<category>Original

<title>Fluid flow and methane occurrences in the Disko Bugt area offshore West Greenland: indications for gas hydrates?

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The present study is the first to directly address the issue of gas hydrates offshore West Greenland, where numerous occurrences of shallow hydrocarbons have been documented in the vicinity of Disko Bugt (Bay). Furthermore, decomposing gas hydrate has been implied to explain seabed features in this climate-sensitive area. The study is based on archive data and new (2011, 2012) shallow seismic and sediment core data. Archive seismic records crossing an elongated depression (20×35 km large, 575 m deep) on the inner shelf west of Disko Bugt (Bay) show a bottom simulating reflector (BSR) within faulted Mesozoic strata, consistent with the occurrence of gas hydrates. Moreover, the more recently acquired shallow seismic data reveal gas/fluid-related features in the overlying sediments, and geochemical data point to methane migration from a deeper-lying petroleum system. By contrast, hydrocarbon signatures within faulted Mesozoic strata below the strait known as the Vaigat can be inferred on archive seismics, but no BSR was visible. New seismic data provide evidence of various gas/fluid-releasing features in the overlying sediments. Flares were detected by the echo-sounder in July 2012, and cores contained ikaite and showed gas-releasing cracks and bubbles, all pointing to ongoing methane seepage in the strait. Observed seabed mounds also sustain gas seepages. For areas where crystalline bedrock is covered only by Pleistocene–

Holocene deposits, methane was found only in the Egedesminde Dyb (Trough). There was a strong increase in methane concentration with depth, but no free gas. This is likely due to the formation of gas hydrate and the limited thickness of the sediment infill. Seabed depressions off Ilulissat Isfjord (Icefjord) previously inferred to express ongoing gas release from decomposing gas hydrate show no evidence of gas seepage, and are more likely a result of neo-tectonism.

<heading1>Introduction

Modelling of gas hydrate generation based on varying physiographic and oceanographic settings indicates that large parts of the continental margins surrounding Greenland could contain hydrates (e.g. Wallmann et al. 2012). In addition, a study addressing as yet undiscovered hydrocarbon resources north of the Arctic Circle suggests that offshore Mesozoic sedimentary basins on the West and Northeast Greenland margins could hold high quantities of oil and gas (Gautier et al. 2011). Due to late Cainozoic uplift and glacial erosion (Japsen et al. 2006), these basins are now exposed at the seabed or found at shallow sub-seabed depth (Hamann et al. 2005; Gregersen and Bidstrup 2008), increasing the probability for seepages of gas and thus for formation of gas hydrates.

Presence of potential reservoirs of methane in the form of gas hydrates is significant for future petroleum exploration offshore Greenland. Gas hydrates are also a potential factor in global climate change. Dissociation of the hydrates may lead to increased acidification of the oceans and may release methane to the atmosphere (e.g. Valentine et al. 2001; Biastoch et al. 2011; Smith et al. 2014). In the past decades the Arctic has experienced rapid warming, which according to present climate predictions may even accelerate in concert with the general decrease of the Arctic Ocean sea ice (Screen and Simmonds 2010). A long-term warming trend started, however, already at the last glacial maximum (LGM), at which time the rising sea level and retreat of grounded ice sheets could have initiated gas hydrate dissociation in shallower shelf areas (Smith et al. 2001; Chand et al. 2012).

Despite the apparent potential of formation of gas hydrates and the sensitivity of Greenland waters to climate change, as well as the presence of gas and fluid flows indicated by earlier studies (for overview, see below), no studies with focus on the occurrence of gas hydrates on the Greenland margins have been performed to date. The present study aims to provide a step in that direction by investigating potential gas hydrates in the vicinity of Disko Bugt (Bay) offshore central West Greenland, where seabed features have been attributed to decomposing gas hydrate (Schumann et al. 2012). The paper provides new information on possible gas hydrate occurrence based on observations of gas/fluid-related features using archive data, new shallow seismic data and geochemical analyses of sediment cores from the Disko Bugt area.

<heading1>Regional setting and former work

The Disko Bugt area (Fig. 1) is part of the eastern Baffin Bay, which over the period 1916–2003 has experienced statistically significant warming (Zweng and Münchow 2006). This warming is associated with the subsurface advection of Atlantic-derived Irminger Sea Water entrained along the West Greenland margin by the West Greenland Current, which also forms the bottom water in the Disko Bugt area (Andersen 1981). In spring time, the Baffin Bay sea ice edge is found immediately northwest of Disko Bugt (Tang et al. 2004).

The Disko Bugt area is characterised by water depths ranging mostly between 200 and 500 m (Fig. 1a). The seabed topography is generally rugged and crisscrossed by widespread iceberg scouring tracks, comprising hummocky glacial deposits as well as abundant outcrops of Mesozoic rocks, Palaeogene basalt and basement rocks (see below; Fig. 1b). The almost 890-m-deep Egedesminde Dyb (Trough) extends northeast–southwest across the bay (Fig. 1a).

