Pockmarks in the southwestern Barents Sea and Finnmark fjords

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A large and diverse dataset has been compiled and analysed in the Barents Sea and Finnmark fjords in northern Norway in order to map and characterise pockmarks. The main data sources are regional side-scan sonar and deep-towed boomer lines and extensive bathymetric datasets of multibeam echo sounding. Small to medium-sized pockmark fields occur in several basins west of Nordkappbanken. The most extensive is in Ingøydjupet, where the largest pockmarks are nearly 100 m wide and up to 8 m deep. Small to medium-sized pockmarks are, however, more common (20–50 m wide, 2–5 m deep). The pockmark density is typically 150–200 per km². North of the Finnmark coast, from Magerøya/Nordkapp to the Russian border, pockmark distribution is nearly continuous. The density varies mainly between 300 and 600 per km², and most pockmarks are small (15–40 m wide, 1.5–4 m deep). Recent studies suggest that the pockmarks in the southwestern Barents Sea were formed from seabed expulsion of gas due to dissociation of gas hydrates during the last deglaciation. Locally, gas has been observed to leak from the Barents Sea floor, but not from pockmarks, suggesting recent inactivity. We further explore the possibility that the pockmarks were formed during a short-lived event and that their shapes have been preserved due to low sedimentation rates and turbulent ocean currents. Numerous small pockmarks also occur in four studied Finnmark fjords. They are most common in Varangerfjorden and Porsangerfjorden where non-gas generating Proterozoic rocks subcrop. The origin of these pockmarks is most likely related to groundwater seepage.

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Introduction

Pockmarks are circular to elongated crater-like depressions on the seafloor. They were first described on the Nova Scotia shelf (King & MacLean, 1970), and have later been reported from many ocean areas around the world (e.g., Hovland & Judd, 1988; Rise et al., 1999; Judd & Hovland, 2007). The diameter (or the longest axis) of the depressions varies from less than ten metres to more than one kilometre, and the largest ones have a depth of several tens of metres (e.g., Bøe et al., 1998; Pilcher & Argent, 2007; Sun et al., 2011). Although most studies of pockmarks are in continental shelf settings where sedimentary rocks occur below Quaternary deposits, pockmarks are also observed in fjords and near-shore areas with crystalline or metamorphic bedrock (Söderberg & Flodén, 1992; Plassen & Vorren, 2003; Webb et al., 2009a; Hammer & Webb, 2010) and even in lakes and brackish water pools (Wessels et al., 2010; L'Heureux et al., 2012).

Pockmarks are generally accepted as morphological expressions of leakage from active subsurface petroleum systems and in most cases attributed to expulsion of gas and/or pore fluids from underlying sedimentary rocks

or sediments (e.g., Hovland, 1982; Hovland & Judd, 1988; Max et al., 1992; Van Weering et al., 1997; Bøe et al., 1998; Heggland, 1998; Chand et al., 2009; Løseth et al., 2009; Hovland et al., 2010, 2012; Bünz et al., 2012). Exploration geologists regard pockmarks as a guide in hydrocarbon exploration. The petroleum industry is also concerned about the processes behind pockmark formation which may represent a potential geohazard to offshore installations and pipelines (Sills & Wheeler, 1992; Hovland et al., 2002; Tjelta et al., 2007). The 'recording medium' of pockmarks is generally soft, fine-grained sediments. Fine-grained sediment particles will, by the expulsion process, be brought into suspension and transported away by currents. In some areas, pockmarks are associated with subsurface chimneys or pipes observed in seismic data (Cartwright et al., 2007; Løseth et al., 2009). At the crest of the Vestnesa Ridge offshore western Svalbard, gas leakages are observed from acoustic data in the water column directly above a pockmark field (Westbrook et al., 2009). The pockmark field is located above hydrate-bearing sediments, and numerous vertical fluid-flow chimney features occur below the seafloor (Hustoft et al., 2009; Bünz et al., 2012).

The regional mapping in this study shows that large parts of the southwestern Barents Sea are densely pockmarked (Figs. 1, 2). We describe pockmarks across diverse settings and discuss their distribution and origin with respect to the subcropping bedrock, the total thickness of Quaternary sediments, as well as the thickness of the uppermost soft clay units.

Pockmarks in the Norwegian offshore

This study focuses on Barents Sea pockmark occurrences but the features have been recognised and explored in many Norwegian offshore areas. An extensive area with numerous pockmarks of 50–150 m width occurs in the

Norwegian Channel off western Norway with measured densities of up to 60 pockmarks per km² (Hovland, 1981, 1982; Judd & Hovland, 2007). The Troll gas production field located here at c. 1500 m depth below the seafloor has been the site of numerous seafloor mapping and inspection surveys over three decades. Yet, to our knowledge, gas or fluid seepage has never been observed from pockmarks in this region during ROV inspections. However, farther west, in the UK–North Sea sector, there is continuously seeping gas emitting from pockmarks (Hovland & Sommerville, 1985; Hovland & Judd, 1988; Judd & Hovland, 2007). One study at the Troll field suggested that the pockmarks are relict, formed by gas hydrate release c. 11,000 cal. yrs. ago (Forsberg et al., 2007; Tjelta et al., 2007). Nevertheless, their fresh-looking

Figure 1. Bathymetry and database applied for mapping of pockmarks. The triangle between 32°E and the Russian border has full coverage of multibeam bathymetry (MBB). The area between the blue line and the coast including the northernmost fjords is also mapped by MBB. The regional seismic and side-scan sonar lines interpreted during this study are shown, as well as four exploration wells mentioned in the text and the locations of later figures. B – Bjørnøya (Bear Island), FB – Fugløybanken, K – Kirkenes, L – Laksefjorden, LY – Lyngenfjorden, M – Magerøya, NK – Nordkinnhalvøya, NKB – Nordkappbanken, P – Porsangerfjorden, T – Tanafjorden, SBR – Sentralbankrenna, SV – Svalisdomen, SØ – Sørøya, TB – Tiddlybanken, TIB – Thor Iversen-banken, U – Ullsfjorden, V – Varangerfjorden. Suffixes 'renna' and 'djupet' refer to troughs and deeper areas, respectively.

appearance, occurrence of unit pockmarks <1 m across, and coincident methane-derived, authigenic carbonates (MDAC) within some, has led others to suggest recent seep activity (R. Lien, pers. comm., 2008; Hovland et al., 2010).

Despite thick units of soft clay presenting a recording medium in the Norwegian Channel off southern Norway, pockmark occurrence is sporadic and far less frequent than in the Norwegian Channel off western Norway (Bøe et al., 1998; Rise et al., 1999; Ottesen et al., 2000). In the Skagerrak (southeastern part of the Norwegian Channel), the highest concentration of pockmarks lies directly above a Middle Jurassic sandstone unit covered by thin Quaternary deposits and was interpreted to

indicate northward migration of gas or liquids from deeper parts of the sedimentary basin (Rise et al., 1999).

