

Pockmarks in Spitsbergen fjords

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Swath bathymetry and high-resolution seismic data, as well as published material are used to analyse pockmarks in Spitsbergen fjords. Up to 250 m wide and 13 m deep pockmarks occur in Grønfjorden, Ymerbukta, Adventfjorden, Billefjorden and van Keulenfjorden. They developed during the past c. 11,300 years, as the result of seepage of thermogenic gas and porewater. Factors controlling the distribution of pockmarks in these subpolar fjords include 1) tectonic lineaments, 2) the lithological composition and lateral outcrop of bedrock, 3) the orientation of glacial lineations and 4) exceptionally rapid deposition of debris lobes related to glacial surges.

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1. Introduction

Pockmarks are concave, crater-like features on the seafloor, generally up to several hundreds of meters in diameter and tens of meters in relief (e.g. King and MacLean 1970; Kelley et al. 1994). 'Mega pockmarks' can have diameters of more than 1.5 km and depths exceeding 150 m (Pilcher & Argent 2007). The formation of pockmarks is mostly caused by the seepage of thermogenic and biogenic gases (Rogers et al. 2006) and the release of pore water (Harrington 1985).

Pockmarks occur in lakes (Pickrill 1993), shallow bays, estuaries and fjords (e.g. Hovland & Judd 1988; Kelley et al. 1994; Plassen & Vorren 2003, Rogers et al. 2006), on continental shelves, slopes and rises, as well as in the deep sea (King & MacLean 1970; Josenhans et al. 1978; Fader 1991; Piper et al. 1999; Paull et al. 2002; Loncke et al. 2004; Gay et al. 2007).

The lateral distribution of pockmarks can be controlled by tectonic lineaments (e.g. Chand et al. 2008), underlying permeable bedrock and lithological boundaries (Solheim & Elverhøi 1985; Paull et al. 2002), as well as buried channels (Gay et al. 2003; Pilcher & Argent 2007). However, they also occur in the vicinity of slope failures (Hovland et al. 2002; Lastras et al. 2004) and in areas of rapid deposition (Syvitski 1997; Pilcher & Argent 2007). Pockmarks are furthermore described from areas that have been affected by the up-drift of ice that detached from the sub-seafloor (Paull et al. 1999), decomposing gas hydrates (Solheim & Elverhøi 1993) and where gas is released due to melting permafrost (Long 1992). They can also be induced by grounded moving icebergs

or anthropogenic activities such as trawling and ship anchoring (Harrington 1985; Fader 1991).

Pockmarks are classified based on their morphology, e.g. *circular, elliptical, asymmetric, composite* (Hovland & Judd 1988; Judd & Hovland 2007), their state of development, e.g. *new, growing, decaying* (Pickrill 1993) or their lateral distribution and formation mechanisms, e.g. *fault-strike pockmarks, iceberg scour pockmarks, current-modified pockmarks* (Pilcher & Argent 2007).

The formation of pockmarks can occur catastrophically (e.g. due to earthquakes, tsunamis, storms, melting of ground ice) or more continuously over longer periods (Judd et al. 1994; Kelley et al. 1994; Hovland et al. 2002 and references therein).

A systematic description of pockmarks from Spitsbergen fjords does not exist. Ottesen et al. (2008) describe circular depressions (some of them with raised rims) on the surface of a sediment lobe in van Keulenfjorden (Fig. 2, below). These are the surface expressions of dewatering pipes penetrating a debris lobe that was deposited at the termination of a glacial surge in the late 19th century. Howe et al. (2003) did not find indications of pockmarks on swath-bathymetry and high-resolution seismic data from the Kongsfjorden-Krossfjorden area (for location see Fig. 1). Neither do swath-bathymetry data from Trygghamna (for location see Fig. 1) reveal pockmarks (Forwick 2005). Knies et al. (2004) measured increased methane concentrations in surface sediments in the vicinity of tectonic structures in the Isfjorden area. They suggest that passive seepage of thermogenic gas was particularly strong along major tectonic lineaments



Figure 1: A, B): Location maps. C) Overview map of the Isfjorden area. Place names mentioned in the text are indicated.

west off Spitsbergen in the past. Furthermore, Forwick & Vorren (2007) found indications of gas in sediment cores from Svensksunddjupet (for location see Fig. 1).

In this paper, we use swath-bathymetry and high-resolution seismic data to describe pockmarks from four fjords on Spitsbergen. We discuss potential fluid sources and how tectonics, bedrock geology and glacial activity influenced the formation of pockmarks. We compile our results together with published data (Ottesen et al. 2008) in a conceptual model for the origin and distribution of pockmarks in subpolar fjords.

2. Physiographic setting and geology

We investigated the bathymetry and the sub-seafloor of the fjords Grønfjorden, Ymerbukta, Adventfjorden and Billefjorden (Fig. 1). All fjords belong to the Isfjorden fjord system, the largest fjord system on Spitsbergen, Svalbard. It is located between c. 78°00' – 78°45' N and c. 13°30' – 17°30' E. Glaciers cover approx. 40 % of the study area (Hagen et al. 1993).

The bedrock geology in most of the Isfjorden system is dominated by partly deformed sedimentary rocks of Devonian to Paleogene age (Fig. 2; Dallmann et al. 2002). The westernmost parts generally comprise intensely deformed metamorphic and sedimentary rocks of Pro-

