Acoustic evidence for a gas migration and release system in Arctic glaciated continental margins offshore NW-Svalbard

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High-resolution 3D and 2D seismic data offshore NW-Svalbard, west of Prins Karls Forland, provide geophysical evidence for geologically controlled fluid migration pathways, gas hydrate occurrence, and an active seabed gas expulsion system. The investigated seabed area covers ~1600 km² and lies between Kongsfjorden cross-shelf trough in the north and Liefdefjorden cross-shelf trough in the south ranging in water depths from ~200 m on the shelf to 800 m on the upper continental slope. Acoustic evidence for present day methane release from the seafloor to the water column comes from more than 220 gas flares at the outer shelf while past methane release activity at the mid-shelf area is evident from pockmarks without flares. The fluid migration pathways towards the seafloor can be drawn from sub-seafloor acoustic anomalies. Fluid migration towards the upper slope occurs mostly along strata in upslope direction and largely prevails over vertical focused migration. Fluids accumulate in the uppermost part of the slope just westward of the shelf break, where they are trapped beneath the prograding glacigenic sequence, which is not permeable enough for fluids to migrate through. Fluids are expelled on the shelf where the base of the glacigenic sequence outcrops. Some gas-charged flares may originate from deep-seated hydrocarbon reservoirs and can be temporally stored in gas hydrates in the shallow subsurface. Though evidence for hydrates on the uppermost slope is missing the seismic data from the lower slope clearly suggest the occurrence of gas hydrate.

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1. Introduction

Focused sub-seafloor fluid flow is a widespread phenomenon in continental margins worldwide (e.g. Berndt, 2005). Here, methane may migrate as free gas through permeable sediments often following lateral extensions of strata boundaries or vertical extension of faults. In shallower water, such as the North or Barents Sea, the release of methane from the seafloor has the potential to enter the atmosphere (Rehder et al., 1998; Reshetnikov et al., 2000) where it is 25 times more effective than the same amount of the greenhouse gas CO₂ (Lelieveld et al., 1993).

In the sub-seafloor methane can form hydrate, an ice-like crystalline solid, formed from water molecules and natural gas mainly methane under low temperature and high pressure condition (Sloan, 1998). The zone where gas hydrates are stable is known as gas hydrate stability zone (GHSZ) (Sloan, 1998). An increase in ocean bottom temperature can cause gas hydrate to dissociate (e.g. Jung and Vogt, 2004; Mienert et al., 2005; Vogt and Jung, 2002) and might release free gas (gas bubbles) into the water column. Offshore NW-Svalbard, such gas releases are widely observed (e.g. Hustoft et al., 2009; Knies et al., 2004; Westbrook et al., 2009), though, a direct link to gas hydrate dissociation has yet to be proven.

Identifying and quantifying the gas hydrate reservoirs, the potential methane release from the reservoir and the state of their current stability in the prevailing condition of global warming is therefore crucial for understanding their potential impact on climate change. Global warming is particularly evident in the Nordic Seas and the Arctic where climate change appears to take place more rapidly than previously predicted by ocean warming models (e.g. Graversen et al., 2008).

Rising methane bubbles from the seafloor have been detected by various acoustic systems (Greinert et al., 2006). Flares discovered in the water column along the shelf and slope of NW-Svalbard corroborate the active release of methane from the seabed (Hustoft et al., 2009; Knies et al., 2004; Westbrook et al., 2009). Gas analysis from water samples along the SW and NW-Svalbard shelf suggests higher amount of methane concentrations in the water column that are elevated with respect to background concentration.
Traces of thermogenic gas in sediments offshore NW-Svalbard suggest emanations from hydrocarbon prolific provinces in deeper sediment formations (Knies et al., 2004). Westbrook et al. (2009) hypothesize that gas originates from dissociating gas hydrates as a consequence of ocean warming.

It appears that lithological variations, e.g. the transition from hemipelagic sediments to glacigenic debris flows (GDF), has an effect on gas hydrate formation (Bünz et al., 2003). Observations from the major gas hydrate field of the mid Norwegian margin north of the giant Storegga submarine slide (Bryн et al., 2005; Haffladason et al., 2004; Mienert et al., 2005) show that the GDF may hinder gas hydrate growth because it clearly interrupts a continuous bottom simulating reflector at the base of the GHSZ (Bünz et al., 2003). However, gas hydrates may also exist without a BSR as documented by Blake Ridge drilling results (e.g. Holbrook et al., 2002).

The main objective of this study is to enhance our understanding of fluid flow pathways in the gas-hydrate prone Arctic continental margins offshore NW-Svalbard. A research cruise on R/V Jan Mayen in July 2009 provided a high-resolution 3D-P-Cable seismic data set, 2D seismic data, swath bathymetry data and CTD casts to investigate the distribution of gas hydrates indicated by a bottom simulating reflector (BSR) in relation to fluid flow pathways (enhanced seismic anomalies) and methane release from the seabed (pockmarks, flares).