The geological setting of the Disko Bugt area has been described by Chalmers and Pulvertaft (2001) and later refined by Marcussen et al. (2002) and Gregersen and Bidstrup (2008). The only outcrops of sedimentary rocks onshore West Greenland are found in the Disko-Nuussuaq-Svartenhuk region (Fig. 1b). Areas to the north and south of this region consist entirely of Precambrian basement rocks. The exposed rocks are of deltaic mudstones and poorly lithified sandstones of Late Cretaceous to Early Palaeocene age, overlain by extensive Middle Palaeocene and Eocene basalts. The sedimentary rocks continue offshore and are found exposed on the seabed in the strait known as the Vaigat and in eastern Disko Bugt (Fig. 1b). This Late Cretaceous–Early Palaeocene depositional area generally trends N–S and is known as the Nuussuaq Basin. This is the eastern basin of a complex of large, deep Mesozoic sedimentary basins extending from the Labrador Sea in the south to the eastern Baffin Bay in the north (Fig. 2). Different fault systems occur within the Nuussuaq Basin and several of the faults are sub- or outcropping on the seabed in the Vaigat.

The regional glaciation and glacimarine sedimentary processes in the area have been outlined in detail in several recent publications (Hogan et al. 2012; Ó Cofaigh et al. 2012; Schumann et al. 2012). Up to 250 m of Quaternary and Holocene sediments is found in the eastern Disko Bugt adjacent to the mouth of Ilulissat Isfjord (Icefjord). Towards the north and into the southern Vaigat, the sediment thickness decreases to about 110 m and decreases further westwards in the strait to less than 40 m (Marcussen et al. 2002). Significant sediment thicknesses are also found in the Egedesminde Dyb (Kuijpers et al. 2001) and in isolated depressions in the western Disko Bugt and inner shelf areas.

In the past two decades the Disko Bugt area has experienced increasing interest from industrial companies exploring its oil and gas potential, promoted by onshore findings of bitumen in the vicinity of the Vaigat (Fig. 1b; Christiansen et al. 1996; Pedersen et al. 2006; Bojesen-Koefoed et al. 2007). Offshore, several hydrocarbon indications have been observed on seismic data from the western Vaigat (Marcussen et al. 2002), and heat flow measurements in the area indicated the presence of gas hydrates in the shallow sub-surface at a central Vaigat locality (Müller et al. 2006). In the eastern Disko Bugt, several pockmark fields near the Ilulissat Isfjord mouth have been interpreted to result from seepage of gas and/or fluids (Hogan et al. 2012; Schumann et al. 2012). More to the west, previous piston cores collected from the Egedesminde Dyb exhibited extreme gas expansion upon retrieval (Kuijpers et al. 2001). Finally, on the inner shelf west of Disko Bugt offshore the small town of Aasiaat, archive seismic data with indications of a bottom simulating reflector (BSR) suggest the occurrence of gas hydrates in Mesozoic strata (Mikkelsen et al. 2012). Based on all these observations and information, four sites within the Disko Bugt area were chosen for further studies and new data acquisition, i.e. the Ilulissat, Egedesminde Dyb, Vaigat and Aasiaat sites (Fig. 1).

<heading1>Materials and methods

Two cruises were conducted aboard the R/V Paamiut in the summers of 2011 (20–26 June) and 2012 (9–17 July; Nielsen et al. 2011, 2012). For reflection seismic profiling a single-channel high-resolution system was used, consisting of a Geo-Source 200 Sparker and a short 8-element Geo-Sense Mini Streamer. Echo-sounding was acquired by the ship's dual-frequency (28 and 50 kHz) system, and continuously observed for any occurrence of flares. Navigation was supplied by the ship's DGPS.

Sediment samples were acquired using a 6-m-long gravity corer and a 2-m-long Rumohr corer. Both coring systems were deployed at each coring site in order to obtain undisturbed samples from the shallow sub-seabed depths and to compensate for eventual over-penetration of the gravity cores. The distance within pairs of gravity and Rumohr cores is less than 150 m. The present study reports data from seven coring sites, three of which were visited during the 2011 cruise, and the other four during the 2012 cruise (Fig. 2, Table 1). The coring sites are prefixed PG2011 and PG2012 for the 2011 and 2012 cruises respectively, while the individual cores from each coring site are suffixed GC for gravity cores, RC for Rumohr cores and GC/RC when data from the two core types are combined.

To obtain downcore samples for geochemical investigations without opening the core, 22-mm-diameter holes were drilled in the core liner each 25 cm (each 10 cm for Rumohr cores), and sealed with tape before launching the system into the water. After retrieval, the gravity cores were cut in 1-m-long sections and securely capped. Immediately after core retrieval, 3 cc of sediments sampled from the pre-drilled holes were transferred to a serum vial containing 3 mL NaOH (2.5%), capped with air-tight lids and stored cold for later methane analysis.

For analyses of bulk sediment water and organic carbon contents, 20 cc of sediments were sampled every 25 cm (where possible). Pore water samples were obtained using the Rhizon method (Seeberg-Elverfeldt et al. 2005) shortly after core retrieval. The Rhizon filter tube (5 cm, 2.5 mm OD) was inserted through the pre-drilled hole in the core liner into the centre of the sediment. The first mL of pore water was discarded. After completion of the pore water extraction (0.5–2 h), the pore water was transferred to a 6 mL Exetainer vial, securely capped and stored cold.

Laboratory methane analyses of the headspace gas were performed within 1 week after each cruise using a Shimadzu GC9 gas chromatograph equipped with a flame ionization detector. Calculation of the methane concentration in the sediment pore water (in mM) was done assuming an average sediment porosity of 0.75. Dissolved ions, chloride and sulphate in the pore water were determined by means of a Waters Ion chromatograph based on conductivity detection after appropriate dilution. Dissolved inorganic carbon (DIC) was assessed for some pore water samples by alkalinity titration.