The continental shelf between Møre and Troms (62°–70°30'N) comprises large bank areas with a surficial layer of sand and gravel above till. Only local occurrences of pockmarks have been reported (Hovland et al., 1998; Judd & Hovland, 2007; Plassen & Knies, 2009), but recent multibeam bathymetry (MBB) mapping shows that pockmarks are more common than previously inferred (www.mareano.no). At Nyegga, north of the Storegga Slide, a pockmark field in 700–800 m water depth (Berndt et al., 2003; Bünz et al., 2003) includes some that are more than 10 m deep and several hundred metres in diameter. These pockmarks were named 'complex

Figure 2. Pockmark distribution in the southwestern Barents Sea. BW – Bjørnøya West licence area. Offshore place names refer to tectonic elements. For other abbreviations, see Fig. 1.

pockmarks' as they contain large blocks (up to 24 m³) of MDAC (Hovland et al., 2005; Mazzini et al., 2006) and also contain shallow occurrences of gas hydrates that form internal 'hydrate pingoes' (Hovland & Svensen, 2006; Ivanov et al., 2007). Reiche et al. (2011) interpreted them as relict, formed by upward fluid migration caused by repeated sediment loading further upslope during the last glacial maximum (LGM).

The widespread occurrence of pockmarks in the Barents Sea has been known for several decades but few data have been published. Small pockmarks (10–20 m wide) are reported southeast of the Hopen island (c. 76°N) (Solheim & Elverhøi, 1985). In this area of 200–250 m water depths, Quaternary deposits less than 10 m thick occur above subcropping Mesozoic bedrock. Solheim & Elverhøi (1993) discovered a cluster of large, crater-like depressions (74°55'N, 27°36'E), which later has been visited by several scientific cruises (Lammers et al., 1995; Long et al., 1998). They are 300–500 m wide, 10–30 m deep, and occur in about 340 m water depth. It has been suggested that they formed during the deglaciation through large outbursts of gas (Long et al., 1998). Based on high-resolution 3D seismic data from gas fields in the southeastern part of Tromsøflaket (Fig. 1), Ostanin et al. (2013) suggested the occurrence of seafloor mega-pockmarks and buried craters. Elsewhere in the southwestern Barents Sea, only a few local occurrences of small to medium-sized pockmarks are known from the literature: (1) southeastern part of Tromsøflaket (site survey at the Snøhvit gas field; Hovland & Judd, 1988); (2) southeastern Ingøydjupet near the Goliat hydrocarbon discovery (Chand et al., 2009); (3) northwestern Ingøydjupet / west of the Loppa High (Chand et al., 2012; Nickel et al., 2012; Pau et al., 2014a); (4) east of Nordkappbanken (Chand et al., 2008).

Geological setting of the Barents Sea

The county of Finnmark comprises Archaean and Palaeoproterozoic rocks of the Fennoscandian Shield, and Neoproterozoic to Early Palaeozoic rocks of the Caledonides which extend several tens of kilometres offshore on the continental shelf (Fig. 3) (Sigmond, 1992, 2002; Siedlecka & Roberts, 1996). Farther offshore, seaward-dipping sedimentary strata of Late Palaeozoic and younger age appear (Bugge et al., 1995). The Barents Sea exhibits a near-continuous sedimentary succession of Carboniferous to Quaternary age (Larssen et al., 2002).

Uplift and erosion during the Cenozoic had a profound effect on the sculpturing of the western Barents Sea (Løseth et al., 1992; Nyland et al., 1992). Glacial erosion of the shelf was severe (Sættem et al., 1992a, 1994; Eidvin et al., 1993; Laberg et al., 2012), but the quantity of sediments removed during the Cenozoic and the timing of the erosion are debated (Henriksen et al., 2011b). Most of the succession in the Bear Island Fan, on the western Barents Sea slope, is of glacial origin (Knies et al., 2009).

The uplift had consequences for the petroleum systems, with fracturing of cap rocks and leakage of reservoir oil and gas (Løtveit et al., 2009; Henriksen et al., 2011b). Removal of perhaps 1–2 km of sedimentary overburden caused cooling of source rocks below the shelf as well as changes of the hydraulic regime (Henriksen et al., 2011b). Residual oil columns found in the Hammerfest Basin possibly indicate that expanding gas resulted in migration of oil from the traps (Carstens & Holte, 2005). The negative effects of erosion on hydrocarbon reservoirs may, however, have been over-stressed (Ohm et al., 2008). Cenozoic deposition on the Bear Island Fan, for example, may have brought sediments into the hydrocarbon maturation window. New hydrocarbon discoveries have renewed the prospecting optimism (NPD, 2013).

East of the Bear Island Fan, a pronounced glacial erosion surface (Upper Regional Unconformity, URU) separates the flat-lying Quaternary succession from sedimentary rocks (Laberg et al., 2012). The Quaternary succession comprises mainly glacially derived diamictic sediments varying in thickness from less than 10 m up to 200 m (Sættem et al., 1992b). During the last glaciation, the ice expanded towards the western shelf edge two or three times (Svendsen et al., 2004; Larsen et al., 2006; Winsborrow et al., 2010). Large morphological features on the seabed illustrate the last dynamic action of the Late Weichselian Ice Sheet (Andreassen et al., 2008; Ottesen et al., 2008).

After the ice sheet retreated, deposition of silt and clay mixed with ice-rafted debris (IRD) continued for a few thousand years. The glaciomarine clays are thickest in depressions and low-lying areas, reaching up to c. 15 m in Ingøydjupet and Djuprenna. In the eastern part of the study area, the fine-grained upper unit is more widely distributed and commonly 2–5 m thick. There is a gradual transition from pro-glacial to a marine depositional environment with less IRD, and during the Holocene (the last 11,700 cal. yrs.) a maximum of c. 1 m of marine sediments were deposited in Ingøydjupet (Chistyakova et al., 2010).

Methods

This study builds on a large database of side-scan sonar and deep-towed boomer lines collected in the 1980s (Fig. 1). In addition, several MBB datasets were available for mapping along the coast and in some Finnmark fjords. MBB acquired recently by MAREANO (www.mareano.no) forms an important part of the dataset. Some very long MBB lines north of Varangerhalvøya have also been used.

Data from IKU's shallow drilling projects

During 1984–1989, IKU Petroleum Research (now Sintef Petroleum Research AS) performed several stratigraphic drilling projects funded by the oil industry in the southwestern Barents Sea (Sintef, 2013)). A total

Figure 3. Distribution of pockmarks superimposed on subcropping bedrock geology at base Quaternary (modified after Sigmond, 1992, 2002). Pockmarks are found in soft clays above rocks of nearly all geological epochs.

of c. 12,000 km of single and multichannel airgun data were acquired (Table 1, Fig. 1). The purpose was to make detailed maps of the subcropping bedrock strata, and find the best sites for continuous coring of the stratigraphy (Rise & Sættem, 1994). More than 50 sites were cored, penetrating up to 200 m into the bedrock, and a total of 3700 m of cores was retrieved (Mørk & Duncan, 1993; Smelror, 1994; Bugge & Fanavold, 1995; Bugge et al., 1995, 2002a, b; Mørk & Elvebakk, 1999).