2. Geological settings

The working area offshore NW-Svalbard lies west of Prins Karls Forland and extends from ~200 m water depth at the shelf to 800 m on the upper continental slope (Fig. 1a–b). The area investigated covers approx. 1600 km². The Svalbard continental margin formed as a result of several rifting episodes in the Late Paleocene/Early Eocene, continental breakup and the development of the Norwegian-Greenland Sea (Sundvor and Austegard, 1990). During the Pleistocene ice ages, ice streams carved cross-shelf troughs into the existing sediment formations (Ottesen et al., 2007). As a result Kongsfjorden in the north and Isfjorden in the south of Prins Karls Forland connect through deep troughs to the shelf break. The fast flowing ice streams caused major erosion on the shelf and sediment transport and deposition in prograding glacigenic sequences (e.g. Laberg and Vorren, 1995; Sættem et al., 1992; Solheim et al., 1998) on the adjacent continental slopes building up the glaciated margin. Glacigenic debris flows (GDF) originated during peak glaciations by sediment release along ice stream fronts at the shelf.
break (e.g. Laberg and Vorren, 1995). Trough mouth fans on the continental slope are the result of these glacier driven sedimentary processes (e.g. Sarkar et al., 2011; Vorren et al., 1998).

The western Svalbard shelf reflects the glacial sedimentary evolution of the margin during the Plio-Pleistocene (Solheim et al., 1998). Glacigenic sediments primarily built the outer shelf of western Svalbard. Highly compacted till deposits are generally absent within the troughs on the inner shelf but they are abundant on the shelf bank areas (Andersson et al., 2000). A previous high-resolution study by Landvik et al. (2005) from the area west of Prins Karls Forland shows a glacigenic unit crossing the Forlandet Moraine Complex and a pronounced ridge in the western part, which was interpreted as a terminal moraine. The lithostratigraphy comprises a matrix-supported diamiction unit interpreted as subglacial till deposited by a grounded glacier (Landvik et al., 2005).

In addition to characteristic glacial sediment formations such as prograding glacigenic sequences, till sediments on shelf banks and debris flows at the continental slope the study area is highly influenced by the West Spitsbergen Current (WSC), a shallow northward flowing warm water branch of the North Atlantic Current (e.g. Slubowska-Woldengen et al., 2007; Spielhagen et al., 2011), which transports heat into the Arctic Ocean. The northward flowing warm current is responsible for maintaining mean annual temperatures around 10°C higher than locations at similar latitudes, e.g. Arctic Canada (e.g. Slubowska-Woldengen et al., 2007).

Westbrook et al. (2009) suggest that the warming of the WSC during the last 30 years reduced the size of the gas hydrate stability zone (GHSZ) at the uppermost continental slope and outer shelf area, leading to the dissociation of gas hydrate and the annual release of ~900 kg of methane per meter length of the margin. It is notable that the area was subjected to a number of oceanographic temperature increases and decreases during the past 17,500 years, as reported by shallow sediment core analysis (Slubowska-Woldengen et al., 2007).

3. Data and methods

3.1. Multi-beam bathymetry data for seabed mapping

Swath bathymetry data (Fig. 1b) were acquired using the Kongsberg Simrad EM-300 system (R/V Jan Mayen, July 2009 and previous RV Jan Mayen cruises; Hustoft et al., 2009). The multibeam system operates at a sonar frequency of 30 kHz with an angular coverage sector of up to 150°. Multibeam data were processed using Neptune software. Gridding and imaging of the acquired data were done using GMT software. Sound velocity profiles for calibration of beams in the water column were extracted from nine CTD stations acquired during the survey and processed using “SBE Data processing”.

3.2. CTD stations for oceanography

Nine CTD casts at 164 m, 193 m, 235 m, 365 m, 423 m, 445 m, 520 m, 616 m and 800 m water depths from Forlandbanken towards the continental slope provided temperature and salinity versus depth measurements (Fig. 2). Furthermore, the use of AWI’s Ocean Data View software (Schlitzer, 2008) allowed to compile and integrate the CTD data into transects for identifying the water masses in the study area (Fig. 2).

Figure 2. CTD station integrated into 2D seismic profile line 009 illustrate the presence of the warm northward flowing Atlantic water marked as West Spitsbergen Current (WSC). A cold current, the East Spitsbergen Current (ESC) flows also northward along the coast and lies east of the WSC. The 2D seismic profile 009 indicates the sub-seabed seismic stratigraphic sequences, the glacial debris flow (GDF) deposits, acoustic blanking, acoustic pipe and enhanced seismic reflection amplitudes (ER). The stippled line shows the modeled and projected gas hydrate stability zone (GHSZ).
3.3. Echo sounder system (EK60) for acoustic flare (bubble) detection in the water column

The Simrad EK60 scientific echo sounder system is designed for fishery research, yet it represents a useful instrument for measuring ocean water density contrasts including objects in the water. The system installed on R/V Jan Mayen consists of a split beam transducer at three different operating frequencies: 18, 38 and 120 kHz. During the survey the equipment was used to detect gas bubble streams in form of acoustic flares using 38 kHz and 120 kHz frequencies. An acoustic flare indicates release of free gas in form of bubbles from the seafloor and it is a first order remote proof for active gas seepage at the respective site (Greinert, 2008). The basic principle for detecting bubbles with an echo sounder is the strong backscattering of the transmitted pressure wave at distinct impedance contrasts between water and gas bubbles. It creates characteristic flare-shaped backscatter features in echograms (Greinert et al., 2006). The visualization of the recovered data was done with the Echoview software and mapped with GMT (Wessel and Smith, 1998). For a better overview of the different seeps, three groups of flares have been used in a map as a cluster according to their flare height. Group 1 contains all flares which are 270–180 m high, group 2 comprises flares from 180 to 90 m high and finally group 3 are the smallest flares with a height range from 90 to 20 m.