The water content of bulk sediment aliquots was determined as the per cent weight loss by freeze drying. The same samples served for subsequent evaluations of total organic carbon (TOC) contents on a LECO CHN200 instrument using CO_2 detection after acid leaching to remove carbonates.

Later comparison of the sulphate concentrations in the paired Rumohr and gravity cores indicated 10 to 80 cm over-penetration of the gravity cores. This has been corrected for in Fig. 3.

<heading1>Results

<heading2>Ilulissat site

In the pockmark fields previously mapped north of the Ilulissat Isfjord mouth (Hogan et al. 2012; Schumann et al. 2012), a bathymetric survey of a selected pockmark cluster conducted during the June 2011 cruise revealed three individual pockmarks (120–220 m wide, 20–24 m deep; Fig. 4). No flare activity was observed on the echo-sounder during this survey (25–26 June). The easternmost pockmark, which is ca. 200 m wide and 23 m deep, was selected for sediment sampling. Coring site PG2011-12 was located inside this pockmark at 433 m water depth, accompanied by reference coring site PG2011-10 adjacent to the pockmark at 408 m water depth (Fig. 4).

The pore water datasets for both inside and outside the pockmark show an almost constant chloride concentration of 540 mM, i.e. slightly below that of seawater (560 mM), and less than 0.002 mM methane over the entire core profiles (for pockmark core PG2011-12GC/RC, see Fig. 3e). Since no effort was made to ensure a methane-free headspace during sampling, the very low methane values detected in the vials likely originated from atmospheric air of the headspace, and thus represent the background level for the Disko Bugt area. The pore water sulphate concentrations decrease almost linearly with depth from 28 mM to 14 mM, although with a distinct shift in gradient about 1 m below seabed. Comparing the sulphate concentrations for the 2-m Rumohr and 6-m gravity cores indicated 60 to 80 cm over-penetration of the latter, which was corrected for in Fig. 3.

Bulk sediment water and organic carbon contents were determined only for the gravity cores because sub-sampling of the Rumohr cores for these components was omitted due to numerous water-filled pockets and fissures in a very unconsolidated sediment column. The TOC values of pockmark gravity core PG2011-12GC decrease from 1% at the top to less than 0.2% at the bottom of the core (Fig. 3e). The water contents of bulk sediments from the gravity cores collected both inside (core PG2011-12GC) and adjacent (core PG2011-10GC) to the pockmark fluctuate with depth, ranging between 80% and 50% (Fig. 5).

<heading2>Egedesminde Dyb site

Archive seismic data show that the 890-m-deep, steep-walled Egedesminde Dyb is carved into bedrock basement (Fig. 1b) and filled with approximately 190 m of stratified sediments. Cores collected in 2000 from the trough (Kuijpers et al. 2001) contained late Holocene fine-grained sediments (2% TOC) that expanded dramatically upon core retrieval due to gas escape.

During the June 2011 cruise, two coring sites located in the deepest part of the trough at 844 and 863 m water depths both had pore water methane concentrations increasing markedly with depth and reaching more than 10 mM within the upper 1 m below seabed. Sulphate values decrease from ca. 28 mM to virtually zero over the same interval. These results for coring site PG2011-05 taken at 863 m water depth are shown in Fig. 3d. These also reveal chloride values remaining fairly constant (about 520 mM) with depth, i.e. slightly below that of seawater. Moreover, TOC is high at about 3.0–3.5% along the entire core (Fig. 3d). Bulk sediment water content decreases gradually with depth from 66% to 55% (Fig. 5).

<heading2>Vaigat site

Archive seismic data revealed that the faulted Cretaceous–Palaeocene strata in the central part of the Vaigat are covered by up to 40 m of younger sediments. Seabed depressions resembling pockmarks were observed directly overlying many of the faults in the strait (Fig. 6a).

The new shallow seismic data collected in July 2012 show that the younger sediments are disrupted by chimneys and diapiric features of acoustic turbidity or blanking. Such acoustic signatures commonly indicate sub-seabed sediment mobilisation and gas/fluid seepage structures (cf. Judd and Hovland 2007). Coring site PG2012-05 (cf. below) is situated where such a feature comes close to the seabed (Fig. 6b). Various forms of mounded seabed features are seen on the shallow seismic data, particular in the central and western Vaigat. Some seem to be composed of acoustically transparent/turbid material rooted in the lower part of the sediment cover with similar characteristics (Fig. 6c). Another sign of an extrusive origin of some of the mounds is the buckled character of the seismic reflections flanking the mounds (Fig. 6c, d). The surface morphology of these features varies from smooth to well-defined rounded and elongated hummocky. The heights vary from a few metres to almost 40 m.

During the 2012 cruise on 13 July, three ca. 50-m-high flares presumably consisting of gas bubbles were observed seeping from the top of two mounded features, one in the central sector of the Vaigat at 365 m water depth (Fig. 7a) and another at 100 m water depth at the north-western outlet of the strait. Another flare, up to 110 m high, was observed the same day in the southern Vaigat within a 30-m-deep pockmark-like seabed depression at about 370 m water depth.

