Geological controls on fluid flow and seepage in western Svalbard fjord, Norway

An integrated marine acoustic study

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Geological controls on fluid flow and seepage in western Svalbard fjords, Norway

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“If we knew what it was we were doing, it would not be called research, would it?”

“It would be possible to describe everything scientifically, but it would make no sense; it would be without meaning, as if you described a Beethoven symphony as a variation of wave pressure.”

- **Albert Einstein**

“The good thing about science is that it's true whether or not you believe in it.”

- **Neil deGrasse Tyson**

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Preface

The work presented in this doctoral thesis was carried out during 2011 to 2014 at the Department of Arctic Geology, The University Centre in Svalbard (UNIS), Longyearbyen, Svalbard. The research work was financially supported by the Norwegian Research Council's Norwegian-Indian bilateral grant. The study contributes to research projects at UNIS: "*Northern Barents Sea Source Rocks and Hydrocarbon Seeps*", funded by the ConocoPhillips and Lundin Norway Northern Area Program, and the "*UNIS Longyearbyen CO_2 Lab*".

High-resolution multibeam bathymetric data were generously provided by the Norwegian Hydrographic Service and used in all the research papers presented in this thesis according to permission number 13/G706. Additional multibeam data were collected on-board R/V Helmer Hanssen from selected locations (used in papers II and III). Sidescan sonar data (used in paper III) and parts of the sub-bottom acoustic profiles (used in papers III and V) were collected using a towed sub-bottom profiler from the UNIS R/V Viking Explorer. The sub-bottom acoustic data presented in paper II were collected on-board R/V Helmer Hanssen. The 2D marine multichannel seismic data, used in papers II-V, comprise several 2D seismic surveys acquired by Statoil in 1985 and 1988; and by the University of Bergen during the Svalex expeditions (co-sponsored by Statoil) conducted between 2004 and 2009. The magnetic data used in papers IV and V were collected during the Svalex expeditions. The onshore 2D seismic data and borehole data (used in papers III and IV) were collected in close collaboration with the *UNIS Longyearbyen CO_2 Lab* project, and supported by numerous partners in academia and industry (http://co2-ccs.unis.no/).

Academic software licenses were kindly provided by Schlumberger (Petrel) and ESRI (ArcGIS), which were extensively used for geophysical data interpretation and integration. Lundin Norway financed the establishment of seismic data lab at UNIS, where most of seismic data interpretation and integration with other geophysical data sets were undertaken. This doctoral thesis consists of a synopsis and five research papers.

Main supervisor:

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List of papers

This thesis presents a collection of five research papers comprising major part of the work conducted as part of the PhD program.

Paper I:

ROY, S., HOVLAND, M., NOORMETS, R., and OLAUSSEN, S., (2015). Seepage in Isfjorden and its tributary fjords, West Spitsbergen. *Marine Geology, 363, 146-159.*

Paper II:

ROY, S., HOVLAND, M., and BRAATHEN, A., (in review).Evidence of fluid seepage in Grønfjorden, Spitsbergen: implications from an integrated acoustic study of seafloor morphology, marine sediments and tectonics. *Submitted to Marine Geology.*

Paper III:

ROY, S., SENGER, K., BRAATHEN, A., NOORMETS, R., HOVLAND, M., AND OLAUSSEN, S., (2014).Fluid migration pathways to seafloor seepage in inner Isfjorden and Adventfjorden, Svalbard. *Norwegian Journal of Geology, 94; 99-119.*

Paper IV:

SENGER, K., **ROY, S.,** BRAATHEN, A., BUCKLEY, S.J., BÆLUM, K., GERNIGON, L., MJELDE, R., NOORMETS, R., OGATA, O., OLAUSSEN, S., PLANKE, S., RUUD, B.O., AND TVERANGER, J. (2013). Geometries of doleritic intrusions in central Spitsbergen, Svalbard: an integrated study of an onshore-offshore magmatic province with implications for CO_2 sequestration. *Norwegian Journal of Geology, 93, 143-166.*

Paper V:

ROY, S., SENGER, K., HOVLAND, M., BRAATHEN, A., NOORMETS, R., AND HAFLIDASON, H., (in review).Geological controls on seep-related acoustic features and pockmarks in Nordfjorden, Spitsbergen. *Submitted to Geo-Marine Letters.*

Abstract

The study of seabed fluid flow facilitates assessment of gas hydrate accumulation, submarine geohazards, localizing shallow and deep hydrocarbon reservoirs. Other fluid flow related studies include for example the benthic ecosystems that develop in seep sites, the input of greenhouse gases (e.g., methane) into the ocean/atmosphere system. Methane gas flares have been recorded in the water column of SW Spitsbergen and on the continental margin of west Spitsbergen, indicating recent active seepage processes. Geochemical analysis of hydrocarbon anomalies in near-surface marine sediments around west Spitsbergen and Isfjorden have indicated a mixture of biogenic and thermogenic signatures. Isfjorden is the largest fjord system in west Spitsbergen, where pockmarks have been described earlier. However, the subsurface fluid flow processes and systems are not well understood. In order to have a better understanding of these fluid flow systems in Isfjorden, it is necessary to study the geological factors affecting the distribution of shallow gas in the marine sediments and occurrence of pockmarks. This study systematically maps the spatial distribution and morphometry of pockmarks on high-resolution bathymetric data from Isfjorden. It further presents an integrated geophysical study of high-resolution shallow acoustic data along with 2D multichannel seismic data, magnetic data, borehole data, DEM from LiDAR scan, and geological maps, to investigate the geological controls on the fluid flow systems in selected areas. Pockmark depressions and pockmark-like features of various sizes and shapes, and submarine landforms related to glacial activities and other processes were identified across the whole study area. Subsurface seep-related acoustic features such as, enhanced reflections, acoustic blanking and turbidity zones were recorded on new high-resolution sub-bottom acoustic data; suggesting possible shallow gas occurrences in the marine sediments beneath the seep-related seafloor features. Mushroom shaped acoustic plumes were imaged in the water column in Nordfjorden, indicating suspected shallow gas escape from the seafloor. Structural features (thrust faults and associated folds) belonging to the West Spitsbergen fold-and-thrust belt and dolerite sills have been interpreted on 2D seismic data and magnetic data. These features occasionally form ridges at the seafloor where pockmarks in high-density and other seep-related acoustic features have been identified. The integrated analysis of these geophysical data sets indicates that the near-seafloor tectonically deformed stratum plays an important role in the up-dip propagation of fluids (liquids and/or gas), distribution of shallow gas in marine sediments, and seepage at the seafloor.

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1. Introduction

1.1 Fluid flow systems and their importance

Subsurface fluid flow is a significant research area of earth science. Recent marine geosciences research has indicated the vital role of subsurface fluid flow and deep sediment remobilization in shaping the seabed morphology (Judd & Hovland, 2007). Transport of buoyant fluids through focused fluid flow systems is a widespread process in continental margins and sedimentary basins (Figure 1). This process is gaining increased attention in the assessment of geohazards, environment conservation, and exploration of fossil energy resources. Studying their abundance, distribution and formation mechanisms is crucial for the understanding of their role in i) the dynamics of gas hydrate accumulation and destabilization, ii) submarine slope stability, iii) the plethora of chemosynthetic benthic ecosystems that develop in seep sites, and iv) the input of greenhouse gases (e.g., methane) into the ocean/atmosphere system, which may influence the atmospheric carbon budget and Earth's paleo- and present climate (Anka et al., 2012).

Submarine fluid flow features are represented by acoustic anomalies, generated during the subsurface flow of fluids (oil, gas, brine, groundwater, etc…) from deeper or shallow sources to the seabed (Cartwright, 2007; Aminzadeh et al., 2013). The discovery of two remarkable seabed fluid flow features: hydrothermal vents and pockmarks provided evidence of extensive emissions of fluids from the seabed (Hovland & Judd, 1988). Pockmarks are depressions of various shapes and sizes in the seabed, caused due to venting of fluids from the seafloor. They were first described on the continental shelf offshore Nova Scotia, Canada by King and Maclean (1970), soon after the introduction of the side-scan sonar technique. Since then, with the advancement in acoustic imaging techniques, a wide range of geological structures have been observed to form on the seabed as a consequence of fluid seepage, for example mud volcanoes, mud diapirs, carbonate mounds, gas hydrate pingoes and related features (Pickrill, 1993; Long et al., 1998; Planke et al., 2005; Holland et al., 2006; Judd & Hovland, 2007; Etiope et al., 2009; Serié et al., 2012). The type of structures generated on the seabed due to focused fluid flow depends on a variety of parameters, as for instance, the source of fluid, the flow type, the structural setting and the nature of the hosting sediment for the fluid flow (Hovland & Judd, 1988; Cartwright, 2007; Huuse et al., 2010). The seep structures exhibit broad diversity yet tend to have some shared similarities which help their identification in a broader context. Aminzadeh et al. (2013) documented some of their common features as:

- The seeping fluid is usually a complex mixture of oil, water, gas, mud, although one phase component might be dominant.
- Display visible traces of hydrocarbon in most cases.
- Often crater or mound shaped or may show no recognizable surface morphology.
- Tend to have circular individual vents that may or may not be fluid filled.
- May consist of several sites, each site having multiple vents.

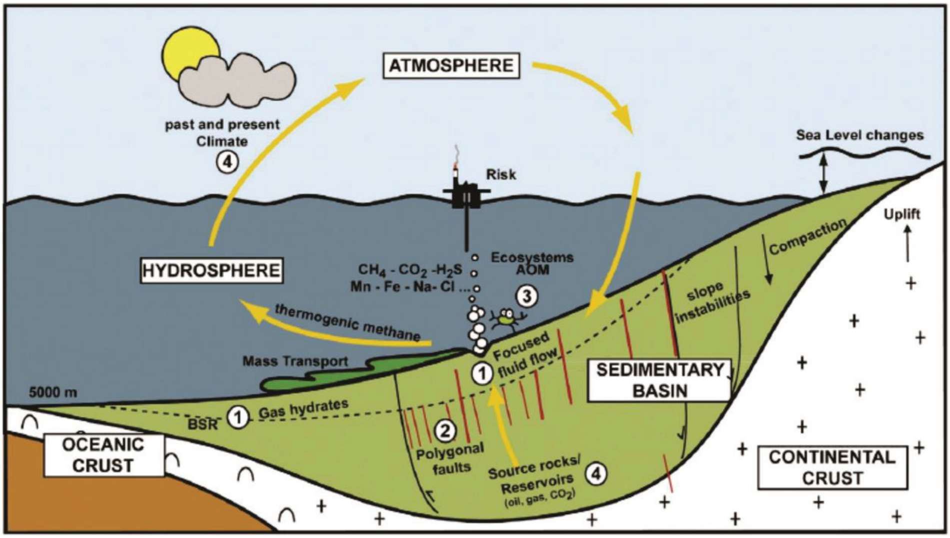


Figure 1: Schematic overview of the main components of hydrocarbon migration through focused fluid flow systems in continental margins and sedimentary basins. The circled numbers illustrate the different research study areas in any fluid flow system: (1) imaging and interpretation of gas migration and fluid flow related acoustic features, (2) polygonal fault systems and their implications on fluid flow and channelized migration, (3) ecosystems, methane-derived carbonates and geochemistry of seeps, and (4) petroleum systems, thermogenic gas release, and hyper-thermal events (Anka et al., 2012).

The impact of fluid flow features on hydrocarbon plumbing systems particularly concerning basin analysis, reservoir connectivity, migration, and risk assessment has been lately realized in various parts of the world (Aydin, 2000; Abrams, 2005; Cartwright, 2007; Andresen, 2012;

Aminzadeh et al., 2013; Ostanin et al., 2013). Although most of the fluid flow studies refer to hydrocarbon leakage from deeper reservoirs, Hovland et al. (2006) have discussed a hypothesis, where it is mentioned that if not all, but some seeps may begin as deep, superheated water plumes, and might include mantle derived elements. On the contrary, Harrington (1985) has discussed seepage at the seafloor and formation of pockmarks by pore-water escape in the North Sea.

The significance of pockmarks as indicators of submarine fluid flow and their link to geohazards have been documented by Hovland et al. (2002). Pockmarks are known to occur in both shallow and deep water depths, being associated with different geological settings such as: along continental margins, on continental slopes, as a consequence of gas hydrate dissociation, in association with slides and slumps, above polygonal fault systems and incised-valley fills (Garcia-Gil et al., 2002; Çifçi et al., 2003; Judd & Hovland, 2007; Gay et al., 2007; Hustoft et al., 2007; Chand et al., 2008; Micallef et al., 2011; Ramprasad et al., 2011; Hill et al., 2012; Ostanin et al., 2013). In some cases, pockmarks have also been found to be linked to the deposition of glacigenic wedges, submarine geomorphology and glaciomarine till (Whiticar & Werner, 1981; Kelley et al., 1994; Hustoft et al., 2009; Baeten et al., 2010; Reiche et al., 2011). These wide varieties of fluid flow systems usually comprise of complex subsurface geological structures linked with surface expressions, chemotropic and microbiotic associations, subsurface conduits, and alteration zones exhibiting complex reactions. Their current or palaeo activities may be observed on geophysical or geochemical data sets. Pockmarks have been further categorized into several types depending on their morphology and related geological and geophysical signatures: growing pockmarks, persistent pockmarks, relict pockmarks, decaying pockmarks, elongated pockmarks, string pockmarks and unit-pockmarks (Hovland & Judd, 1988; Pickrill, 1993; Çifçi et al., 2003; Hovland et al., 2010), as shown in Figure 2.

Identification of seep structures like pockmarks on seafloor geophysical data such as, sidescan sonar data, bathymetric and/or backscatter data, along with shallow gas occurrences recorded on seismic data, are possible indicators of deeper prospective reservoirs (Løseth et al., 2009; Dandapath et al., 2010). Many authors have attempted to establish a genetic link between the seafloor pockmarks and buried seepage structures such as seismic chimneys, acoustic blanking, turbidity zones, sand injection bodies, positive high amplitude anomalies, flat-spots and polarity inversions (Judd & Hovland, 1992; Andreassen et al., 2007; Løseth et al., 2009; Ho et al., 2012). Commonly used imaging tools for such geophysical identification and analysis include 2D/3D high-resolution multichannel seismic reflection, multi-frequency echo sounder and sub-bottom acoustic profilers. Examples of fluid flow related acoustic features, identified on high-resolution sub-bottom acoustic profiles are shown in Figure 3. The review of the worldwide association of faults and seeps in diverse tectonic regimes suggests that fault permeability is the most important controlling factor for the distribution and temporal and spatial variability of seeps (Ligtenberg, 2005; Talukder, 2012).