3.4. High-resolution 3D-P Cable seismic data for imaging sub-seabed/sub-seabed seismic architecture and attributes

The University of Tromsø’s high-resolution 3D seismic acquisition system (P-Cable) consists of up to 20 streamers, each 25 m long with 8 recording channels (Petersen et al., 2010). In 2009, the survey was carried out with 12 streamers together with a Granzow high pressure (140 bar) compressor that provided the pressure for one GI gun with a total volume of 150 in\(^3\) (\(G = 45 \text{ in}^3\) and \(I = 105 \text{ in}^3\)) shot at a rate of 5 s. The 3D seismic cube covers an area of 6.1 km × 1.41 km (Fig. 1c).

Data processing was done using the RadExPro 3.96 software package and consisted of navigational correction, binning, static and tidal correction, bandpass filtering (35–300 Hz), amplitude correction, trace editing, normal move out, 3D stack and 3D stolt migration (velocity 1500 m/s). Two seismic attribute maps (RMS amplitude and Variance attribute) were produced using Petrel 2010 interpretation software. The RMS amplitude map indicates elevated gas concentrations or geological features with increased amplitude response. The Variance attribute map measures the dissimilarity between adjacent seismic traces, and can enhance structural features such as faults but it also can enhance for example depositional/erosional features such as channels (Bemmel et al., 2000; Chopra and Marfurt, 2007).

3.5. 2D seismic data for imaging sub-seabed structures

Four regional 2D seismic lines are used to complement the 3D seismic data (Fig. 1b). 2D single channel reflection seismic data across the margin off Prins Karls Forland were acquired using the same GI gun system and a single channel streamer. A DelphSeismic system was used to record the 2D single channel seismic data. Data processing included bandpass filtering (35–300 Hz), trace editing, muting and stolt migration (velocity 1500 m/s).

3.6. Modeling of the base of the gas hydrate stability zone (BGHSZ)

In this study we modeled the GHSZ thickness using site specific parameters and the methods explained by Sloan (1990). The specific parameters of the study area encompass water depth (pressure) derived from the bathymetry, bottom water temperature derived from CTD measurements (Figs. 1 and 2), geothermal gradients derived from Vanneste et al. (2005) and observed BSR depth, pore water salinity from fresh to seawater and gas compositions from pure methane to heavier carbon contributions. The results demonstrate how changes in the parameters impact on the calculated thickness of the GHSZ.

The Svalbard-Barents Sea seabed lies close to the gas hydrate stability zone which makes it particularly sensitive to changes in sea level and bottom water temperature (e.g. Chand et al., 2008; Mienert and Posewang, 1999; Mienert et al., 2005). Often, one assumes a constant geothermal gradient for a region, and the gas hydrate stability modeling is carried out accordingly. However, observations from the Gulf of Mexico (Ruppel et al., 2005) and the Barents Sea (Bugge et al., 2002) suggest that the geothermal gradient can be highly variable due to changes in the underlying sediment formations.

The average geothermal gradient observed in NW-Svalbard region is ~70 °C/km (e.g. Hustoft et al., 2009; Vanneste et al., 2005). We estimated the geothermal gradient from a clearly observable BSR and found the geothermal gradient to be 55 °C/km with an inferred decrease towards the upper slope to 44 °C/km. Different water masses control the bottom water temperatures at the study area showing a major boundary between cold water from the eastern Svalbard margin occupying the shelf and the warm water from the Atlantic influencing the upper water column across the continental slope (Fig. 2). The bottom water temperature in the study area varies from 1 °C at the lower continental slope at ~700 m water depth to 3.5 °C close to the shelf edge at ~250 m water depth (Fig. 2). We choose an average bottom water temperature of 3.3 °C for the gas hydrate stability modeling since most of the seabed is bathed in such temperature.

The calculations of the gas hydrate stability curve (Sloan, 1990) and the implementation for areal prediction (Chand et al., 2008) allowed estimating BSR depths for different gas composition and salinities. Carbon isotope studies from the NW-Svalbard region show that higher order hydrocarbons in bottom waters occur preferably in the vicinity of active seepage sites on the shelf (Knies et al., 2004). Hence, we modeled the GHGZ within the study area for both pure methane structure I hydrates and structure II hydrates with small amounts (4%) of higher order hydrocarbon (propane, ethane) (Appendix, Fig A.1). To estimate the BSR depth from seismic data we used an average sediment velocity of 1630 m/s (Vanneste et al., 2005) from the seabed to the observed BSR and an average velocity of 1450 m/s in the water column above. The modeled BGHSZ was plotted on the 2D and high-resolution 3D seismic dataset using the geothermal gradient (55 °C/km) and BWT (3.3 °C).