Gravity core PG2012-05GC taken at 588 m water depth contained 451 cm of homogenous, dark and light greenish mottled clayey silt with scattered and fragmented shells from bivalves and occasional dropstones. Shortly after retrieval, the lowermost 2 m of the core showed signs of sediment and gas expansion. After opening of the core, vertical cracks and gas bubbles appeared from about 110 cm downcore, showing maximum abundances about 200–250 cm downcore but continuing to the bottom of the core. Pore water analyses revealed a marked increase in methane concentration reaching more than 10 mM at 250 cm downcore depth (Fig. 7b). Moreover, a 6-cm-long ikaite crystal was recovered in the gravity core catcher (Fig. 7c) and two other large ikaite crystals were found at 277 and 355 cm downcore depths.

<heading2>Aasiaat site

The Aasiaat site comprises an elongated depression ca. 20×35 km large and 575 m deep in the seabed exposing faulted Cretaceous–Palaeocene strata within an area otherwise characterised by out-cropping Palaeocene basalt to the west and a thick late Cainozoic sediment cover to the east (Fig. 1b). The archive seismic data show that the Cretaceous–Palaeocene strata are covered by a few tens of meters of younger sediments (Fig. 8a). A BSR can be observed at about 75 ms TWT (two-way travel time) below seabed within the Cretaceous–Palaeocene strata (Fig. 8a). The new shallow seismic data of July 2012 confirmed an up to 40-m-thick cover of a younger sediment sequence that comprises three units; a transparent/chaotic lower unit filling lows in the Mesozoic surface, a layered middle unit draping the entire depression, and a transparent upper unit found in the deepest part of the depression (Fig. 8b). The sediment cover is disrupted by numerous diapir-like features of acoustic turbidity or blanking plausibly indicating gas/fluid escape structures (cf. Judd and Hovland 2007; Fig. 8b–d). The July 2012 coring sites (PG2012-01, -02 and -03) were placed where some of these gas/fluid escape features lie close to the seabed. Coring site PG2012-03 lies in the deepest part of the depression at 557 m water depth (Fig. 8b, c), where the upper unit is ca. 10 m thick and a 3-m-deep seabed low overlies diapiric features. Coring site PG2012-01 lies on the northern flank of the depression at 489 m water depth, where closely spaced diapiric features pierce through the exposed middle unit (Fig. 8b, d). Coring site PG2012-02 is located in a similar setting, but on the opposite side of the depression at 510 m water depth (Fig. 8b).

The gravity cores from the 2012 coring sites had lengths of 4.8–5.6 m, with sediments composed mainly of olive grey, silty clay with scattered, up to a few cm large dropstones and a few bivalve remains. Most sediments are weakly mottled/burrowed and display occasionally darker grey banding. An exception is gravity core PG2012-01GC taken at the flank of the depression (Fig. 8b, d), where the lower part of the core shows numerous silt and fine sand stringers and lamination with several dropstones and a dominance of more purely grey tones. In addition, this core section displays an interval characterised by vertically aligned dark discolorations suggesting in situ (‘pre-coring’) sediment remoulding or pore water diffusion processes. The lithology of the lower section of gravity core PG2012-01GC indicates the presence of increased amounts of slightly coarser, terrestrial material, which is comparable with observations reported from a nearby sediment record where this type of sediment has been assigned to the early Holocene (Perner et al. 2013).

The pore water methane concentration ranges from 0.01 to 0.06 mM, increasing with depth at two of the three coring sites (cores PG2012-01GC/RC and -02GC/RC; Fig. 3a, b). Note that a slight stepwise increase in methane can be recognized for these two coring sites (Fig. 3a, b), which may be caused by the variable coarse-grained nature of the sediment. However, the steps correspond to the length of the gravity core sections and thus may result from the sub-sampling process. A similar but more pronounced stepwise methane increase was noted for a gravity core collected at the Aasiaat site during the 2011 cruise, where the sub-sampling procedure was slower. The third core (core PG2012-03GC/RC) shows higher methane concentrations (0.01 to 1.1 mM) and a distinct increase with depth, whereas sulphate decreases from 28 mM to zero from 0.2 to 4 m below seabed (Fig. 3c).

The chloride concentration decreases with depth at all three coring sites from that of normal seawater (560 mM) to 400–500 mM (Fig. 3a–c), the decrease being most pronounced for coring site PG2012-01 (Fig. 3a). This latter coring site also showed more variable water contents ranging between 37–50% (Fig. 5).

The TOC contents of bulk sediment decreased with downcore depth at all three coring sites. However, the TOC range was clearly related to the sampled sediment unit, being 1.2–2.7% at coring site PG2012-03 where the upper unit was sampled (Figs. 3c and 8a), and only 0.4–1.7% at coring sites PG2012-01 and -02 where the middle unit was sampled (Figs. 3a, b and 8b).

<heading1>Discussion

<heading2>Ilulissat site

The Ilulissat site lies at the south-western flank of the Nuussuaq Basin (Fig. 2), where the Mesozoic strata are covered by up to 250-m-thick Quaternary–Holocene sediments. Hitherto, no acoustic indications for hydrocarbons within the Mesozoic strata have been reported for this distal part of the Nuussuaq Basin.