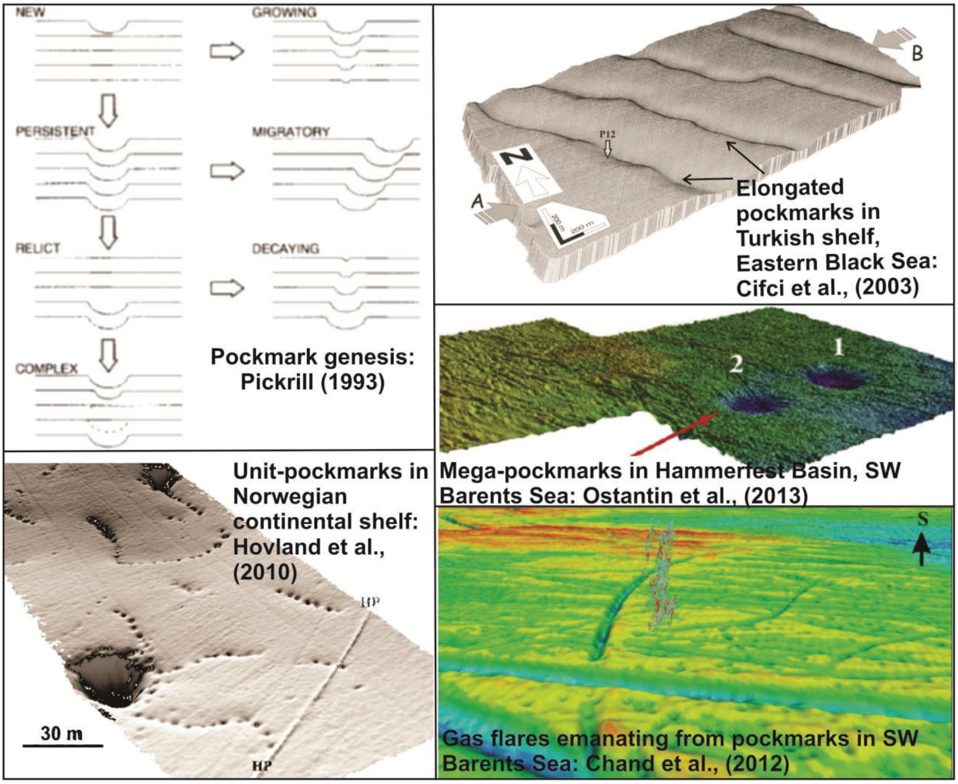
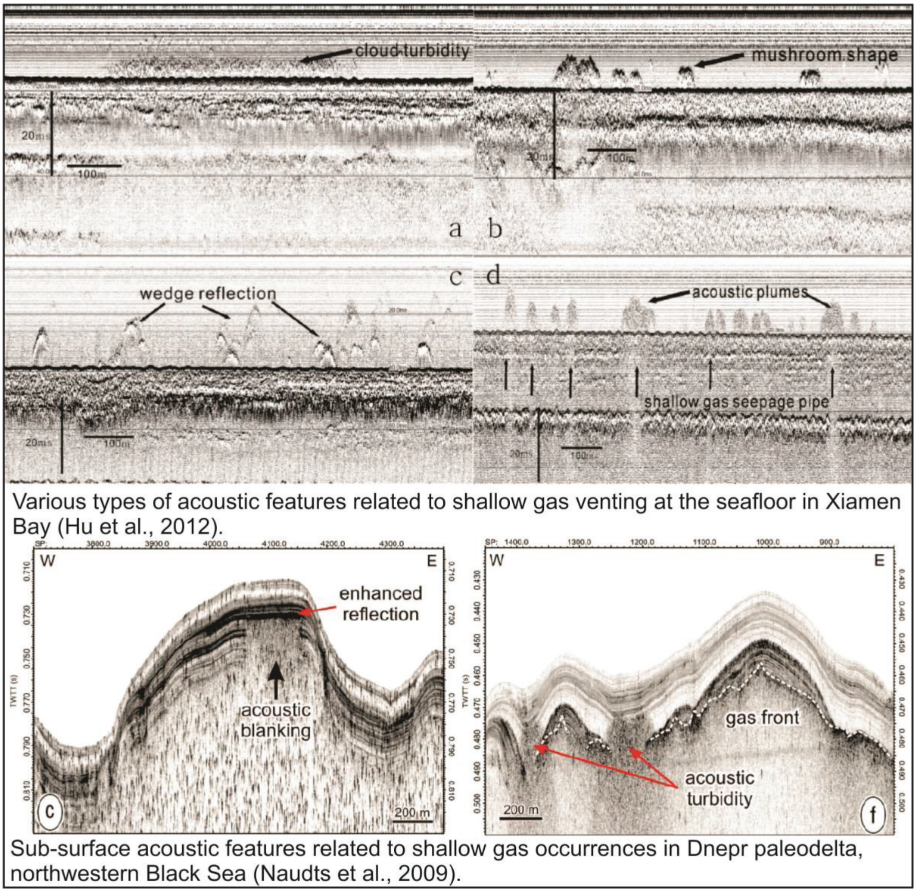


Figure 2: Various pockmark genesis and types observed in different parts of the world.



Various types of acoustic features related to shallow gas venting at the seafloor in Xiamen Bay (Hu et al., 2012).

Sub-surface acoustic features related to shallow gas occurrences in Dnepr paleodelta, northwestern Black Sea (Naudts et al., 2009).

Figure 3: Various types of shallow gas-related acoustic features identified on high-resolution sub-bottom acoustic data (Naudts et al., 2009; Hu et al., 2012).

1.2 Regional background

1.2.1 Bedrock geology and tectonics

The Svalbard archipelago represents an uplifted part of the NW margin of the Barents shelf (Nøttvedt et al., 1993b; Harland, 1997; Worsley, 2008) (Figure 4B). The geological evolution and tectonostratigraphy of Svalbard has been described by several authors (Steel & Worsley, 1984; Haremo & Andresen, 1992; Braathen & Bergh, 1995; Harland, 1997; Bergh et al., 1997; Braathen et al., 1999a; Worsley, 2008; Bælum & Braathen, 2012). Intrusions of dolerites took place in Svalbard during the early Cretaceous, majority of which occur in the Mesozoic strata (Nejbert et al., 2011; Corfu et al., 2013). Their thicknesses vary between 1 to 100 m, extending 1-30 km laterally (Senger et al., 2014b).

Spitsbergen is the largest island in Svalbard archipelago. This study emphasizes on Isfjorden which is the largest fjord system in Spitsbergen (Figures 4A, & C). The bedrock structures in Isfjorden area span from Paleozoic carbonates and evaporites to Mesozoic and Paleogene sandstones and shales (Dallmann, 1999). This 4 to 6 km thick succession is truncated by tectonic structures linked to the Tertiary West Spitsbergen Fold-and-Thrust Belt (WSFTB) (Bergh et al., 1997; Braathen et al., 1999b; Leever et al., 2011). The WSFTB consists of three major belts in Isfjorden (Figure 4D): (a) a basement involved fold-thrust complex in the western zone, (b) central zone consisting of three thin-skinned fold-thrust sheets with thrusts splaying from décollement layers, east of a frontal duplex system, and (c) eastern foreland province showing décollement in Mesozoic shales with some thrust splays, and with the décollement interacting with reactivated, steep and basement-rooted faults (Dallmann et al., 1993; Wennberg et al., 1994; Braathen & Bergh, 1995; Bergh et al., 1997; Bælum & Braathen, 2012; Blinova et al., 2013). The north-south trending Billefjorden Fault Zone is a major tectonic lineament, cutting across the eastern part of Isfjorden (Haremo & Andresen, 1992; Johannessen & Steel, 1992; Maher & Braathen, 2011; Braathen et al., 2011; Bælum & Braathen, 2012).

1.2.2 Hydrocarbon potential of organic rich rocks in Spitsbergen

The Upper Paleozoic to Cenozoic stratigraphy of Spitsbergen is similar to the Barents Shelf area (Stemmerik & Worsley, 1989; Nøttvedt et al., 1993a). The latter comprises of several economic oil and gas discoveries (Nøttvedt et al., 1993b; Doré, 1995; Grogan et al., 1999; Ohm et al., 2008; Henriksen et al., 2011a). Commercial discoveries of hydrocarbon prospects could not be ascertained in Spitsbergen despite drilling of 17 deep wells. Although there have been numerous technical discoveries including over-pressured reservoirs along the SW coast of Isfjorden and in the Billefjorden Trough. The major organic rich rocks in Spitsbergen, with moderate-good hydrocarbon potential are the shales of the Upper Jurassic- Lower Cretaceous Janusfjellet Subgroup and the Middle Triassic Botneheia Formation (also named as Bravaisberget Formation) (Mørk & Bjorøy, 1984; Dypvik, 1985; Nøttvedt et al., 1993b; Bjorøy et al., 2010).

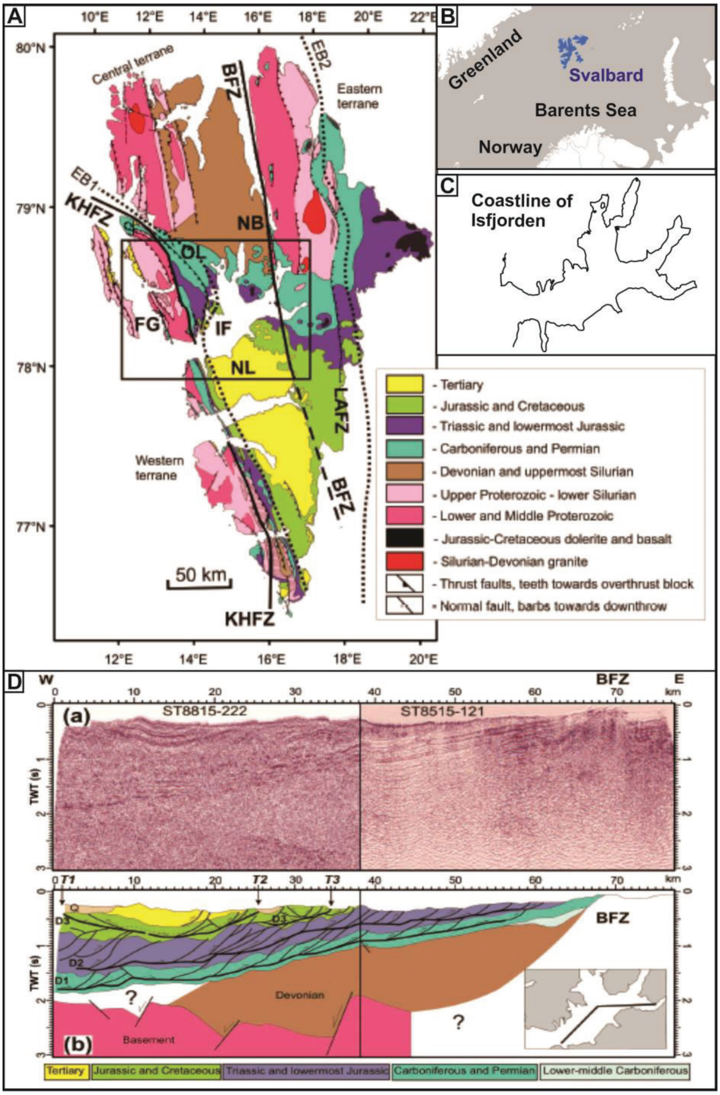


Figure 4: (A) Geological map of Spitsbergen (Blinova et al., 2013). KHFZ: Kongsfjorden–Hansbreen Fault Zone; BFZ: Billefjorden Fault Zone; LAFZ: Lomfjorden–Agardbukta Fault Zone; FG: Forlandsundet Graben; OL: Oscar II Land; IF: Isfjorden; NB: Nordfjorden block; NL: Nordenskiöld Land; EB1: boundary of the West Spitsbergen Fold-and-Thrust Belt structures; EB2: eastern boundary of folding and thrusting. Isfjorden is outlined by black rectangle. (B) Svalbard in NW Barents Sea. (C) Coastal outline of Isfjorden. (D) Seismic reflectivity in Isfjorden and its interpretation (Blinova et al., 2013). Q: Quaternary; T1,T2, T3: major thrust faults; bold lines: décollement layers; fine lines: thrust faults.

1.2.3 Glacial geology

The deglaciation pattern of the Late Weichselian ice-sheet from the west Svalbard margin to the main trunk of Isfjorden and its tributary fjords has been studied based on dated lithological records correlated with high-resolution sub-bottom acoustic profiles and bathymetric data (Landvik et al., 1988; Mangerud et al., 1992; Elverhøi et al., 1995; Svendsen et al., 1996; Plassen et al., 2004; Ottesen et al., 2005; Landvik et al., 2005; Ottesen et al., 2007; Forwick & Vorren, 2009; Forwick & Vorren, 2010; Forwick et al., 2010; Ingólfsson & Landvik, 2013). The fjords of Spitsbergen acted as pathways for fast-flowing ice streams draining the ice-sheet. Submarine landforms related to the deglaciation and glacial readvances of the ice-sheet, tide water glaciers and possible surging have been recorded on the swath bathymetry in Isfjorden (Plassen et al., 2004; Ottesen & Dowdeswell, 2006; Forwick & Vorren, 2007; Baeten et al., 2010; Flink et al., 2015). They include recessional moraines, push moraines, glacial lineations, terminal ridges, interconnected network ridges and glacigenic debris flows. The typical thickness of permafrost in Spitsbergen is about 100-150 m near the bottom of major valleys and about 400-500 m in mountains rising above 500 m a.s.l (Humlum, 2005; Christiansen et al., 2010). Kristensen et al. (2008) have illustrated the existence of coastal permafrost and possibility of sub-sea permafrost in Van Mijenfjorden (located south of Isfjorden).

1.3 Motivation

The motivation in choosing the research questions addressed in this thesis has been derived from the following two research gaps: (i) seep-related acoustic and seafloor features have been documented in offshore Spitsbergen before; however the fluid flow mechanisms (geological controls) associated with the pockmarks in Isfjorden have not been addressed so far; (ii) characterization of seeps in the vicinity of the outcropping cap-rock and mapping of the possible migration pathways from the planned CO_2 aquifer have not been carried out previously. These two research gaps have been briefly described in the following two sections.

1.3.1 Insight into fluid flow and seeps in Spitsbergen

Recent studies revealed methane gas hydrates, shallow free gas accumulation in the marine sediments and ebullition of methane into the water column of the West Spitsbergen continental margin (Westbrook et al., 2009; Sarkar et al., 2012; Thatcher et al., 2013; Gentz et al., 2014), as shown in (Figure 5). Seasonal fluctuations of 1-2^o C in the bottom water temperature cause periodic gas hydrate formation and dissociation, resulting in focused seepage at the seafloor of the West Spitsbergen continental margin.

Evidences of past oil and gas seeps have been found on onshore Jurassic-Cretaceous boundary outcrops (Hammer et al., 2011; Hryniewicz et al., 2012), and offshore sediments, and water column (Knies et al., 2004; Damm et al., 2005) in Spitsbergen. Pockmarks have been identified in Isfjorden, suggesting fluid expulsion at the seafloor (Forwick et al., 2009). However, their formation mechanisms and link to subsurface structural features and shallow gas occurrences in marine sediments is not well understood.

1.3.2 Longyearbyen CO_2 Lab project

The Longyearbyen CO_2 Lab project of Svalbard was initiated by Gunnar Sand (former Director of UNIS) and Alvar Braathen (Professor at UNIS and UiO) with the purpose to carry out research related to CO_2 behavior in high-pressure conditions and to assess the properties of potential reservoir rocks. Braathen et al. (2012) identified a tight unconventional aquifer for long term subsurface CO_2 storage within the Late Triassic to Middle Jurassic heterolithic siliciclastic Kapp Toscana Group. A comprehensive study on various aspects of this CO_2 target aquifer as shown in Figure 6, has been presented in the PhD thesis of Senger (2013). The aquifer and cap rock succession dips at 1-3^o SW and crops out 14-20 km onshore to the NE of the injection site, in central Spitsbergen. The buoyant CO_2 has the potential to migrate upwards from the storage site along permeable pathways such as faults, fracture networks, weak geological boundaries, or well bores to the land surface or water column (Lewicki et al., 2007). Owing to the regional dipping nature of the target aquifer, upward migration of injected CO_2 could reduce the efficacy of carbon storage there. It is the responsibility of the research and engineering community to be able to detect, quantify, and characterize possible CO_2 migration from the aquifer, in order to assess the risk and long term liability of the storage unit. Hence it is necessary to know the current state of seep-related seafloor features and their possible linkage to fluid migration pathways, which will help in the assessment of possible future migration and seepage of CO_2 from the seafloor.

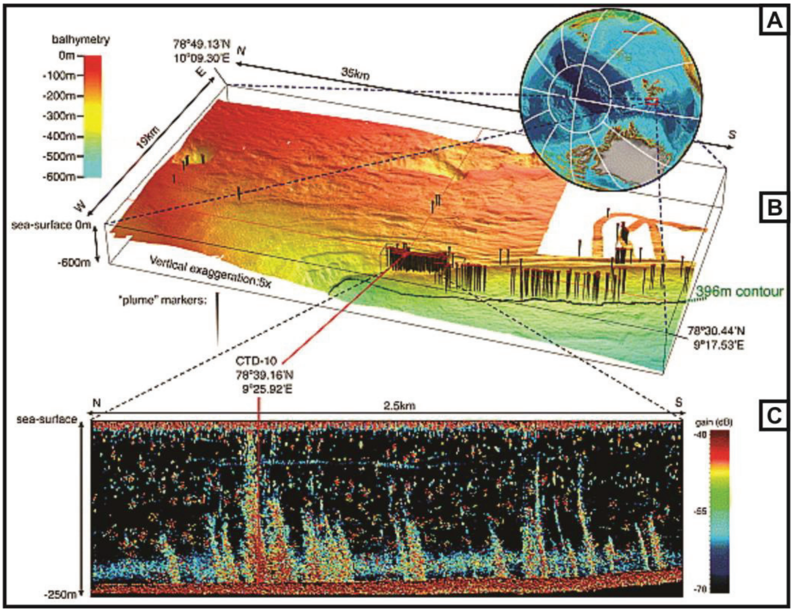


Figure 5: (A) Location of survey area west of Svalbard. (B) Positions of plumes acoustically imaged with the EK60 sonar, depicted by ''pins'', superimposed on the bathymetric data. (C) Part of record from an EK60 acoustic survey showing examples of observed plumes. Amplitude of acoustic response is given by the color of the ''bubbles'' (Westbrook et al., 2009).