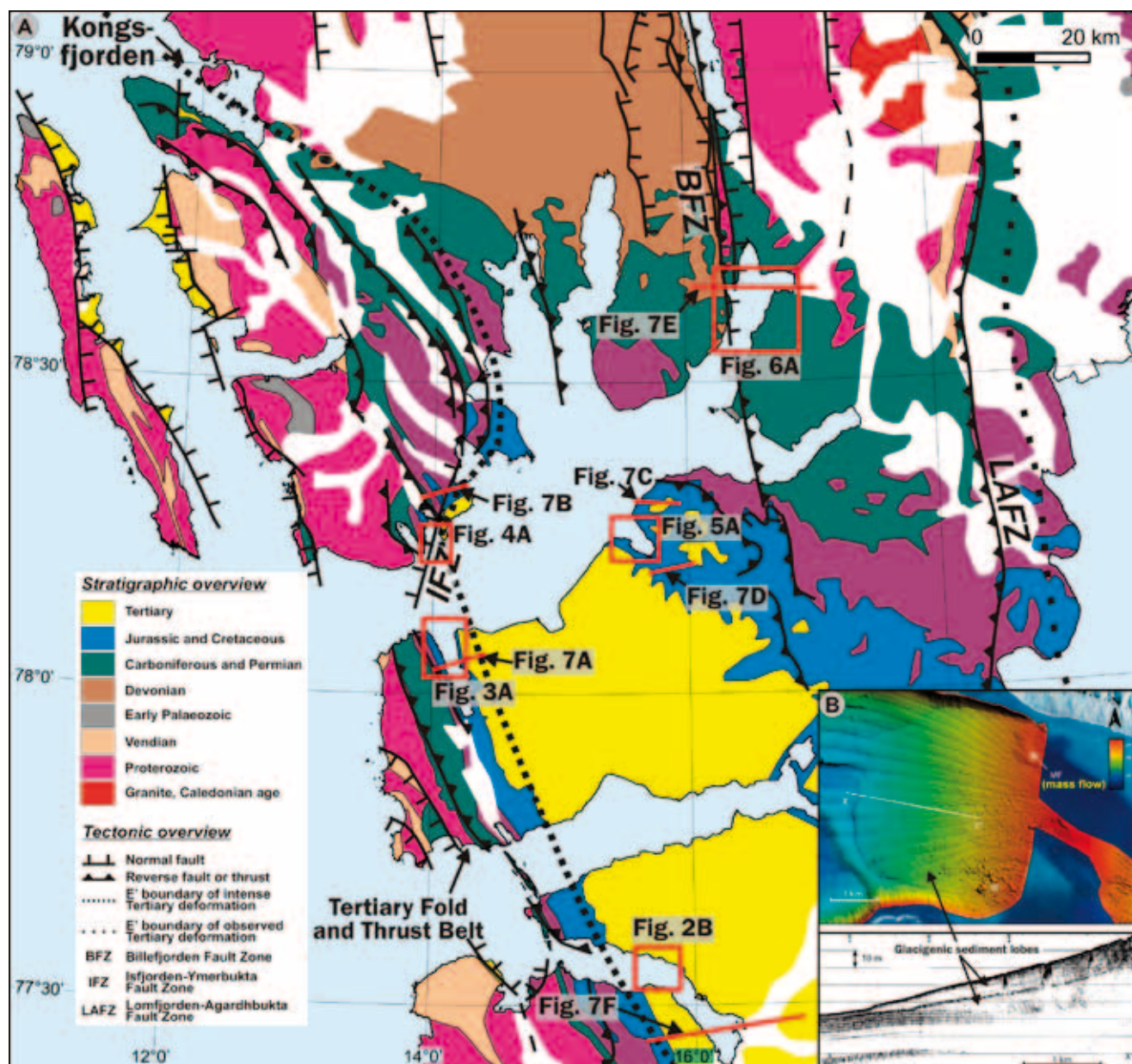


Figure 2: A) Stratigraphic and tectonic overview of central Spitsbergen (modified after Dallmann et al. 2002; for location see Fig. 1B). B) Bathymetry map (above) and 3.5 kHz penetration echo sounder profile (below) of debris lobes in van Keulenfjorden (from Ottesen et al. 2008). The upper debris lobe was deposited at the termination of a glacier surge in the late 19th century.

terozoic to Mesozoic age. Smaller areas of volcanic and metamorphic rocks occur in the east and northeast. Unconsolidated Quaternary fluvial and marine sediments occur in surrounding valleys and on raised strandflats (Dallmann et al. 2002).

The largest fault systems in the study area are the Tertiary Fold and Thrust Belt in the western parts and the Billefjorden Fault Zone in the eastern parts of the Isfjorden system (Fig. 2; e.g. Dallmann et al. 2002).

The following lithological units are of particular significance for our study: 1) the *Janusfjellet Subgroup* of Middle Jurassic to Lower Cretaceous age. It is sub-divided into the lower *Agardhfjellet Formation* comprising considerable amounts of organic-rich shales, and the overlying *Rurikfjellet Formation* containing shales, siltstones and sandstones (Dallmann et al. 2001); 2) the *Helvetiafjellet and Carolinefjellet Formations* that were deposited during the Lower Cretaceous. These formations are composed of sandstones and shales with significantly lower organic contents (Ohta et al. 1992; Dallmann 1999; Dallmann et al. 2001, 2002). They overlie the *Janusfjellet Subgroup*.

3. Material and Methods

Swath bathymetry and high-resolution seismic data collected with R/V Jan Mayen provide the basis for this study.

The swath bathymetry data were acquired in the summers of 2005 and 2006 using a *Kongsberg Maritime EM 300 multibeam echo sounder*. CTD (conductivity-temperature-depth) casts prior to bathymetry surveying provided sound-velocity profiles through the water column for calibrating the equipment. The data were processed using the software programme *Neptune* version 4.12. For visualisation and cross profiling *ArcMap* version 9.2 was used.

High-resolution seismic data were collected in the summers of 1997, 2004 and 2008 using 1) a 700 J Bennex multi-electrode sparker (bandpass-filter setting 500–2000 Hz); 2) a 3.5 kHz penetration echo sounder (10 kW hull-mounted echo sounder; bandpass-filter setting 3–5 kHz); 3) and an *EdgeTech 3300-HM* hull-mounted sub-bottom profiler (Chirp; bandpass-filter setting 2–12 kHz). The digital interpretation and visualisation of the seismic data were performed using *Kingdom Software* from *Seismic Micro-Technology Inc.* (version 8.2) and *EdgeTech Discover – Sub-Bottom 3.41*.

4. Results

4.1 Grønfjorden

Grønfjorden has an inner basin and a sub-horizontal plateau in its outer parts (Figs. 1, 3A). The plateau comprises randomly distributed, circular and elliptical pockmarks (Fig. 3). They appear as either single features or *composite pockmarks* (cf. Hovland & Judd 1988; Judd & Hovland 2007). Several pockmarks located on slopes are asymmetric in vertical cross sections (Figs. 3C, D). Their maximum diameter is 240 m (Fig. 3D). Symmetrical pockmarks are maximum 9 m deep (Fig. 3D), asymmetrical up to 13 m deep (Fig. 3E). Raised rims occur occasionally (Figs. 3B, C). The appearance of the pockmarks varies from sharply outlined, with well-defined edges and steeper slopes, to less sharply outlined, with smooth edges and gentler slopes.

The pockmarks appear as V- to U-shaped depressions with smooth slopes and enhanced underlying acoustic amplitudes on the seismic profiles (Figs. 3F, G). Occasionally, the dip of the seafloor reflection is steeper than the dip of underlying reflections (Fig. 3G). Inclined reflections beneath several pockmarks are in direct contact with, or seem to penetrate, a deformation till of Younger Dryas age (Forwick & Vorren 2005A) that is located on a bedrock high (Figs. 3F, G).

4.2 Ymerbukta

Ymerbukta comprises an inner basin, a cross-cutting ridge and a southward inclined slope in its outer part (Figs. 1, 4A). The ridge and the south-facing slope are covered with randomly occurring circular and elliptical pockmarks. They appear as sharply to less sharply outlined single features or as *composite pockmarks*. The largest single pockmark is approx. 250 m wide and 7 m deep. Raised rims occur occasionally (Figs. 4B, D).

A seismic profile across two less sharply outlined pockmarks reveals a U-shaped morphology with smooth slopes (Fig. 4D). The bottom of the larger pockmarks is characterised by a stronger reflection. The inclinations of the reflections generally decrease upward in the sediment column (Fig. 4D).

4.3 Adventfjorden

In Adventfjorden, the water depth increases gradually from the fjord head to the fjord mouth (Figs. 1, 5A). The bathymetry is smooth in the inner parts of the fjord and more irregular in the outer parts.

Circular and elliptical pockmarks with and without raised rims occur in the outer parts of the fjord (Fig. 5). They are sharply to less sharply outlined (Fig. 5B), up to 140 m wide and maximum 8 m deep (Fig. 5C). *Composite pockmarks* occur occasionally (Fig. 5D). In the north-