The various clusters of circular to oval shaped, 25-m-deep and 100–500-m-wide seabed depressions were observed in the sediment cover by Schumann et al. (2012) and Hogan et al. (2012), who interpreted these features as pockmarks formed by gas and/or fluid escape. A lack of sediment infill in some of the pockmarks led those authors to conclude that active seepage is taking place in the eastern Disko Bugt today. Although acoustic signs for upward gas and/or fluid flow were observed in connection with some of the seabed pockmarks, many were apparently classified as pockmarks based only on their seabed morphology or v-shaped cross sections on shallow seismic profiles (Hogan et al. 2012, e.g. their Fig. 3). In the present study, gravity core PG2011-12GC was taken in one of the pockmarks found clustered within a WSW-trending depression northwest of the Ilulissat Isfjord mouth. Schumann et al. (2012) studied this pockmark cluster by shallow seismic and multibeam bathymetry mapping, and argued that the pockmarks resulted from the dissociation of gas hydrates due to an increase in bottom water temperature and crustal uplift. However, the very low pore water methane concentrations found in pockmark gravity core PG2011-12GC, i.e. 0.002 mM or less (Fig. 3e), indicate that gas migration is not active in pockmark formation today. Rather, the presence of discrete water pockets and fluid conduits observed in the pockmark Rumohr core PG2011-12RC, together with the scattered downcore bulk sediment water content in pockmark gravity core PG2011-12GC (Fig. 5), suggest that the pockmark could have resulted from expulsing fluids. The essentially constant chloride concentration in the latter core (Fig. 3e) implies that the fluid flow is not driven by hydrostatic pressure caused by freshwater inflow. Hogan et al. (2012) found several lines of evidence for neo-tectonic faulting in the eastern Disko Bugt and agreed with Kuijpers et al. (2001) that this relates to isostatic readjustment and rebound after the retreat of ice from the coastline about 7,600 years ago, a process that is still ongoing. The neo-tectonic activity has resulted in, among others, the formation of some well-defined WNW–ESE-oriented ridge-depression morphologies north of the fjord mouth (Schumann et al. 2012). The cluster of pockmarks in which coring site PG2011-12 is located (cf. Fig. 4) lies in one of these fault-defined depressions. Given that pockmark gravity core PG2011-12GC shows signs of neither methane nor freshwater seepage, it can be speculated that the pockmarks are the result solely of neo-tectonic activity and that dissociated gas hydrate was not involved in their formation. This scenario would also account for the apparent lack of erosion evidenced by the parallel-aligned, v-shaped reflections defining several of the pockmarks previously observed (Hogan et al. 2012). Iglesias et al. (2010) found similar non-truncating pockmark-like features in the Bay of Biscay, and argued that the absence of reflection truncation indicates that the features were not formed by the removal of sediment, and thus did not conform to the conventional definition of pockmarks (cf. Judd and Hovland 2007). Those authors therefore proposed to term these features ‘pockforms’ and suggested that they formed by post-depositional plastic deformation of the sediments following movement of an underlying fault. In the present article, it is suggested that the pockmarks clustered in the WNW–ESE ridge-depression morphology where coring site PG2011-12 was placed formed in a similar manner. The fact that the pockmarks found south of the Ilulissat Isfjord mouth likewise cluster within a ridge-depression morphology trending WSW–ENE (Hogan et al. 2012) further strengthens this interpretation.

The fluid escape structures observed at pockmark coring site PG2011-12 could be a result of deformation of the sediment column caused by the neo-tectonic movements. However, fluid escape structures and bulk sediment water content were equally high for the coring sites inside and outside the pockmark (Fig. 5), which may suggest that the entire area is covered by unconsolidated sediments likely originating from contemporary meltwater discharge from the Greenland Ice Sheet.

<heading2>Egedesminde Dyb site

The Egedesminde Dyb site is located inside a deep trough that is carved into the structural basement high known as the Disko Gneiss Ridge (Fig. 2), subsequently filled with up to 190 m of sediments. The steep increase in methane (28 mM per m) below the sulphate–methane transition zone (SMTZ) at about 1 m below seabed observed at coring site PG2011-05 (Fig. 3d) suggests pronounced organic matter degradation fuelled by fast deposition (3mm/year; Moros et al. 2006) of organic-rich sediment (bulk sediment TOC contents of 3–3.5%; Fig. 3d). A further increase in methane with depth was not observed. According to Wallmann et al. (2006), methane production continues with depth, although at a slower rate. Given the water depth (890 m) and temperature (4 °C) in the Egedesminde Dyb (Kuijpers et al. 2001), free gas would be expected to form when saturation is reached at about 115 mM CH_4 (Sun and Duan 2007). Assuming a continued increase in methane with depth only half of that observed just below the SMTZ due to decrease in organic matter reactivity with age (Wallmann et al. 2006), free gas would be expected 10–20 m below seabed. However, no signs of free gas or a BSR can be observed on the acoustic profile recorded in the Egedesminde Dyb by Hogan et al. (2012, their Fig. 5). According to those authors, the upper part of the sediment infill consists of up to 40-m-thick hemipelagic sediments. This could explain the lack of a BSR because gas hydrates form as discrete layers, lenses, nodules or within thin, sub-vertical veins in fine-grained sediments (Clennell et al. 2000; Rees et al. 2011). The most likely explanation for the absence of free gas is a fairly rapid formation of gas hydrate following the initial free gas formation above the saturation point (Klapp et al. 2012). Given the water depth (800–890 m) and temperature (~4 °C), gas hydrates should be stable at methane concentration above 72–75 mM CH_4 (Sun and Duan 2007). Assuming a geothermal gradient of 30 °C/km, the gas hydrates should be stable down to 250 m below seabed before free gas is formed. As the observed maximum thickness of the sediment covering the bedrock in the Egedesminde Dyb is about 190 m, no free gas is likely to occur.