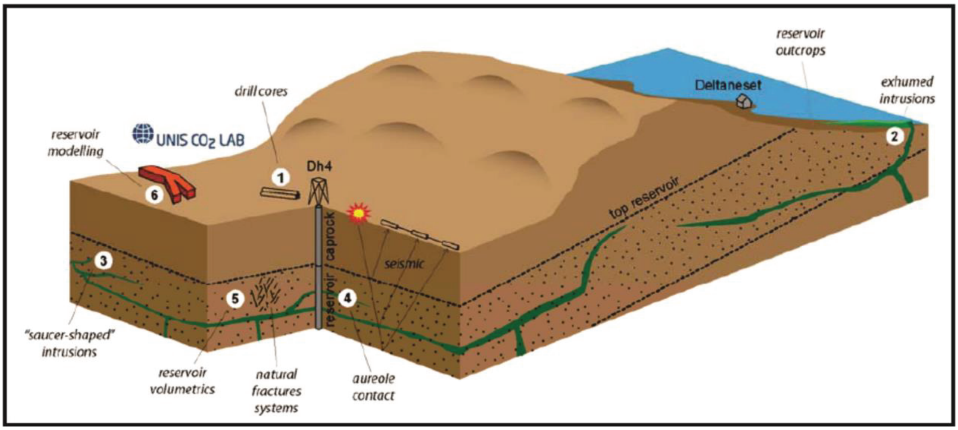


Figure 6: Conceptual synthesis of the various aspects of the Svalbard unconventional CO_2 target aquifer addressed by Senger (2013).

1.4 Aims and Objectives

The following research objectives are addressed in the papers included in this PhD thesis, keeping in mind the varying glaciological and geological settings in different parts of the Isfjorden fjord system:

- What is the distribution pattern and morphology of the pockmarks in the Isfjorden fjord system, and how do they spatially correlate with the glacial landforms, tectonic lineaments and underlying organic rich rocks?
- Which factors influence the formation of various types of seep-related features (seafloor and subsurface) in the western part of Isfjorden (Grønfjorden), which is characterized by the basement-involved fold-and-thrust belt?
- How one can characterize the seep-related features and associated fluid flow processes in the central zone of Isfjorden (inner Isfjorden and Adventfjorden), where the stratigraphy consists of three thin-skinned fold-thrust sheets, with thrusts splaying from décollement layers? How can this study contribute to the future leakage monitoring of the planned Longyearbyen CO_2 unconventional aquifer?
- What are the possible implications of igneous intrusions/dolerite sills on regional fluid flow processes and reservoir compartmentalization, in the CO_2 aquifer?
- What are the geological controls on the seep-related features and shallow gas occurrences in the north-central part of Isfjorden (Nordfjorden)? Is there any sign of on-going fluid escape from the seabed?

2. Methods

This PhD study has integrated a range of geophysical data sets along with published geological maps and outcrop data from Spitsbergen. The geophysical methods used in each of the papers, and their respective applications are summarized in Figure 7 and Table 1. Each method is further described in each of the papers included in this thesis.

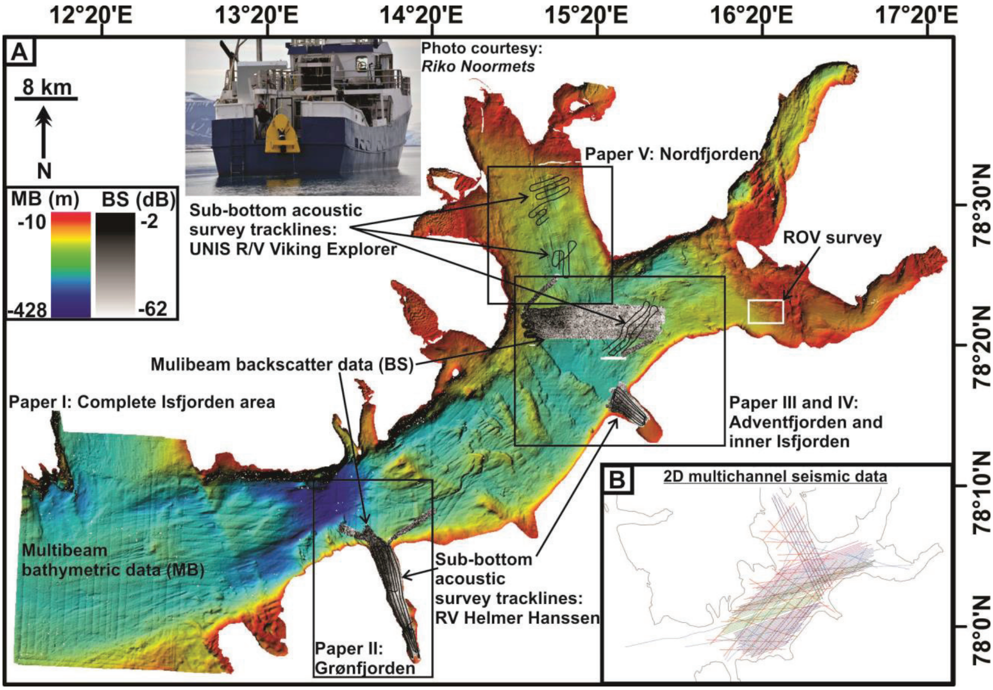


Figure 7: (A) Extent of high-resolution multibeam bathymetric data, backscatter data, and sub-bottom acoustic profiles used in respective papers. (B) Overview map of available marine 2D multichannel seismic data in Isfjorden.

Table 1: Types of data sets, methods applied to acquire them, and their applications in context to this study.

Type of data (Papers used in)	Instruments / Survey details	Software used and geological/geophysical application
Multibeam bathymetric data (Papers I-V)	The Norwegian Hydrographic Survey used Kongsberg EM1002, EM3000, EM3002 and the R/V Helmer Hanssen used the EM300 multibeam echo-sounders during 2000-2010 to acquire this huge data set. CTD measurements were done at several locations in order to calculate the velocity profile in the water column.	IVS 3D Fledermaus v.7.0 and D Magic software were used to process and grid the bathymetric data, as well as visual examination of the morphological details of the various types of submarine landforms and seep locations. Thereafter, ArcGIS software was used to map the geological features and perform spatial analysis between them.
Multibeam backscatter data (Papers II and III)	The seafloor backscatter data were collected using a Kongsberg Maritime EM300 multibeam echo sounder operating at a frequency of 30 kHz, onboard R/V Helmer Hanssen in 2010.	IVS 3D Fledermaus v.7.0 and D Magic software were used to process and grid the backscatter data. Thereafter, Petrel software was further used to integrate backscatter with bathymetric data for analysis of seafloor sediments at seep locations.
Sub-bottom acoustic data (Papers II, III and V)	The shallow high-resolution sub-bottom acoustic profiles were acquired with an EM3300 hull-mounted sub-bottom profiler on the R/V Helmer Hanssen in 2010, and towed EdgeTech 2000– CSS sub-bottom profiler from UNIS R/V Viking Explorer.	Edgetech Discover II software was used for visual interpretation of the seismostratigraphic units and identification of seep-related acoustic anomalies on the sub-bottom acoustic profiles.
Side-scan sonar data (Paper III)	Sidescan sonar records were collected with the EdgeTech 2000–CSS simultaneously with the sub-bottom acoustic profiles.	Edgetech Discoverer II software was used to identify geomorphological features on the seafloor with anomalous reflectivity, which may be related to seepage or coarse seabed sediments.
2D-Multichannel marine seismic data and onshore seismic data (Papers II-V)	The 2D multichannel marine seismic surveys were acquired by Statoil in 1985 and 1988, and by the University of Bergen during the Svalex field course conducted between 2004-2009. The onshore seismic data was collected with a 60 channel 1500 m snow streamer pulled by bandwagon using dynamite (Dynacord) charges of 2–4 kg/shot as source.	Petrel software was used to interpret the stratigraphic units, tectonic features and dolerite sills on the 2D multichannel seismic data.
Magnetic data (Paper V)	The magnetic data was acquired during the Svalex2009 survey, using a Geometrics G-882 cesium magnetometer.	Integrated geological interpretation of the magnetic, seismic and bathymetric data was performed using the Petrel software to identify the extent and morphology of dolerite sills.

3. Main Results

This section outlines the main results drawn from each paper included in this thesis.

Paper I:

Seepage in Isfjorden and its tributary fjords, West Spitsbergen:

This study systematically maps the spatial distribution and morphometry of pockmarks and various submarine landforms based on comprehensive high-resolution bathymetric data set. A total of 1304 pockmarks occur in Isfjorden at water depths of 40 to 320 m, varying from circular to elongate in plan-view. Their diameter ranges from 14 to 265 m and their depths from 1 to 11 m. Pockmarks have been found in the troughs of glacial lineations (in Billefjorden, Tempelfjorden and Nordfjorden). Elongated pockmarks are relatively more abundant in the outer parts than in the inner areas of the Isfjorden. Cluster of unit-pockmarks have been identified in Colesbukta, Adventfjorden and Sassenfjorden.

The density distribution of pockmarks has been calculated in the study area using the Kernel Density function (Spatial Analyst tool) in ArcGIS. The highest density has been found in Nordfjorden, inner Isfjorden and Sassenfjorden areas, followed by the Billefjorden Trough and Tempelfjorden areas. They are most abundant in the areas underlain by Jurassic–Cretaceous and the Triassic–Lower Jurassic bedrock. High concentration of individual pockmarks and pockmark strings in the troughs associated with the seafloor expressions of sub-cropping thrust faults and dolerite intrusions are apparent in Sassenfjorden, inner Isfjorden and Nordfjorden. The empirical correlation between the distribution of pockmarks and the fault systems has been confirmed by the pockmark–fault near distance analysis.

Submarine sediment debris lobes have been found to originate from pockmarked regions along steep slopes in Billefjorden and Svensksunddjupet Basin. On the contrary, several pockmarks in Tempelfjorden, Grønfjorden, Borebukta and Ymerbukta have been identified in front of the submarine sediment debris lobes.

Paper II:

Evidence of fluid seepage in Grønfjorden, Spitsbergen: implications from an integrated acoustic study of seafloor morphology, marine sediments and tectonics.

This study integrates high-resolution surface and subsurface geophysical data to investigate possible fluid (gas and/or liquids) migration pathways to the seafloor in Grønfjorden, which is located in the western part of the Isfjorden fjord system. A distinct NNW-SSE strike characterizes the thick-skinned basement-involved fold-thrust complex in the study area. 19 pockmark depressions (100-240 m diameter and 6-10 m deep) could be identified in the northern part of the fjord. Smaller pockmark depressions (20-60 m diameter and < 3 m deep) have been found in the southern part of the fjord. High backscatter values in the centre of deep pockmark depressions have been found in the northern part of Grønfjorden. In addition, pockmark-like 16 circular patches (40-70 m diameter) of relatively high-backscatter values (as compared to surrounding values) have been identified in the central basin. The central basin has a smooth seafloor and is devoid of pockmark depressions or any other submarine landforms.

Five seismo-stratigraphic units (A1-A5) have been interpreted on the sub-bottom acoustic data, based on the variation of acoustic signature and bounding coherent seismic reflector geometry. The acoustic basement is 15-20 m below the seafloor. Three types of subsurface seep-related acoustic features have been identified in the shallow marine sediments of Grønfjorden: i) enhanced reflections, ii) acoustic turbid zones, and iii) acoustic blankings. They occur beneath some of the pockmarks and circular patches of high-backscatter identified on the seafloor. Further, a steeply dipping (*c.* 70^{o} dip angle), SW-NE striking normal fault with 4-5 m offset has been identified, which displaces units A1, A2 and A3.

In the southern part of the study area, 6-8 km long NNW-SSE striking ridges have been identified on the bathymetric data. Thrust faults have been interpreted on 2D multichannel seismic data in the Triassic, Jurassic and Cretaceous successions of western Isfjorden, located north of Grønfjorden. A possible linkage of these fault systems (part of the West Spitsbergen fold-and-thrust belt complex) have been found with the seafloor ridges which strike in a similar direction to the faults.

Paper III:

Fluid migration pathways to seafloor seepage in inner Isfjorden and Adventfjorden, Svalbard

This study presents a marine baseline study for the Longyearbyen CO_2 lab, in which CO_2 may be injected in the Upper Triassic–Middle Jurassic Kapp Toscana Group aquifer. High-resolution multibeam bathymetric and backscatter data, sub-bottom acoustic profiles, sidescan sonar data and 2D multichannel seismic data have been used to analyze seep-related features on the seafloor and their link to subsurface tectonic structures. In total, 398 individual normal-sized pockmark depressions have been identified on the seafloor bathymetric data. Unit-pockmarks (1 to 5 m diameter; depth < 0.6 m) are occasionally observed in the vicinity of normal-sized pockmarks. Pockmarks occur in the central and outer parts of Adventfjorden, whereas they are found to be mostly aligned along the troughs associated with NNW-SSE trending ridges in inner Isfjorden.

Backscatter profiles across the pockmark depressions show low backscatter anomalies in comparison to the surrounding seafloor backscatter values. 27 pockmark-like circular patches of high backscatter values were recorded with the sidescan sonar. Beneath the pockmarks, seep-related acoustic features such as, enhanced reflections; acoustic turbid zones and acoustic blankings have been interpreted on sub-bottom acoustic profiles. Three medium–high amplitude, consistent reflectors have been identified in the upper part of the 2D seismic profiles: (i) near the top of the Wordiekammen Formation, (ii) near the top of the Kapp Starostin Formation, and (iii) near the top of the top of the Kapp Toscana Group. The time-structure map of the near-top Kapp Toscana Group gently dips to the SW at 2–3^{o}, and reaches the seafloor *c.* 13 km northeast of the injection site. Correlation of the Dh4 borehole with onshore seismic line UNIS-Line 1 marks the top of Kapp Toscana Group (Knorringfjellet Formation) at 450-500 ms (TWT), corresponding to *c.* 670 m depth. Very strong horizontal reflectors with abrupt reflection terminations and discordant relationship with stratal reflections have been interpreted as igneous intrusions within the Kapp Toscana Group. Interpretation of fold-and-thrust belt structures has been done by identifying dip-domains as well illustrated with large and long fold limbs that terminate at certain levels. Integrated analysis of 2D seismic and bathymetric data suggests that the NNW-SSE trending ridges are seafloor expressions of sub-cropping thrust faults and the near top of the Kapp Toscana Group geological boundary.

Paper IV:

Geometries of doleritic intrusions in central Spitsbergen, Svalbard: an integrated study of an onshore-offshore magmatic province with implications for CO_2 sequestration.

This study aims to map the distribution of the igneous complexes in both onshore and offshore areas of central Spitsbergen, with particular focus on the CO_2 storage target aquifer in the Kapp Toscana Group. This has been done by using an integrated data set comprising of 2D seismic data along with magnetic profiles, high-resolution multibeam bathymetric data, digital elevation models (DEM), aerial photos, geological maps, LiDAR data and fieldwork data. Characterization of the igneous features has been documented in Table 3 of this paper. The prevalent geometry of the igneous system is dominated by layer-parallel sills in shale-dominated lithology, with a few subordinate dykes. In the lower part of the target aquifer (the De Geerdalen Formation), numerous thick igneous intrusions are present at Diabasodden and Hatten. Thinner intrusions (*c.* 2 m thick) are present throughout the De Geerdalen Formation and the overlying Knorringfjellet Formation. On Dickson Land (northern part of central Isfjorden area), sills are aligned with the regional stratigraphic dip with a dip azimuth of *c.* 190–220° and a dip of *c* .3–13°. In contrast, the southern shore of Isfjorden is characterized by complex intrusion geometry with an unclear directional component and a dip of *c.* 1–40°. Orientations of the sub-vertical and vertical intrusions line up with other mapped lineaments in Botneheia. Structural complexity appears to decrease with depth in the stratigraphy.

The offshore-onshore linkage of the igneous bodies is evident using magnetic, seismic, bathymetric and topographic data. Linear magnetic highs aligned along the NNW–SSE striking positive relief features, appear to link the southern and northern shores of Isfjorden. They may be related to a series of interconnected dykes and sills. Alternatively, they may be associated with thrust faults, which developed during the Paleogene compression. A positive relief feature on the seabed clearly coincides with a residual magnetic low, southeast of Kapp Thordsen. A seismic profile across this feature depicts a flowering structure of complex faults. This feature is interpreted as a hydrothermal vent complex. Pockmarks have been found in the vicinity of these positive relief features on the seabed.

Paper V:

Geological controls on seep-related acoustic features and pockmarks in Nordfjorden, Spitsbergen

This study integrates high-resolution shallow- and deep-geophysical data sets to investigate the fluid flow processes in Nordfjorden, which is one of the most densely pockmarked tributary fjords of Isfjorden. 535 pockmarks have been identified on the multibeam bathymetric data. Their diameters range from 10 m to 212 m, and relief varies between 1 m to 8 m. Seafloor ridges have been identified with two major strike directions: NW-SE and E-W to SW-NE. Other submarine landforms identified on the bathymetric data include glacial lineations, irregular mounds and drumlin-like features. Pockmarks are found in high densities along the troughs associated with the ridges, around the mound and troughs of the glacial lineations.

