadily with depth, ranging from

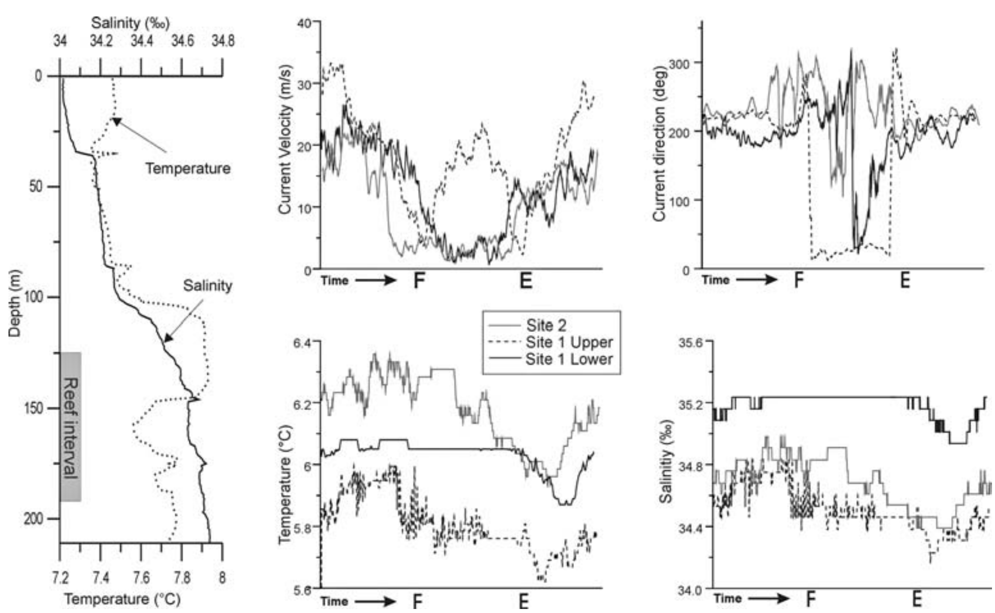

Fig. 3 CTD (depth versus salinity and temperature) and current meter measurements (plotted against time) from locations close to the largest identified reefs (see Fig. 2 for location). **F** and **E** represent high tide (flood) and low tide (ebb), respectively. In general there is a clear tidal signal in velocity and current direction, whereas salinity and temperature point towards different characteristics of the water flowing in (higher T and S) and out (lower T and S)

34 at the sea surface to 34.7 at 210 m water depth. The temperature also increases with depth down to ~105 m. This is the depth of the thermocline evidenced by an abrupt temperature increase from 7.4°C to almost 8°C. A decrease in temperature occurs at ~145 m, below which the temperature is between 7.6°C and 7.8°C all the way to 210 m. These observations concur with data from Norwegian College of Fisheries Sciences (NFH) collected annually from a location close to the study area (NFH 2003).

Seismic facies of the sediments

Two dominating seismic facies are found in the study area, one in the basin and one on the highs. The basin sediments display sub-horizontal sub-seafloor reflections in the uppermost 100 ms twt under a generally flat seafloor. On the highs, the acoustic sediments properties do not permit penetration, and the seafloor is the only interpretable reflection. Frequent iceberg plough-marks are observed in shallower areas (down to ~200 m), and the reefs are generally found in the shallow part of the study area. All identified reefs in this study are found where adjacent seafloor displays hummocky relief and no sub-seafloor reflections are observed either in airgun or 3.5 kHz seismic data.

Seismic character of the reefs

The reefs are consistently located on topographic highs, and appear as prominent cone-shapes on 3.5 kHz data (Fig. 4). Generally, the Fugløy Reefs show an acoustically transparent signature and some of the reefs are 'capped'—they exhibit a pronounced surface reflection (Fig. 4d). The largest reefs seem to absorb and scatter most of the acoustic energy, thus preventing identification of the underlying mound base reflection. However, some of the seismic profiles show the reefs thinning out gradually displaying sub-horizontal internal stratification (Fig. 4b, f), indicating that there is a lateral change within the reef framework. The reefs are not easy to detect with seismic equipment producing lower frequency signals, but are still clear on sleeve-gun data from the study (Fig. 5). Also in the sleeve-gun seismic data the reefs stand out as acoustically transparent cone-shapes without internal reflections. One