<heading2>Vaigat site

The Vaigat site lies in the centre of the N–S-trending Nuussuaq Basin (Fig. 2), which is expected to contain hydrocarbons (Christiansen et al. 1996; Bojesen-Koefoed et al. 2007; Gregersen and Bidstrup 2008). The archive seismic data from the strait indicate that gas and/or fluid seep from the deeper Cretaceous–Palaeocene strata towards the seabed along faults (Marcussen et al. 2002). This is consistent with the numerous gas/fluid seepage signatures observed on the shallow seismic profiles. Seepage activities are also supported by the presence of pockmark-like seabed features overlying faults and the occurrences of flares in the water column. Additional support for upward movement of gas and/or fluid has been provided by the sediment heat flow measurements conducted in 2006 aboard the RD 'Dana', which indicated gas hydrates in the shallow sub-surface in the central Vaigat (Müller et al. 2006). The results from coring site PG2012-05 point to gas rather than fluids having caused the seepages features. The observed expansion during retrieval of gravity core PG2012-05GC and the formation of gas bubbles and numerous vertical fissures in the sediment during opening of this gravity core indicate a large gas content, which was confirmed by the relatively high methane concentration measured in the pore water (core PG2012-05GC/RC, Fig. 7b).

Further support for venting gas is the presence of ikaite crystals found in gravity core PG2012-05GC. Greinert and Derkachev (2004) argued that methane-dominated fluid venting influences ikaite genesis, whereby an increase in anaerobic decomposition of organic matter during the early stages of fluid venting fuels geochemical conditions that are ideal for the generation of ikaite near the sediment surface. Thus, the ikaite crystals sampled at coring site PG2012-05 and the relatively high DIC levels in the pore water (around 50 mM, core PG2012-05GC/RC; Fig. 7b), plausibly resulting from organic matter degradation, are in good accordance with the interpretations of Greinert and Derkachev (2004). The archive seismic data show no sign of a BSR, despite the many expressions of gas. However, gas hydrates do not show up invariably as a BSR (e.g. Clennell et al. 2000).

Correlation of the mounded seabed features observed on the 2012 shallow seismic profiles with the archive seismic data shows that the southernmost features are part of large slump deposits deriving from the steep mountains flanking the strait (Marcussen et al. 2002; Dahl-Jensen et al. 2004). The mounded features found in the central part of the strait show no obvious correlation to any features observed on the archive seismic data, and are thus likely ‘stand-alone’ mounds. The morphology and chaotic interior of these mounds, in combination with the buckled reflections at their flanks (Fig. 6c, d), suggest that they are large mud diapirs. The sediments expulsed in the mud diapirs may consist of mudstones and poorly lithified sandstones derived from the underlying Cretaceous–Palaeocene strata and/or fine-grained sediments from the overlying sediment cover. There is a considerable variety of mechanisms by which mud diapirs can form (cf. Judd and Hovland 2007). Given the faulted nature of the Cretaceous–Palaeocene strata, and the many indications of gas occurrence in both these strata and the overlying sediment cover, the mounded features could be mud diapirs fed by the migration of gas and/or fluid along a fault that extends to the surface. An alternative interpretation could be that the mounded features are different stages of submarine pingo-like structures (Hovland and Svensen 2006; Serié et al. 2012). Hovland and Svensen (2006) suggested that submarine pingoes form as a result of sub-surface gas hydrate build-up at focused seepage locations, and that the pingoes grow and collapse over time due to cycles of freezing and thawing of hydrates in the shallow sub-surface. Pingo-like structures may also be formed by sediment mobilisation caused by gas hydrate decomposition at depth (Paull et al. 2007). Regardless of whether the mounded features are mud diapirs or submarine pingo-like structures, seeping gas and/or fluids are an important factor in their formation. Giving the results from coring site PG2012-05, seeping methane may likely be involved in the formation of the seabed mounds in the Vaigat.

<heading2>Aasiaat site

The Aasiaat site is located at the south-eastern flank of the N–S-trending Ilulissat Graben (Fig. 2) that has been suggested to hold hydrocarbons (Gregersen and Bidstrup 2008). At this study site methane is present in the sediment several metres above the SMTZ at all three coring sites (PG2012-01, -02 and -03; Fig. 3a–c). Although methane is low in the sulphate zone (0.01–0.1 mM), it is definitely above the background level of <0.002 mM found at the Ilulissat site (core PG2011-12GC; Fig. 3e). The high sulphate concentration at the Aasiaat site (generally >10 mM) and the low organic carbon content (TOC generally <1.0%; Fig. 3a–c) argue against in situ methane production, and thus suggest migration of methane from below. Upward migration of gas is also supported by the numerous diapiric features identified on the shallow seismic profiles (Fig. 8b–d).