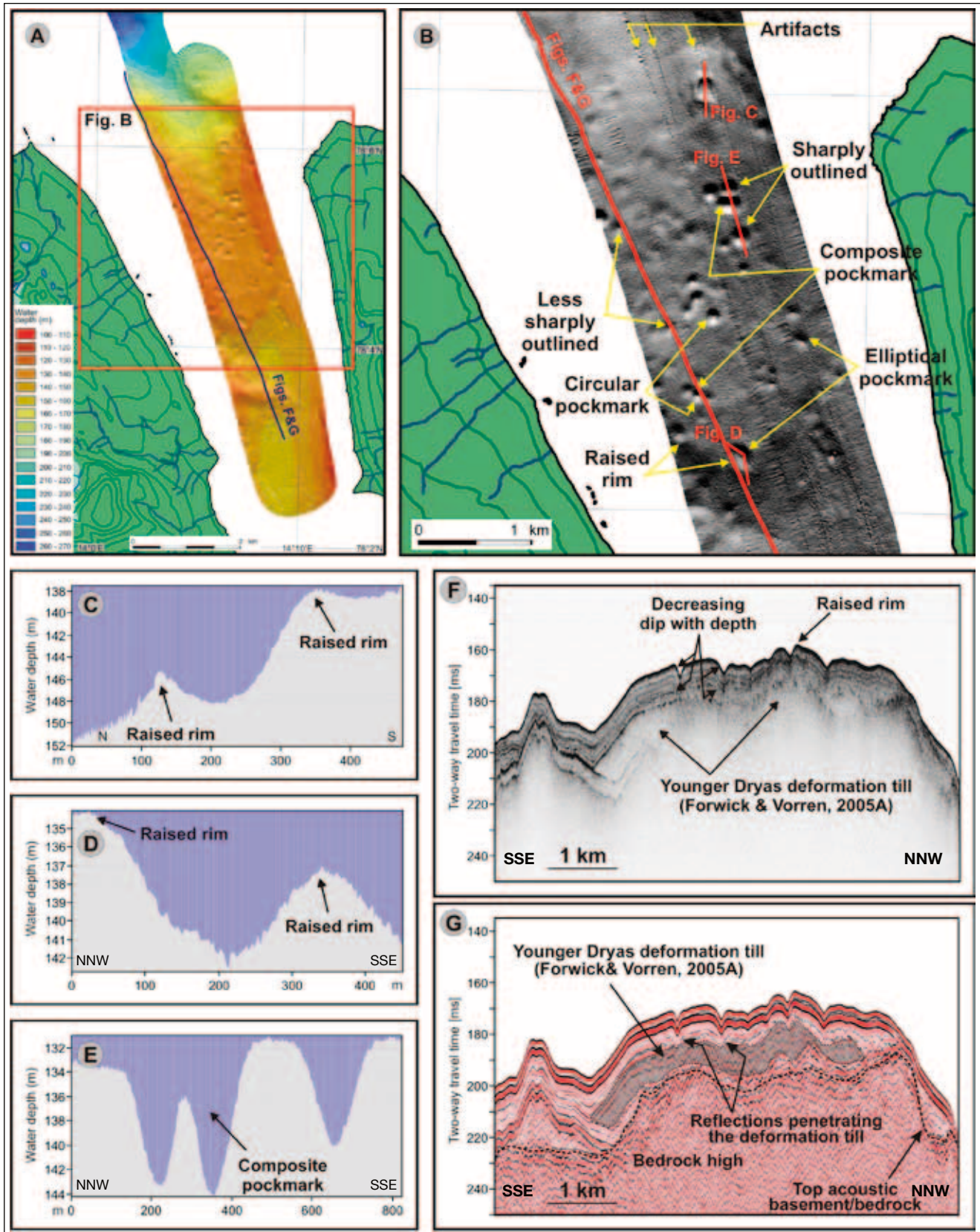


Figure 3: Acoustic data from Grøn fjorden. A) Swath-bathymetry map. B) Shaded-relief map with interpretations. C-E) Examples of the morphologies of pockmarks. F) Section of the 3.5 kHz penetration echo sounder profile F97-163. G) Section of the Sparker profile SS97-163.

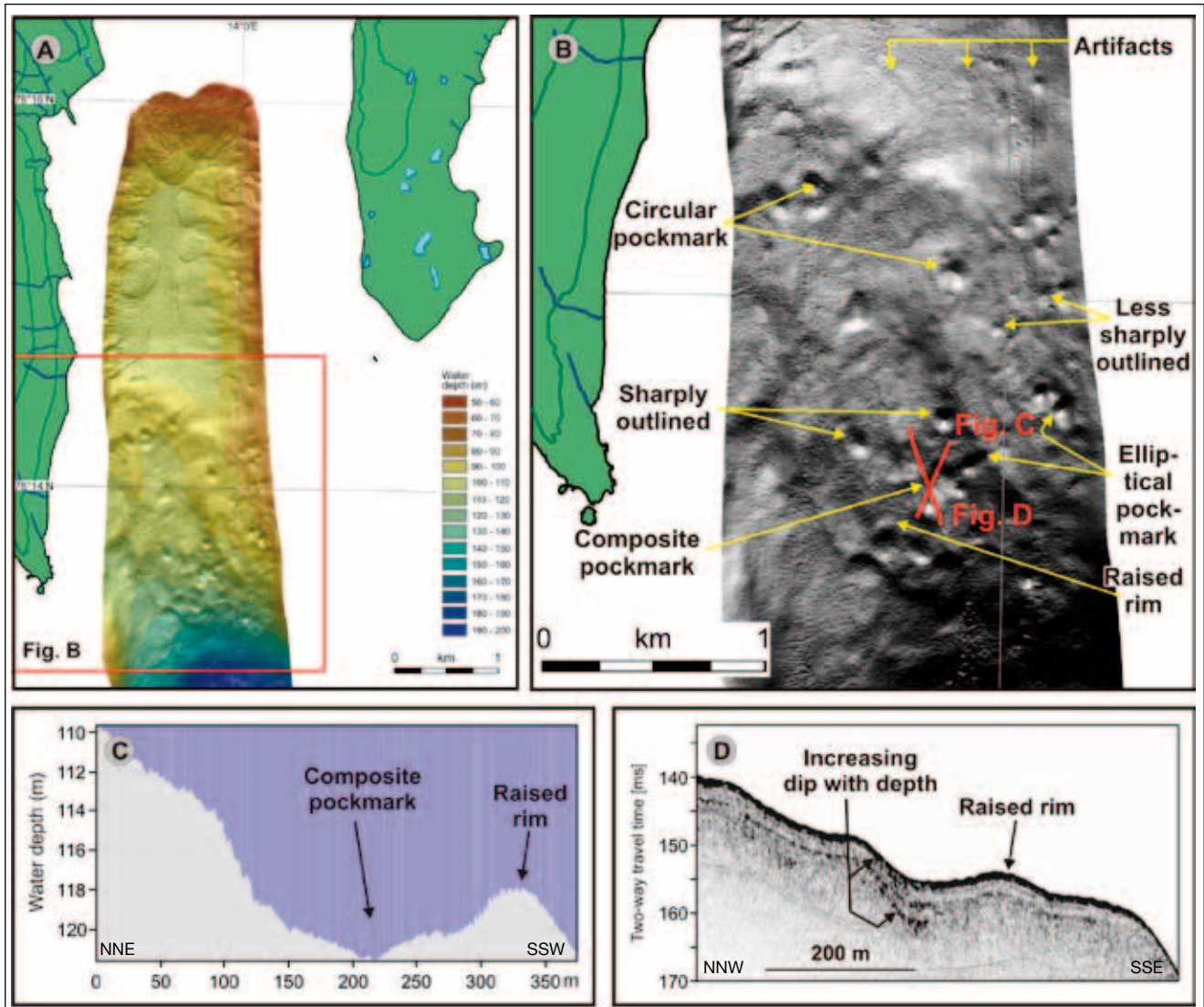


Figure 4: Acoustic data from Ymerbukta. A) Swath-bathymetry map. B) Shaded-relief map with interpretations. C) Example of the morphology of a composite pockmark. D) Section of the 3.5 kHz penetration echo sounder profile F04-021.

westernmost corner of the surveyed area, a more than 600 m long elongated depression with uneven morphology occurs (Fig. 5B). We suggest that this is a *pockmark trough* that has evolved from several single pockmarks (cf. Hovland & Judd 1988; Judd & Hovland 2007).

On seismic profiles, the pockmarks appear as V-shaped incisions with smooth slopes, partly surrounded by raised rims (Figs. 5E, F). Hyperbolas and increased acoustic amplitudes appear directly beneath them. Occasionally, the inclination of the reflections decreases with depth.

A comparatively large number of relatively small and partly elongated depressions occurs between c. 110 and 130 m water depth in the northeastern part of the study area (indicated with "?" on Fig. 5B). These may be pockmarks, too. However, because of their limited vertical distribution they might also be iceberg ploughmarks (compare with Baeten et al. *subm.*; Fig. 6B, below)

4.4 Billefjorden

Billefjorden comprises a rough sill in its outer parts, a comparatively flat central area, an inner basin, and several plateaus in the innermost parts (Figs. 1, 6A). Sharply to less sharply outlined, circular and elliptical pockmarks, as well as *composite pockmarks* occur in the flat, central area, and in the southern parts of the inner basin (Fig. 6B-F). They appear randomly or as *pockmark strings* (cf. Hovland & Judd 1988; Judd & Hovland 2007). The latter are mostly located within elongated grooves that are interpreted as glacial lineations formed during the Late Weichselian glaciation (Fig. 6B; Baeten et al. *subm.*). The pockmarks are up to 120 m in diameter and up to 5.5 m deep (Fig. 6E).