During acquisition of the airgun data, simultaneous recording of side-scan sonar (SSS) and deep-towed boomer was performed on most of the lines. These data were originally used for detailed planning of drilling sites, but in this study we have utilised the data for regional interpretation of the uppermost sediment layers and mapping of pockmarks. Regional SSS surveys cover approximately 500 m-wide corridors along the seafloor. The distance between survey lines varies from a few to several tens of kilometres. SSS data (50 kHz and 100 kHz) have been most important for the mapping of

pockmarks. The quality of the data vary from moderate to good, and the records are commonly slant-range corrected showing the true scale in metres perpendicular to the sailing line. Some data are uncorrected and show two-way transit time from the sonar fish to the seafloor in milliseconds (the scale varies over the range). The quality is commonly the best in the inner half of the recorded range. A few lines were also acquired in the 400–500 m-deep Bjørnøyrenna, where the SSS was towed high above the seafloor. This has resulted in difficulties recognising small pockmarks.

Huntec deep-towed boomer was run on most lines, applying various energy levels (240–540 J). Both external and internal hydrophones recorded the returned signals; the latter gave the best resolution of the uppermost soft sediment layer applying a filter interval of 1–5 kHz. The external hydrophone provided better penetration, and was most useful for mapping of the uppermost layers and to search for shallow gas near the seafloor. Deep-towed boomer represented a valuable supplement for

Table 1. Database of side-scan sonar (SSS) survey lines and Huntec deep-towed boomer (DTB) collected during shallow stratigraphic drilling projects performed by IKU Petroleum Research (for locations of lines and reference to names, see Figs. 1, 2). Multibeam bathymetry (MBB) data have been collected by the Norwegian Defence Research Establishment (FFI), the Norwegian Hydrographic Service and different companies contracted by the MAREANO programme.

Client and year	Studied areas and structural provinces	Data	Length of profiles/size of MBB area
IKU 1984	Stappen High, Svalis Dome, Loppa High, north of Sørøya	SSS, DTB	3100 km
IKU 1985	Stappen High, Loppa High, Bjørnøyrenna, Ingøydjupet	SSS, DTB	3500 km
IKU 1986	Nordkapp Basin	SSS, DTB	880 km
IKU 1987	Finnmark coast, Nordkapp Basin	SSS, DTB	1295 km
IKU 1988	Finnmark coast, Nordkapp Basin, Bjørnøyrenna	SSS, DTB	1800 km
IKU 1989	Bjørnøya West	SSS, DTB	550 km
IKU 1989	Troms	SSS, DTB	850 km
FFI/SKS – MAREANO 2005–2013	Multibeam areas; see Fig. 1	MBB	100,000 km ²

pockmark mapping, particularly in areas without side-scan sonar data or where these data were of poor quality. Mini airgun records were not systematically used in the present study, but several lines were interpreted in all areas to confirm Quaternary sediment thickness and indications of shallow gas.

Site surveys

A site survey is performed before exploration drilling, primarily to identify geo-hazards and investigate the seafloor conditions. Previously, side-scan sonar was the most important equipment for mapping seafloor features, but MBB mapping has partly replaced this technology in recent years. Site surveys commonly cover only a small area (20–30 km²), but represent an important database of detailed seafloor information which can roughly be extrapolated to neighbouring areas of similar environmental character (water depth, topography, ocean currents). Approximately 15 site survey reports were examined, prioritising areas with little or no bathymetry data coverage otherwise. Of these, four sites are specifically referred to in this paper (Fig. 1).

Multibeam bathymetry

We have utilised MBB data from northernmost Troms to eastern Finnmark, covering an area of about 100,000 km² (Fig. 1). Various Simrad multibeam systems (EM100, EM300, EM1000, EM1002, EM3000, EM3002, EM710) were used to collect bathymetry by the Norwegian Hydrographic Service and the Norwegian Defence Research Establishment (FFI) between 1989 and 2012, covering most of the inner shelf and fjord areas along Finnmark to the Russian border. The data were gridded with 5 m and 10 m horizontal spacing. The bathymetry was processed by the Norwegian Hydrographic Service and FFI using Kongsberg Simrad NEPTUNE (data correction and cleaning). The depth accuracy of the MBB data is between 0.5% and 1% of the water depth.

In addition, backscatter has been used where available. A high backscatter signal is generally an indicator of coarser and/or harder seafloor sediments.

Pockmark areas offshore northern Troms and Finnmark

The regional map of pockmark distribution in the SW Barents Sea shown in Figs. 2, 3 is the first for this area, resembling that produced for parts of the North Sea by Hovland & Judd (1988). In areas of poor data coverage, the distribution of pockmarks is tentative. One single survey line and/or a single site survey may be the only source of information, but extrapolation of interpretation is possible in areas of uniform topography and water depth.

Pockmarks are formed in soft, glaciomarine/marine clays deposited after the marine ice sheet retreated (i.e., postglacial sediments). They commonly occur in topographical lows or deep, flat areas. Locally, they also occur across broadly mounded, muddy areas below certain water depths. Table 2 summarises pockmark parameters in the various areas, and further description of the largest fields follows.

Håkjerringsdjupet

Håkjerringdjupet is an up to 400 m-deep cross-shelf trough in the southwesternmost part of the Barents Sea (Fig. 1). Mesozoic bedrock subcrops below glacial sediments in the inner half of the trough. In some areas, the trough exhibits a hill-hole topography caused by glaciotectionic processes (Sættem, 1990). Postglacial sediments are 15–20 m thick in depressions, and mainly comprise glaciomarine stratified clays, sometimes deposited directly on the sedimentary bedrock (Fig. 4B). Pockmarks 2–4 m deep and 20–50 m wide are common

Table 2. Pockmark (PM) inventory, Norwegian Barents Sea. Abbreviations: MBB – Multibeam bathymetry, SSS – Side-scan Sonar.