The two geological unit boundaries interpreted on the 2D seismic profiles are: (i) near the top of the Wordiekammen Formation, and (ii) near the top of the Kapp Starostin Formation. Thrust faults (belonging to the West Spitsbergen fold-and-thrust belt) have been interpreted by identifying areas of inconsistent dip and thereby defining possible hanging wall and matching footwall ramps. A north-south trending steeply inclined reverse fault extends from the base of Wordiekammen Formation to the top of Kapp Starostin Formation. This probably corresponds to the Blomesletta Fault. A combination of high magnetic values and very high-amplitude reflectors, suggests the presence of dolerite sills at several locations and depths. Morphology of these igneous bodies resembles irregular saucer- and elliptical-shapes. Occasionally, the thrust faults and up-thrusted dolerite sills reach the seafloor to form seafloor ridges and mounds.

Subsurface seep-related acoustic features such as, enhanced reflections, acoustic blanking and turbidity zones have been recorded beneath the pockmarks, on recently acquired high-resolution sub-bottom acoustic data. These acoustic features are attributed to suspected shallow gas occurrences in the marine sediments. Mushroom shaped acoustic plumes have been imaged in the water column, indicating active seepage. However, pockmarks did not form yet at these actively seeping locations.

4. Discussions and Conclusions

This PhD thesis addresses the various types of fluid flow features and processes (subsurface and at the seafloor) prevailing in the Isfjorden fjord system. It further investigates the linkage between these fluid flow features with the regional structural geology, underlying organic rich rocks, submarine glacial landforms and processes.

Paper I provides insight into the possible mechanisms of pockmark formation, high density pockmark field evolution, and their correlation with the distribution of organic rich rocks and tectonic lineaments in the whole of Isfjorden fjord system. The occurrence of individual pockmarks, string pockmarks and unit-pockmarks on the Isfjorden seafloor suggests a hydraulically active seafloor. Small amounts of pore fluids are tidally pumped out of the seafloor through the small unit-pockmarks. The well-defined morphology of the pockmark strings found within the troughs of the glacial lineations in Billefjorden and Nordfjorden suggests that they have been formed after the ice retreat. Predominance of elongate pockmarks in the outer parts of Isfjorden and Isfjordbanken as compared to the inner tributary fjords of Isfjorden suggests that the morphology of the pockmarks could have been influenced by the bottom-currents at the entrance of Isfjorden. The high density pockmarked zones, with more than 5–10 pockmarks per km^2 have been classified as more hydraulically active zones. The density of pockmarks varies with thickness of glacial sediments, the presence of glacial landforms, underlying bedrock geology and distribution of fault systems. Some of the high density pockmarked zones are discussed below.

Deposition of the glacigenic debris flow lobes (in Grønfjorden, Ymerbukta, Borebukta and Tempelfjorden) might have caused over pressure in the sediment pore-fluids, leading to pore-fluid expulsion, and thereby resulting in the formation of pockmarks in high density. Pockmarks in high density are located in the troughs of sub-cropping ridges, where the postglacial sediment layer is thicker than that on the ridges itself. 10-15 m thick sediment layer within the troughs seems crucial for the formation of pockmarks in comparison to the hard bedrock at the ridges, where there is relatively less marine soft sediments. These sub-cropping ridges have been interpreted as seafloor expressions of various fault systems (normal, strike-slip, thrust faults of the WSFTB) and dolerite sills (Papers I, III, IV and V). 52% of the pockmarks lie on the Upper Permian - Lower Jurassic strata in Nordfjorden, inner Isfjorden and parts of Sassenfjorden. The

Middle Triassic Botneheia and Upper Jurassic Agardhfjellet formations found in Spitsbergen are the main source rocks for hydrocarbon reservoirs in the southwestern Barents Sea (Mørk & Bjorøy, 1984; Bjorøy et al., 2009; Henriksen et al., 2011b). Marine and terrestrial investigations in and around Isfjorden have revealed the presence of hydrocarbons in the marine sediments (Knies et al., 2004), water column (Damm et al., 2005) and in outcrops (Nøttvedt et al., 1993b; Hammer et al., 2011). The occurrence of high density pockmarked zones underlain by organic rich rocks, along with their proximity to the sub-cropping faults, doleritic intrusions and geological unconformities suggests that these structural features could be influencing the high density pockmarked seafloor in Isfjorden. However, fluid expulsion directly from organic rich sub-cropping bedrocks into the soft sediments of the seafloor could be an alternative pockmark formation mechanism. Extent and thickness of potential gas hydrate stability zone (HSZ) have been calculated through modeling of thermo-baric conditions in Isfjorden (Figure 8). More than 600 pockmarks are estimated to be located within the potential HSZ extent in Isfjorden. Thus, it cannot be excluded that the pockmarks in Isfjorden might have resulted from the dissociation of suspected gas hydrates due to warming of fjord waters and post-glacial rebound following deglaciation of the fjords.

Results from Paper I combined with the knowledge of the regional geology of Isfjorden area, led to the selection of the following specific areas for detailed investigation of the fluid flow systems:

i) The largest pockmark has been found in Grønfjorden, located over the thick skinned basement involved fold-thrust belt: addressed in Paper II.

ii) High density of pockmarks (in inner Isfjorden and Nordfjorden) overlies organic rich rocks, thrust faults and dolerite sills sub-cropping at the seafloor: addressed in Papers III, IV and V.

Papers II, III, IV and V investigate the subsurface and seafloor seep-related features and fluid flow processes in order to have a better understanding of their connection to the complex deeper geological setting in Grønfjorden, inner Isfjorden and Nordfjorden, respectively.

In Grønfjorden, pockmark-like circular patches of high-backscatter on the central basin smooth seafloor, and high-backscatter at the center of deep pockmark depressions probably attribute either to biological activity, coarse lag deposits, or mineral precipitates following fluid seepage

(Paper II). Pockmark-like circular patches of high-backscatter values have been recorded with the sidescan sonar in inner Isfjorden in the vicinity of pockmarks depressions (Paper III). Their circular shapes suggest that they are possibly related to focused seepage of fluids through the seafloor. On the contrary, low-backscatter values associated with pockmark depressions in inner Isfjorden are assumed to result from enhanced porosity contrasts caused due to trapped overpressured fluids in the shallow sediments beneath the pockmarks, or due to their crater-like morphology (Paper III).

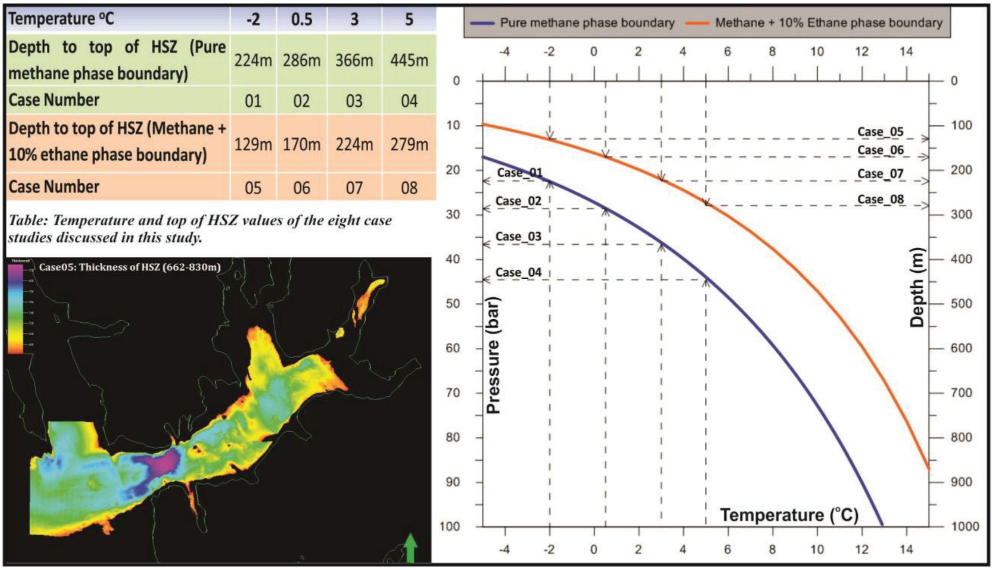


Figure 8: Gas Hydrate Stability Zone (HSZ) modeling in Isfjorden (Roy et al., 2012). Right: Calculating the water depth required for each of the ocean bottom temperatures mentioned in each of the case studies (table on the top-left) with the help of hydrate phase boundaries (using HWHydrate software). The water depth is considered as the depth to the top of HSZ at different ocean bottom temperatures. Case_04 deals with pure methane hydrate formation at 5 °C at the sea-bottom does not find a match in Isfjorden, as the maximum water depth is 428 m. Thereafter, a geothermal gradient of 25 °C/km has been used for the HSZ thickness calculations in this study. Left: Thickness map of HSZ Case_05 (pure methane + 10% ethane at -2°C).

Three types of acoustic anomalies have been identified in the marine sediments of Grønfjorden, inner Isfjorden and Nordfjorden (Papers II, III and V): i) enhanced reflections, ii) acoustic turbid zones, and iii) acoustic blankings. They occur beneath some of the pockmark depressions, which are regarded as direct evidence of seafloor seepage. These three types of acoustic anomalies are attributed to suspected shallow gas occurrences. However, quantification of shallow gas based on only sub-bottom acoustic data is difficult. Gas concentrations as low as 0.5-1% in the sediment pore space can cause a significant drop in the P-wave velocity, and be detected on sub-bottom acoustic profiles as one of these three acoustic anomalies (Schubel, 1974; Judd & Hovland, 1992; Wilkens & Richardson, 1998). The vertical acoustic blanking zones distorting the continuous reflections bounding stratigraphic units suggest possible upward gas migration or mobilized sediments. Discrete gas voids within fine grained shallow marine sediments cause zones of acoustic turbidity, whereas higher concentration interconnected gas-filled pore spaces result in enhanced reflections. Acoustic plumes in the water column of Nordfjorden are indications of fluids venting out of the seafloor.

The largest pockmark depression and other seep-related seafloor and subsurface features in Grønfjorden are apparently located above the mapped syncline-anticline pair, deep rooted thrust faults, and fractured bedrock, which are characteristic structures of the WSFTB. Similarly, pockmark depressions, pockmark-like circular features with high-backscatter, suspected zones of subsurface shallow gas occurrences, and acoustic plumes/gas flares have been found to be closely associated with various types of sub-cropping faults and dolerite sills, interpreted in the top-most stratigraphic layer in Nordfjorden and inner Isfjorden areas (Papers III, IV and V).

Faults and fractures have been widely recognized as possible conduits for fluid migration from deeper reservoirs to shallow sequences and the seafloor (Ligtenberg, 2005; Cartwright et al., 2007; Gay et al., 2007; Aminzadeh et al., 2013; Ostanin et al., 2013). The role of fault zones and décollement layers as conduits for channelled fluid flow due to permeability anisotropy has been analysed by Tobin et al. (2001). Based on these observations and descriptions, it is suspected that the dipping nature of the overall stratigraphy in Nordfjorden and inner Isfjorden, and fracture permeability in the Sassendalen shale décollement layer, facilitate lateral and vertical migration of buoyant fluids. In this reasoning, fluids would reach the roots of the thrust faults via the décollement layer, and become preferentially transported up-dip to the seafloor along the well-developed fracture network within and around the thrusts. Accordingly, it is suggested that tectonic features of the WSFTB facilitates buoyant up-dip migration of fluids from deeper stratigraphy to the seafloor. Increased fracturing is observed within the dolerite sills as well in the surrounding host rock (Ogata et al., 2012; Senger et al., 2014a). Fluids can preferentially migrate along these fracture networks which have increased permeability. High concentration of pockmarks and seep-related acoustic features above these sub-cropping dolerite sills suggest focused fluid transport associated with these igneous intrusions.

Several pockmarks and seep-related features have been found on the exposed cap-rock succession in the inner Isfjorden area providing evidence of natural fluid seepage through the seafloor (Papers III and IV). Presence of faults in the cap-rock succession possibly plays a vital role in the vertical ascent of fluids and hence formation of these seep-related features. Hence, the thrust faults sub-cropping at the seafloor, and seep locations identified on bathymetric data and sidescan sonar data could be potential sites for future monitoring, in case CO_2 is injected for research purposes.

5. Outlook

The Isfjorden fjord system is an excellent natural lab to study submarine fluid flow features and processes in the context of varying geological and glaciological settings. In this thesis, the fluid flow systems in Isfjorden have been studied in terms of geophysical evidences only. However, the thesis lacks investigations on the composition and source identification of the seeping fluids. Geochemical analysis of surface marine sediments and pore water from pockmarks and other seep locations should be done in order to establish the composition and origin of the seeping fluids. It is also important to study the timing of the formation of the pockmarks in detail. Integrating sub-bottom acoustic data, sediment cores, velocity logs and rock physics modeling could further help in the estimation of the amount of shallow gas in place within the marine sediments. Sampling and analysis from the pockmarks located in front of the debris flow lobes may supplement more information on the nature of venting fluids and timing of the seeps.

ROV surveys should be conducted accurately along tectonic lineaments and prominent seep locations, which have been identified in this thesis. Measuring the flux rate of escaping gas bubbles from active seep sites could help in estimating the total amount of gas venting in a relatively longer time period. Studies on the fate and transport of these escaping gas bubbles could contribute to the total methane budget reaching the atmosphere.

The décollement layers, thrust faults and surrounding host rocks of the dolerite sills (where intense zones of fracturing have been found) should be investigated for direct signs of fluid saturation and migration. Along-fault versus cross-fault fluid flow processes should be investigated. Reflection seismic data could be used to examine the acoustic character of the décollement layer and to characterize fluid pressure within the fault zone both qualitatively and quantitatively. Comparison of these results with laboratory experimental observations could provide more information on fluid pressure and saturation within these weak low-velocity zones.

Gas hydrate stability zone modeling has shown the possible existence of gas hydrates in Isfjorden. However, BSRs have not been imaged on seismic data in Isfjorden. Sub-sea near-coastal permafrost and trapped gas under onshore permafrost have been confirmed through modeling results and drill-cores in central Spitsbergen, respectively. Gas hydrates could potentially form in association with onshore and offshore permafrost. Hence, integrated study of numerical heat flow models and drill-cores could be employed in order to quantify and prove the physical existence of gas hydrates in Isfjorden.

Based on the key findings of this thesis, the following sites are recommended for detailed fluid flow investigations:

- Pockmarks found in troughs of ridges and glacial lineations in Billefjorden, Tempelfjorden, inner Isfjorden and Nordfjorden (Paper I and III).
- Central part of Grønfjorden, where circular patches of high backscatter anomalies were identified (Paper II).
- The possible hydrothermal vent identified in the inner Isfjorden (Paper IV).
- Active seepage site in Nordfjorden (Paper V).

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Seepage in Isfjorden and its tributary fjords, West Spitsbergen

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ABSTRACT

This study analyses pockmark morphology and their spatial distribution in Isfjorden relative to seabed morphology, bedrock geology, fault systems, glacial landforms and processes using multibeam bathymetric data. It provides insight into the possible mechanisms of pockmark formation, high density pockmark field evolution, and fluid migration pathways. A total of 1304 pockmarks occur in the Isfjorden at water depths of 40 to 320 m, varying from circular to elongate in plan-view. Their diameter ranges from 14 to 265 m and their depths from 1 to 11 m. Elongate pockmarks are dominant in the Isfjordbanken and outer Isfjorden where the seafloor is influenced by the West Spitsbergen Current. The West Spitsbergen fold-and-thrust belt and other fault systems subcropping at the Isfjorden seafloor correlate spatially with the high density pockmark zones. The pockmarks are preferentially located on the marine sediments draping the bedrock of Isfjorden fjord system. They are most abundant in the areas underlain by Jurassic–Cretaceous and the Triassic–Lower Jurassic bedrock. Pockmarks found ahead of submarine slope failures may have formed due to dewatering of soft sediments as a result of rapid increase of overpressure caused by deposition of glacigenic debris lobes. Fault conduits, potential source rock and thin postglacial sediment layers are found to be crucial for the formation of pockmarks. Modeling results of the near-shore subsea permafrost and potential gas hydrate stability zone imply thawing permafrost and gas hydrate dissociation as additional possible mechanisms for pockmark formation in Isfjorden.

1. Introduction

Pockmarks were discovered and described by King and MacLean (1970) as local seabed features on the Nova Scotian shelf, and later documented in a variety of geological settings from all over the world (Judd and Hovland, 2007). They are normally regarded to be manifestations of fluid escape through the seabed. Pockmark sizes range from less than ten to over several hundreds of meters in diameter (Hovland and Judd, 1988). They occur as single units or as kilometer long chains. The formation of pockmarks is mostly related to the seepage of hydrocarbon fluids either of biogenic or thermogenic origin; as well as to the release of pore water from the sea bed (Chand et al., 2012; Harrington, 1985; Judd and Hovland, 2007). Groundwater seepage, thawing permafrost, gas hydrate dissociation and up-drifting ice detached from the seafloor have also been considered as important factors contributing to the formation of pockmarks in high latitudes (Paull et al., 1999; Ruppel, 2011; Walter Anthony et al., 2012).