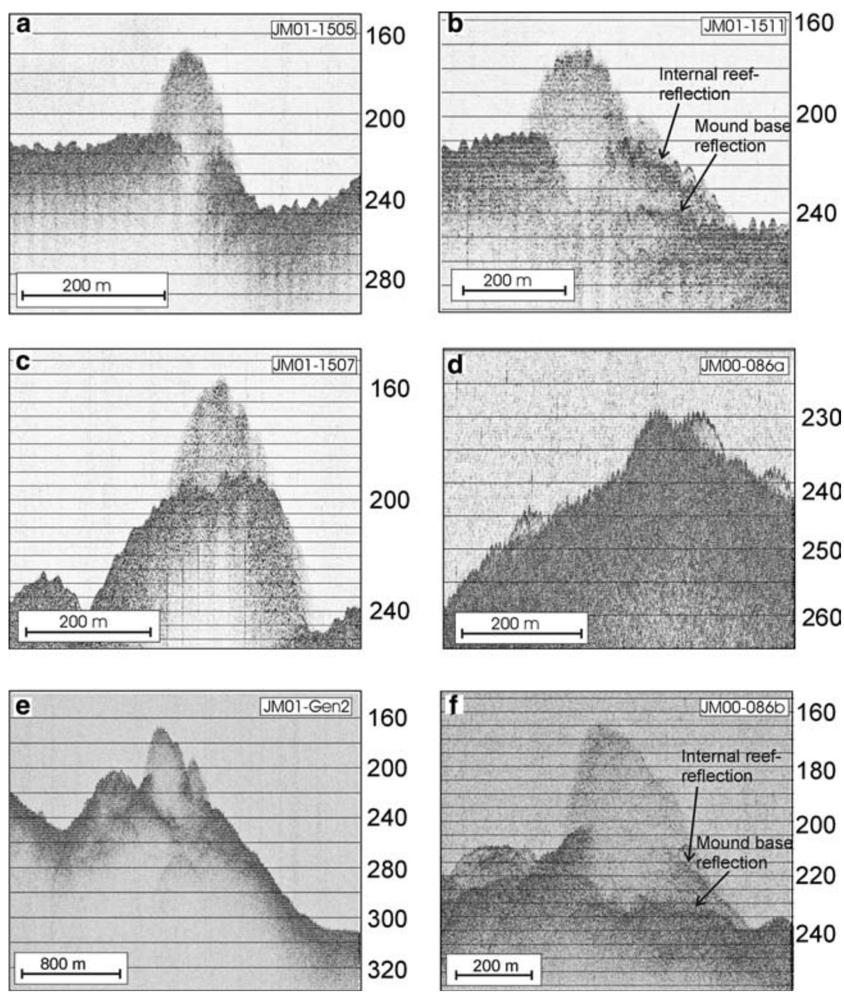

Fig. 4 Examples of the reefs' appearance on 3.5 kHz seismic (vertical scale in ms twt). The largest reefs are up to 50 m high and several hundred meters long. Note the distinguishable transition in facies on **b** and **f**, where the flank of the reef displays internal reflections. The smaller reefs **d** exhibit an outer rim. For location of the profiles see Fig. 2

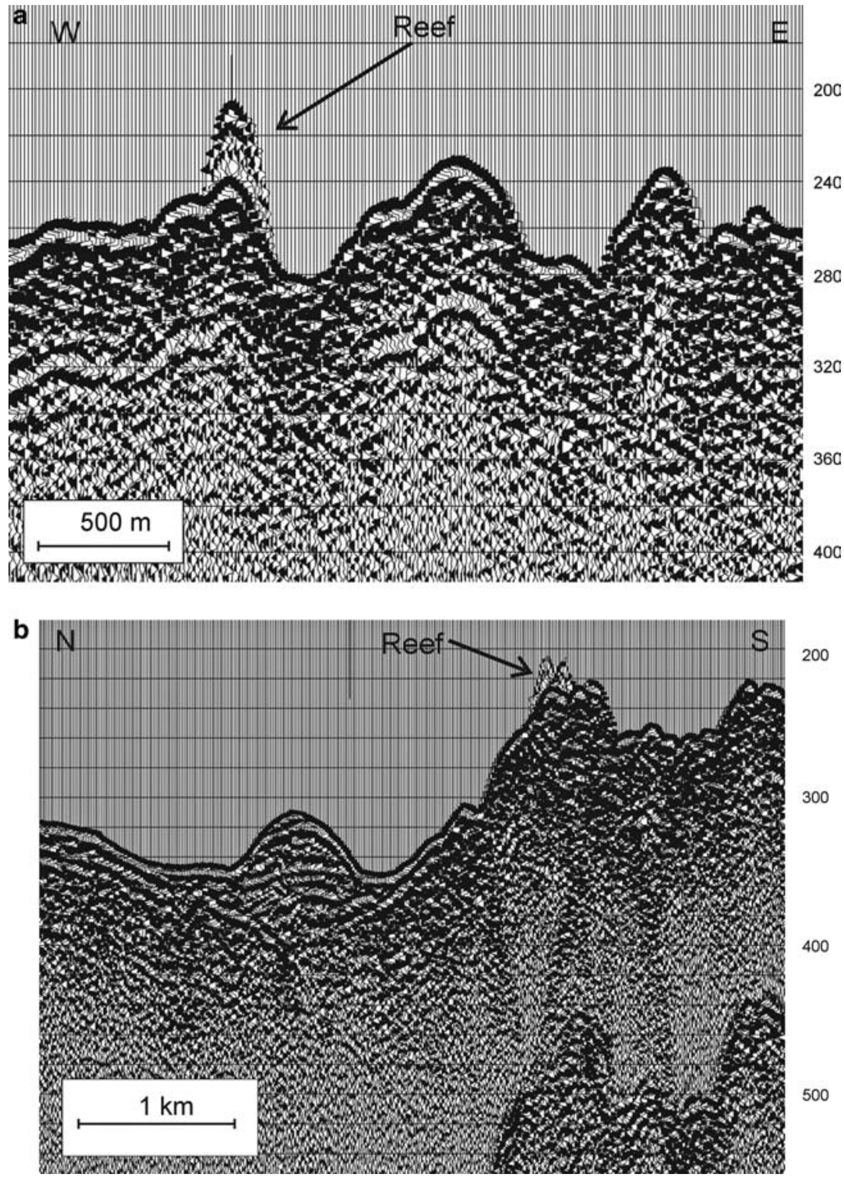

Fig. 5 Sleeve-gun profiles over two of the larger reefs, showing that the reefs appear similarly here as on 3.5 kHz data. Lower frequency allows full penetration of the reefs and identification of the mound base, but also decreases resolution and makes identification of the reefs more difficult. In **b**, some reflections below seafloor are observed on the mound downslope from the reef. For location of the profiles see Fig. 2

disadvantage with the sleeve-gun data is that even though the reefs are prominent features on the seafloor, they are only imaged on 10–20 traces, as the shooting rate and speed of the vessel implies 15–20 m shot spacing.

Side-scan sonar character of the reefs

The areas where the reefs are found are of high relief and therefore appear as areas of highly varying backscatter on side-scan sonar images (Fig. 6). The reefs themselves appear as areas of 'spotted' reflectivity with a clear acoustic shadow on the far side due to the reef's elevation. The undulating surface (individual colonies) of the reefs creates varying backscatter, thereby giving a mottled/spotted character on side-scan records. The reefs display high reflectivity, the edges of the reefs along-track are distinct, and the transition from reef to uninhabited seafloor is for the most part easy to identify. It is clear from the side-scan data that the reefs are cutting other features in the area, particularly the prominent iceberg plough-marks disappear under the reefs, demonstrating that the reefs are younger than the iceberg plough marks.