Area	Size of pockmark field/area (~km ²)	Common pockmark diameter/ depth (m)	Highest pockmark density per km ²	Data source(s)	Comment
Håkjerringdjupet	850	20–50 / 2–4	150–200	MBB/SSS	PM occur mainly at w.d. >250 m
West of Sørøya	550	20–50 / 1–2.5	150–180	MBB	PM occur mainly at w.d. >250 m
Depression west of Ingøydjupet	900	10–30 / 1–2	200?	MBB/site survey	PM occur mainly at w.d. >300 m (near Snøhvit)
Ingøydjupet	7400	40–50 / 4–5 20–30 / 2–3	210 200	MBB/SSS MBB/SSS	Southern part (deepest area) Northern part
15 km-wide corridor east of Ingøydjupet (i.e., crossing parts of Nordkappbanken)	60?	15–39 / 1–3	150–200	MBB	PM occur mainly at w.d. >250 m Common south of 72°20' N
Djuprenna (wide part)	5,500	10–30 /	40–60	MBB/SSS	Elongated PM (parallel to trough axis)
North of easternmost Varangerhalvøya (north of narrow part of Djuprenna)	1000?	40–50 /	400–600	MBB/SSS	
Easternmost Norwegian sector (previously disputed area or TOO)	>27,000	20–30 / 2–4	c. 500–800	MBB	High density of PM is very common
Nordkapp Basin	19,000	15–25 / 1–2	300–700	SSS	
Depression east of Nordkappbanken	18,000	10–40 / 2–3	700–900	MBB/SSS	Few lines. PM statistics from site survey 7131/4–1
North of Nordkapp Basin	>5,000	10–20 / 1–2	50–150?	SSS	Information from some lines at c. 30°E

at more than 320 m water depth. Pockmark density is up to 150–200 per km², but there is some variation in both size and density (Fig. 4A). Pockmarks locally form clusters, also in areas of positive topography. High backscatter is often recorded in the largest pockmarks, but rarely in the smallest ones. Pockmarks also occur along the lower slopes of the glaciotectonic hills.

Ingøydjupet

Ingøydjupet is a wide, 150 km-long glacial trough north of Sørøya. It separates the banks Tromsøflaket and Nordkappbanken, and is more than 400 m deep in its southern part. In the northwest, a broad topographic ridge separates Ingøydjupet from the trough Bjørnøyrenna (Fig. 1). The ridge is heavily ploughed by icebergs, and strong currents have prevented deposition of fine-grained sediments.

The major part of Ingøydjupet is located above the Hammerfest Basin (Fig. 2), which comprises a more than 5000 m-thick succession of Late Palaeozoic to Early Tertiary deposits (Gabrielsen et al., 1990; Sigmond, 1992). Palaeocene rocks subcrop below a 30–80 m-thick Quaternary till unit in the central part of the trough (Chand et al., 2009). The southeasternmost part of

Ingøydjupet is on the Finnmark Platform, where Triassic deposits subcrop (Figs. 2, 3). The northern part of the trough is above the southwestern flank of the Loppa High, where Triassic rocks subcrop below a Quaternary cover.

MBB northeast of the Goliat hydrocarbon field, in the southern and deepest part of Ingøydjupet, shows numerous pockmarks (Chand et al., 2009) (Fig. 5A). High-resolution seismic data show at least 12 m of acoustically stratified sediments in the deep part of the basin (Svitzer, 2001), and that the pockmarks occur in the upper transparent part of the succession. Buried pockmarks are not observed. The glaciomarine succession consists of normally consolidated silty clay with various amounts of ice-rafted coarse sand and gravel (Aagaard-Sørensen et al., 2010; Risebrobakken et al., 2010). The upper 0.5–1 m comprises fine-grained Holocene clay (Hald et al., 1989; Johannesen, 2006; Chistyakova et al., 2010).

An average of 210 pockmarks per km² were counted in water depths greater than 420 m. They are commonly 40–50 m wide and 4–5 m deep (Table 2), but some are twice as large (Fig. 5C). The pockmarks are generally randomly distributed, although locally forming lineaments. Central parts of some pockmarks exhibit

Figure 4. Pockmarks in Håkjerringdjupet. (A) Pockmarks 2–4 m deep occur where water depths exceed c. 320 m. Blue tone shows pockmark distribution. (B) Topas line (white line in A) showing the stratified postglacial sequence of glaciomarine and marine sediments where pockmarks occur in the uppermost part. There is no evidence of buried pockmarks. See Fig. 1 for location.

Figure 5. Pockmarks in the southern part of Ingøydjupet. (A) Water depth and shaded relief image of multibeam data. The targeted position of a gravity core, which indicated a hydrocarbon source in deep strata, is shown as a green star. (B) Multibeam backscatter showing higher reflectivity in the central part of many pockmarks, probably indicating a coarser-grained seafloor. (C) Vertical profile across the sampled pockmark. See Fig. 1 for location.

higher backscatter than the surrounding seafloor (Fig. 5B). The uppermost clay sequence thins towards the flanks of the depositional basin where pockmarks become smaller and less common. They are rare at depths shallower than 330 m. The high density of small pockmarks on side-scan sonar and deep-towed boomer lines in the southern, eastern and northern parts of the trough indicates a distribution across the entire trough (Fig. 2).

North of Magerøya

MBB data from a 15 km-wide N–S corridor across western Nordkappbanken (Fig. 1) show that pockmarks, mainly less than 25 m wide, are common south of 72°20'N, in water depths greater than 250 m (Table 2). No other seafloor data are available from this area, thus their distribution to the west and north may be more extensive than suggested (Fig. 2).

Djuprenna and areas directly to the north

Djuprenna is a trough following the northeastern Finnmark coast (Fig. 1). The western part is wide and bounded by Nordkappbanken to the west and northwest. The deepest part with water depths of more than 410 m occurs 25 km north of Nordkinnhalvøya. North of Finnmark, the bedrock comprises a 600–700 m-thick succession of Palaeozoic and Lower Triassic sedimentary rocks (Bugge et al., 1995). On top, there is an up to 80 m-thick succession of glacial sediments, covered by soft postglacial clays up to 15 m thick (Fig. 6B). In the wide, central part of Djuprenna, up to 60 pockmarks occur per km² (Fig. 6A). Many are elongated in the direction of the trough. The longest axis is commonly 30–60 m, up to twice the length of the shortest. Seismic data show no clear evidence of shallow gas in the subsurface. In the central part of the trough, pockmark density is highest where Lower Triassic rocks subcrop (Sigmond, 1992; Bugge et al., 1995). The southern pockmark boundary occurs in the deepest part of the trough north of Nordkinnhalvøya, where the upper unit of fine-grained sediments pinches out. In the northern slope of Djuprenna along Nordkappbanken, pockmarks only occur in water depths >250 m.

Towards the east, Djuprenna narrows and comes closer to the coast (Fig. 1). Pockmarks are rare in the deepest part, but directly north of the trough, numerous 15–30 m-wide pockmarks and a few larger ones occur above a Palaeozoic sequence (Bugge et al., 1995) (Fig. 7). The density of small pockmarks increases eastwards, and side-scan sonar data show up to 600 pockmarks per km² north of the narrowest part of Djuprenna (Fig. 8). They occur above Upper Permian strata in a c. 5 m-thick unit of soft, fine-grained sediments in a vague depression. Farther north, the density of pockmarks increases towards shallower depths while their size decreases. This change correlates with a gradual thinning of the

Figure 6. Pockmarks in the widest part of Djuprenna. (A) Water depth and shaded relief image illuminated from the northwest. (B) Topas line (red line in figure A) showing the c. 12 m-thick stratified sequence of two postglacial units where pockmarks occur in the upper part of the succession. Holocene deposits are probably less than 1 m thick. See Fig. 1 for location.

uppermost layer of soft clay. In this area, Lower Triassic rocks subcrop below till less than 50 m thick (Sættem et al., 1992b; Bugge et al., 1995).