Forwick et al. (2009) have proposed pockmark formation mechanisms based on the bathymetric and sub-bottom acoustic data from four tributary fjords of the Isfjorden. They mentioned four major controlling factors affecting the distribution of pockmarks which include tectonic lineaments, bedrock outcrops, glacial lineations and rapid deposition of debris lobes. However, the entire Isfjorden fjord system and Isfjordbanken is densely populated with pockmarks in both the shallow coastal regions and in the deep parts of the fjord system (Roy et al., 2012). Their formation mechanisms and link to tectonic and glaciological features are not well understood. This study systematically maps the spatial distribution and morphometry of pockmarks based on comprehensive high-resolution bathymetric dataset from the Isfjorden fjord system (Fig. 1). Focus is on the spatial distribution and morphological variability of pockmarks, and their relation to the seafloor expressions of the tectonic faults, bedrock outcrops, distribution of potential hydrocarbon source rocks and the submarine glacial landforms. Establishing these links will facilitate the understanding of the mechanisms of fluid migration and formation of the pockmarks in Isfjorden.

2. Regional setting of Isfjorden

2.1. Geological and tectonic setting

Spitsbergen is the largest island of the Svalbard archipelago which represents an uplifted northwestern part of the submerged Barents Sea shelf (Fig. 1). Isfjorden is the largest fjord system in West Spitsbergen

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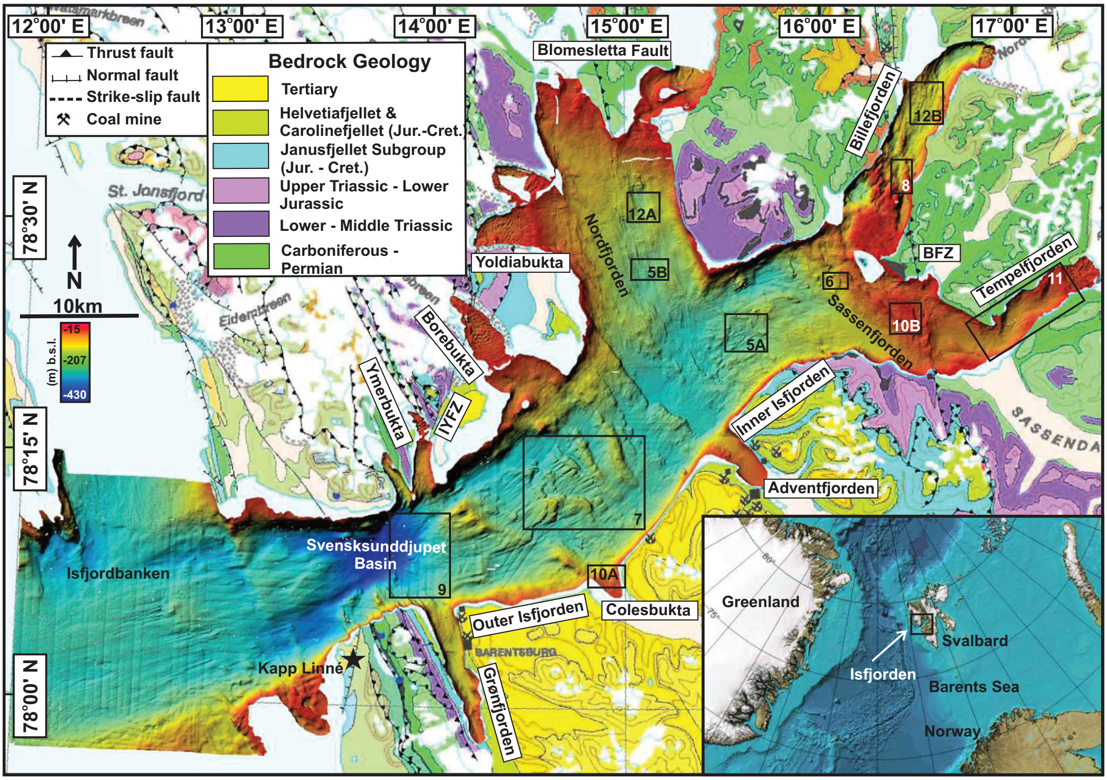

Fig. 1. The extent of high-resolution multibeam bathymetric data from the Isfjorden fjord system combined with the bedrock geological map (Dallmann et al., 2002) of western Spitsbergen. Location of Svalbard is shown in the inset map taken from IBCAO version 3.0 (Jakobsson et al., 2012). BFZ — Billefjorden fault zone and IYFZ — Isfjorden Ymerbukta fault zone. The numbers within the black boxes refer to the figure numbers presented later in the paper.

comprising the Isfjorden main trunk (IMT) and thirteen tributary fjords. The bedrock structures in Isfjorden and Isfjordbanken span from Paleozoic carbonates and evaporites to Mesozoic and Paleogene sandstones and shales (Dallmann et al., 1999). Hydrocarbon source rocks occur at several stratigraphic levels in the Svalbard archipelago, having the potential to expel oil or gas (Mørk and Bjorøy, 1984; Nøttvedt et al., 1993).

To the west of Isfjorden, there is the N–S trending Hornsund Fault Zone (HFZ), the E–W trending dextral transverse fault, and also the normal faulting and reverse faulting in the Bellsund Graben (Blinova et al., 2009). The central basin of Isfjorden is bounded to the west by the thick-skinned basement involved West Spitsbergen fold-and-thrust belt (WSFTB) which interacts with the Billefjorden Fault Zone (BFZ) in the eastern part of Spitsbergen (Bergh et al., 1997; Bælum and Braathen, 2012; Dallmann et al., 2002) (Fig. 2). Borebukta and Ymerbukta are located in the zone of intensive Cenozoic deformation with overthrust faults and the 500 m wide Isfjorden Ymerbukta Fault Zone (IYFZ) (Braathen et al., 1999) (Fig. 1). Blinova et al. (2012) mapped several thrust faults in the IMT with NW–SE and NNW–SSE strike directions (Fig. 2). Finally, the high angle reverse Blomesletta Fault is located north of Nordfjorden (Bergh et al., 1997; Blinova et al., 2013; Dallmann et al., 2002).

2.2. Glaciological setting

Retreat of the ice sheet margin from the Isfjorden Trough begun *c.* 15,000 BP (calendar years), by 12,000 BP the shelf was ice free, and by *c.* 11,200 BP the ice margin had retreated completely from the inner fjords (Baeten et al., 2010; Forwick and Vorren, 2009; Ottesen et al., 2007). The sedimentary environment of Isfjorden was influenced by the nine tidewater glaciers terminating into the IMT, during the Younger Dryas and the Allerød (Forwick and Vorren, 2009). The Late Weichselian–early Holocene glacial, subglacial and deglacial deposits unconformably overlie the bedrock basement of Isfjorden (Elverhøi et al., 1995; Forwick and Vorren, 2010; Levitan et al., 2008; Svendsen and Mangerud, 1997).

3. Data acquisition and methods

High-resolution multibeam bathymetric data used in this study were acquired by the Norwegian Hydrographic Service over a number of years since 2000 using Kongsberg EM1002, EM3000, EM3002 and EM300 multibeam echo-sounders. These data cover an area of *c.* 2734 km^2 comprising the IMT and its tributary fjords and bays (Fig. 1). Fledermaus and ArcGIS software packages were used to grid, visualize and interpret the data. The bathymetric data were gridded with a 5 m isometric cell size for detailed visual examination of the morphology of the pockmarks and other submarine landforms.

4. Observation and interpretation of submarine landforms

The IMT is 8–25 km wide and characterized by several bedrock sills and sub-parallel ridges. The deepest point of the IMT is 430 m depth, in the Svensksunddjupet basin (Fig. 1). We have identified sub-parallel

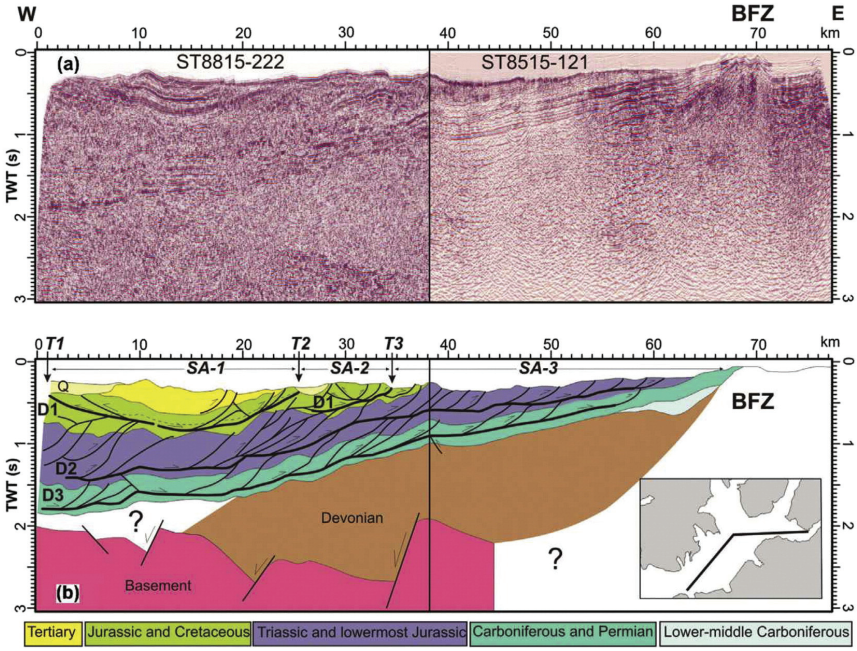

Fig. 2. Interpretation of the fold-and-thrust belt sub-cropping at the seafloor of the Isfjorden fjord system (Fig. 4 from Blinova et al., 2012). BFZ — Billefjorden Fault Zone and Q — Quaternary sediments. T1, T2 and T3 are major thrust faults. SA-1, SA-2 and SA-3 denote the defined three subareas. Thick lines indicate décollements D1, D2 and D3. Thin lines indicate thrust faults.

ridges, bedrock knobs, streamlined bedforms, sediment debris lobes, and numerous pockmarks in the study area (Figs. 3 and 4).

4.1. Sub-parallel ridges

We have divided the IMT into inner and outer parts on the basis of seafloor morphology (Fig. 1). Characteristic to the outer Isfjorden is 30–80 m high NW–SE striking ridges extending across the entire width of the fjord in water depths of 140–280 m. NNW–SSE aligned, 20–60 m high ridges occur in inner Isfjorden in water depths of 190–260 m (Fig. 5A). The ridges in the inner part are less continuous and do not extend across the entire width of the fjord like the ones in outer Isfjorden. We found two sets of ridges in Nordfjorden, one with E–W and the other one with N–S to NW–SE strike direction, in water depths of 160–220 m (Figs. 3 and 5B). Ridges in water depths of 40–120 m in Sassenfjorden dip towards SW (Fig. 6). We identified N–S striking ridges in Billefjorden in water depths of 110–150 m and at the mouth of Tempelfjorden in water depths of 30–50 m. Location, extent and morphological parameters of these ridges are provided in Fig. 3 and Table 1. From the integrated analysis of bathymetric data, offshore 2D multichannel seismic data and bedrock geological maps, we suggest that these ridges are seafloor expressions of the WSFTB, doleritic intrusions, BFZ, normal and strike slip faults (Blinova et al., 2012; Dallmann et al., 2002; Roy et al., 2014; Senger et al., 2013) (Fig. 2).

4.2. Bedrock knobs

We could identify bedrock knobs with relatively blunt upflow sides and tapered lee sides (considering glacier advance from NE in the IMT) in outer Isfjorden (Figs. 1 and 7). They have elongation ratios of 2:1 to 3:1 (0.5–1.2 km long and 250–400 m wide) and relief of 15–22 m. Their elongation is along the fjord axis of the IMT. We interpret the bedrock knobs as glacially sculptured seafloor expressions of steep anticlinal structures which were formed as a result of fault propagating folds of the WSFTB (Bergh et al., 1997; Blinova et al., 2012; Roy et al., 2014). Based on their morphology and regional glacial setting, the glacially eroded bedrock knobs could be named as crag and tails, whalebacks or drumlins (c.f. Benn and Evans, 2010).

4.3. Streamlined bedforms

We observed streamlined bedforms usually in groups of several parallel ridges separated by troughs that are oriented parallel to the fjord axis (Fig. 3, Table 1). We interpret them as glacial lineations, formed by soft sediment deformation at the base of a fast flowing ice stream. Glacial lineations and moraine ridges have been interpreted as evidence for paleo-ice streams in the study area by Baeten et al. (2010) and Ottesen et al. (2007).

4.4. Sediment debris lobes

We have identified sediment lobes at several locations in the study area (Fig. 3). Most of them are located on the distal flanks of terminal moraines, as seen in Tempelfjorden, Yoldiabukta, Borebukta and Ymerbukta. We interpreted the lobe-shaped features as glacigenic debris flow deposits, constituting of debris extruded from the tidewater glacier terminus. Similar interpretations have been done in other tributary fjords of the Isfjorden fjord system (Forwick and Vorren, 2012; Ottesen and Dowdeswell, 2006; Plassen et al., 2004). They were triggered by high sediment supply from tidewater glaciers. Some of the sediment lobes are deposited along the steep sides of the fjords as observed along the coastlines of inner Isfjorden and Grønfjorden (Fig. 3). They are specially located in front of glacier fronts, suggesting that they were possibly triggered by the high sediment supply from the meltwater runoff from the glaciers. However, sea level changes and submarine slope

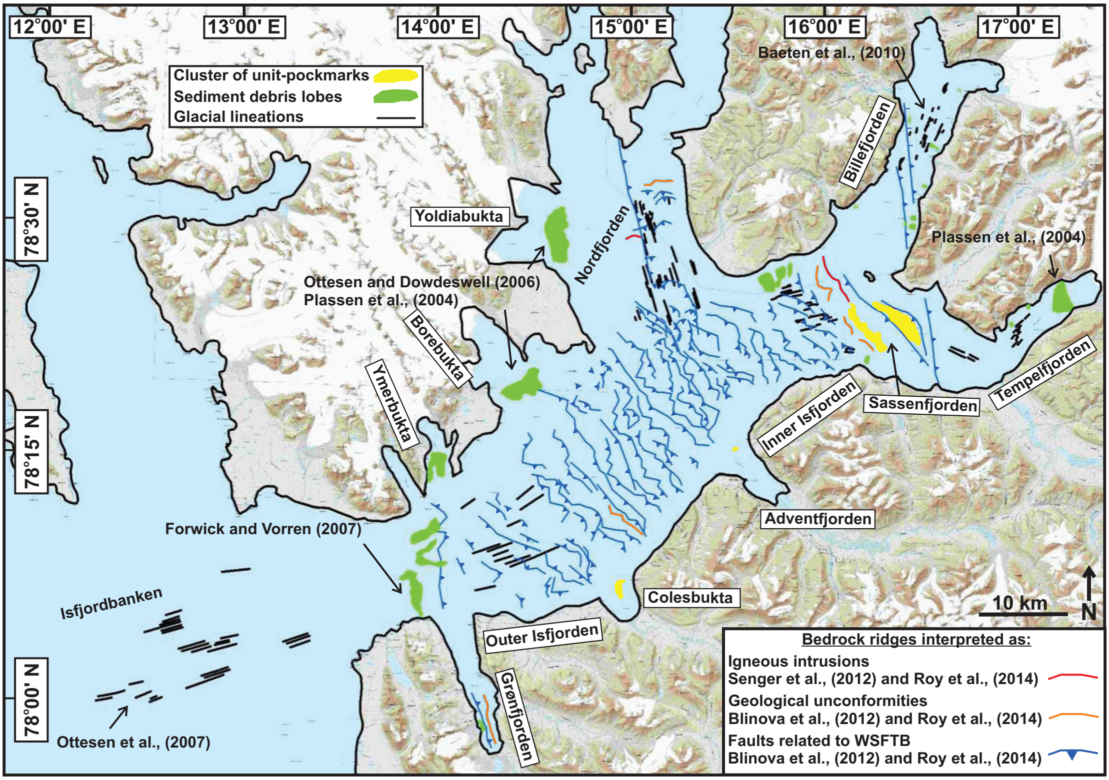

Fig. 3. Spatial distribution of submarine landforms related to glacial and tectonic activities. Clusters of unit-pockmarks are also shown. The basemap is provided by the Norwegian Polar Institute, showing the present location of glaciers in study area.

instabilities at high altitudes could be alternative possible triggering mechanisms for these slope failures.