4. Results and observations

4.1. Stratigraphic interpretation and seismic anomalies

4.1.1. High-resolution 3D seismic reflection data

In general, 3D seismic data (Fig. 3a) show increasing acoustic penetrations from the shelf to the upper slope due to decreasing acoustic attenuation. The decreases in amplitude may be partly due to the less compacted sediments further downslope (i.e. at distal areas from the former ice sheet margin) and comparatively lower gas content in the pore space of sediments. At the Svalbard shelf seaward dipping reflectors are visible (Fig. 3a). They mark seismic sequences and can be divided into six units (Fig. 3a) based on higher seismic amplitudes at the sequence boundaries, the seismic character such as internal seismic reflection pattern, and the overall shape of the adjacent units so that they become distinctive.
They are interpreted to be prograding glacigenic sequences, deposited in front of an advancing ice sheet (e.g. Vanneste et al., 2007). The six prograding glacigenic sequences I (youngest) to VI (oldest) (Fig. 3a) suggest major glacier advances at the Svalbard continental margin at peak glaciations during the last 3.2 million years (Dowdeswell and Elverhøi, 2002; Elverhøi et al., 1995; Landvik et al., 1998; Sarkar et al., 2011). Sedimentary sequences IV and VI may correspond to ages ~1.5–1.0 Ma and ~2.8 Ma respectively (e.g. Sarkar et al., 2011). The sequences indicate significant shelf progradations (Fig. 3a) building the continental margin westward by several tens of kilometers. Downslope, the sequences are thinning, poorly stratified and discontinuous with semi-transparent to opaque reflections (Fig. 3a). Chaotic, lens-shaped seismic features are noticeable in the prograding glacigenic sequences II, V and VI, which show internally chaotic reflection pattern enveloped by high amplitude reflections.

Figure 3. (a) High-resolution 3D P-Cable seismic data (inline 56) shows prograding glacigenic sequences at the shelf, a major GDF, enhance seismic reflection amplitude (ER) beneath the GDF and a phase reversal within the well-stratified seismic reflector sequence at the continental slope. The phase reversal occurs at 0.67 TWT. The interpreted sedimentary sequences I (youngest)–VI (oldest) are marked along the seismic profile. The stippled line shows the modeled GHSZ. The green box in the seismic section indicates the high RMS amplitude area in the region of phase reversal (black rectangular box). (b) The RMS amplitude map extracted from a search window of 10 ms at the area of enhanced reflections and a phase reversal.
(Fig. 3a). The wedges are thinning towards the west (continental slope) (Fig. 3a). Enhanced seismic reflection anomalies (ER) are observed at the upper continental slope below the base of the prograding glacigenic sequence I encompassing the GDF (Fig. 3a). Glacigenic sequence I consists mainly of a major GDF deposit that is acoustically defined by a chaotic and partly transparent seismic character (Hjelstuen et al., 2004). Enhanced seismic reflection anomalies and a phase reversal at 0.67 s TWT over a lateral distance of ~ 1 km suggest a potential gas accumulation area (Fig. 3a). The 3D seismic profile does not show evidence for a BSR within the GDF deposits or beneath them (Fig. 3a) indicating that gas hydrate might be lacking in the area covered by the 3D seismic data at the upper slope of the W-Svalbard continental margin.

The RMS attribute map (Fig. 3b) derived from a time window of 10 ms centered around the horizon (phase reversal marked as blue line in Fig. 3a) shows the distribution of the high amplitude anomalies in the region of the polarity reversal indicating gas accumulation at the lower continental slope.

The volume (a short window of 15 ms) attribute map of variance at a depth of ~750 ms TWT shows a number of north-south trending lineations (Fig. 4). In accordance with interpretations elsewhere (Chopra and Marfurt, 2007) these spatially coherent lineations indicate the presence of small-offset faults. The faults interrupt the well-stratified seismic reflection pattern in the upper continental slope, though they are more difficult to identify on the 3D seismic profile in Figure 4. The faults occur at depths below the gas hydrate stability zone (GHSZ), but the data does not allow us to determine the depth to which they extend.

The RMS amplitude map of the seabed extracted from a time window of 10 ms clearly shows high amplitude anomalies suggesting gas accumulation and migration at the upper slope and shelf area (Fig. 5a). The amplitudes relate to the numerous enhanced reflections (ER) and the phase reversal observed in the high-resolution 3D seismic data (Fig. 3a). Negative relief features, interpreted as pockmarks are also observed in the RMS amplitude map for the seabed (Fig. 5a). The variance surface map of the seabed calculated from a time window of 10 ms clearly indicate the crop out zone of the glacigenic sequence I boundary (Fig. 5b), which coincides well with the flare locations mapped on the shelf (Fig. 1b). Most of the flares are concentrated along the glacigenic sequence I outcrop zone whereas only a few flares are scattered within close vicinity.

4.1.2. 2D seismic reflection data

2D seismic data (Fig. 1b) encompass part of the shelf that lies immediately south of the Kongsfjorden cross-shelf trough, the shelf break and part of the upper continental slope (Fig. 1a and b). All 2D seismic profiles (line-002, line-008, line-009 and line-011) show acoustic transparent and/or chaotic sub-seabed reflections from the Kongsfjorden cross-shelf trough over a distance of ~4 km beyond the shelf break followed by well-stratified seismic sequences downslope (Figs. 2, 6–8). The modeled GHSZ depth is projected on the seismic data (Figs. 2, 7 and 8).

2D seismic line-002 (see Fig. 1b for location) runs from north to south crossing a shelf bank (Fig. 6). High amplitude reflections are visible at ~50 ms TWT below the seabed indicating the possible presence of shallow gas or sediment facies changes causing enhanced acoustic impedance contrasts. Below the enhanced reflections a distinct acoustic turbidity zone exists (Fig. 6).