Structure of the reefs based on video images

One of the Fugløy reefs was imaged by b/w video, giving more detailed information about the reefs than the acoustic data. The video-images provide important information about the smaller scale structure and zonation of the reefs. The video transect reveals at least two reef-zones, the living coral zone, and the coral rubble zone.

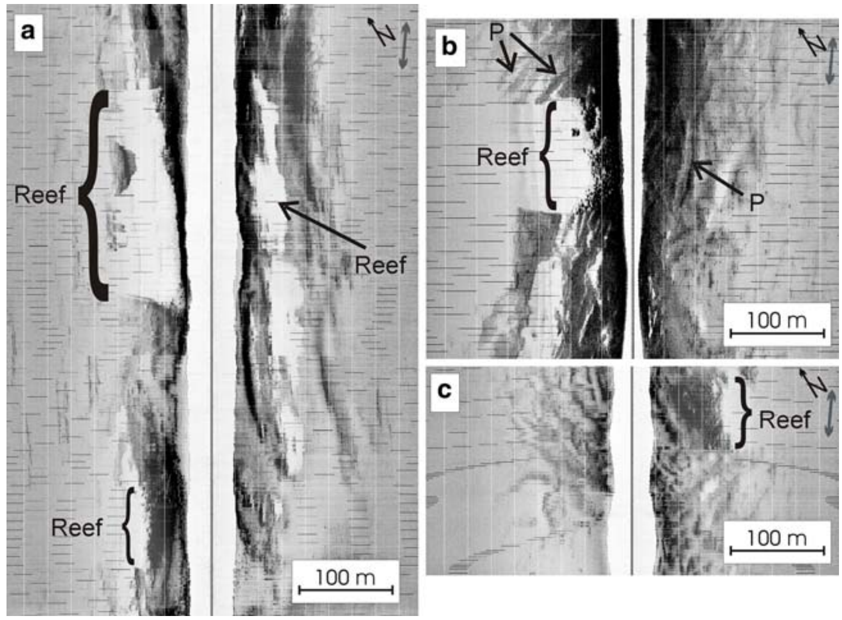

Fig. 6 Side-scan sonar records of reefs (high backscatter: *black*, low backscatter: *white*). The *white vertical line* in the center is the ship's track, and the *black horizontal lines* are noise. Individual colonies account for the mottled texture on the nearside of the reefs, especially evident on (**b**) and (**c**). The reefs are clearly delimited in extent along line (as seen on seismics as well), and are younger than prominent iceberg plough-marks (indicated by *arrows* and *P*). Due to the acoustic shadow (*white* on far side of reef), the backside of the reefs cannot be distinguished on side-scan sonar. For location (see Fig. 2)

The upper part of the reef is characterized by abundant living corals, dominated by *Lophelia pertusa*, but *Paragorgia arborea* and *Paramurica placomus* were also observed. The *Lophelia* constitute a dense network of branches, and individual colonies are ~1 m in diameter and hemispherical in shape (Fig. 8). Together with the living corals, a high biodiversity is observed, including fish, squat lobster, and echinoids. The slope of the living reef is vertical in places, and the well-developed cauliflower-shape of the individual colonies is lacking on these steep cliffs.

Downslope from the proliferating part of the reef, the coral rubble zone is found. This is characterized by coral debris derived from the living reef, and there is markedly less bioactivity in the rubble zone than on the living reef. The relief is also much flatter.

Geometry and distribution of the reefs

Some of the reefs studied here are among the highest *Lophelia*-colonies along the Norwegian margin. The height of the reefs varies greatly, from < 10 m up to > 40 m, as does the diameter of their base (< 80 to > 400 m) (Table 1). The base of the reefs is found at water depths from 140 m to 190 m, and the shallowest reef reaches up to 110 m. No reef-growth is observed above the thermocline that appears at ~105 m water depths on the CTD (Fig. 3). As the seismic coverage is not equally dense for all the reefs, good control on the individual reefs' shape is not obtained for all the reefs. The available data indicates that the reefs have a circular base and a cone-shape in vertical section, and for the most part the transition from living reef to surrounding areas is sharp.

The reefs are consistently found on, or close to topographic highs (moraine ridges), which becomes clear when the reefs are plotted on the bathymetric map (Fig. 2). The reefs found on the high in the central part of the study area are all located on the flanks of the channels cutting through the central high. Few reefs are found elsewhere in the study area at similar depths.

A conservative estimate of the volume of Reef 68 based on 3.5 kHz data gives 250,000 m^3 of corals (assuming that the mound entirely consists of corals), with average angle of the flanks being ~17°. In the most densely populated area, the occurrence of reefs is ~0.6 reefs/km^2.

Table 1 Overview of height, water depth and diameter of the reefs observed at Fugløy

Reef	Depth to base (m)	Max height	Diameter	Line coverage (seismic)
68 (Figs. 4a, b, 6a)	160	> 30 m	~180 m	> 10
86 (Fig. 4f)	160	> 50 m?	~300 m?	86, 67, G2, 1507
1507 (Fig. 4c)	150	~26 m	140 m	68, 1507, 2G
1505 South	160	> 30 m	112 m	1505
1511 West (Fig. 6b)	150	40 m	120	1511
Small reefs in north (Figs. 4d, 6 c)	176–190	4 m	77 m max	86
Reef North (Fig. 4e)	160	~40 m	280 m (large part) 580 m (both)	2G
Small reef (2_genbat on central high)	140	12	120	2G

The name (*number*) of the reefs refer to the seismic lines they were first identified on (not indicated on *figures*)

Acoustic character of pockmarks

The pockmarks found in the deeper parts of the study area in water depths greater than ~200 m are prominent on the acoustic data. On 3.5 kHz seismic, the pockmarks appear as depressions down to 5 m deep and ~30 m wide (Fig. 7). They are morphologically fresh and not discernibly covered by any sediment. Older and buried pockmarks appear further down in the stratigraphy, and reflections directly underneath one of the buried pockmarks exhibit stronger amplitudes (Fig. 7). Reflections are continuous underneath the surface pockmarks, without any disturbance from the seepage, which must have caused/causes the over-lying and under-lying pockmarks. Because of their relatively small dimensions, the pockmarks are hard to spot on sleeve-gun data. The pockmarks are easily identified on most of the side-scan sonar records, appearing as circular features with an occurrence of up to 100 pockmarks/km^2 in places. In the deeper parts of the basin at water depths greater than 230 m, the pockmarks are the only features contrasting with the otherwise flat seafloor. No pockmarks are observed shallower than ~200 m.