On the seismic profiles, the pockmarks appear as V- to U-shaped incisions that are underlain by generally increased acoustic amplitudes and hyperbolas. In the presented example, the inclinations of the reflections decrease in shallower parts of the sediment column (Fig. 6F).

5. Discussion

5.1 General remarks

Based on the occurrence of many circular pockmarks (Figs. 3, 4, 5, 6) we assume that the bottom-current activity in the fjords is generally low (compare with Josenhans et al. 1978). This is also supported by the generally draping character of the sediments as shown on the seismic profiles (e.g. Figs. 3F, 3G, 4D, 5F, 6F).

We assume that thermogenic gas, originating in the sub-seafloor, led to the formation of pockmarks in the studied fjords, rather than biogenic gas originating in the soft sediments, because 1) the production of biogenic sediments in Spitsbergen fjords is comparatively low (Elverhøi 1984); 2) the distribution of pockmarks correlates well with the bedrock stratigraphy and tectonic lineaments (see below); 3) seepage of thermogenic gas along major tectonic lineaments west off Spitsbergen in the

past has been suggested (Knies et al. 2004).

It is reasonable to assume that permafrost occurs beneath the fjord floors, because the thickness of the permafrost in Adventdalen (for location see Fig. 1) is between 200 and 450 m (Liestøl 1980). Melting of permafrost can release trapped gas that may form pockmarks (Long 1992). We do not, however, regard the melting of permafrost as an important factor contributing to the formation of pockmarks in Spitsbergen fjords, because their lateral distribution can be mostly related to the sub-bottom geology (see below). Based on this, we also exclude up-drifting ice detaching from the sub-seafloor (Paull et al. 1999) as an important factor for the formation of pockmarks in the study area.

The available data do not give us the opportunity to determine the origin of the raised rims. However, we assume that they comprise debris which vented upwards from the pockmarks (compare with Vogt et al. 1999).

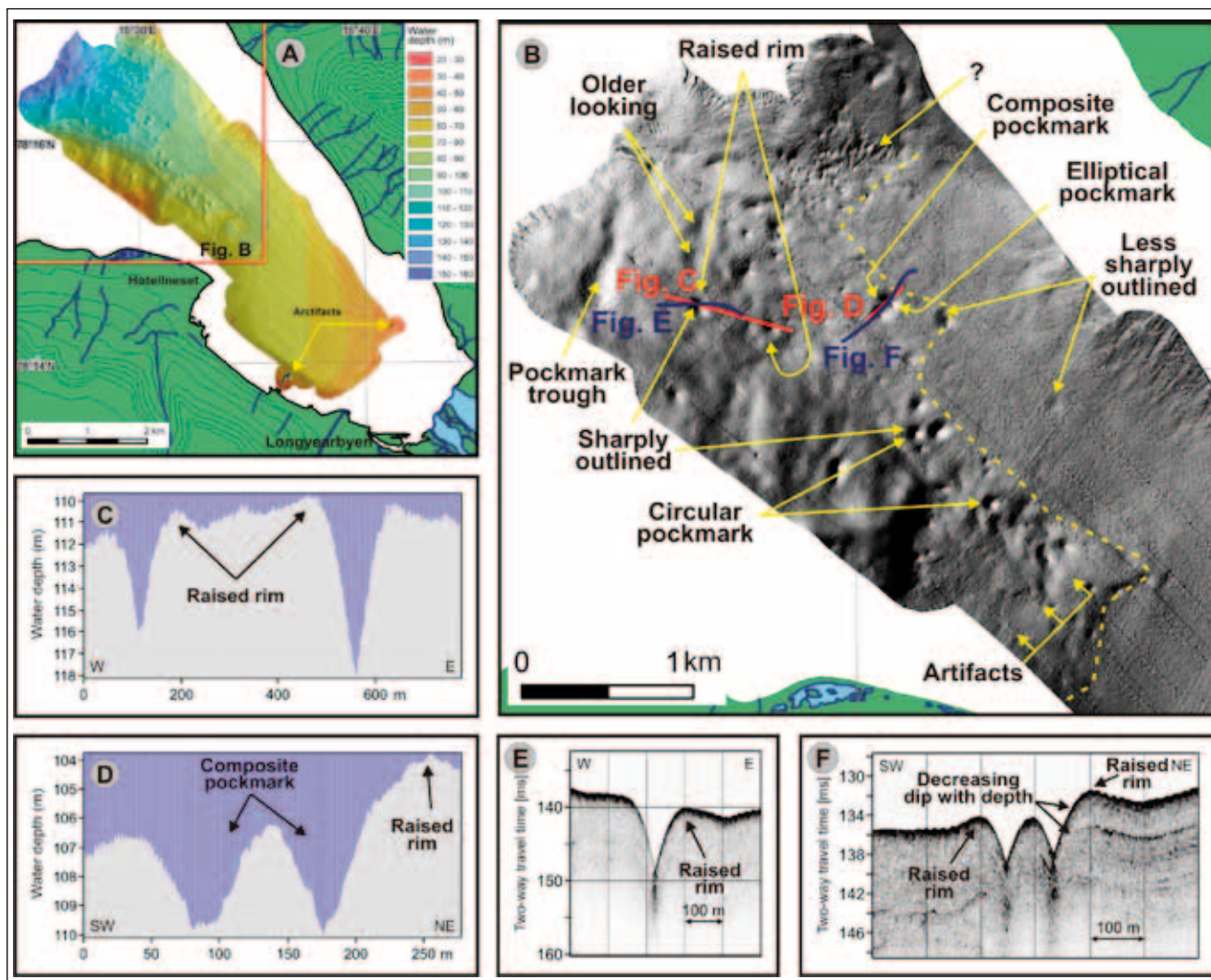


Figure 5: Acoustic data from Adventfjorden. A) Swath-bathymetry map. B) Shaded-relief map with interpretations. The dashed line indicates the northeastern boundary of the area with relatively high numbers of pockmarks. The “?” indicates an area with comparatively many small and partly elongated depressions. See main text for further explanations and discussion. C, D) Examples of the morphologies of pockmarks. E, F) Sections of the Chirp profile GEO8144-043.