2D seismic line-008 (see Fig. 1b for location) has a length of approx. 32 km (Fig. 7). The subsurface strata shows fairly well-stratified units beyond the shelf break (Fig. 7). At the western end of the seismic line a high amplitude reflection at ~240 ms TWT below the seafloor cuts across the strata and mimics the seafloor. This high amplitude reflection matches well with the predicted depth of the base of the GHSZ. Beneath the BGHSZ indicated by

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**Figure 4.** High-resolution 3D P-Cable (inline 96) shows prograding glacigenic sequences at the shelf, enhanced seismic reflections beneath the GDF and fault zones interrupting stratified seismic reflector sequences in the continental slope. The volume (a short window of 15 ms) attribute map at a depth of ~750 ms TWT highlights the small offsets of the faults below the theoretical GHSZ.
a BSR, a number of enhanced reflections (ER) are visible indicating the presence of appreciable amounts of gas in the sub-seabed (Fig. 7). The BSR cannot be traced further upslope towards the shelf.

A zone of acoustic masking is visible beneath the seabed at approx. 300 ms TWT (Fig. 7). It is either related to the attenuation of seismic energy caused by the overlying ER or the occurrence of gas in the masking zone. The masking zone shows individual occurrences of lens-shaped ER with reversed polarity compared to the seafloor (Fig. 7). The observations suggest that free gas is trapped locally beneath the BSR but also further down at greater depth in areas outside the GHSZ and upper slope where a BSR is absent. Few, more than 260 ms TWT long vertical and seismically transparent features similar to pipes or chimneys exist beneath the seafloor. They are not connected to pockmarks at the seabed (Fig. 7). The transparent pipe structures terminate beneath the seafloor somewhere within the GHSZ.

Seismic profile line-009 (see Fig. 1b for location) (Fig. 2) runs along the centre of the 3D seismic data. The seismic profile is characterized by well-stratified continuous reflections downslope (westward) and prograding glacigenic sequences in the shelf area (Fig. 2). Polarity-reversed and enhanced seismic reflections within an otherwise low amplitude zone approx. 200 mbsf suggest the widespread occurrence of gas (Fig. 2). The seismic data also confirms the presence of a lens-shaped acoustic transparent unit at the seafloor between 5 and 14 km comparable to a low permeable glacigenic debris flow (GDF lobe) (Laberg and Vorren, 1995; Nielsen et al., 2005; Ottesen et al., 2008; Vorren and Laberg, 1997) extending from the shelf break to the upper continental slope.

Figure 5. (a) High-resolution 3D P-Cable RMS amplitude map calculated from a search window of 10 ms integrated with mapped flake locations and pockmarks. High amplitude anomalies indicate shallow gas accumulations. Note that the pockmarks are not associated with flares. Within the pockmark field no evidence from active fluid expulsion was detected during the time of the survey (July 2009). (b) Seafloor variance map extracted from a search window of 10 ms show the crop out zone of the glacigenic sequence 1 boundary. The color dots indicate the flare locations based on 2009 survey.
(Fig. 2). No BSR was observed on this seismic line. However, the predicted base of the GHSZ lies within the GDF and theoretically outcrops at 370 m water depth approx. at the foot of the upper continental slope (Fig. 2). Faults marked by small offsets of high amplitude reflections are clearly visible at the western end of the line (Fig. 2). This observation could indicate migration of fluids along faults similar to previous observations from this area (Hustoft et al., 2009; Vanneste et al., 2005).

2-D seismic profile line-011 (Fig. 8, see Fig. 1b for location) is located ~7 km south of the 3D seismic area and also confirms the presence of a prograding glacigenic sequence comprising GDF deposits in the upper slope area. At the lower slope area, a prominent cross-cutting BSR exists above an area of enhanced seismic amplitudes. The BSR can be traced along the slope at ~190 ms below sea floor between SP 30 and 100 (Fig. 8). Enhanced seismic amplitudes reflections beneath the BSR are probably due to the accumulation of gas while the reflection amplitude just above the BSR is subdued due to gas hydrates (Hustoft et al., 2009). No distinct BSR is observed towards the shelf but several acoustic anomalies (ER) inferred to be caused by shallow gas accumulations can be noticed (Fig. 8). Close to the shelf edge very chaotic seismic reflection patterns occur beneath the GDF deposit and the prograding glacial sequence I to a water depth of approx. 400 m (Fig. 8). This zone of brightened and dimmed amplitude anomalies resemble those of very wide hydrocarbon leakage features (Løseth et al., 2009) and could be a gas cloud.