The eastern Norwegian sector

The MAREANO programme (www.mareano.no) has surveyed the southeasternmost part of the Norwegian Barents Sea by multibeam echosounder (Fig. 1), and the pockmark distribution has been mapped in detail south of 72°30'N (Fig. 9). Approximately 85% of the seafloor in this c. 13,000 km² large area is covered by a high density of pockmarks (300–800 per km²), 9% by medium density (50–300 per km²), 3% by low density (5–50 per km²), while 3% has either less than five pockmarks per km² or no pockmarks at all. The pockmark distribution is more variable north of 72°30'N. Extensive fields of high pockmark density occur, but also areas without pockmarks or with very low pockmark density. In the mapped area north of 72°30'N (Fig. 2), areas without pockmarks or with less than 5 pockmarks per km² make up nearly 25% of an area of c. 19,000 km².

Areas with very few or no pockmarks frequently coincide with topographic highs with water depths less than 240 m, some of which are expressions of salt diapirs. The largest area without pockmarks occurs on a diapir on Tiddlybanken (Fig. 9A) (Bøe et al., 2013). In shallow areas with few pockmarks, there are occasional pockmarks along iceberg scours. There are also small basins of very low pockmark density at water depths >300 m, e.g., directly south of Tiddlybanken (Fig. 9B). This basin has relatively thick postglacial deposits (Fig. 10). Towards its flanks, where the postglacial unit thins, the pockmark density increases and pockmarks become smaller (Figs. 9C, 10). Up to 800 pockmarks per km² are

Figure 7. Pockmarks off Varangerhalvøya. (A) Mini airgun acquired by FFI showing Late Palaeozoic and Mesozoic sediments subcropping below Quaternary sediments of variable thickness. The arrow shows where the line in figure B intersects at a large angle. (B) Side-scan sonar line IKU-103–88–SSS showing pockmarks above subcropping Permian–Carboniferous rocks. See Fig. 1 for location.

Figure 8. Pockmarks northeast of Varangerhalvøya. (A) Side-scan sonar example of line IKU-315230-88 showing a very high density of very small pockmarks. (B) Deep-towed boomer of the same section showing that the small pockmarks occur in a c. 5 m-thick unit of soft stratified postglacial deposits above till. See Fig. 1 for location.

present where the uppermost sediment layer is less than 2–3 m thick.

Numerous small pockmarks occur locally in areas where gravity cores sample 2–3 m of soft postglacial clays, although seismic data do not clearly indicate an upper fine-grained unit (Figs. 11, 12), especially north of 72°30'N. The importance of soft clay as a recording medium for pockmarks is very well illustrated in Fig. 11, where the boundary of a succession of deglaciation sediments corresponds to a sharp pockmark boundary. Very few pockmarks occur east of this boundary where firm to hard till outcrops.

The seafloor above the Nordkapp Basin

The Nordkapp Basin is a WSW-ENE-oriented, fault-bounded sedimentary basin, c. 50 km wide and 300 km long (Gabrielsen et al., 1990) (Fig. 2). Numerous salt diapirs occur, and petroleum exploration has focused on

salt traps. Diapirism has uplifted and folded the Mesozoic strata above the salt diapirs, and later erosion has left the strata truncated beneath a 20–40 m-thick Quaternary succession. IKU Petroleum Research retrieved 1500 km of high-resolution seismic data from the central and southwestern part of the basin (Fig. 1) and performed continuous coring at eleven locations from a drill ship. Nearly 600 m of cores at the flanks of the salt diapirs showed varied lithologies spanning in age from Mid Triassic to early Late Cretaceous (Bugge et al., 2002a).

The data acquired northeast of Nordkappbanken (Fig. 1) show a high density of small pockmarks (Fig. 12). Most of the pockmarks are 15–25 m wide; few are larger than 40 m. The uppermost layer of soft clay is generally 3–5 m thick, but numerous pockmarks also occur on gentle slopes and local highs where the upper soft layer appears to be less than 2 m. In general, pockmark size and density decrease as the thickness of the upper soft layer decreases. Shallow areas are ploughed by icebergs, and pockmark density is usually higher in furrows. Pockmarks are absent in water depths shallower than c. 270 m on Nordkappbanken, i.e., above the southernmost part of the Nordkapp Basin.

Nordkappbanken to Tiddlybanken

Between central Djuprenna and Tiddlybanken, the 300 m depth contour encircles a wide depression less than 360 m deep (Fig. 1). SSS line IKU-0-88, along the western flank of this depression, and two MBB lines crossing more centrally, show numerous small pockmarks (Figs. 1, 2). SSS data from the site survey at well 7131/4-1 show 700–900 pockmarks per km² (Fig. 13). The pockmarks are randomly distributed, have diameters of 10–30 m, and are on average 2–3 m deep. A Quaternary succession about 30 m thick occurs above Cretaceous bedrock in this area (Gardline, 2005). MBB acquired along 32°E from Djuprenna to 73°N shows numerous pockmarks, except in two small areas less than 250 m deep. This demonstrates that pockmarks occur nearly everywhere between 32°E and line IKU-01-88 (Figs. 1, 2).

North of the Nordkapp Basin

The SSS line along 30°15'N, crossing Sentralbankrenna, shows a variable number of pockmarks, but the density is much lower than in the Nordkapp Basin. A deep-towed boomer profile along the same transect shows that the upper soft sediment layer is 1–5 m thick. Two N-S MBB lines confirm that pockmarks occur almost everywhere, possibly excluding a 250–300 m deep area with intense iceberg ploughing on the shallowest hills at c. 73°N (Fig. 2).

Bjørnøyrenna

At the southern flank of Bjørnøyrenna, numerous very small pockmarks occur on the flat seabed around

Figure 9. Pockmarks rendered in multibeam bathymetry images along the border to Russia. (A) Pockmark density subdivided into three classes. D – Outcropping salt dome at Tiddlybanken. (B) Seafloor image from the deepest part of a local depression. The pockmark density is low to medium, and the pockmarks are medium to large. (C) High pockmark density in a shallower area. Pockmarks are much smaller than in the deepest area (in B). For locations of figures B and C, see figure A. See Fig. 1 for location.

Figure 10. Topas profile collected by the MAREANO project showing thinning of the postglacial sedimentary units towards the flanks of a basin. For location of profile see Fig. 9.

Svalisdomen (Figs. 1, 2). Svalisdomen is a topographic high where Permian rocks subcrop thin Quaternary deposits (Bugge & Fanavoll, 1995). The topographically highest area is devoid of pockmarks and the seafloor is characterised by intense iceberg ploughing. An inclined, layered succession of Early to Mid Triassic age occurs at the flanks of the dome. The bedrock is covered by c. 100 m of mainly till, with only a few metres of soft clay on top. Pockmarks indenting this clay layer occur at a water depth of around 400 m.