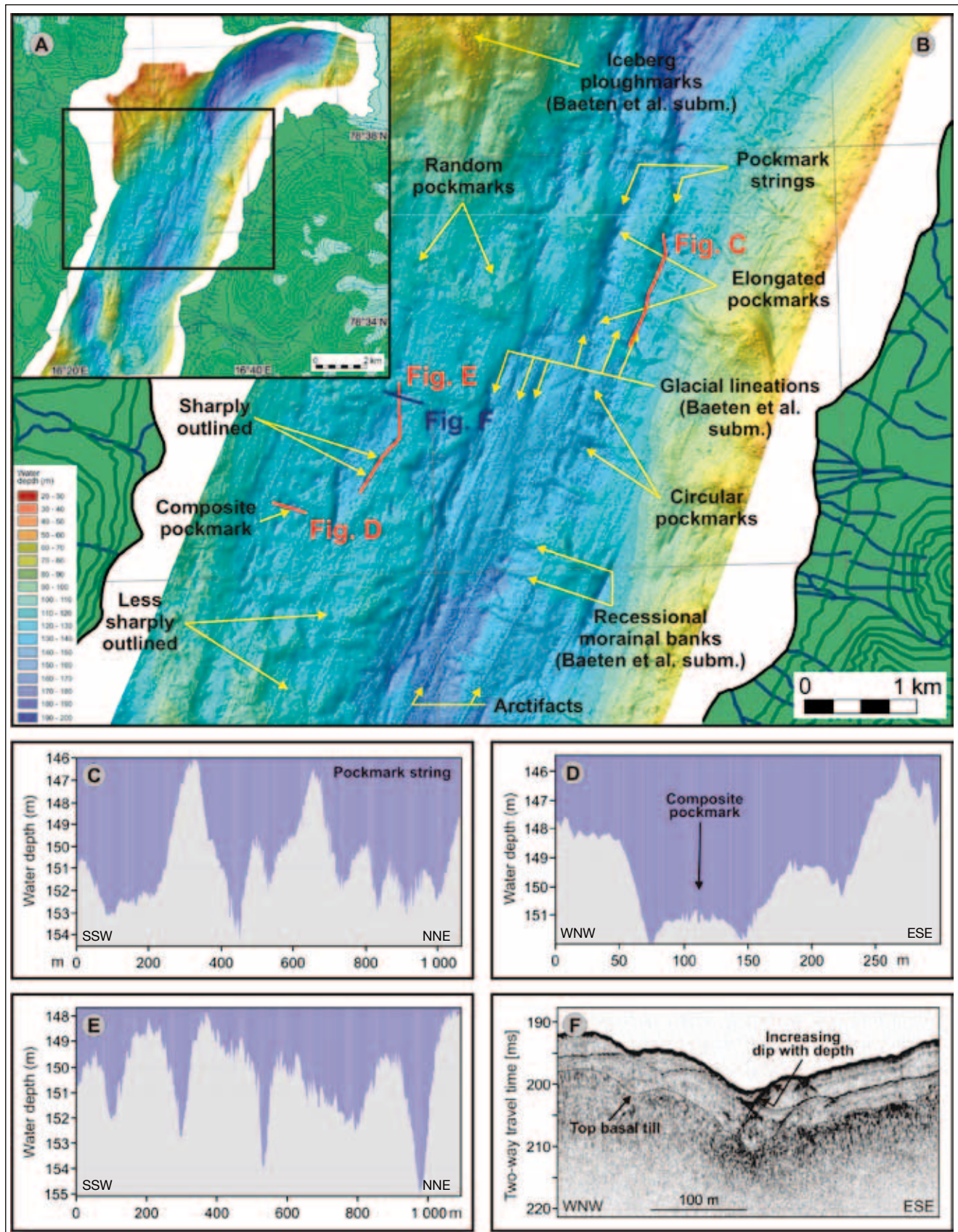


Figure 6: Acoustic data from Billefjorden. A) Swath-bathymetry map (modified from Baeten et al. *subm.*). B) Detailed swath-bathymetry map of the area comprising pockmarks, including interpretations. C-E) Examples of the morphologies of pockmarks. F) Section of the 3.5 kHz penetration echo sounder profile F97-208.

5.2 Geological controls

5.2.1 Grøn fjorden

Pockmarks occur in the outer fjord (Fig. 3). We suggest that they are formed from thermogenic gas that originated from the organic-rich shales of the *Janusfjellet Subgroup*, because 1) the entire fjord is underlain by this unit (Fig. 7A), and 2) the absence of steeply inclined, deep-penetrating faults in the sub-seafloor (Ohta et al. 1992; Dallmann et al. 2002) without any connection to greater depth restricts the seepage of thermogenic gas from deeper sources.

The deposits of the *Janusfjellet Subgroup* are entirely covered with the *Helvetiafjellet* and *Carolinefjellet Formations* (Fig. 7A; Ohta et al. 1992), so that direct seepage of gas into the soft sediments cannot occur. However, the outer parts of Grøn fjorden belong to the hanging wall of a reverse fault with a low dip angle within the *Helvetiafjellet* and *Carolinefjellet Formations* (Fig. 7A; Ohta et al. 1992) that may have acted as a pathway for seepage.

5.2.2 Ymerbukta

The occurrence of pockmarks in Ymerbukta is limited to the outer parts of the fjord (Fig. 4). We suggest that they were caused by the seepage of thermogenic gas from organic-rich bedrock directly into the soft sediments and/or by seepage which originated at greater depths that migrated along faults.

Ymerbukta is located within the area of intense Tertiary deformation and its outer parts are underlain by the Isfjorden-Ymerbukta Fault Zone (Figs. 2, 7B; Ohta et al. 1992; Dallmann et al. 2002). Since the Isfjorden-Ymerbukta Fault Zone is significantly more steeply inclined and deeper penetrating than the fault in Grøn fjorden (Figs. 2, 7A, B; Ohta et al. 1992), it is reasonable to assume that thermogenic gas migrated within this fault zone. Comparatively high concentrations of methane in the surface sediments in the basin Svenssunddjupet, immediately south of Ymerbukta (for location see Fig. 1C; Knies et al. 2004), and signs of gas in sediment cores from this basin (Forwick & Vorren 2007), may indicate the seepage of gas within the fault zone.

The gas may also originate from the underlying organic-rich *Janusfjellet Subgroup* and/or *Bravaisberget Formation*. The *Janusfjellet Subgroup* makes up a significant part of the footwall of the Isfjorden-Ymerbukta Fault Zone and appears to pinch out at the top of the bedrock sequence to the northeast of Ymerbukta (Fig. 7B; Ohta et al. 1992). Gas that originates from the bituminous black shales within this subgroup can either migrate along the fault (when originated at greater depths) or it can be released directly into the soft sediments overlying the bedrock. The *Janusfjellet Subgroup* occurs also to the west of Ymerbukta and apparently underlies the outer parts of the fjord. The *Bravaisberget Formation* is oriented parallel to the *Janusfjellet Subgroup* west of Ymerbukta (Ohta

et al. 1992). Therefore, it also appears to underlie the outer parts of the fjord. The *Bravaisberget Formation* is regarded as a potential source, because it belongs to the few rock formations representing the "most promising hydrocarbon source rock potential of Svalbard" (Dallmann 1999).

One can only speculate as to the exact fluid source(s), because the bedrock geology of the sub-seafloor of Ymerbukta is not known in detail. However, we assume that the formation of pockmarks is either related to one of the above-mentioned sources or to a combination of several of them.

5.2.3 Adventfjorden

The highest Holocene sedimentation rates in the Isfjorden area occur in the inner parts of Adventfjorden (Forwick & Vorren 2005B). However, pockmarks occur exclusively in the outer parts of the fjord (Fig. 5) where the sediment cover is thinner. This indicates that their formation is not necessarily dependent on sediment thickness.

We suggest that the pockmarks have formed from gas that originated in the *Agardhfjellet Formation*. The entire fjord is underlain by this formation and no deep-penetrating faults that could act as fluid pathways occur (Figs. 7C, D; Major et al. 2001; Dallmann et al. 2002). In the inner parts of the valley Adventdalen, the *Agardhfjellet Formation* is overlain by the *Rurikfjellet*, *Helvetiafjellet* and *Carolinefjellet Formations* (Fig. 7D; see Fig. 1C for the location of Adventdalen). However, north of the fjord mouth, the *Agardhfjellet Formation* extends outwards underneath the seafloor (Fig. 7C). We suggest that the lateral extension of this formation underneath the soft sediments determines the distribution of the pockmarks in the outer parts of Adventfjorden. The small number or the absence of pockmarks altogether in the rest of the fjord resulted presumably from the sealing effect of the overlying formations.

5.2.4 Billefjorden

Randomly distributed single pockmarks and *pockmark strings* occur in the central part of Billefjorden. We suggest that their formation is related to the seepage of thermogenic gas migrating along faults within the Billefjorden Fault Zone.

The study area is located within this Fault Zone, one of the largest and most complex fault systems on Spitsbergen (Figs. 2, 7E; e.g. Dallmann et al. 2002, 2004). Slightly increased methane concentrations have been measured in surface sediments in Sassenfjorden (for location see Fig. 1C; Knies et al. 2004), a fjord that is also affected by this fault zone (Fig. 2; Dallmann et al. 2002). It is therefore reasonable to assume that deep penetrating faults within the fault zone acted as pathways for the gas seepages.