### 4.2. Vertical acoustic pipes and sub-seabed acoustic anomalies

Geological structures within the area covered by 2D seismic data provide evidence for vertical focused fluid flow. Acoustic pipe and acoustic turbidity areas suggest various forms of vertical gas migration. The presence of gas is characterized by amplitude dimming, amplitude enhancement or complete disruption of reflection as seismic energy gets scattered by gas (Gay et al., 2007; Judd and Hovland, 1992). The most prominent features are the vertical and narrow zones of acoustic wipe out zones with upward bending marginal reflections (Fig. 7). These structures, referred to as acoustic pipes or gas chimneys, are often connected to pockmarks at the present day seafloor (e.g. Hovland and Judd, 1988; Plaza-Faverola et al., 2010). The high-resolution bathymetry from 3D seismic survey shows clearly round to oval depressions (Fig. 9a and b) at the seafloor on the shelf, which are also observed in the 2D seismic profiles on the slope (Figs. 2 and 7). The largest prominent pipe structure within the 3D seismic dataset (Inline-163) on the shelf (Fig. 9a) can be followed down to 0.5 s TWT. This structure shows only high amplitudes directly beneath the seafloor. The diameters of the pipes on the slope vary between 20 and 450 m (Fig. 7). Some pipe structures indicate seismic reflection pull-up by as much as 8–10 ms (Fig. 7) towards their central zone, which progressively decreases with decreasing depth. The depth determination of the base of the acoustic pipe structures are difficult due to poor signal strength with increasing depths. However, the prominent pipe structures in the 2D seismic profiles are traceable down to 1.5 s TWT (Fig. 7).

#### 4.3. BGHSZ (BSR) depth prediction and observed BSR depth distribution

The BGHSZ was modeled for the available 2D and high-resolution 3D dataset using a bottom water temperature of 3.3 °C, a geothermal gradient of 55 °C/km and the pressure (water depth). The predicted BGHSZ for a composition of 100% methane is shown in Figures 2, 7 and 8 and the predicted BSR for 96% methane, 3% ethane, 1% propane is shown in the appendix (Fig. A1). Changes in the salinity from fresh water to sea water resulted in a shoaling of the BGHSZ while a contribution of ethane and propane caused a deepening of the BGHSZ (Fig A1). Noteworthy, the BGHSZ for pure methane and fresh water matches well with the present day observed BSR position. The modeled BGHSZ varies laterally in thickness from ~200 m below the seafloor at the lower continental slope at ~800 m water depth and gradually decreases to a theoretical pinch out zone towards the uppermost continental slope at 370 m water depth (Figs. 2, 7 and 8). The GHSZ extends from the
Vestnesa Ridge, a major sediment drift on young oceanic crust (Fig. 1, Hustoft et al., 2009) to the upper continental slope of the NW-Svalbard continental margin resting on continental crust, thereby linking the gas hydrate field to an area of active fluid escape features on the outer shelf. No BSR has been observed near the shelf or upper slope at the theoretical BGHSZ pinch out zone.

4.4. Seabed fluid flow expressions

The high-resolution bathymetry covers the shelf bank area, 28 km west of Prins-Karls Forland (Fig. 1b). Echosounder information reveals the presence of flares in the water column associated with a vigorous release of gas from sub-seafloor sediments at the outer shelf high (Figs. 5a and 9a-c). However, the flare sites do not have any seafloor expressions (pockmarks) normally associated with the focused expulsion of gas. Approximately 3 km eastward of the flare area, the mid-shelf region shows round to oval depressions interpreted as pockmarks (Fig. 9a and b). Active gas release from these pockmarks is lacking. However, their formation may be caused by past seepage of thermogenic gas as suggested from observations from NW-Svalbard fjords (e.g. Forwick et al., 2009). The pockmarks on the shelf are ~20–30 m deep and ~80–100 m wide (Fig. 9b). Their occurrence on the shelf bank suggests that this area must have experienced active fluid expulsion after the last glaciation.

The flares are the ultimate proof for active fluid venting (Fig. 9c). Figure 1b shows clusters of flares in which more than 220 flares occur (Figs. 5a and 9a-c). The flares are concentrated on the NW-Svalbard continental margin at a water depth of ~253 m. The size or height of the flares varies from 20 m to 270 m where the highest flares may reach the sea surface. The highest concentration of flares lies in the northern area at the outer shelf, clearly outside and east of the pinch out of the projected gas hydrate stability zone (Figs. 2, 6 and 8).
4.5. Ocean water masses across the shelf-slope transect

The temperature transect (Fig. 2) illustrates the presence of warm and saline Atlantic water belonging to WSC at the shelf edge. This water mass is particularly evident in the uppermost 300 m of the water column at the outer shelf area while cold water masses of < 1°C exist below ~600 m water depth at the continental slope (Fig. 2). The oceanographic observations together with seismic evidence for the existence of gas hydrate along the continental slope suggest that the NW-Svalbard margin oceanic gas hydrate fields may be impacted by deep and to a lesser extent by increases in shallow ocean warming.

5. Discussion

High concentrations of methane in the water column offshore Svalbard are most probably caused by the release of sub-seabed methane at seepage sites on the SW-Svalbard shelf (Damm et al., 2005). In the Svalbard shelf and slope area deep-seated hydrocarbon sources (Knies and Mann, 2002), shallow gas hydrates (Hustoft et al., 2009; Posewang and Mienert, 1999; Vogt et al., 1994) and natural seabed seeps (Knies et al., 2004; Solheim and ElverhøI, 1985; Vogt et al., 1999; Westbrook et al., 2009) all may contribute via natural seep processes at still unknown rates over time to elevated dissolved methane concentrations in the water column. Methane gas released from sub-seabed environments as a result of destabilization of gas hydrates due to ocean warming in the last 10–30 years (Westbrook et al., 2009) is considered as one of the possible processes that may contribute methane to the ocean. However, warm water masses need to be in more or less continuous contact with the seabed in order to send a warming pulse to the gas hydrates causing gas hydrate dissociation. Our seismic data provide evidence for the presence of gas within the upper slope and shelf sediments but not for the occurrence of gas hydrate. Amongst the most prominent indicators for active gas release are gas flares in the water column. While high amplitude seismic anomalies and a BSR exist at the lower slope, vertical acoustic pipes and pockmarks occur upslope. The locations of fluid flow indicators point to very complex gas migration systems that can be split up into the lower and upper continental slope zone, where gas hydrate can exist, and into the shelf break zone with water depth too shallow for gas (methane) hydrate to exist. This following discussion focuses on elucidating the pathways and mechanisms by which gas migrates, and on evaluating the source of the gas expelled from the seabed of the shelf.