Discussion

Oceanography, availability of hard substrate, and elevated currents have all been shown to be essential for the establishment and growth of cold-water coral reefs. We discuss these factors as well as the possible influence of seepage from the sub-seafloor, and the reefs' choice of habitat and growth conditions.

Role of oceanography

The current measurements in Fig. 3 show that the water flowing southward into the fjords during high tide has a higher velocity than the water flowing out during low tides. This is true for the individual metres as well as for the average values. Furthermore, the direction of flow for the upper current metre at site 1 is parallel to the channel in which the metre is placed during both in-flow and out-flow, whereas the other two meters, just above the seafloor, show flow parallel to the channel only during inflow.

We attribute these flow patterns to different pathways of the water during in-flow and out-flow. During inflow, the expected current direction would be towards the north, parallel to the Norwegian Current, but due to the gyre around Tromsøflaket, the Norwegian Current is steered in a southerly direction in the study area, resulting in a southward flowing high tide, confined on a local scale by the topographic channel. This implies that there is a diurnal supply of water to the reef area from the pockmark basin (Fig. 1).

The incoming water is warmer and more saline than the water flowing out during low tide (Fig. 3). The temperature and salinity intervals indicate that the influx of water is of Atlantic origin, and the lowered temperature and salinity values during outflow (with a certain offset) indicate that the outflow is a mixture of Atlantic and coastal water.

The largest reefs are situated at the flanks of the tidally active channels, where influx of water is continuous and currents are periodically high. The reefs are found on or close to topographic highs, or they constitute highs by their own build-up. This seems to be consistent for all reefs on the Norwegian margin, a strong indicator that there is a causal relationship be-

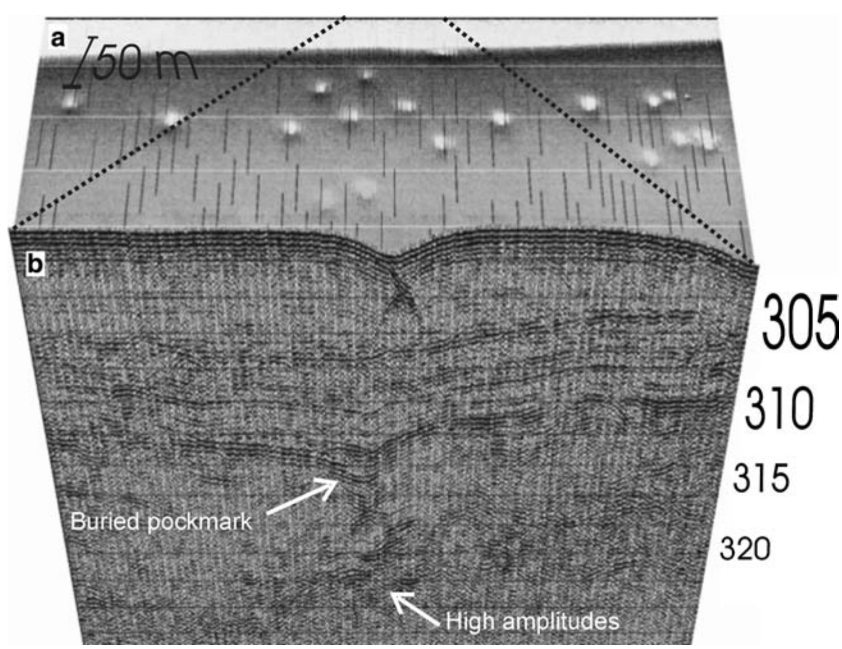

Fig. 7 Side-scan (**a**) and seismic (**b**) records of the pockmarks from the basin in the northeastern part of the study area, the *dotted lines* indicate the origin of the seismic profile. The pockmarks are ~5 m deep and up to 70 m wide, appearing in an area with otherwise very low relief. Little or no overlying sedimentation is found on the pockmarks. A buried pockmark appears at ~312 ms on the seismic profile

tween the reef building processes and the abundance of currents, something which Dons pointed out already in 1944.

However, the current measurements also show that there is a steady supply of water from the pockmark area in the north towards the reefs pointing towards a *possible* second control on reef growth.

As no palaeoceanographic studies have been conducted, it is necessary to point out that the recorded measurements need not be representative of the entire time-interval in which the reefs have lived.

Pockmarks and seep-theory

A potential link between (micro-)seepage and reef growth has been suggested—fluid venting is favourable for bacteria and thereby organisms higher up in the food chain, all the way up to zooplankton such as copepods and small crustaceans that *Lophelia* preys on (Hovland and Mortensen 1999). It is therefore of interest to investigate the relationship between the pockmarks and the reefs, as well as the origin of the pockmarks. Pockmarks are the result of fluid expulsion from the subseafloor (Hovland and Judd 1988). Other mechanisms for pockmark formation have been suggested, such as sediment rafting by gas hydrates and freshwater ice formation (Paull et al. 1999), but these mechanisms are not applicable in our study area since the bottom water temperatures are above freezing point throughout the year and no evidence for gas hydrates in this area exists.