The randomly distributed pockmarks are most probably related to more diffuse flows of gas through the soft

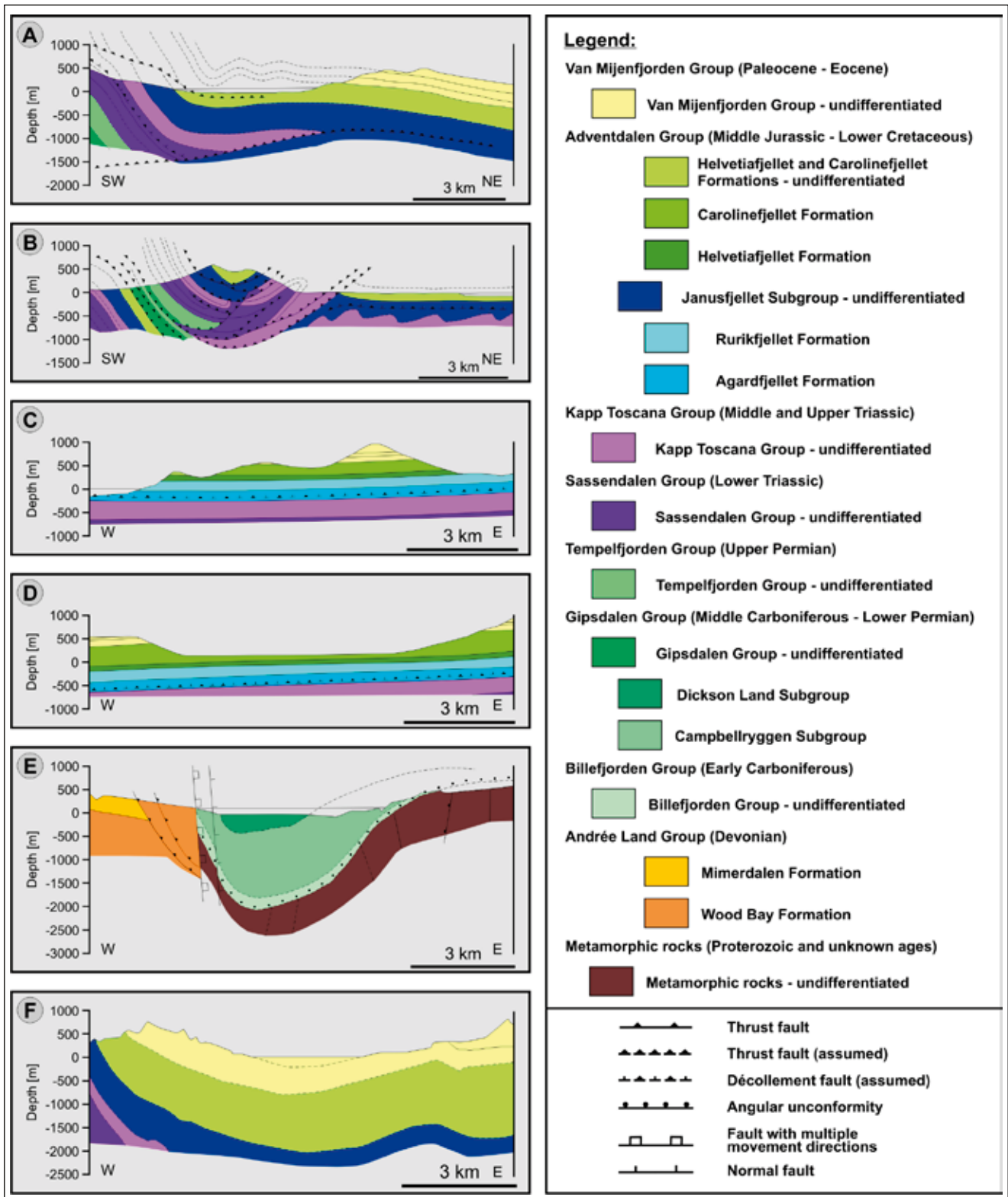


Figure 7: Geological profiles (for locations see Fig. 2). A) Profile across Grøn fjorden (modified after Ohta et al. 1992). B) Profile north of Ymerbukta (modified after Ohta et al. 1992). C, D) Profiles north and southeast of Adventfjorden (modified after Major et al. 2001). E) Profile across Billefjorden (modified after Dallmann et al. 2002). F) Profile across the southern parts of van Keulen fjorden (modified after Dallmann et al. 2002).

sediments. However, we suggest that the formation of the *pockmark strings* in the grooves is related to differential sealing of the till in the glacial lineations. Gas could most probably migrate more easily through the thinner till in the grooves than through thicker till composing the ridges in between.

5.3 Time of activity

We suggest that the sharply outlined, fresh-looking pockmarks on the swath-bathymetry data have formed recently or that they have been active at relatively recent times, i.e. that their shape has not been modified or smoothed by overlying sediments and/or water currents. The increasing inclination of the reflections with decreasing depth shown on the examples from Adventfjorden (Fig. 5F) and Grønfjorden (Fig. 3G) suggest that fine-grained sediments were expelled and removed from the pockmarks temporarily, resulting in gradually steeper side walls over time. This indicates that the formation of these particular pockmarks started some time ago and that they have been active since then. We therefore regard them as *persistent pockmarks* (cf. Pickrill 1993). Some *persistent pockmarks* in Grønfjorden are

rooted in the deformation till of Younger Dryas age (Fig. 3F, G; Forwick & Vorren 2005A), indicating that their formation started shortly after the deglaciation of Grønfjorden c. 11,300 years ago. Whether they have been continuously or intermittently active cannot be determined from our data.

The less sharp appearance of other pockmarks on the swath-bathymetry data (Figs. 3B, 4B, 5B, 6B) is most probably the result of infill and smoothing by overlying sediments. This is supported by the decreasing inclinations of the acoustic reflections in the examples from Ymerbukta (Fig. 4D) and Billefjorden (Fig. 6F). It indicates that these pockmarks have been inactive for a longer period and we regard them therefore as *relict pockmarks* (Josenhans et al. 1978).

5.4 Conceptual model

Based on our results and published data (Ottesen et al. 2008), we propose a conceptual model for the distribution and origin/formation mechanisms for pockmarks in subpolar fjords (Fig. 8).