The middle sediment unit was sampled at coring sites PG2012-01 and -02 (Fig. 8b, d). The lithology of gravity core PG2012-01GC, together with preliminary radiocarbon dating of material from the upper 2 m of this core (unpublished results), indicate that the middle unit (Fig. 8b) consists of early to pre-Holocene glacial-related sediments deposited in a non-marine environment. The latter is further supported by the observed decrease in pore water salinity with depth (core PG2012-01GC/RC; Fig. 3a). According to Ó Cofaigh et al. (2012), the Aasiaat site was covered by a grounding ice stream during the LGM and Younger Dryas. It is therefore not unlikely that the lower parts of the sediment cover (i.e. the lower and middle units; Fig. 8b) contain organic-poor glacial deposits less capable of generating methane. Thus, the methane observed at coring sites PG2012-01 and -02 is probable sourced from the underlying Cretaceous–Palaeocene strata, which form part of the assumed hydrocarbon-bearing Ilulissat Graben (Gregersen and Bidstrup 2008).

Free gas features can be observed on the shallow seismic profiles, although the sediment methane content of 0.01–1 mM recorded at all three coring sites (Fig. 3a–c) is far below the 75 mM saturation level for seawater methane at 500 m water depths and 4 °C (Sun and Duan 2007). This indicates that methane observed above the SMTZ most likely exists in the free gas phase. It is worth mentioning that, although the methane content (0.01–0.1 mM, core PG2012-01GC/RC; Fig. 3a) was below saturation (1.5 mM) at ambient pressure, the caps on the core sections of gravity core PG2012-01GC bulged out during storage, indicating gas release (Nielsen et al. 2012). Furthermore, the slight stepwise increase in methane recognized to correlate to core sections (Fig. 3a) may also indicate a fast methane loss from a gas phase, rather than exsolution from pore water. A low content of free methane in the sulphate zone in silty, sandy clays was previously observed by Laier and Kuijpers (2000), who suggested diffusion of gaseous methane in micro-cracks and fissures. The decrease in sulphate with depth in the organic-poor glacial sediments (e.g. coring site PG2012-01, Fig. 3a) would be partly due to oxidation of migrating methane and not just degradation of organic matter, as previously observed in studies of migrating methane above gas hydrates (Borowski et al. 1999; Pohlmann et al. 2013).

Coring site PG2012-03 sampled the upper sediment unit (Fig. 8c). The more pronounced decrease in sulphate with depth observed in core PG2012-03GC/RC (Fig. 3c) is likely due to a higher organic matter content in this unit compared to the middle sediment unit sampled at the two other coring sites (PG2012-01 and -02). As the upper sediment unit overlays the middle unit, it must necessarily post-date the early Holocene and may likely consist of more organic-rich glacimarine and/or hemipelagic sediments. The higher methane content found at coring site PG2012-03 might therefore result from in situ formation of methane in the upper

sediment unit. However, a higher flux of gas from below, indicated by the diapir feature underlying the coring site (Fig. 8c), may also contribute to the higher methane content.
Gas hydrates would be stable under the seabed conditions observed at the Aasiaat site, i.e. 490–560 m water depth and bottom water temperature of 4 °C (Fig. 9), and should be stable down to 50–100 m below seabed assuming a geothermal gradient of 30 °C. The BSR observed on the archive seismic data ca.75 ms TWT below seabed (Fig. 8a) is therefore most likely caused by the boundary between gas hydrates and free gas.

<heading1>Conclusions

The investigation of gas hydrate occurrence in the Disko Bugt (Bay) area offshore central West Greenland is in an early stage. Nevertheless, several conclusions can be drawn already from the present study.

- Gas hydrates in the Disko Bugt area appear to exist mainly in sectors with a thin sediment cover over Cretaceous–Palaeocene strata or in restricted areas with very high postglacial sediment accumulation rates.
- The investigated pockmark at the Ilulissat site is one of several pockmark sites previously observed around the mouth of Ilulissat Isfjord (Icefjord). No sign of present-day gas seepage was found in the area, but sediment structure and geochemical data indicate that fluid flow takes place today. The formation and distribution of these pockmarks are likely controlled primarily by neo-tectonic activity and associated tectonic structures, whereas dissolving gas hydrates are probably not involved in their formation.
- The sediments in the up to 890-m-deep Egedesminde Dyb (Trough) most likely do contain gas hydrate. The hydrates may be present throughout the sedimentary sequence and extend down to the bottom of the 190-m-thick sediment infill. The sediments have a high content of TOC that, together with a high sedimentation rate, suggests that the methane present here is of biogenic origin.
- The Vaigat lies in the centre of the N-S-trending Nuussuaq Basin, which presumably contains hydrocarbons. A variety of acoustic features observed in a ca. 40-m-thick sediment sequence covering faulted Cretaceous–Palaeocene strata signifies upward migration and seepage of gas and/or fluid. Geochemical data from sediment cores, one of which contained ikaite crystals, together with offshore and numerous onshore signs of an active hydrocarbon system, point to the presence of gas rather than fluid. Thus, gas hydrates are likely to occur in the strait.

- The Aasiaat site on the inner shelf west of Disko Bugt lies in a large seabed depression that forms a window to Mesozoic strata, which is part of the presumed hydrocarbon-bearing Ilulissat Basin. The setting of the depression resembles that of the Vaigat, i.e. faulted Cretaceous–Palaeocene strata covered by an up to 40-m-thick sediment layer that show acoustic features indicating upward migration of gas and/or fluid. Sediment and geochemical data indicate gas migration, and thus gas hydrates may be present at the site. The gas most likely originates from the underlying Cretaceous–Palaeocene strata.