5.1. Fluid migration pathways

Most evidence for fluid and gas accumulations stems from high amplitude anomalies in the mostly well-stratified upper slope. Some of the gas accumulations occur beneath a BSR at the lower slope in a very similar way as observed at other locations of the NW-Svalbard area (Hustoft et al., 2009; Vanneste et al., 2005). However, here a BSR can only be observed in water depth exceeding approx. 800 m (Figs. 7 and 8), which is ~20–25 km westward of the shelf break. The theoretical GHSZ thins eastward towards the shelf but without any evidence for a BSR. Only patches of enhanced seismic reflections exist beneath the BSR and predicted BGHSZ. The acoustically masked area indicates a unique gas cloud at the most upper slope and outer shelf area between the theoretical GHSZ pinch out and the location of the observed acoustic flare area.
entering the GHSZ. As a consequence, the area beneath the shelf break is a major gas transport and gas release zone, which is supported by the seismic data, which show the strongest enhanced reflections stacked over up to 200 ms TWT (Figs. 3a-b and 4) interpreted to be a gas cloud (Figs. 7 and 8).

Acoustic pipe structures are commonly associated with focused migration of fluids (e.g. Hustoft et al., 2007). Acoustic pipes in the seismic profiles line-008 and line 009 (Figs. 2 and 7) show pull-up effects. These may be associated with locally high velocity zones caused by either authigenic carbonate build ups or gas hydrate plugs (e.g. Hustoft et al., 2007; Plaza-Faverola et al., 2010) or a combination of both. However, the pipe structures terminate beneath the seafloor, which suggests that they are either a paleo-feature or that there was not enough overpressure build up for gas to reach the seafloor.

Other possible pathways for gas migration are through faults that have been detected in the 3D seismic data on the upper slope (Fig. 4). These small-offset faults are very typical for this setting and have been associated with fluid flow (Hustoft et al., 2009; Vanneste et al., 2005). The origin of the faulting is difficult to identify based on the available data but it might be related to the stretching of the continental crust since the opening of the northern North Atlantic along the Hornsund fault complex (Fig. 1a) (Faleide et al., 1991).

3D and 2D seismic data provide clear evidence for well-developed prograding glacigenic sequences and encompassing GDF deposits that determine the sedimentary architecture of the

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**Figure 9.** (a) High-resolution 3D P-Cable (inline 163) shows a prominent pipe structure, pockmarks on the shelf, prograding glacigenic sequences at shelf and GDF deposit on the slope. (b) Swath bathymetry shows the pockmarks field. The cross profile (yellow line) depicts the depth (~10 m) and the width (~50 m) of the pockmarks. (c) EK 60 acoustic record shows examples of flares observed in the flare field areas west of the pockmarks.
outer shelf and uppermost slope area (Figs. 2 and 3a). GDF deposits concentrate at slope areas (Figs. 2, 3a, 4 and 8) and their distribution varies along the uppermost slope in the prograding glacigenic sequence I. On some seismic lines the BGHSZ falls within the GDF (Figs. 2–4) while on others it seems to connect to the base of the GDF (Fig. 8). The physical properties of GDFs (Sættem et al., 1992) are not seen to be conducive for gas hydrate growth and their reduced permeability may provide an effective trapping mechanism for gas (Bünz et al., 2003). The prograding glacigenic sequences control fluid migration pathways (Figs. 3a, 4 and 8). The location, where the prograding glacigenic sequence I intersects the seafloor coincides well with the location of the gas flares on the shelf (Fig. 5b), clearly showing that gas mostly migrates along its base (Figs. 3a, 4 and 9a).

Acoustic flares on the outer shelf appear not to be connected to pockmarks at the seabed (Fig. 9a, b and c). In contrast, the pockmark field at the inner shelf shows no flares. Evidence for gas conduits below the widespread pockmark field is relatively scarce (Figs. 5 and 9a). The fluid escape features on the seafloor within the zone of acoustic flares are thought to be in their infancy because there are no recognizable pockmark expressions in the very high-resolution multibeam data. Seafloor expressions of pockmarks may develop if both the fluid flow increases and its activity occur over longer time periods.

The location of the pockmarks further eastward from the gas flares is difficult to explain based on our seismic data. One possible mechanism obviously is that gas has migrated along the boundaries of some of the older prograding glacigenic sequences (Fig. 9a). Another explanation for the origin of the pockmark field could be that they were fed from a yet unknown source area. The fact that gas flares are absent at the pockmark field suggests that activity has been significantly reduced or has ceased. This might be further corroborated by the absence of seismic amplitude anomalies in the sub-seabed indicating the absence of appreciable amounts of gas.