Forwick and Vorren (2007) have discussed in detail the surface expressions of the sediment lobes deposited at the southern flank of Svensksunddjupet Basin. Sediment lobes have also been observed along the flanks of the ridges, identified as seafloor expressions of tectonic faults in the eastern slope of Svensksunddjupet Basin and Billefjorden (Figs. 3, 8 and 9). Unlike the glacigenic debris lobes, these slope failures have a relatively smoother surface, lacking surface structures like transverse, undulating sub-parallel ridges, tongue-like features, channels, levees and lineations (Forwick and Vorren, 2007; Plassen et al., 2004). Tectonic activities, sea level changes and the presence of gas in the shallow sediments could possibly trigger these slope failures located along the steep flanks of the faults.

4.5. Pockmarks

Local depressions on the seafloor with various sizes and shapes were interpreted as pockmarks in the study area. 1304 pockmarks were identified in the Isfjorden fjord system. In addition to these individual pockmarks, clusters of unit-pockmarks (<5 m in diameter and 0.5–1 m deep) have been mapped in the NE Adventfjorden (water depth of 105–125 m), Colesbukta (water depth of 70–95 m) and Sassenfjorden (water depth of 105–135 m) (Figs. 3 and 4). The pockmarks are regarded as clear evidence of past and/or ongoing fluid seepage from the seafloor.

4.5.1. Spatial distribution and morphology

We calculated the density of pockmarks in the study area using the Kernel Density function (Spatial Analyst tool) available in ArcGIS software (Fig. 4). This density calculation includes only the 1304 individual pockmarks, excluding the cluster of unit-pockmarks. The highest density of pockmarks is found in Nordfjorden, inner Isfjorden and Sassenfjorden, followed by the Billefjorden Trough and Tempelfjorden. Concentration of individual pockmarks and pockmark strings in the troughs associated with the seafloor expressions of faults is apparent in Sassenfjorden, inner Isfjorden and Nordfjorden (Figs. 5 and 6). We could not identify pockmarks in the troughs in between the bedrock knobs which are interpreted as glacially eroded bedrock remnants (Fig. 7).

We observed that the distribution of unit-pockmarks in Colesbukta and Adventfjorden is confined to small areas (0.83 and 0.15 km^2, respectively) whereas in Sassenfjorden they are spread over two large areas (4.64 and 7 km^2) (Figs. 3 and 10). The clusters of unit-pockmarks in Sassenfjorden are aligned along the ridges interpreted as thrust faults and geological unconformities (Blinova et al., 2012) (Fig. 10B). Furthermore, we have identified pockmark strings in the troughs of glacial lineations in Tempelfjorden, Billefjorden, and Nordfjorden (Baeten et al., 2010) (Figs. 11 and 12). These pockmarks are 1–2 m deep, 20–40 m in diameter. We observed pockmarks in Tempelfjorden, Grønfjorden, Borebukta and Ymerbukta ahead of the submarine sediment lobes (Fig. 3). On the contrary sediment debris lobes originate from iceberg ploughmarks and pockmarks along steep slopes in Billefjorden and Svensksunddjupet Basin respectively (Figs. 8 and 9).

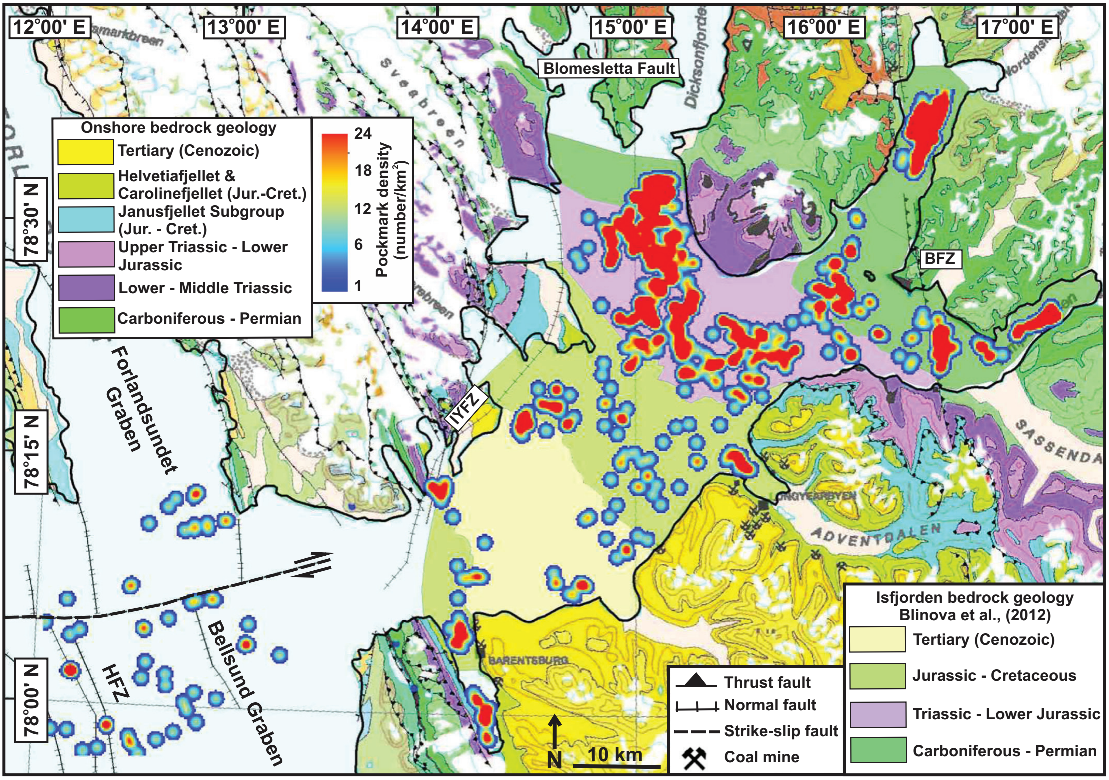

Fig. 4. Density of pockmarks (number/km^2) in the Isfjorden fjord system superimposed on the bedrock geology (Blinova et al., 2012) and fault systems (Blinova et al., 2009; Dallmann et al., 2002). BFZ — Billefjorden fault zone, HFZ: Hornsund fault zone, IYFZ — Isfjorden Ymerbukta fault zone, and WSFTB: West Spitsbergen fold and thrust belt. Note the two different legends for onshore and offshore bedrock geology due to the unavailability of the same unconformities mapped on offshore seismic data equivalent to onshore ones.

The depth and diameter of the 1304 pockmarks in each of the fjords are provided in Table 1. The edges of the pockmarks are generally well defined by the slope of the seabed changing from horizontal to 20–30° within a distance of 1–2 m. The size of pockmarks varies greatly in the Isfjorden fjord system. The average depth and diameter of pockmarks in the study area is 2.39 m (STD = 1.70 m) and 62.84 m (STD = 40.84 m) respectively. An average pockmark in Isfjorden has an area of 4412 m^2 (STD = 6167 m^2). We observed the deepest (11 m) and largest (diameter 265 m) pockmarks in Grønfjorden. The shapes of pockmarks found in Isfjorden are 90% circular and 10% elongate (plan-view) (Fig. 13 A and B). Relative abundances of both pockmark shapes in each of the tributary fjords are shown in Fig. 13C. Circular pockmarks dominate the inner parts of the fjord system whereas the elongate ones are mostly found in Isfjordbanken. The alignment distribution of the elongated pockmark's major axis in outer Isfjorden and Isfjordbanken is shown in Fig. 14.

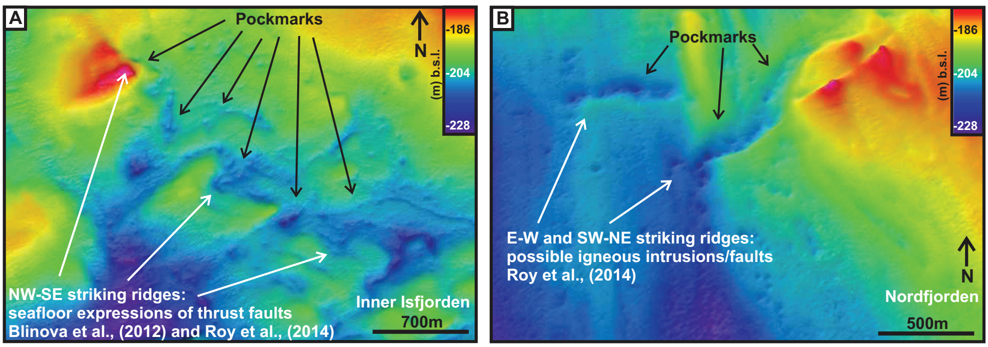

Fig. 5. Individual pockmarks and pockmark strings located in the troughs associated with seafloor expressions (ridges) of thrust faults and doleritic intrusions in (A) Inner Isfjorden and (B) Nordfjorden (refer to Fig. 1 for location).

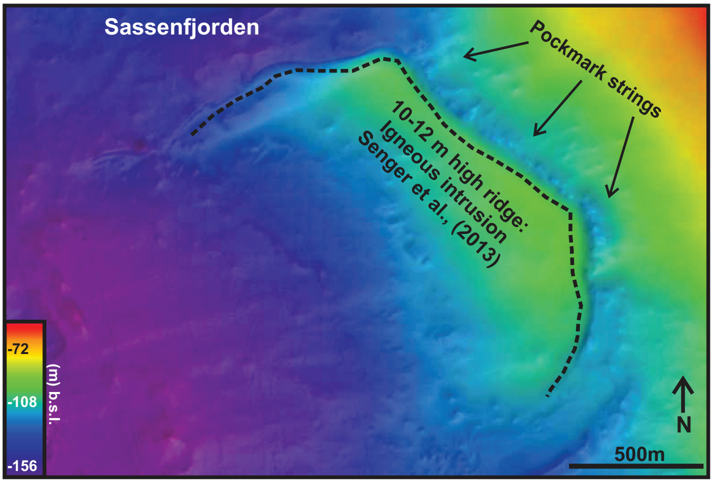

Fig. 6. Pockmark strings in the trough associated with the seabed expression of a doleritic intrusion in Sassenfjorden (refer to Fig. 1 for location).

4.5.2. Correlation between faults and pockmarks

The distance between the various fault types varies from 500 m to 5 km in the study area. A near-distance analysis with a search radius of 5 km was done on all the pockmarks to calculate their proximity to the mapped faults using the Spatial Analyst tool in ArcGIS software. The calculated distances are the perpendicular shortest distance from the fault polylines to the pockmarks. We found that 87 pockmarks were out of the search radius, of which 63 were in Tempelfjorden. Fig. 15 illustrates the number of pockmarks within each fault–pockmark distance range in the study area. A strong correlation (R^2: 0.62) exists between the spatial distribution of pockmarks and faults. 229 pockmarks lie within 100 m from the faults, which are mostly in Nordfjorden and inner Isfjorden area. 42% of the pockmarks lie within 1 km radius from the faults. 30% and 28% of them lie within and outside 2 km radius from the faults, respectively.

5. Discussion

5.1. Age and morphology of pockmarks

The glacial front retreated from the mouth of Isfjorden to the heads of its tributaries between *c.* 14,100 and 11,200 calendar years BP (Forwick and Vorren, 2010). The well-defined morphology of the pockmark strings found within the troughs of the glacial lineations in Billefjorden and Nordfjorden suggests that they were formed after the ice retreat (Baeten et al., 2010; Forwick et al., 2009). The sharp outline of the pockmarks suggests that they have formed in the recent past or are still active probably in some cases. Forwick et al. (2009) has documented certain *relict pockmarks* having less sharp appearance in Grønfjorden, Ymerbukta, Adventfjorden and Billefjorden. Pockmarks occur as individual and composite depressions as well as in the form of a string of several depressions on the Isfjorden seabed (Forwick et al., 2009; Roy et al., 2012). Certain factors could influence the morphology of pockmarks, such as spatial differences in sediment accumulation, geometry of subsurface bedding, availability of migration paths (fractures and faults), differences in expulsion rates and action of bottom currents (Bøe et al., 1998; Hovland and Judd, 1988). Shape of pockmarks in the study area is primarily circular and elongate. Elongate pockmarks are predominant in the Isfjordbanken (30%) as compared to other inner tributary fjords in Isfjorden (Fig. 13C). The major axes of the elongate pockmarks are oriented NE–SW suggesting that the morphology of the pockmarks could have been influenced by the bottom currents at the entrance of Isfjorden (Fig. 14A). The bottom currents are affected by the water mass exchange between the Transformed Atlantic Water originating outside Isfjorden and the Winter Water created inside the fjord system (Nilsen et al., 2008). Circular pockmarks dominate the inner parts of Isfjorden and its tributary fjords where the bottom water is relatively more stable as compared to the Isfjordbanken. However, a few elongate pockmarks are found in the inner parts of Isfjorden (Fig. 13C). They may have formed as a result of amalgamation of more than one circular pockmark.

We have analyzed the average diameter/depth ratio of pockmarks in Isfjorden. The ratio was found to be ~30 (STD = 14.64), which is similar to values observed in pockmark fields in other parts of the world, e.g., Belfast Bay (Andrews et al., 2010), inner Oslofjord (Webb et al., 2009) and Scotian Shelf (Fader, 1991). Andrews et al. (2010) suggested that the pockmarks found in relatively thin layers of bottom sediments in Belfast Bay have shallow depth with respect to their diameters. This is similar to the relatively "shallow pockmarks" (diameter/depth > 30) we find occurring in Nordfjorden and Sassenfjorden, where relatively thin Late Holocene bottom sediment layers drape the bedrock (Forwick and Vorren, 2010). Thus, the widening of pockmark diameter could be attributed to reduced sealing capacity caused by the thin overlying marine sediment layers. In contrast to this, pockmarks with smaller diameters relative to their depths have also been found in Isfjorden. Most of these relatively "deep pockmarks" (diameter/depth < 30) have been identified along the ridges in inner Isfjorden. These ridges are interpreted as seafloor expressions of bedrock outcrops and thrust faults that provide either organic rich source rocks and/or migration pathways for fluids to the pockmarks (Roy et al., 2014). Thus, prolonged escape of fluid at the same location in the seabed removes fine sediments and deepens the pockmarks over time. Hence, it is suspected that focused fluid flow along leaking faults and bedrock outcrops could lead to the formation of such relatively "deep pockmarks".

5.2. Spatial distribution of pockmarks

The occurrence of individual pockmarks, string pockmarks and unit-pockmarks on the Isfjorden seafloor establishes a hydraulically active seafloor whereby small amounts of pore fluids are tidally pumped out of the seafloor through the small unit-pockmarks. As per the definition of hydraulically active seafloor (Hovland and Judd, 1988), we can classify the high density pockmarked zones in the fjord system with more than 5–10 pockmarks per km^2 as more hydraulically active zones,

Table 1
Morphometric parameters and water depth at which the pockmarks occur, seafloor features and their interpretation, bedrock geology, available potential source rocks (Nøttvedt et al., 1993) and possible fluid migration pathways in each of the tributary fjords in Isfjorden fjord system. Avg. — average and S.D. — standard deviation.