The lack of overlying sediments on the pockmarks found in our study area indicates that these were recently, or are still active sites of seepage. There are numerous pockmarks in the basin north of the main reef concentration (Fig. 2), but no clear signs of seepage on the central high where most of the reefs occur. We cannot rule out that seepage occurs in shallower area and in the immediate vicinity of the reefs. If this is the case, the surface expression of the seep is disguised and/or overprinted by the far more prominent plough-marks and other high relief features. In addition, potential seepage sites directly below the reefs would be masked by the reefs. The most likely fluid sources for the pockmarks include groundwater, shallow gas of biogenic origin, and thermogenic gas from deep reservoirs.

Groundwater

Seeping of groundwater would imply that water with a pressure head above the basin floor is present, or that a reservoir of water with higher buoyancy than the seawater, i.e. fresh water, exists in the area. This could be groundwater fed from the adjacent land areas, or a fossil groundwater reservoir, e.g. from the last glacial. A conduit leading to the study area through the metamorphic, massive bedrock is somewhat difficult to envisage. The permeability in metamorphic rocks is significantly lower than in sedimentary rocks or unlithified sediments. A lateral brittle fault system would be the most plausible way for groundwater to permeate through the bedrock, but this should also result in an aligned, fault oriented and not so much scattered pockmarks as is the case in the study area. Limited knowledge on the extensional faults in the study area exists, but several of the NE–SW trending faults in northern Scandinavia offset post-glacial topographic elements. This includes the Kvaløysletta–Straumhella Fault, whose northern extension possibly reaches into our study area (Gabrielsen et al. 2002).

Gas

In some areas of the pockmark field, high amplitudes reflections are observed in the sub-seafloor (Fig. 7), indicating either a lithological change, or other change of sedimentary properties affecting their acoustic impedance. High amplitudes (bright spots) are often associated with free gas, lowering the seismic velocity, and commonly inducing seismic polarity reversals. No obvious polarity reversals are seen that could provide additional evidence for free gas in the pore space of the sediments. However, the signal to noise ratio is low at depth, and the small wavelength of the reflection band on 3.5 kHz makes a reversal difficult to identify.

Thermogenic gas

The old, metamorphic bedrock in the study area is not a likely source for thermogenic hydrocarbons. The closest known sources of thermogenic hydrocarbons are the oil and gas fields of Snøhvit and Goliat, 130 km to the north of the study area. The westward dipping Mesozoic strata connected to Snøhvit could provide conduits for leaking hydrocarbons, but the closest subcrop of Mesozoic sediments is ~20 km to the north of the study area. This leaves a possible but very unlikely scenario that fluids migrate the final 20 km along the boundary between bedrock and glacial moraine or within the moraine material southwards to the study area where they finally reach the seafloor creating the observed pockmarks.

Biogenic gas

After withdrawal of the last ice-sheet, marine and glaciomarine sediments along with organic matter were deposited, and burial and decay of the latter produces biogenic gas. Bright spots on seismic data are often indicative of some gas in the system, but large amounts are not thought to be present. As mentioned above, the 3.5 kHz system makes it difficult to identify any polarity reversals due to the short wavelength and fairly long wavelet.

The available data is not conclusive regarding the origin of the fluids that create the pockmarks. Both groundwater expulsion from a fossil groundwater reservoir and escape of biogenic gas are plausible explanations. Given the high amplitude reflections from underneath the pockmarks and the strong smell of H_2S of some sediment cores from the pockmark area (Lindberg and Mienert 2005), we are more inclined to believe that biogenic gas is causing the pockmarks. However, geochemical analysis of shallow cores has to be conducted in order to clarify this.

Seep theory versus benthic-pelagic coupling

There is general agreement that the occurrence of reefs in Norwegian waters is related to the influx of Atlantic water from the NAC, but a recurring question is whether there are other, non-oceanographic factors that influence the distribution of the reefs. As mentioned above, the Fugløy Reefs are predominantly found on topographic highs and in areas of high relief. Numerous reefs are associated with clear seep-indicators such as enhanced reflections, elevated HC-level in the sediments, and pockmarks (Hovland et al. 1998). This is also the case for the Fugløy Reefs that are located in the vicinity of pockmarks and enhanced reflections, although the origin of the escaping fluids generating the pockmarks is yet unknown. The tidally active waters transport water masses from the pockmark area to the main reef area diurnally.

Studies on the Stjernsund reef (Fig. 1) have resulted in the conclusion that the location of the reef is linked to local upwelling and supply of suspended particles generated seasonally in the euphotic high productivity zone (Freiwald and Henrich 1997). Isotopic analyses of the coral skeletons have yielded no indications of influence of light hydrocarbons. Likewise have the corals on the Darwin Mounds in the northern Rockall Trough been linked to topography and currents rather than fluid escape (Masson et al. 2003).

In our opinion, no convincing direct evidence linking the cold-water coral reefs to seep has been presented, although abundant circumstantial evidence exists.

Age and growth-rate of corals

The variation in height of the reefs (< 5–40 m) can have several explanations: different growth rates, existence/non-existence of seep, and non-concurrent incipient reef growth are all conceivable explanations. Different time for incipient reef-growth can be explained by the reefs being established during different (non-concurrent) spatfall episodes, but this is difficult to verify from the available data. A lower growth rate, for whatever reason, will obviously give smaller reef framework. As the oceanographic factors seem consistent during our 'snapshots', although based on limited quantitative data, there is no apparent oceanographic reason for different growth rates in the study area, and an endogenous explanation could be plausible. The seep-theory (Hovland et al. 1998) is one way to explain the scattered distribution of reefs, as the ephemeral nature of seeps can be thought to turn reef growth on and off or at least affect the growth-rate, hence producing reefs of varying sizes. Given one major episode of larval spatfall, where the reefs distribute 'randomly' and then do not spread, this would also explain the irregular distribution of the reefs (Freiwald et al. 2002). More data would be needed to substantiate this explanation for the Fugløy reef with confidence.