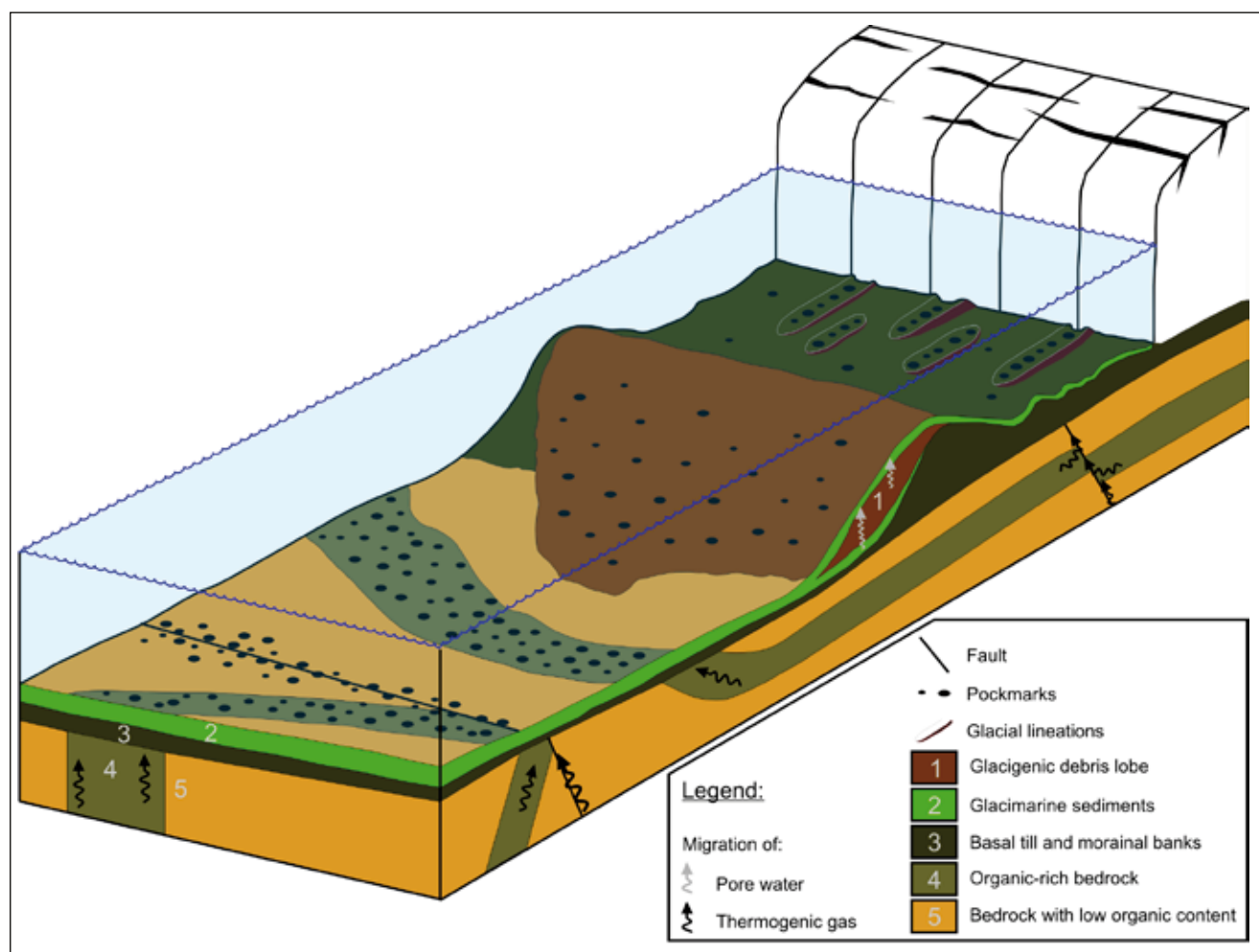


Figure 8: Conceptual model for the origin and distribution of pockmarks in subpolar fjords.

Pockmarks occur as single features, *composite pockmarks*, in *pockmark strings* or as *pockmark troughs*. Their formation is related to the seepage of thermogenic gas (this study), and the seepage of porewater through debris lobes (Ottesen et al. 2008).

The lateral distribution of the pockmarks is controlled by various geological factors including their occurrence in relation to faults/fault zones which in turn act as migration paths for gas, as, for example, in Grønfjorden, Ymerbukta and Billefjorden (Figs. 7A, B, C). The random occurrence of pockmarks in these areas (Figs. 3B, 4B, 6B) may indicate that the fault zones are not very sharply defined and/or that fluid migration has changed from focussed flow within the structural lineaments to more diffuse flow in the soft sediments (compare with Van Rensbergen et al. 2007).

Pockmark formation can also be controlled by sub-cropping bedrock geology, i.e. that gas can be expelled directly from organic-rich bedrock into the soft sediments of the seafloor, as for example, in Adventfjorden (Figs. 5B, 7C).

Pockmark strings occur in grooves of glacial lineations in Billefjorden (Fig. 6B). This indicates that gas can probably migrate more easily through a thinner cover of till. The orientation of glacial lineations is therefore regarded as an important factor for pre-determining the orientation of *pockmark strings* in subpolar fjords.

The absence of pockmarks in the inner parts of Adventfjorden, where the highest sedimentation rates in the Isfjorden area occur (Forwick & Vorren 2005B), indicates that sedimentation rates from tidewater glaciers and rivers in these subpolar fjords are generally not sufficiently high to cause the formation of pockmarks. However, Ottesen et al. (2008) describe up to 80 m wide and maximum 4 m deep circular depressions with raised rims from the surface of a debris lobe in van Keulenfjorden that was deposited at the termination of a glacial surge in the late 19th century (Fig. 2B). They suggest that these features are surface expressions of dewatering features that formed by upwelling porewater from underlying porous marine sediments. We support this formational mechanism, because 1) the lateral distribution of these pockmarks is limited to the extent of the debris lobe, and 2) neither intense deformation nor sub-cropping organic-rich bedrock that could promote the migration of gas occur in the area (Figs. 2A, 7F). This indicates that events of exceptionally high sediment deposition related to glacial surges can lead to the formation of pockmarks in subpolar fjords.

6. Conclusions

- Up to 250 m wide and maximum 13 m deep pockmarks occur in Ymerbukta, Grønfjorden, Adventfjorden, Billefjorden and van Keulenfjorden, Spitsbergen.
- They occur as single circular and elliptical pockmarks, *composite pockmarks*, *pockmark strings* and *pockmark troughs*.
- The formation of the pockmarks is caused by the seepage of thermogenic gas and the migration of porewater.
- *Persistent pockmarks*, as well as *relict pockmarks* also occur in these fjords. Pockmark formation in Grønfjorden has taken place since the deglaciation of the fjord c. 11,300 years ago.
- The distribution of pockmarks in these subpolar fjords depends on tectonic controls (orientation of faults), the sub-outcropping of organic-rich bedrock, the orientation of glacial lineations and exceptionally rapid deposition of debris lobes related to glacial surges.

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References

- Baeten, N.J., Forwick, M., Vogt, C., Vorren, T.O.: Late Weichselian and Holocene sedimentary environments and glacial activity in Billefjorden, Svalbard. Submitted to: Howe, J.A., Austin, W.E.N., Forwick, M. & Paetzel, M. (eds.): *Fjords: Depositional Systems and Archives*. *Geological Society of London, Special Publication*.
- Chand, S., Mienert, J., Andreassen, K., Knies, J., Plassen, L. & Fotland, B. 2008: Gas hydrate stability zone modeling in areas of salt tectonics and pockmarks of the Barents Sea suggest an active hydrocarbon venting system. *Marine and Petroleum Geology* 25, 625-636.
- Dallmann, W.K. (ed.) 1999. Lithostratigraphic Lexicon of Svalbard. Upper Palaeozoic to Quaternary bedrock. Review and recommendations for nomenclature use. Committee on the Stratigraphy of Svalbard / Norsk Polarinstittutt, Tromsø, 318 pp.
- Dallmann, W.K., Kjærenet, T. & Nøttvedt, A. 2001: Geological Map of Svalbard 1:100,000, sheet C9G Adventdalen – text. Norsk Polarinstittutt Temakart Nr. 31/32.
- Dallmann, W.K., Ohta, Y., Elvevold, S. & Blomeier, D. 2002: Bedrock map of Svalbard and Jan Mayen. Norsk Polarinstittutt Temakart No. 33.
- Dallmann, W.K., Piepjohn, K. & Blomeier, D. 2004: Geological map of Billefjorden, Central Spitsbergen, Svalbard – with geological excursion guide. Norsk Polarinstittutt Temakart 36.
- Elverhøi, A. 1984: Glacigenic and associated marine sediments in the Weddell Sea, fjords of Spitsbergen and the Barents Sea: a review. *Marine Geology* 57, 53-88.
- Fader, G.B.J. 1991: Gas-related sedimentary features from the eastern Canadian continental shelf. *Continental Shelf Research* 11, 1123-1153.