Fjord and embayments	Pockmarks				Seafloor features			Bedrock geology	Potential source rocks	Inferred interpretation of ridges — possible migration pathways	Remarks
	Numbers	Depth (m)	Diameter (m)	Water depth (m)	Ridges	Submarine debris lobes	Glacial Lineations				
Billefjorden	198	1–4, avg. = 1.6, S.D. = 0.7	15–97, avg. = 37.7, S.D. = 17	102–180	2 (11.5 and 8. 5 km long, 40–80 m high), N–S aligned	Eight lobes (0.35, 0.18, 0.10, 0.17, 0.30, 0.44,0.16 and 0.15 km^2)	36 lineations (146–1171 m long). amplitude: 2–5 m, wavelength: 50–200 m.	Lower Carboniferous–Lower Permian	Shales and coal in Hørbyebreen and Svenbreen Fms., organic rich limestone and dolomites in Nordenskiöldbreen Fm. (Carboniferous)	Billefjorden Fault Zone	Pockmarks are located in the Billefjorden Trough, preferentially in the troughs of glacial lineations
Tempelfjorden	108	1–3, avg. = 1.3, S.D. = 0.4	15–102, avg. = 32.5, S.D. = 15.6	54–101	1 (10.2 km long, 20–25 m high), N–S aligned	Three lobes (5.88, 0.20, 0.22 km^2)	15 lineations (250–1991 m long); amplitude: 2–3 m, wavelength: 150–300 m	Upper Carboniferous–Lower Permian	Same as above	Billefjorden Fault Zone	Pockmarks are found within troughs of glacial lineations and ahead of debris lobes
Sassenfjorden	93 + cluster of unit-pockmarks	1–7, avg. = 1.6, S.D. = 0.9	14–122, avg. = 46, S.D. = 28.4	42–128	3 (14.4,9, 3.3 and 2.6 km long, 8–35 m high), NW–SE aligned	One lobe (0.42 km^2)	22 lineations (287–2324 m long); amplitude: 4–6 m, wavelength: 200–400 m	Upper Carboniferous–Middle Triassic	Same as above + M. Triassic Botneheia Fm.	Top Kapp Starostin unconformity and thrust faults of WSFTB	Clusters of unit pockmarks are aligned along the ridges
Inner Isfjorden	141	1–7, avg. = 2.2, S.D. = 1.3	18–213, avg. = 56.2, S.D. = 33	162–270	53 (0.5–21.8 km long, 5–40 m high), NW–SE aligned	Three lobes (1.85, 0.69 and 2.84 km^2)	–	Upper Permian–Lower Jurassic	M. Triassic Botneheia Fm.	Top Kapp Toscana unconformity and thrust faults of WSFTB	Pockmarks are aligned along ridges and not associated with debris lobes
Nordfjorden	535	1–8, avg. = 2.4, S.D. = 1.4	24–212, avg. = 70.1, S.D. = 31.6	100–225	15 E–W aligned (0.4–3.2 km long, 2–15 m high); 17 N–S to NW–SE aligned (0.4–16.8 km long, 2–10 m high)	–	41 lineations (139–2600 m long); amplitude: 2–6 m, wavelength: 100–200 m	Upper Permian–Middle Triassic	M. Triassic Botneheia Fm.	Blomesletta Fault and thrust faults of WSFTB	Pockmarks are aligned along ridges and also ahead of debris lobes.
Yoldiabukta	–	–	–	–	–	One lobe (12.7 km^2)	–	Upper Triassic–Lower Jurassic	–	–	–
Adventfjorden	17 + cluster of unit-pockmarks	1–6, avg. = 3, S.D. = 1.7	35–114, avg. = 82.4, S.D. = 22.1	69–120	–	–	–	Lower Cretaceous	U. Jurassic–L. Cretaceous Janusfjellet Fm.	Thrust faults of WSFTB	–
Colesbukta	Cluster of unit-pockmarks	1.00	<5	80–120	–	–	–	Cenozoic	Coal seams in Tertiary Firkanten Fm.	Thrust faults of WSFTB	–
Outer Isfjorden	60	1–8, avg. = 3.5, S.D. = 1.9	36–265, avg. = 106.1, S.D. = 56.1	62–249	46 (0.6–24 km long, 30–80 m high), NW–SE aligned	Four lobes (4.29, 1.5, 2.2, 5.8 km^2)	12 lineations (1574–3280 m long); amplitude: 5–10 m, wavelength: 600–1000 m	Upper Jurassic–Lower Cretaceous and Cenozoic	U. Jurassic–L. Cretaceous Janusfjellet Fm. and coal seams in Cenozoic Firkanten Fm.	Thrust faults of WSFTB	Few pockmarks are aligned along ridges
Borebukta	40	2–8, avg. = 3.5, S.D. = 1.4	45–133, avg. = 87.5, S.D. = 14.7	62–166	–	One lobe (9.1 km^2)	–	Upper Triassic and some Upper Jurassic–Lower Cretaceous	U. Jurassic–L. Cretaceous Janusfjellet Fm.	IYFZ and thrust faults of WSFTB	Pockmarks form in close proximity with IYFZ and ahead of debris lobes
Ymerbukta	13			55–238	–	One lobe (5 km^2)	–	Upper Jurassic–Lower Cretaceous and some Cenozoic	U. Jurassic–L. Cretaceous Janusfjellet Fm.	IYFZ and thrust faults of WSFTB	
Grønfjorden	40	1–10 m, avg. = 2.72, S.D. =2.15	10–265, avg. = 67.8, S.D. = 70.6	70–145	2 (5.7 and 6.8 km long, 5–10 m high), NW–SE aligned	One lobe (0.54 km^2)	–	Upper Jurassic–Lower Cretaceous	M. Triassic Botneheia Fm. and U. Jurassic–L. Cretaceous Janusfjellet Fm.	Thrust faults of WSFTB	Pockmarks form ahead of debris lobes and in close proximity to ridges
Isfjordbanken	59	1–11, avg. = 5.2, S.D. = 2	48–218, avg. = 111.9, S.D. = 39.1	128–318	1 (17.7 km long, 70 m high), NW–SE aligned	–	26 lineations (669–4569 m long); amplitude: 4–10 m, wavelength: 200–450 m	Meso- and Neoproterozoic, Paleozoic and Cenozoic	Organic rich sediments of U. Cenozoic	Normal faults, strike slip faults, Hornsund Fault zone	Very few pockmarks are located above mapped faults, and not associated with glacial lineations

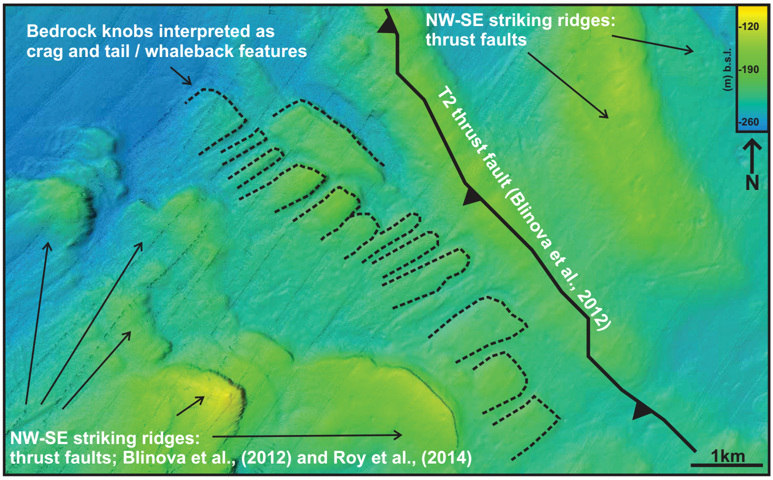

Fig. 7. NW–SE striking ridges, interpreted as seafloor expressions of thrust faults (Blinova et al., 2012) and crag and tail glacial features in the central part of Isfjorden (refer to Fig. 1 for location).

when compared to low density or no pockmarked areas (Fig. 4). The density of pockmarks on the seabed varies with thickness of glacial sediments, the presence of glacial landforms, underlying bedrock geology (availability of potential source rocks) and distribution of fault systems. The formation mechanism and density distribution of pockmarks have been categorized based on the following sections.

5.2.1. Submarine sediment lobes

We found pockmarks ahead of sediment lobes in four tributary fjords — Grønfjorden, Ymerbukta, Borebukta and Tempelfjorden (Fig. 3). Deposition of these glacigenic debris flow lobes could apparently cause overpressure in the sediment pore-fluids, leading to pore-fluid expulsion which causes the formation of pockmarks. The increase in overburden induced by the deposition of the sediment lobes may induce lateral migration of fluids towards the distal area (that is not covered by the debris). This mechanism seems feasible when the permeability of the sediment lobe deposits is lower than the underlying fjord bottom sediments. Rapid sediment loading represents a mechanism to drive extensive and intensive fluid expulsion, is also suspected to have triggered the Nyegga pockmark field, offshore mid-Norwegian continental margin (Hustoft et al., 2009). The seabed beyond the sediment lobe in Tempelfjorden consists of pockmarks within locally inflated areas (Fig. 11). We suggest that the massive submarine sediment debris lobe in Tempelfjorden has pressurized the pore-fluid system in the underlying and adjacent marine sediments (ahead of the debris lobe) causing inflation of the seafloor. Thereafter, escape of pore-fluids has led to the formation of the pockmarks. Similar formation mechanism has been proposed by Hovland and Judd (1988) in Ullsfjord, where the seabed inflation was caused by expansion of sediment-trapped gases.

We found pockmarks in the upslope of the sediment lobes located at the eastern part of the Svensksunddjupet Basin (Fig. 9). We also identified relatively smaller sediment lobes originating from iceberg ploughmarks in Billefjorden (Fig. 8). At high-latitude areas, high sediment supply following deglaciation and seismicity increases the likelihood of slope failures and formation of such sediment debris lobes (Owen et al., 2007). Vertical weakness zones due to fluid seepage and decrease in sediment shear-strength due to excess pore-water pressure could develop in steep seafloor areas. Based on the presence of pockmarks and iceberg ploughmarks in the upslope of the sediment lobes and extensive fault zones in Svensksunddjupet Basin and Billefjorden

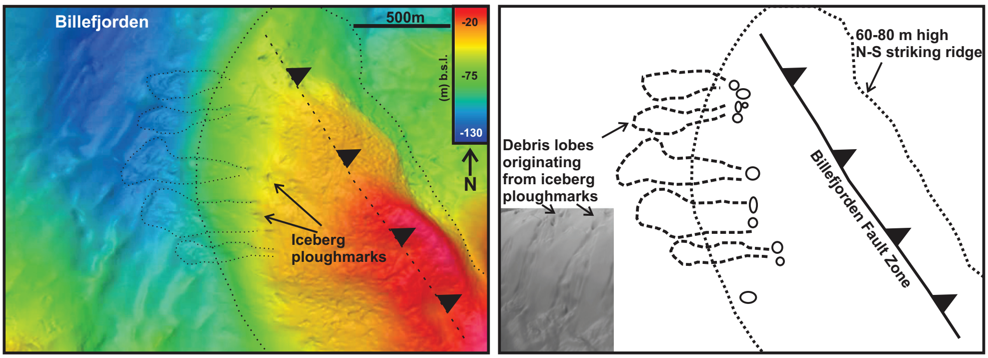

Fig. 8. Submarine sediment lobes originating from the iceberg ploughmarks in the vicinity of the Billefjorden fault zone (refer to Fig. 1 for location).

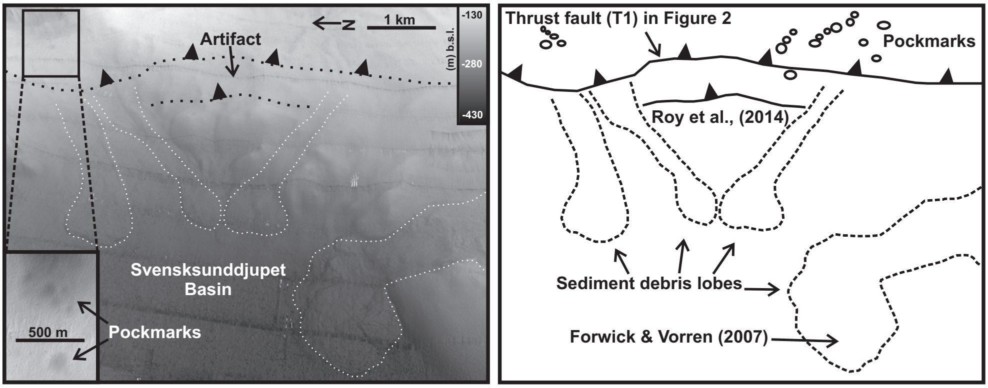

Fig. 9. Submarine sediment lobes in Svensksunddjupet Basin. Note the pockmarks located at the upslope of the slope failures and interpretation of ridges as thrust faults (refer to Fig. 1 for location).

(Pirli et al., 2010), we suggest that fluid seepage through the pockmarks, instability in sediments induced by the impact of icebergs and/or low magnitude seismic activities might have triggered the sediment lobes (Figs. 3, 8 and 9). Hovland et al. (2002) have documented similar cases where pockmarks are found often upslope of the sediment lobes. Alternatively, it could be the iceberg scouring process in Billefjorden which released the fluids trapped in the top sediment layer and thereby triggered the debris lobes. The mechanism of fluid seepage and pockmark formation induced by iceberg scouring is described in Fader (1991) and Hovland and Judd (1988). They are also known as *iceberg scour pockmarks* (Pilcher and Argent, 2007) (Fig. 8).

5.2.2. Glacial landforms and sediments

The glacial lineations in Billefjorden, Tempelfjorden and Nordfjorden have amplitudes of 3–8 m with the pockmarks preferably located in the troughs of the lineations (Fig. 12). The extent and style of deformation in sediments beneath glaciers could result in numerous minor fractures and fissures in the troughs of glacial lineations (Boulton et al., 2001). Such localized zones of increased permeability could be utilized by fluids as migration paths and considered preferable for pockmark formation. Fluids can migrate and escape more easily through the thinner till in the grooves of the lineations (Forwick et al., 2009).

The topmost Mid to Late Holocene glacimarine sediment layer in Isfjorden is typically 4–20 m thick (Forwick and Vorren, 2009, 2010). Pockmarks are located at the troughs of sub-cropping ridges, where the postglacial sediment layer is thicker than that on the ridges itself. Soft sediment layer within the troughs seems crucial for the formation of pockmarks in comparison to the hard bedrock at the ridges with relatively less marine soft sediments.

More than 55 m of postglacial sediments fill the Svensksunddjupet Basin (Forwick and Vorren, 2010). In spite of the WSFTB crossing this basin, the presence of Paleozoic and Mesozoic source rocks, high gas concentration in the marine sediments (Dallmann et al., 2002; Forwick and Vorren, 2007; Mørk and Bjorøy, 1984; Nøttvedt et al., 1993), it is devoid of pockmarks (Fig. 4). Partly discontinuous reflection beneath the mass-transport deposits identified on the sub-bottom acoustic data (Fig. 3A in Forwick and Vorren (2007)) could be related to gas migration. However, it seems that the fluids in the shallow sediments are sealed by several layers of mass-transport deposits which took place between *c.* 9650 and 3000 calendar BP in the basin (Forwick and Vorren, 2007). An alternative explanation could be that the gas within the sediments escaped through the seafloor in a diffusive manner (at a very low flux rate), which was not enough to create pockmarks.

5.2.3. Potential source rocks and tectonic faults

The Middle Triassic Botneheia and Upper Jurassic Agardhfjellet formations found in Spitsbergen are the main source rocks for oil and gas in the southwestern Barents Sea (Bjorøy et al., 2009; Henriksen et al., 2011; Mørk and Bjorøy, 1984). The Botneheia and Agardhfjellet

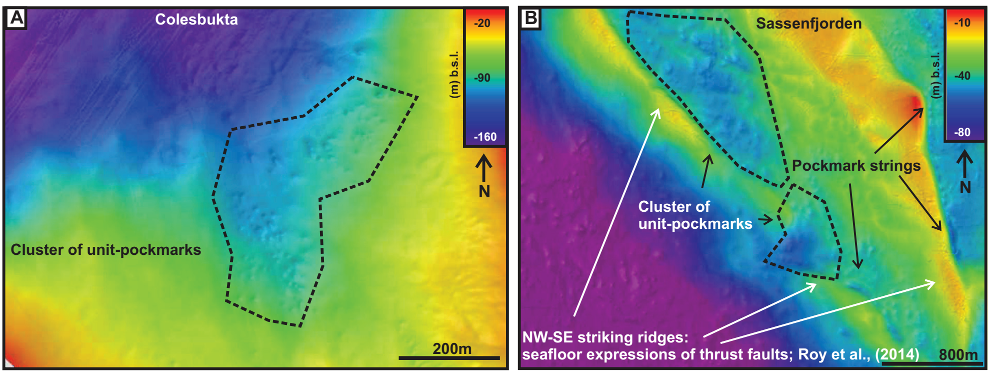

Fig. 10. (A) Cluster of unit-pockmarks in Colesbukta. (B) Pockmark strings and cluster of unit-pockmarks in Sassenfjorden along the NW–SE striking ridges (refer to Fig. 1 for location).