Site survey data at well 7324/10-1 east of Svalisdomen show numerous small pockmarks (diameter 10–25 m; depth 1–2 m) at around 400 m water depth. Pockmarks of this size were also detected at site surveys 7321/9-1 and 7321/8-1 northwest of Svalisdomen (Figs. 1, 2) at

water depths of 460–470 m. Seafloor images presented in the site survey reports show a pockmark density of around 100 per km².

No pockmarks were observed on the regional profiles crossing the deep part of Bjørnøyrenna. The sonar fish was, however, towed too high above the seafloor to observe small pockmarks. The regional survey lines acquired by Sintef Petroleum Research show pockmarks at 400–460 m water depths in the Bjørnøya West license area and on Stappen High (Fig. 2). The pockmark density is very low (c. 10 per km²), and their diameter is 15–25 m. They occur in a local deposition area where only the rims of the iceberg ploughmarks are visible on the sonar records. Southwest of the pockmark field, the seafloor is intensely ploughed down to nearly 500 m water depth,

Figure 11. A well-defined pockmark boundary in eastern Sentralbankrenna. (A) Water depth and shaded relief image of multibeam data. (B) Topographic profile showing a succession of sedimentary units thinning towards the east. The upper soft postglacial unit with pockmarks is difficult to distinguish from the underlying deposits. Note the sharply defined sediment pinch-out coinciding with the pockmark boundary, the high density of pockmarks west of the boundary, and the smooth till surface to the east. See Fig. 1 for location.

indicating that postglacial deposits are either absent or very thin.

On the northwestern flank of the Loppa High, pockmarks occur at water depths greater than 400 m (Chand et al., 2012, 2013), suggesting the presence of numerous pockmarks in Bjørnøyrenna. Based on the limited database, it is impossible to draw a reliable distribution map (Fig. 2).

Figure 12. Pockmarks in the Nordkapp Basin. (A) Side-scan sonar line IKU-302230-88 showing a high density of very small pockmarks. (B) Deep-towed boomer line at the same location showing that pockmarks occur in the c. 5 m-thick upper unit which is slightly more acoustically transparent than the unit below. The base of the upper unit and the base of the Quaternary deposits are indicated with dashed lines. The upper unit is not stratified, but we infer that it was deposited during the deglaciation and comprises soft glaciomarine sediments. See Fig. 1 for location.

Figure 13. Side-scan sonar image acquired during site survey at exploration well 7131/4-1 (Gardline, 2005). See Fig. 1 for location.

Pockmarks in the Finnmark fjords

Based on MBB data, numerous pockmarks have been detected in four of the Finnmark fjords (Fig. 2). In Varangerfjorden, a 10 m bathymetric grid was available for interpretation. In Porsangerfjorden, Laksefjorden and Tanafjorden, detailed bathymetry was available only in the outer parts of the fjords, and the extent of pockmarks in the inner fjord areas is probably more extensive than shown in Fig. 2. It is not possible to detect small pockmarks from the available 50 m bathymetric grid cells. Pockmarks in Lyngenfjorden and Ullsfjorden in northern Troms (Fig. 2) have been described and discussed by Hovland & Judd (1988) and Plassen & Vorren (2003).

In Varangerfjorden, pockmarks occur over more than 50% of the total area (Figs. 2, 14A). They are generally 20–50 m wide and 1.5–3 m deep. The pockmark density is partly controlled by the topography (Fig. 14C). Ridges and narrow troughs sub-parallel to the fjord axis mirror the topography of the underlying bedrock and till surface (e.g., Ottesen et al., 2008). Pockmarks are most frequent above positive landforms and along steep slopes (100–200 per km²), whereas only 20–50 pockmarks per km² occur in flat areas or basins. In some smaller areas, pockmarks do not occur (Fig. 14C). The thickness of Quaternary deposits in Varangerfjorden is generally 10–15 m, mainly comprising glaciomarine clays (Fig. 14B). In the deep and flat part of the fjord, where 50–100 m of deglaciation sediments were deposited, very few pockmarks occur (Fig. 14A). In one of the narrow tributary fjords to Varangerfjorden, northwest of Kirkenes (Fig. 1), there are up to 150 pockmarks per km². They are usually 30–50 m wide, but some reach 100 m.

In outer Porsangerfjorden, pockmarks are common in flat areas with water depths >220 m. The largest pockmarks found are 40–80 m across and up to 5 m deep. Pockmark density may reach 100–200 per km² on the upper basin flanks and on ridges. Strings of pockmarks occur along ridges which mimic the subsurface topography. Also where the seafloor is flat, strings of pockmarks may

Figure 14. Pockmarks in Varangerfjorden. (A) Numerous small pockmarks occur over extensive areas of Varangerfjorden. (B) Topas line (red line in figure A) showing the deep fjord basin at the southern end with very few pockmarks and thick deglaciation deposits. Pockmarks are common at shallower depths where there is 10–15 m of postglacial clay above a discontinuous thin till unit and subcropping Neoproterozoic metasedimentary rocks. (C) Water depth and shaded relief image of multibeam data showing the uneven distribution of pockmarks, which are most common along positive topographic elements. The red line marks where Fig. 14B is located. See Fig. 1 for location.

occur with the same orientation, commonly trending along the axis of the fjord. In depressions where the topography has been smoothed by postglacial clay deposition, the highest pockmark densities coincide with steep subsurface bedrock slopes and ridges (A. Lepland, pers. comm., 2014).

Discussion

Pockmarks are usually explained by gas escape, either thermogenic or biogenic (Hovland & Judd, 1988; Judd & Hovland, 2007). At Vestnesa and in some other areas, pockmarks are clearly associated with active gas seepage (Gay et al., 2006; Hustoft et al., 2009; Chen et al., 2010; Dondurur et al., 2011; Bünz et al., 2012), or palaeo-seeps evidenced by carbonate crusts in pockmarks (Hovland & Judd, 1988; Paull et al., 2008). A full understanding

of pockmark formation and the relation to sub-seafloor hydraulic systems has yet to be established (Hovland et al., 2010). For example, pockmarks in Norskerenna (Troll gas field) and at Nyegga (north of the Storegga Slide) are interpreted as intermittently active and associated with dynamic gas hydrate occurrences (Hovland et al., 2005, 2010; Hovland & Svensen, 2006; Ivanov et al., 2007; Chen et al., 2010). Other researchers interpret them as relict (Forsberg et al., 2007; Tjelta et al., 2007; Paull et al., 2008; Reiche et al., 2011).