- Forwick, M. 2005. Cruise report – marine-geological cruise to west Spitsbergen fjords on R/V Jan Mayen, July 29th – August 2nd 2005. Unpublished report, University of Tromsø, 21 pp.
- Forwick, M. & Vorren, T.O. 2005A: Late Weichselian deglaciation history of the Isfjorden area, Spitsbergen. *In*: Forwick, M. (ed.): Sedimentary processes and palaeoenvironments in Spitsbergen fjords, Dr. Scient. Thesis, University of Tromsø.
- Forwick, M. & Vorren, T.O. 2005B: Late Weichselian and Holocene sedimentation and environments in the Isfjorden area, Spitsbergen. *In*: Forwick, M. (ed.): Sedimentary processes and palaeoenvironments in Spitsbergen fjords, Dr. Scient. Thesis, University of Tromsø.
- Forwick, M. & Vorren, T.O. 2007. Holocene mass-transport activity and climate in outer Isfjorden, Spitsbergen: marine and subsurface evidence. *The Holocene* 17, 707-716.
- Gay, A., Lopez, M., Berndt, C. & Séranne, M. 2007: Geological controls on focused fluid flow associated with seafloor seeps in the Lower Congo Basin. *Marine Geology* 244, 68-92.
- Gay, A., Lopez, M., Cochonat, P., Sultan, N., Cauquil, E. & Brigaud, F. 2003: Sinuous pockmark belt as indicator of a shallow buried turbiditic channel on the lower slope of the Congo basin, West African margin. *In*: Van Rensbergen, P., Hillis, R.R., Maltman, A.J. & Morley, C.K. (eds.): *Subsurface Sediment Mobilization*, 173-189. *Geological Society of London, Special Publication* 216.
- Hagen, J.O., Liestøl, O., Roland, E. & Jørgensen, T. 1993: Glacier atlas of Svalbard and Jan Mayen. Norsk Polarinstitutt Meddelelser 129, 141 pp.
- Harrington, P.K. 1985: Formation of Pockmarks by Pore-Water Escape. *Geo-Marine Letters* 5, 193-197.
- Hovland, M. & Judd, A.G. 1988: Seabed Pockmarks and Seepages: Impact on Geology, Biology and the Marine Environment. Graham & Trotman Ltd., London, 293 pp.
- Hovland, M., Gardner, J.V. & Judd, A.G. 2002: The significance of pockmarks to understanding fluid flow processes and geohazards. *Geofluids* 2, 127-136.
- Howe, J.A., Moreton, S.G., Morri, C. & Morris, P. 2003: Multibeam bathymetry and the depositional environments of Kongsfjorden and Krossfjorden, western Spitsbergen, Svalbard. *Polar Research* 22, 301-316.
- Josenhans, H.W., King, L.H. & Fader, G.B. 1978: A side-scan sonar mosaic of pockmarks on the Scotian Shelf. *Canadian Journal of Earth Sciences* 15, 831-840.
- Judd, A., Long, D. & Sankey, M. 1994: Pockmark formation and activity, U.K. block 15/25, North Sea. *Bulletin of the Geological Society of Denmark* 41, 34-49.
- Judd, A.G. & Hovland, M. 2007: Seabed Fluid Flow: The Impact on Geology, Biology and the Marine Environment. Cambridge University Press, Cambridge, 475 pp.
- Kelley, J.T., Dickson, S.M., Belknap, D.F., Barnhardt, W.A. & Henderson, M. 1994: Giant sea-bed pockmarks: Evidence for gas escape from Belfast Bay, Maine. *Geology* 22, 59-62.
- King, L. & MacLean, B. 1970: Pockmarks on the Scotian Shelf. *Geological Society of America Bulletin* 81, 3141-3148.
- Knies, J., Damm, E., Gutt, J., Mann, U. and Pinturier, L. 2004: Near-surface hydrocarbon anomalies in shelf sediments off Spitsbergen: Evidences for past seepages. *Geochemistry, Geophysics, Geosystems* 5, Q06003, doi:10.1029/2003GC000687.
- Lastras, G., Canals, M., Urgeles, R., Hughes-Clarke, J.E. & Acosta, J. 2004: Shallow slides and pockmark swarms in the Eivissa Channel, western Mediterranean Sea. *Sedimentology* 51, 837-850.
- Liestøl, O. 1980: Permafrost conditions in Spitsbergen. *Frost i jord* 21, 23-28.
- Loncke, L., Masclé, J. & Fanil Scientific Parties 2004: Mud volcanoes, gas chimneys, pockmarks and mounds in the Nile deep-sea fan (Eastern Mediterranean): geophysical evidences. *Marine and Petroleum Geology* 21, 669-689.
- Long, D. 1992: Devensian Late-glacial gas escape in the central North Sea. *Continental Shelf Research* 12, 1097-1110.
- Major, H., Haremo, P., Dallmann, W.K. & Andresen, A. 2001: Geological Map of Svalbard 1:100,000, sheet C9G – map. Norsk Polarinstitutt Temakart Nr. 31/32.
- Ohta, Y., Hjelle, A., Andresen, A., Dallmann, W.K. & Salvigsen, O. 1992: Geological Map Svalbard 1:100,000, sheet B9G Isfjorden. Norsk Polarinstitutt Temakart Nr. 16.
- Ottesen, D., Dowdeswell, J.A., Benn, D.I., Kristensen, L., Christiansen, H.H., Christensen, O., Hansen, L., Lebesbye, E., Forwick, M. & Vorren, T.O. 2008: Submarine landforms characteristic of glacier surges in two Spitsbergen fjords. *Quaternary Science Reviews* 27, 1583-1599.
- Paull, C., Ussler III, W., Maher, N., Greene, H.G., Rehder, G., Lorenson, T. & Lee, H. 2002: Pockmarks off Big Sur, California. *Marine Geology* 181, 323-335.
- Paull, C.K., Ussler III, W. & Borowski, W.S. 1999: Freshwater ice rafting: an additional mechanism for the formation of some high-latitude pockmarks. *Geo-Marine Letters* 19, 164-168.
- Pickrill, R.A. 1993: Shallow seismic stratigraphy and pockmarks of a hydrothermally influenced lake, Lake Rotoiti, New Zealand. *Sedimentology* 40, 813-828.
- Pilcher, R. & Argent, J. 2007: Mega-pockmarks and linear pockmark trains on the West African continental margin. *Marine Geology* 244, 15-32.
- Piper, D.J.W., Cochonat, P. & Morrison, M.L. 1999: The sequence of events around the epicenter of the 1929 Grand Banks earthquake: initiation of debris flows and turbidity current inferred from side-scan sonar. *Sedimentology* 46, 79-97.
- Plassen, L. & Vorren, T.O. 2003: Fluid flow features in fjord-fill deposits, Ullsfjorden, North Norway. *Norwegian Journal of Geology* 83, 37-42.
- Rogers, J.N., Kelley, J.T., Belknap, D.F., Gontz, A. & Barnhardt, W.A. 2006: Shallow-water pockmark formation in temperate estuaries: A consideration of origins in the western gulf of Maine with special focus on Belfast Bay. *Marine Geology* 225, 45-62.
- Solheim, A. & Elverhøi, A. 1985: A pockmark field in the Central Barents Sea; gas from a petrogenic source? *Polar Research* 3, 11-19.
- Solheim, A. & Elverhøi, A. 1993: Gas-related sea floor craters in the Barents Sea. *Geo-Marine Letters* 13, 235-243.
- Syvitski, J.P.M. 1997: Water-Escape Sea Floor Depressions. *In*: Davies, T.A., Bell, T., Cooper, A.K., Josenhans, H., Polyak, L., Solheim, A., Stoker, M.S. & Stravers, J.A. (eds.): *Glaciated Continental Margins – An Atlas of Acoustic Images*, 160-161. Chapman & Hall, London.
- Van Rensbergen, P., Rabaute, A., Colpaert, A., Chislain, T. St., Mathijs, M. & Bruggeman, A. 2007: Fluid migration and fluid seepage in the Connemara Field, Porcupine Basin interpreted from industrial 3D seismic and well data combined with high-resolution site survey data. *International Journal of Earth Sciences* 96, 185-197.
- Vogt, P.R., Gardner, J., Crane, K., Sundvor, E., Bowles, F. & Cherkashev, G. 1999: Ground-truthing 11- to 12-kHz side-scan sonar imagery in the Norwegian-Greenland Sea: Part I: Pockmarks on the Vestnesa Ridge and Storegga slide margin. *Geo-Marine Letters* 19, 97-110.