The high-resolution 3D seismic data image one distinct acoustic pipe in shelf sediments that connects to one of the pockmarks observed in the swath bathymetry and the 3D seismic data (Fig. 9a). The seismic profile shows a high amplitude anomaly directly beneath the seafloor indicating trapped shallow gas accumulations and possibly a plugged pockmark (Fig. 9a). Since the pockmark lies outside the GHSZ, plugging by gas hydrates has to be ruled out but authigenic carbonate formation may be a possible long-term plugging mechanism (Pierre et al., 2010; Zhu et al., 2003).

5.2. Origin of fluids

Whether the source of the gas expelled at the seafloor on the uppermost slope and shelf break area is from deep-seated hydrocarbon systems or dissociating gas hydrates is obviously of environmental importance given the ongoing climate change debate (Kerr, 2010). The seismic observations presented herein support a deep-seated source as there are many locations where gas accumulations occur at significant depth beneath and outside the BGHSZ (Figs. 2, 7 and 8). This is in good agreement with observations by Knies et al. (2004), which showed that traces of both biogenic and thermogenic methane gas exists in the sediments of the Kongsfjorden shelf. Also, high carbon content measured in Miocene deposits of the Fram Strait further north suggest a high potential for hydrocarbon source rocks along the continental margin of NW Svalbard (Knies and Mann, 2002; Knies et al., 2004).

However, we cannot rule out that some of the gas that is expelled comes from dissociating gas hydrate, though, a clear evidence for gas hydrate is lacking in sediments of the uppermost slope. But it is certainly possible that some of the gas that is migrating from depth enters the GHSZ in the vicinity of its outcrop zone. There, it might be temporally stored as gas hydrates and released during changes in the stability field as e.g. changes in bottom–water temperatures due to seasonal changes or due to
long-lasting temperature changes as a consequence of global warming. The released gas could then migrate further upslope trapped beneath a GDF deposit until it can be expelled through one of the many gas expulsion sites.

5.3. Conceptual fluid flow

Based on our seismic observations, we develop a conceptual model that intends to explain and summarize the geologically-controlled gas migration system on the uppermost continental slope and shelf on the NW-Svalbard margin (Fig. 10). In the uppermost 300–400 mbsf seismic evidence for migration of gas-charged fluids along strata greatly prevails over focused vertical fluid flow migration. Typical expressions of vertical fluid flow such as pipes or chimneys are scarce. Gas migrates along permeable strata upslope thereby eluding the theoretical GHSZ, which pinches out at the uppermost part of the slope at 370 m water depth (Figs. 2, 7 and 8). A clear seismic marker for the BGHSZ such as a BSR is only evident at the lower continental slope in water depth exceeding 800 m, where the GHSZ becomes ~190 m thick (Fig. 8). Gas seems to be trapped beneath the prograding glaciogenic sequences I encompassing GDF deposits, which generally have greatly reduced permeability and which also inhibit gas hydrate and BSR formation (Bünz et al., 2003). Fluids continue to migrate upslope along permeable layers at the base of the prograding glaciogenic sequence I until the layers intercept with the seafloor and fluids are expelled on the shelf.

Studies of glacial landforms at continental margins of the Nordic Sea by Vorren et al. (1989) demonstrated that during the time when glaciers reach the shelf edge high sedimentation rates prevail due to glaciogenic sediment input in form of debris flows. If sedimentation rates are high enough, the speed of sediment burial exceeds their rate of compaction. Thus if the drainage of gas is hindered by low permeability sediments on top, overpressures may develop (e.g. Hustoft et al., 2009). The area beneath the upper slope may therefore still be overpressurized. If the pressure cannot be reduced and increases further, the overpressure build up within sediment layers may initiate lateral fluid migration and/or vertical focused fluid migration through micro fracturing (Judd and Hovland, 2007) when fluids rise, they experience a decrease in pressure. This will allow the gas to come out of solution, resulting in the formation of bubbles. The free bubbles will expand and reduce the bulk density of the material even further. Once initiated, gas migration may lead to a self perpetuating situation wherein gas bubbles develop, and therefore increase the buoyancy and gas may migrate upward along the area beneath the upper slope (Judd and Hovland, 2007).

6. Conclusion

The integration of high-resolution 3D and 2D seismic data reveals the presence of active fluid escape from sediments of the W-Svalbard continental margin. High concentrations of flares (>220) at the shelf break area provide a first order proof for active fluid seepage. The westward prograding shelf consists of glaciogenic sequences and a glacial debris flow deposit (GDF), which are spatially confined. Their geological setting controls gas migration pathways and hence, the location of gas leakage zones at the seafloor on the shelf.

Gas migration occurs towards the upper slope along strata, whereas vertical focused fluid flow indicators are scarce. Vertical migration of thermogenic methane from deep hydrocarbon reservoirs may be caused by diffusive processes. Seismic evidence for gas hydrates exists only at the lower continental slope in water depth exceeding 800 m. The hypothesis that gas hydrates may also occur in close vicinity to the theoretical outcrop zone of the GHSZ has still to be proven. Widespread occurrence of gas release from the shelf area may be driven by free gas supply from lower continental slope regions.

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Appendix. Supplementary data

Supplementary data related to this article can be found online at doi:10.1016/j.marpetgeo.2011.12.008.

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