Pockmark age and formation

Detailed studies of pockmarks on the floor of the Hammerfest Basin and the western flank of the Loppa High point towards relict pockmarks (Chand et al., 2012; Nickel et al., 2012; Pau et al., 2014a). These pockmarks were interpreted to have formed by methane released due to gas hydrate dissociation during the last deglaciation. There are no indications of catastrophic events similar to those suggested in the northeastern Barents Sea (Solheim & Elverhøi, 1993; Lammers et al., 1995; Long et al., 1998). Pau et al. (2014a) suggested that the pockmarks started to form in the early Bølling Interstadial (*c.* 14,500 cal. yrs. BP), and that they continued to be intermittently active until recent. Neither Nickel et al. (2012) nor Pau et al. (2014a) found evidence of upward methane flux in analysed samples. Also pockmarks in the Norwegian Channel near the Troll platform were found to be relict; and carbonate crust within one gave an age of *c.* 11,000 cal. yrs. BP (Forsberg et al., 2007). Farther south in the North Sea, pockmarks are also assumed to have formed by destabilisation of gas hydrates (Fichler et al., 2005); this despite the fact that there are large pockmarks in the Central North Sea which are continuously active, such as the 15 m-deep 'Scanner Pockmark' with thermogenic gas ebullition (Hovland & Sommerville, 1985; Hovland & Judd, 1988).

High-resolution seismic data (Figs. 4, 6, 8) suggest that pockmarks formed late during the postglacial sedimentation. If gas seepage was slow compared to rapid settling of sediment particles, it may have started shortly after the ice sheet disappeared. However, we have not observed acoustic chimneys indicating upward leakage of gas towards pockmarks. The lack of an upper, well-defined acoustically laminated unit, such as we see in the Nordkapp Basin and in the northeastern part of the study area (Figs. 11, 12) may, however, tentatively be related to seepage of gas disturbing the sedimentation.

In Ingøydjupet, higher backscatter within some pockmarks is interpreted to reflect a higher content of sand and gravel. In areas of weak bottom currents and no seepage, a pockmark may act as a sediment trap, but video inspections at several sites reveal cobbles and boulders at the bottom of some pockmarks (www.mareano.no). Coarse sediments within pockmarks may indicate active fluid seepage causing winnowing

of sediments and preventing fine-grained sediment deposition (Pau et al., 2014a). A coarse-grained seafloor may also be due to high biological activity (Webb et al., 2009b), or turbulence caused by local gyres that winnow glaciomarine clays or prevent sedimentation in pockmarks (Pau et al., 2014b). The chemistry of samples from pockmarks in Ingøydjupet (Fig. 5) suggests a hydrocarbon source in deep strata (Boitsov et al., 2009, 2011).

The Barents Sea, excluding Bjørnøyrenna, is outside of the methane hydrate stability zone (MHSZ) (structure I gas hydrate) due to the shallow water depths (Chand et al., 2008), but modelling has shown that structure II gas hydrate (methane, CO₂ and/or higher-order hydrocarbons) may occur in some areas. Gas hydrate has been observed in a gravity core from the Nordkapp Basin (Chand et al., 2008). Modelling shows that the Barents Sea ice cap was at least 1200 m thick during LGM at about 18,000 ¹⁴C yrs. ago (Siegert et al., 2001). Under such conditions, methane hydrate would have been stable over the entire SW Barents Sea down to at least 600 m below the present seafloor (Chand et al., 2012).

Present gas hydrate stability in the SW Barents Sea is highly variable and mainly controlled by spatial variability in the geothermal gradient and amount of higher-order hydrocarbon gases (Chand et al., 2008; Rajan et al., 2013). Structure II gas hydrates may therefore occur locally and be unstable. Acoustic reflections within the water column above the Hammerfest Basin, up to 200 m high, most likely represent gas bubbles from expulsion of gas at the seafloor (Chand et al., 2012), but gas leakages have so far not been observed above pockmarks.

Pockmark origin and distribution

Pockmarks may be linked to leakage from active subsurface petroleum systems (Løseth et al., 2009; Hovland et al., 2010, 2012), but this study has not detected any hydrocarbon discharge from petroleum reservoirs. In the following discussion we will show that pockmark distribution is almost independent of the Quaternary sediment thickness, age and lithology of subcropping bedrock and subsurface structural elements. Pockmarks can only form in areas of soft, fine-grained sediments (Chand et al., 2009).

The thickness of Quaternary deposits west of 30°E varies generally between 15 m and 100 m (Sættem et al., 1992b). In the eastern part of the study area, the thickness is poorly known as only Topas lines with limited penetration have been available (Figs. 10, 11). The deposits are dominated by till with a total organic content of 0.4–1.2% (Sættem et al., 1992b). Our data show no correlation between Quaternary sediment thickness and distribution of pockmarks, and it is unlikely that the low content of organic matter in a few tens of metres of glacial deposits have created enough gas to form the

observed pockmarks. The main source of the gas, also in areas of thicker till deposits, is thus sedimentary bedrock. In the Norwegian Channel in Skagerrak, the highest occurrence of pockmarks is above a Jurassic sandstone covered by thin Quaternary deposits (Rise et al., 1999).

The largest pockmarks usually occur in the deepest parts of the troughs where postglacial clays are thickest, whereas they become smaller towards basin flanks where the deposits gradually thin. Where the soft clay is thin, the base of pockmarks probably corresponds to the base of the soft clay. In Ingøydjupet and other depressions in the west, the density is highest in the deepest areas, whereas the opposite is observed at several locations in the east (Figs. 9, 10). Gas and/or fluids appear to less easily penetrate the postglacial clays when the unit becomes thicker than 5–10 m. Also in Varangerfjorden, very few pockmarks occur in the deepest fjord basin where the deglaciation sediments are thick (Fig. 14A, B).

Pockmarks occur above Cenozoic, Mesozoic and Palaeozoic strata as well as in fjord areas with Proterozoic metasedimentary rocks (Fig. 3). The southern pockmark boundary in the deep eastern part of Djuprenna coincides closely with the Triassic–Permian boundary (Sigmond, 1992). High-resolution seismic data show, however, that this is related to the absence of fine-grained sediments above the Palaeozoic rocks due to strong bottom currents along the lowermost slope north of Finnmark. We find no clear relationship between pockmark distribution and subcropping bedrock type. This is best illustrated within the Nordkapp Basin (Fig. 12), where salt diapirism has uplifted and tilted the Mesozoic strata (Bugge et al., 2002a). A high concentration of pockmarks occurs above both permeable sandstones and tight claystones and even above glacially eroded salt diapirs.

Uplift and erosion of the western Barents Sea during the Neogene was 1–2 km (Nyland et al., 1992; Riis & Fjeldskaar, 1992), and the uppermost unconformity, URU, has been modified several times. Laberg et al. (2012) estimated that glacial erosion has been up to 1 km in troughs during the Quaternary. Eroded sediments were transported beyond the shelf edge and deposited on the extensive Bear Island Fan as a thick succession of dominantly glacial debris units (Eidvin et al., 1993; Knies et al., 2009; Laberg et al., 2012). Erosion and unloading of the shelf probably caused stress release and fracturing of the bedrock (Løtveit et al., 2009; Henriksen et al., 2011a, b), and pressure fluctuations may have reactivated faults and broken seals. Also, release of pressure from the overlying ice cap resulted in release of dissolved gas within pore fluids which had accumulated over the glacial period (Chand et al., 2012). Moreover, in both deep and shallow reservoirs, gas expanded and affected spill points, and created new migration routes.