The waxing and waning of the ice-sheet in the area during the last glacial will have removed any previous reefs that were growing in the area and transported most of the remnants to the shelf edge and towards the deep sea. Thus, the reef framework of the Fugløy Reefs is built up after the last retreat of the ice-sheet, dated to ~13.5 ka (Vorren and Kristoffersen 1986). Given that the entire shelf along Norway and north up to Svalbard was glaciated, we assume that migration of the corals was from south to north. ^{14}C-datings from the Sula Reef offshore mid-Norway suggest an age of 8,060 ± 130 years BP of the oldest coral fragments recovered (Hovland et al. 1998). Freiwald et al. (2002), state that the reefs developed with the onset of the Holocene climatic optimum period from 8 ka to 5 ka.

Reported growth rates of *Lophelia* range from 5.5 mm/year to 25 mm/year (Mortensen and Rapp 1998; Mikkelsen et al. 1982), and average values from direct observation of *Lophelia* in aquarium were found to be 9.4 mm/year (Mortensen 2001). Assuming that the Fugløy Reefs consist predominantly of corals, and that they established immediately after the ice retreated, the largest reef (~40 m high) has a net growth rate of 3 mm/year. This is a conservative estimate as colonization probably did not occur until favourable oceanographic conditions were stabilized and migration had reached these latitudes. Using the same age (8,060 year BP) for initiation for reef growth as for the oldest Sula Reef fragments, the calculated net growth for the Fugløy Reefs would be 5 mm/year. Note that the estimates for the Fugløy Reefs are net growth rate for the entire reef, and the other reported growth rates are for individual corallites. For comparison, the net growth rate of the largest Sula Reef (maximum 30 m) is 3.7 mm/year. There is no doubt that the growth rate of individual corallites at the Fugløy Reefs will surpass the estimate of net growth rate for the reef, but precise figures cannot be deduced based on the available data. However, based on the available data, it seems that the largest Fugløy Reefs are the highest and fastest growing known reefs on the Norwegian margin.

Acoustic signature of the reefs

The 3.5 kHz seismic data generally show a low-amplitude reef top reflection, which is followed by arrivals of similar low amplitudes. Both the reef top reflection and

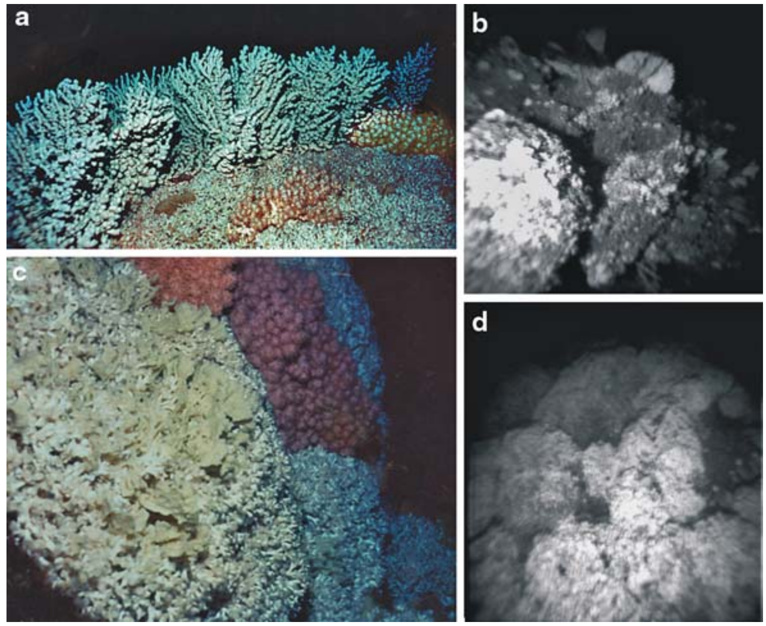

Fig. 8 The top (**a**, **c**, **d**) and slope (**b**) of one of the Fugløy reefs. Various cold-water coral species are represented in the pictures, including the upright *P. arborea* (**a**) and the *white/yellow Lophelia pertusa* in (**b** and **c**). **a, b** Courtesy of M. Hovland and Statoil

the subsequently arriving energy are above the ambient noise level but distinctly lower than the amplitude of the seafloor reflections from the adjacent areas (Fig. 4). The fact that the top of the reef is not represented by a single reflection (except reefs in Fig. 4d) implies scattering of the seismic energy. This scattering occurs not only at the top of the reef, but also within the reef edifice, because there are no observed diffraction hyperbolae from a rough reefs surface. Thus, there must be abundant heterogeneities within the reefs. Taking into account the structure of the reefs, which consists at least in their upper part of individual coral colonies, we ascribe these heterogeneities to cavities within the reefs. Furthermore the absence of continuous reflections from within the reefs implies that the reefs do not have a consolidated core. This is supported by the fact that a base mound reflection is observed for some reefs (Fig. 4b, f). Thus, the reef material at the base must have acoustic impedance sufficiently low to cause a significant impedance contrast with the substratum, which can cause a discernable reflection even though most of the seismic energy has already been scattered while passing through the overlying reef material. The reefs display few internal reflections (Figs. 4, 5), but on some seismic profiles, there is a lateral facies change visible (Fig. 4b, f). This is interpreted to be related to the different facies of the reef as described by Mortensen et al. (1995) and Freiwald et al. (2002) on the Sula reef, and also visible on the video images (Fig. 8). Below the proliferating framework, there is a zone with dead coral framework clogged by sediment, thus creating a stronger acoustic return than merely organic matter. Further division into the