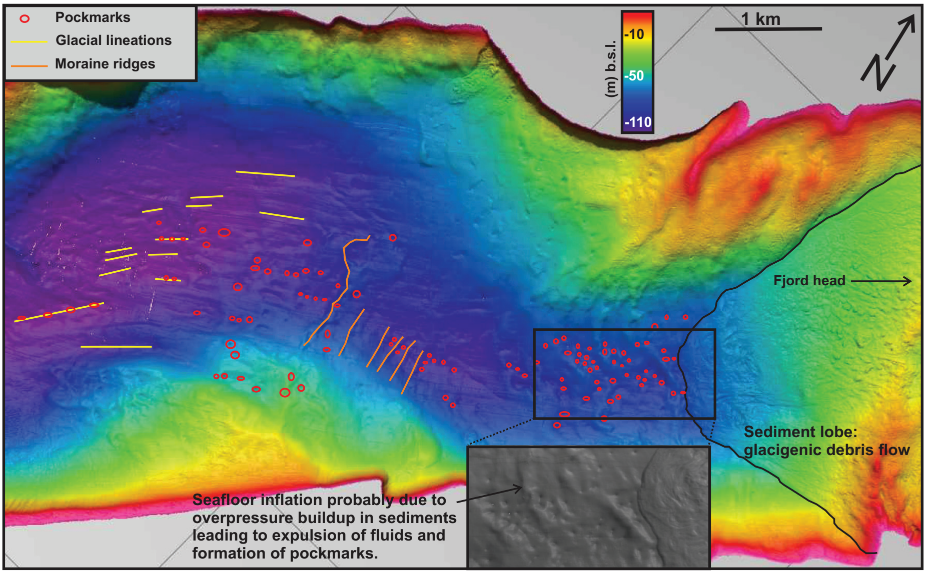

Fig. 11. Pockmarks located in front of the glacigenic debris flow in Tempelfjorden. Note the pockmarks within the glacial lineations in the central part of the fjord (refer to Fig. 1 for location).

formations have been attributed to onshore hydrocarbon seeps near the Jurassic–Cretaceous boundary in the Sassenfjorden area of West Spitsbergen (Hammer et al., 2011). In addition, potential deeper source rocks occur in Lower Carboniferous shales and coals (Michelsen and Khorasani, 1991) and Upper Carboniferous/Lower Permian carbonate mudstone and shale (Nøttvedt et al., 1993). Marine and terrestrial investigations in and around Isfjorden have revealed the presence of hydrocarbons in the marine sediments (Knies et al., 2004), water column (Damm et al., 2005) and in outcrops (Hammer et al., 2011; Nøttvedt et al., 1993). Thermogenic, an admixture of biogenic as well as mixed bio- and thermogenic gas have been documented in the marine sediments of Isfjorden (Knies et al., 2004). The traces of hydrocarbons found in the seafloor sediments of Isfjorden originate most likely from the potential source rocks which occur at various stratigraphic levels in Spitsbergen (Nøttvedt et al., 1993).

Pockmarks are preferentially located in the fine-grained marine sediments draping the fjord bedrock. 30% of the total pockmarks in Isfjorden have been found over the Carboniferous–Permian strata in the Billefjorden Trough, parts of Sassenfjorden and Tempelfjorden (Fig. 4 and Table 1). Pockmarks in Billefjorden and Tempelfjorden are concentrated east of the BFZ. We suggest that the complex tectonic geometry of the BFZ played an important role in the formation of the high density pockmark area (>20 pockmarks/km^2) in the Billefjorden Trough and at the mouth of Tempelfjorden (Bælum and Braathen, 2012). The absence of pockmarks in the SW part of the BFZ in Billefjorden might be attributed to the erosion of the potential Paleozoic source rocks in the area as a result of the extensive fault throw (~10 km) of the western block placing the metamorphic basement on top of the Devonian sedimentary units (Bælum and Braathen, 2012; Johannessen and Steel, 1992; Nøttvedt et al.,

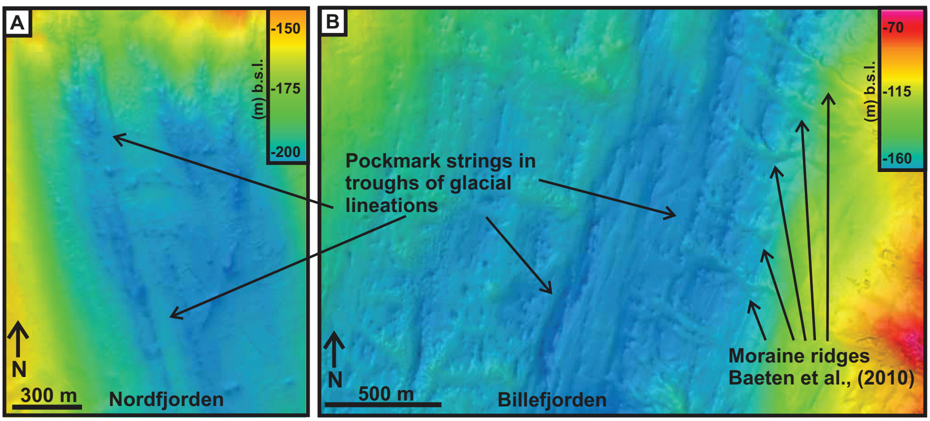

Fig. 12. Pockmarks in the troughs of glacial lineations in (A) Nordfjorden and (B) Billefjorden (refer to Fig. 1 for location).

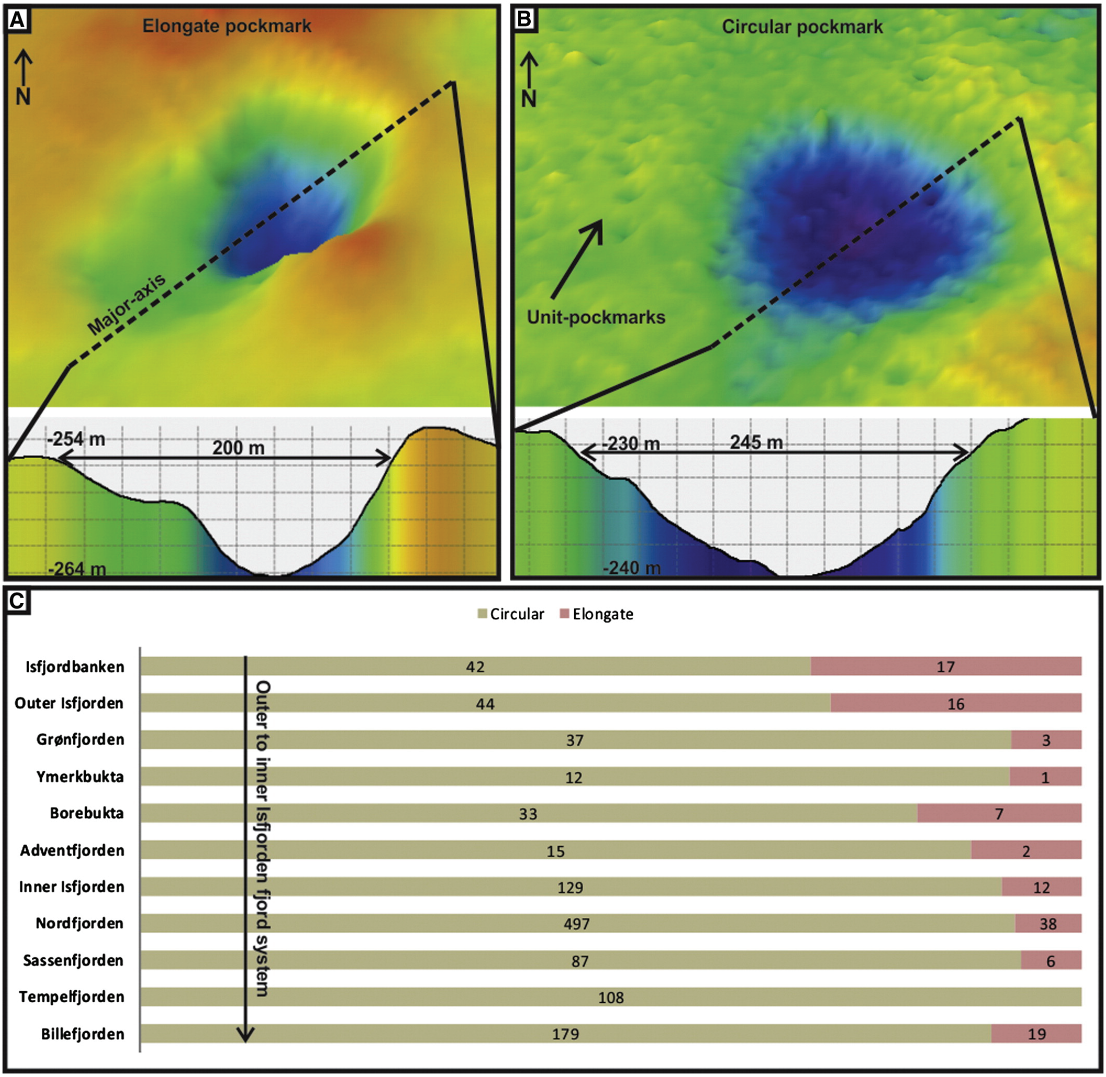

Fig. 13. (A) and (B) Morphology and cross profile of an elongate and circular pockmark located in Isfjordbanken and central Isfjorden respectively. (C) Distribution of circular and elongate pockmarks in the study area. The gray and pink colors within the color-bars represent the percentage of circular and elongate pockmarks and the numbers within the color-bars denote the number of pockmark within their respective class.

1993). Michelsen and Khorasani (1991) documented large amounts of Tertiary gas generation from the Lower Carboniferous coals in this region. Usually gas is stored in coal seams in the form of coal bed methane (Scott, 2002). This methane gas could be desorbed and released as free gas following post-glacial rebound, leading to seepage at the seafloor and the formation of pockmarks. 52% of the pockmarks lie on the Upper Permian–Lower Jurassic strata in Nordfjorden, inner Isfjorden and parts of Sassenfjorden (Fig. 4 and Table 1). The NW–SE striking thrust faults, N–S striking Blomesletta Fault, doleritic intrusions and geological unconformities reach the seafloor and form ridges in this area (Blinova et al., 2012; Roy et al., 2014; Senger et al., 2013) (Figs. 3 and 4). Pockmark densities are high at the Cretaceous–Cenozoic erosional boundary at the mouth of Borebukta (Fig. 4). Pockmarks in Borebukta and Ymerbukta are closely spaced with the IYFZ and thrust faults in the IMT (Fig. 4). The largest pockmark (265 m diameter) in Grønfjorden is located over the thick skinned basement involved fold-thrust belt (Bergh et al., 1997; Blinova et al., 2013) (Fig. 2). 45 of 59 pockmarks in Isfjordbanken are closely associated with the Hornsund Fault Zone and the Bellsund fault systems (Blinova et al., 2009) (Figs. 3 and 4).

The empirical correlation between the distribution of pockmarks and the fault systems is confirmed by the pockmark–fault near-distance analysis (Fig. 15). The occurrence of high density pockmarked zones in the areas of potential source rocks (as explained in the previous paragraph) in the proximity of the fault zones, doleritic intrusions and geological unconformities suggests that the various types of fault systems (normal, strike-slip, thrust faults) in Isfjorden could be major conduits for fluid migration and influence high density pockmarked

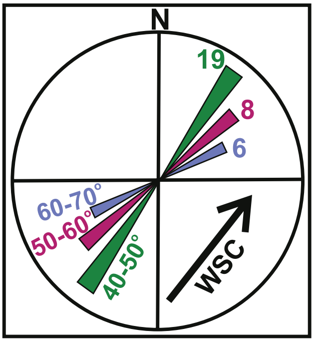

Fig. 14. Three major alignments of the major axis of the 33 elongated pockmarks in outer Isfjorden and Isfjordbanken coincide with the direction of the West Spitsbergen Current (SW–NE) at the mouth of Isfjorden fjord system.

seafloor. This supports the conclusion of Knies et al. (2004) who suggested the migration of hydrocarbons from potential source rocks based on the strong thermogenic signature observed in the surface sediments along tectonic lineaments. Forwick et al. (2009) suggested that gas expulsion directly from organic rich sub-cropping bedrocks into the soft sediments of the seafloor to be an alternative pockmark formation mechanism in Isfjorden. Pockmark formation at a greater distance from the tectonic lineaments could be attributed to diffuse fluid flow through the marine sediments or seepage of biogenic gas formed in the shallow sediments. Similar formation mechanism of pockmarks has been suggested in the Goliat area of the Barents Sea (Chand et al., 2009). Fewest pockmarks have been found on the Cenozoic bedrock in the central IMT (Fig. 4). This is probably due to the absence of deep fault conduits in the Cenozoic rocks, sub-cropping in this area (Blinova et al., 2012) (SA1 in Fig. 2). Alternatively, lack of potential source rocks in the bedrock itself could also be a possible reason for the lack of seepage features on the seafloor.

5.3. Gas hydrates, subsea permafrost and pockmarks

Extent and thickness of potential gas hydrate stability zone (GHSZ) have been calculated by modeling of thermo-baric conditions in Isfjorden (Roy et al., 2012). More than 600 pockmarks are located within the potential GHSZ. Thus, it cannot be excluded that, in addition to the factors affecting the seafloor seeps mentioned above, the pockmarks in Isfjorden could partly also result from the dissociation of gas hydrates due to warming of fjord waters and post-glacial rebound following deglaciation of the fjords. Dissociating gas hydrates are known to produce gas plumes on the West Spitsbergen continental margin, at and above the present upper limit of the GHSZ (Bünz et al., 2012; Gentz et al., 2014; Westbrook et al., 2009).

The permafrost thickness in West Spitsbergen has been in the range of 3–100 m in low altitude valleys since 3000 calendar years BP (Harada and Yoshikawa, 1996; Humlum, 2005). Kristensen et al. (2008) have modeled the subsea permafrost distribution in Van Mijenfjorden (central Spitsbergen). Depending on the temperature and sediment properties, a thin layer of permafrost could exist below the seabed. Fluids can get trapped below the permafrost layer due to reduced permeability of the frozen ground. Thawing of the thin impermeable seal of the near-shore subsea permafrost layer in the Arctic can result in enhanced methane emissions due to microbial degradation of newly released organic carbon from the permafrost or release of methane trapped under the permafrost seal (Ruppel, 2011; Shakhova et al., 2010; Walter Anthony et al., 2012). Proximity of the cluster of unit-pockmarks to the shoreline in Colesbukta and NE Adventfjorden suggest that they could potentially be formed due to thawing of possible near-shore subsea permafrost. It is likely that there is sub-surface trapped free gas beneath the unit-pockmarks which acts as a dynamic pump causing upward movement and seepage of pore-water through the sediments. The significance of unit-pockmarks for predicting fluid flow systems has been described by Hovland et al. (2010).

6. Conclusions

1304 individual pockmarks, pockmark strings and clusters of unit-pockmarks were recorded in water depths of 40–320 m in the Isfjorden fjord system. Their shapes vary between circular to elongate. The main findings of this study are:

1. Combined presence of fault conduits, potential source rock and thin postglacial sediment layer has been found to be crucial for the formation of pockmarks in Isfjorden. Increased overpressure in the sediments (ahead of the debris lobes) and subsequent expulsion of pore-fluids due to submarine sediment debris lobe deposition in Tempelfjorden, Borebukta, and Ymerbukta are probably the major

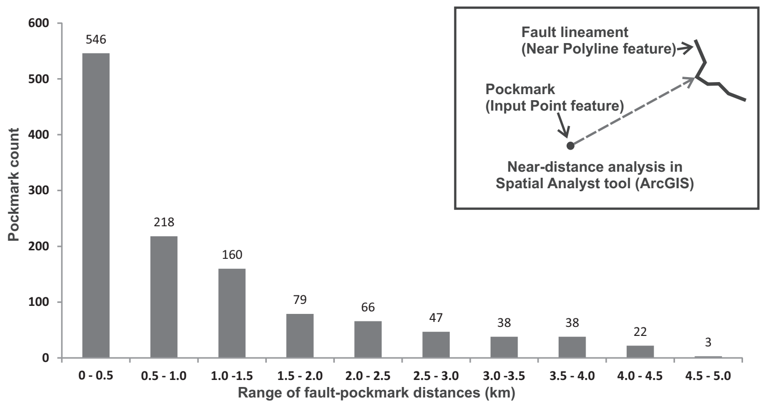

Fig. 15. Number of pockmarks plotted as a function of pockmark–fault distance range (km), calculated from the near-distance analysis algorithm (with ArcGIS Spatial Analyst Tool), discussed in the text. The near-distance analysis determines the shortest distance from one defined feature (pockmarks) to another type of feature (here, fault lineament). The inset, upper right, illustrates this.

reason for pockmark formation.
2. Elongated pockmarks are relatively more abundant in the outer parts than in the inner areas of the Isfjorden. This has been likely attributed to the effect of West Spitsbergen current, aligned along the major axis of the elongated pockmarks.
3. Occurrence of pockmarks within postglacial marine sediments and in the troughs of glacial lineations suggests their formation to be after the deglaciation of Isfjorden.
4. The doleritic intrusions and thrust faults are critical in the migration of fluids and hence in forming pockmarks in the seafloor troughs associated with them. For instance, the proximity of 546 pockmarks within 500 m from the thrust faults suggests focused fluid migration along the fault conduits.
5. The high density pockmark zone in Billefjorden is probably associated with the complex geometry of the BFZ in the Billefjorden Trough.
6. Low magnitude seismic activities, impact of icebergs at steep slopes and fluid seepage from pockmarks probably triggered the sediment lobes in the eastern part of Svensksunddjupet Basin and Billefjorden.
7. Modeling results of near-shore subsea permafrost and potential GHSZ imply thawing permafrost and gas hydrate dissociation as possible mechanisms for pockmark formation in Isfjorden.

Geochemical analysis of surface sediments and pore water from pockmark locations could further delineate the specific nature and composition of the seeping fluids.

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