The extensive pockmark distribution reflects a nearly continuous cover of fine-grained sediments, and MBB

mapping of pockmarks therefore indirectly provides information about the type of sediments in the upper metres below the seafloor. The pockmark density is highest in the east (Fig. 13) where the postglacial clay is thinnest. This may suggest that more gas has leaked from the seafloor in the east than in the west. If the gas originates from deep strata, few barriers have prevented migration towards the seafloor. During the Late Weichselian glaciation, migrating gas was trapped as gas hydrates in the upper part of the seafloor. Dissociation of this unstable gas reservoir is a plausible explanation of pockmark formation. It is, however, difficult to explain the very uniform distribution of pockmarks.

In the Barents Sea, shallow gas may be of mixed origin, both sourced from deep strata and from bacterial alteration of organic matter in the upper part of the bedrock. A model proposed by Formolo et al. (2008) may indirectly also have relevance to the understanding of pockmarks. They proposed that microbial methanogenesis along the shallow margins of sedimentary basins provides a source of atmospheric CH_4 temporally connected with both advance and retreat of continental ice sheets. Extensive biodegradation of hydrocarbons in organic shales was stimulated when the saline pore water became diluted by fresh water due to the hydraulic gradient generated by overriding Pleistocene ice sheets.

Most of the subcropping sediments in our study area have a lower organic content than the organic-rich shale studied by Formolo et al. (2008), raising uncertainties about the applicability of this model to the Barents Sea Ice Sheet. If applicable for the Barents Sea, the resultant enhanced production of methane would help explain the extensive distribution of pockmarks. It is also possible that the biogenic zone was deeper during glacial times. The microbial methanogenic zone can extend up to 110°C (Gold, 1992; Hond et al., 2004), so given the low geothermal gradient in the SW Barents Sea (22–27°C km^{-1}) combined with freshwater percolation to greater depths from the hydraulic pressure exerted by the glaciers, this zone could be at comparable depths thus reaching source rocks beneath the SW Barents Sea (Henriksen et al., 2011a, b).

An experimental study by Hermanrud et al. (2013) emphasised the importance of rapid sea-level drops which can result in significant fluid overpressure, causing fluidisation and vertical fluid leakages. Fluid overpressure is significantly enhanced with the presence of gas and dissociation of gas hydrates. Their simulations suggested that the expansion of gas in shallow vertical migration routes is the main mechanism for pockmark formation. Apparently, this theory does not fit our observations, which show that pockmarks formed during a period of rapid sea-level rise or towards the end of this period. However, the sea-level drop during the Early Weichselian may have enhanced the gas migration towards the seafloor (Hermanrud et al., 2013). Some of

this gas may have been captured as hydrates (or as free gas below the Gas Hydrate Stability Zone; GHSZ) during the first, extensive Weichselian glaciation when the entire Barents Sea was glaciated. The gas hydrates probably started to dissociate some time after the Late Weichselian ice-sheet retreat, as we rarely see pockmarks in the lower part of the stratified glaciomarine clay unit. Pockmarks probably deepened as a result of reduced sedimentation or non-deposition above active seeps or due to erosion by active seeps (Pau et al., 2014a).

Pockmarks in Finnmark fjords

The pockmark density in the Finnmark fjords is much higher than in most other Norwegian fjords (Plassen & Vorren, 2003; Webb et al., 2009a). Pockmarks in fjords or near-shore areas are thought to be related to groundwater flow from neighbouring mountain areas or to be related to microbial gas from Quaternary deposits (Hovland & Judd, 1988; Judd & Hovland, 2007).

Although it has been reported that the thick Neoproterozoic sedimentary successions of onshore and offshore northwestern Russia have a fairly considerable hydrocarbon potential (Lyubtsov et al., 1999), it is unlikely that the comparatively thin Neoproterozoic succession in inner Varangerfjorden would be capable of producing hydrocarbon gases. Very few pockmarks occur where the Quaternary succession is thickest, suggesting that they are unrelated to microbial methane from deglaciation sediments. This assumption is supported by the higher density of pockmarks where these deposits are only 5–15 m thick (Fig. 14B). The location of pockmarks in flat parts of Porsangerfjorden commonly coincides with subsurface bedrock slopes or ridges, and may therefore be linked to groundwater flow from mountain areas surrounding the fjord. It appears that buried, yet sloping, bedrock surfaces present a conduit for ascent of water along the bedrock–till interfaces, and from there then follow the shortest pathway to the seafloor. If this is the case, it introduces the possibility that the pockmarks in the fjords may be intermittently active also at present, an expression of leaking artesian flow. We suggest groundwater flow also in Varangerfjorden, where pockmarks are most frequent over mounded landforms and in the upper part of steep slopes (Fig. 14B, C). In the Norwegian Skagerrak, groundwater flow from Denmark has been suggested by Hübscher & Borowski (2006) to explain the mega-pockmarks described by Bøe et al. (1998).

Conclusions

The following conclusions can be drawn:

- Small pockmarks (20–50 m wide; 2–4 m deep) are very common in the southern part of the Norwegian Barents Sea. The most extensive pockmark areas occur east of the 26°E meridian (Magerøya). At least 75% of the area is covered by hundreds of pockmarks per

km². Several hundred million pockmarks occur in the studied area.

- Pockmarks occur in areas where soft glaciomarine and marine sediments were deposited after the ice margin retreated. The pockmark map reflects the distribution of soft, fine-grained postglacial deposits in the southwestern Barents Sea.
- In basins with thick glaciomarine/marine deposits, pockmarks occur mainly in the uppermost part of the succession, which is more transparent and less stratified than the lower part. Buried pockmarks have not been observed. Thus, the pockmarks formed after the main period of glaciomarine sedimentation.
- Various data suggest that the pockmarks formed due to melting of gas hydrates. Dissociation probably started c. 14,500 cal. yrs. ago, after the ice cap had melted and the bottom water temperature and thus the seabed temperature had increased due to inflow of warm Atlantic water.
- There is no evidence to suggest that pockmarks formed by catastrophic outbursts.
- There is a clear correlation between pockmark size and thickness of fine-grained deposits. Very small pockmarks occur where the soft sediment layer is thin.
- There is no correlation between pockmark occurrence and tectono-morphological elements such as basins, platforms and highs.
- There is no correlation between bedrock lithology and pockmark occurrence. Pockmarks occur above both shale/claystone and permeable sandstone units.
- Pockmarks occur in areas both with and without shallow gas identified in seismic data.
- There is no obvious connection between pockmark density and Quaternary sediment thickness. The pockmarks are rarely related to leakage of biogenic gas from Quaternary deposits.
- Pockmarks in Varangerfjorden and Porsangerfjorden are most likely formed by groundwater flow from surrounding mountain areas.

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