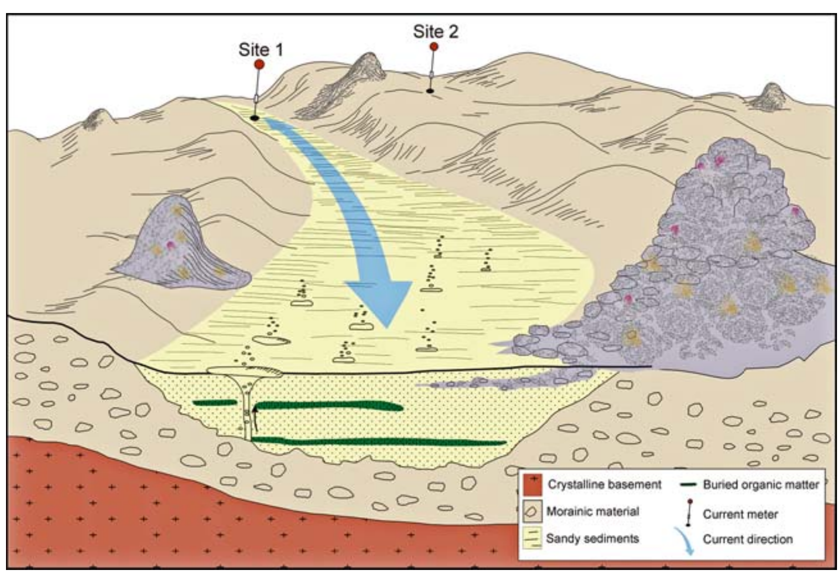

Fig. 9 A schematic representation of Fugløy Reefs and adjacent area, viewed from the north. The proliferating parts of the reefs are found on topographic highs in the depth interval 140–190 m, and often on the levee of tidally active channels cutting through the morainic high in the central part of the study area. Following the slope of this high towards the north, we enter into a sandy basin perforated with morphologically fresh, and probably still active, pockmarks due to fluid migration from the sub seafloor

facies pattern described by Mortensen et al. (1995) and Freiwald et al. (2002) is not possible from the acoustic data. Particularly the small reefs are characterized by a single top reflection (Fig. 4d). A possible explanation for this is that the reefs are no longer alive, and that sedimentation on the reef has resulted in a cap creating the imaged contrast in acoustic impedance.

Northernmost corals in the world?

Reports of coral locations further north than the Fugløy Reefs exist, and are mostly based on information from fishermen (Fosså et al. 2000). These occurrences are all located along the Norwegian coast, and not yet verified by scientists. As one moves northwards into the Barents Sea, the NAC follows the shelf edge, and is renamed the West-Spitsbergen Current. The oceanography is fairly similar to the Norwegian Current, and the temperature, salinity and current parameters are all within the required range for *Lophelia* (Loeng 1991). On the seafloor, topographic highs and presence of hard substrate are abundant as the Barents Sea was overrun by ice during the last glacial and subsequent ice-bergs have left prominent plough-marks on the sea-floor (Rafelsen et al. 2002) Seepage of hydrocarbons is documented in several places on the Barents Sea shelf, including features in connection with the Snøhvit hydrocarbon field (Hovland and Judd 1988; Solheim and Elverhøi 1993). The lack of reports on *Lophelia* north of the Norwegian coast is either due to a limited extent of the corals in latitude, or it is an artefact in the database due to disproportional seabed mapping and information on sea-floor conditions. It seems that all the known prerequisites for Lophelia are fulfilled for the western Barents Sea and along the Western Svalbard margin, and therefore we expect the discovery of coral reefs further north as data-coverage increases and awareness of how to identify them is more common knowledge.

Conclusions

The first in-depth study of the Fugløy Reefs documents the presence of a cluster of large, undamaged reefs consisting mainly of *L. pertusa* that are thriving at latitudes of more than 70°N. A synthetic and schematic model of the area is presented in Fig. 9. The reefs are among the highest reported on the Norwegian margin, and a conservative estimated growth rate reaches 5 mm/year.

The reefs are found in locations with high currents and influx of Atlantic water, on rough topography, and in areas with availability of hard substrate, similarly to other reefs on the Norwegian margin.

Oceanographic and geologic conditions are similar to those previously described for documented deep-water reefs, but the reefs are unevenly distributed and mostly found on a moraine ridge centrally in the study area.

The corals are found in the vicinity of pockmarks interpreted to originate from seeping biogenic gas, but possible seepage directly at coral sites cannot be identified due to the reefs themselves, iceberg plough-marks and rough topography.

It is tempting to link the Fugløy Reef occurrences with seepage based on circumstantial evidences, but here, as for other published reefs, no *direct* evidence is found.

There is a lack of general awareness of cold-water corals, and many reefs are probably ignored and regarded as noise. So far, no cold-water coral reefs are documented further north than the Fugløy Reefs, but we expect that reefs will be discovered as data coverage and awareness increases. High-resolution acoustic data, and in particular high-resolution 3D seismic data, is best to identify and describe the reefs.

Acknowledgements This is a contribution to the ECOMOUND-project (Contract number EVK3-CT-1999-00013) and the project kindly provided the first author with three year financing for a PhD. The captain and crew of R/V Jan Mayen are acknowledged for good help in acquiring the data, as is engineer Steinar Sivertsen at the University of Tromsø. We would like to thank T. Midtun who produced one of the figures. Processing of the seismic reflection data was done using ProMAX. Figures 1 and 2 were made using GMT (Wessel and Smith 1991). The University of Tromsø acknowledges support by Landmark Graphics via the Landmark University Grant Program. M. Vanneste made many valuable comments for improvement on the manuscript. We extend our thanks also to Pieter Van Rensbergen and one anonymous reviewer for constructive comments.

References

Blindheim J (1990) Arctic intermediate water in the norwegian sea. Deep Sea Res 35:1475–1489

Dons C (1944) Norges korallrev. Det Kongelige Norske Videnskabers Selskabs Forhandlinger 16:37–82

Fosså JH, Mortensen PB, Furevik DM (2000) Lophelia-korallrev langs norskekysten. Forekomst og tillstand (in Norwegian). Fisken og Havet 2, 94 pp

Frederiksen R, Jensen A, Westenberg H (1992) The distribution of the scleractinian coral lophelia pertusa around the faroe islands and the relation to internal tidal mixing. Sarsia 77:157–167

Freiwald A, Henrich R (1997) Anatomy of a deep-water coral reef mound from stjernsund west finnmark, northern Norway. In: James NP, Clarke JAD (eds) Cool-water carbonates, society for sedimentary geology, special volume 56, pp 141–162

Freiwald A, Wilson JB, Henrich R (1999) Grounding pleistocene icebergs shape recent deep-water coral reefs. Sediment Geol 125:1–8

Freiwald A, Hühnerbach V, Lindberg B, Wilson J, Campbell J (2002) The sula reef complex, norwegian shelf. Facies 47:179–200

Gabrielsen RH, Braathen A, Dehls J, Roberts D (2002) Tectonic lineaments of Norway. Nor J Geol 82:153–174

Henrich R, Baumann K-H (1994) Evolution of the norwegian current and the scandinavian ice sheets during the past 2.6 m.y.: evidence from ODP Leg 104 biogenic carbonate and terrigenous records. Palaeogeogr Palaeoclimatol Palaeoecol 108:75–94

Henriet JP, de Mol B, Pillen S, Vanneste M, Van Rooij D, Versteeg W, Croker PF, Shannon PM, Unnithan V, Bouriak S, Chachkine P, the Porcupine-Belgica 97 Shipboard Party (1998) Gas hydrate crystals may help build reefs.Nature 391:648–649

Hovland M, Judd A (1988) Seabed pockmarks and seepages. Graham and Trotman, London, 293 pp
Hovland M (1990) Do carbonate reefs form due to fluid seepage? Terra Nova 2:8–18
Hovland M, Farestveit R, Mortensen PB (1994) Large cold-water coral reefs off mid-Norway—a problem for pipe-laying? In: Proceedings 8th international coral reef symposium, vol 2, Brighton, pp 1203–1206
Hovland M, Thomsen E (1997) Cold-water coralsare they hydrocarbon seep related? Mar Geol 137:159–164
Hovland M, Mortensen PB, Thomsen E, Brattegard T (1997) Substratum-related ahermatypic corals on the Norwegian continental shelf. In: Proceedings of the 8th. international coral reef symposium, vol 2, Panama City, pp 1203–1206
Hovland M, Mortensen PB, Brattegard T, Strass P, Rokoengen K (1998) Ahermatypic coral banks off mid-Norway: evidence for a link with seepage of light Hydrocarbons. Palaios 13:189–200
Hovland M, Mortensen PB (1999) Norske korallrev og prosesser i havbunnen (in Norwegian). John Grieg forlag, Bergen, 155 pp
Lindberg B, Mienert J (2005) Sedimentological and geochemical environment of the Fugløy reefs off northern Norway. In: Freiwald and Roberts (eds) Deep-water corals and ecosystems. Springer, Berlin Heidelberg New York
Linjordet A, Grung Olsen R (1992) The jurassic Snøhvit gas field, hammerfest basin, offshore northern Norway. In: Halbouty Michel T (ed) Giant oil and gas fields of the decade 1978–1988. AAPG Memoir, vol 54. American Association of Petroleum Geologists, Tulsa, pp 349–370
Loeng H (1991) Features of the physical oceanographic conditions of the Barents Sea. Polar Res 10:5–18
Masson DG, Bett BJ, Billett BSM, Jacobs CL, Wheeler AJ, Wynn RB (2003) The origin of deep-water, coral-topped mounds in the northern Rockall Trough, Northeast Atlantic. Mar Geol 194:159–180
Mikkelsen N, Erlenkeuser H, Killingley JS, Berger WH (1982) Norwegian corals: radiocarbon and stable isotopes in *Lophelia pertusa*. Boreas 11:163–171
Mortensen PB, Hovland M, Brattegard T, Farestveit R (1995) Deep water bioherms of the scleractinian coral *lophelia pertusa* (L.) at 64 N on the norwegian shelf: structure and associated megafauna. Sarsia 80:145–158
Mortensen PB, Rapp HT (1998) Oxygen- and carbon isotope ratios related to growth line patterns in skeletons of *Lophelia pertusa* (L) (Anthozoa: Scleractinia): implications for determination of linear extension rates. Sarsia 83:433–446
Mortensen PB (2001) Aquarium observations on the deep-water coral *Lophelia pertusa* (L. 1758) (Scleractinia) and selected associated invertebrates. Ophelia 54:83–104
NFH Norwegian College of Fishery Science (2003) Annually collected CTD-data from northern Norway; http://lupus.nfh.uit.no
Paull CK, Ussler W III, Borowski WS (1999) Freshwater ice rafting: an additional mechanism for the formation of some high-latitude submarine pockmarks. Geo Mar Lett 19:164–168
Poulain P-M, Warn-Varnas A, Niiler PP (1996) Near-surface circulation of the Nordic seas as measured by Lagrangian drifters. J Geophys Res 101:18237–18258
Rafelsen B, Andreassen K, Kuilman LW, Lebesbye E, Hogstad K, Midtbø M (2002) Geomorphology of buried glacigenic horizons in the barents sea from 3-dimensional seismic data. In: Dowdeswell J, Ò Cofaigh C (eds) Glacier-influenced sedimentation on high-latitude continental margins. Geol Soc Spec Publ 203:259–276
Rokoengen K, Bugge T, Løfaldli M (1979) Quaternary geology and deglaciation of the continental shelf off Troms, north Norway. Boreas 8:271–227
Sigmond EMO (1992) Bedrock map of Norway and adjacent ocean areas. Scale 1:3 million. Geological Survey of Norway, Norway
Solheim A, Elverhøi A (1993) Gas-related sea floor craters in the Barents Sea. Geo Mar Lett 13:235–243
Vorren TO, Hald M, Thomsen E (1984) Quaternary sediments and environments on the continental shelf off northern Norway. Mar Geol 57:229–257
Vorren TO, Kristoffersen Y (1986) Late quaternary glaciation in the south-western barents sea. Boreas 15:51–59
Wessel P, Smith WHF (1991) Free software helps map and display data. EOS Trans Agu 72:441