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Fig. 1 The Disko Bugt study area in the vicinity of Disko Island and the Nuussuaq Peninsula: **a** GEUS bathymetric map with locations of the four study sites Vaigat, Ilulissat, Egedesminde Dyb and Aasiaat; **b** pre-Quaternary geological setting (adapted from Henriksen 2008; *full* *tones* onshore geology, *half tones* offshore geology), including locations of study sites and onshore bitumen occurrence

Fig. 2 Simplified map of the mainly Cretaceous–Palaeogene major structural elements of the central West Greenland margin (modified from Gregersen and Bidstrup 2008), with locations of shallow seismic lines and sediment coring sites (*stars*) reported in this article: *red* Vaigat coring site PG2012-05, *green* Ilulissat coring sites PG2011-12 (pockmark) and PG2010 (reference), *yellow* Egedesminde Dyb coring site PG2011-05, *black* Aasiaat coring sites PG2012-01, -02 and -03. For structural type definitions, see Gregersen and Bidstrup (2008)

Fig. 3 Pore water chemistry profiles for selected cores. Aasiaat: **a** PG2012-01GC/RC, **b** PG2012-02GC/RC, **c** PG2012-03GC/RC; Egedesminde Dyb: **d** PG2011-05GC/RC; Ilulissat: **e** PG2011-12GC/RC (pockmark core). Over-penetration of the gravity cores was corrected for by comparison with sulphate concentrations obtained from the Rumohr cores (see text), whereby the estimated over-penetration for the gravity cores was 30, 40, 10, 20 and 80 cm respectively

Fig. 4 Bathymetry map based on echo-sounder data collected during the June 2011 cruise, showing a cluster of three pockmarks at the Ilulissat study site off the mouth of Ilulissat Isfjord (*IIF*). The displayed pockmarks are 120–220 m wide and 20–24 m deep. Coring site PG2011-12 was located inside the easternmost pockmark at 433 m water depth and reference coring site PG2011-10 outside the pockmark at 408 m water depth

Fig. 5 Downcore profiles of bulk sediment water content at coring sites Aasiaat (core PG2012-01GC/RC), Egedesminde Dyb (core PG2011-05GC/RC) and Ilulissat (pockmark gravity core PG2011-12GC, reference gravity core PG2011-10GC)

Fig. 6 Shallow seismic lines and coring site location for the Vaigat site. **a** Archive multichannel seismic record from the southern Vaigat, showing a pockmark-like structure in younger sediments overlaying faulted Cretaceous–Palaeocene strata (*yellow lines*). **b** Part of sparker line PG12-06 showing up to 40 m of stratified younger sediments with chimneys and diapiric disruptions of acoustic turbidity (*dashed orange lines*). Coring site PG2012-05 was located on top of one of these features. **c** Part of sparker line PG12-05 showing a mounded seabed feature in the north-eastern Vaigat. **d** Part of sparker line PG12-05 showing a mounded seabed feature found offshore the Aaffarsuaq valley that contains several pingo structures. The seabed mounds are suggested to be mud diapirs or submarine pingo structures (see text). Note the buckled reflectors at the flanks of the seabed mounds in both **c** and **d**, which support the extrusive nature of the mounds

Fig. 7 The Vaigat site, July 2012 Paamiut cruise: **a** flares detected by the echo-sounder, interpreted to be gas bubbles seeping out from the top of a mounded seabed feature; **b** pore water profiles for coring site PG2012-05; **c** 6-cm-long ikaite crystal collected from the core catcher of gravity core PG2012-05GC

Fig. 8 Seismic sections and core locations for the Aasiaat site. **a** Archive multichannel seismic record showing a seabed depression with sub-cropping faulted Cretaceous–Palaeocene strata (*yellow lines*) and a BSR at about 75 ms sub-bottom depth (*red dashed line*), suggesting the presence of gas hydrates. **b** SSW–NNE-trending sparker line PG12-01 crossing the depression. The top of the Cretaceous–Paleocene strata (*green dashed line*) is overlain by a ca. 40-m-thick sediment sequence composed of three units: a lower unit (top, *dark blue dashed line*), a middle unit (top, *light blue dashed line*) and an upper unit. Locations of the coring sites are also shown. **c** Part of sparker line PG12-03 inside the depression, where the Cretaceous–Palaeocene strata are overlain by ca. 30 m of younger sediments disrupted by gas/fluid escape features (*orange dashed lines*). Coring site PG2012-03 is located in a pockmark-like structure in the upper sediment unit underlain by a large diapiric feature. **d** Coring site PG2012-01 and part of sparker line PG12-01 from the northern flank of the depression, where the middle sediment unit is exposed at the seabed and disrupted by several gas/fluid escape features (*orange dashed lines*)

Fig. 9 Gas hydrate pressure–temperature stability field including the four Disko Bugt area sites examined in the present study

Table 1 Location, coordinates, water depth and core length of the seven coring sites described in the text

Coring site	Location	Latitude N, longitude W	Water depth (m)	Recovery (cm)
PG2011-05	Egedesminde Dyb	68°51.978, 53°19.465	865	482
PG2011-10	Ilulissat	69°12.412, 51°27.392	408	554
PG2011-12	Ilulissat	69°12.762, 51°27.541	431	560
PG2012-01	Aasiaat	68°27.838, 55°46.901	489	562
PG2012-02	Aasiaat	68°22.685, 55°49.510	510	482
PG2012-03	Aasiaat	68°24.148, 55°43.383	557	516
PG2012-05	Vaigat	70°18.561, 53°33.837	587	446

Figure 1

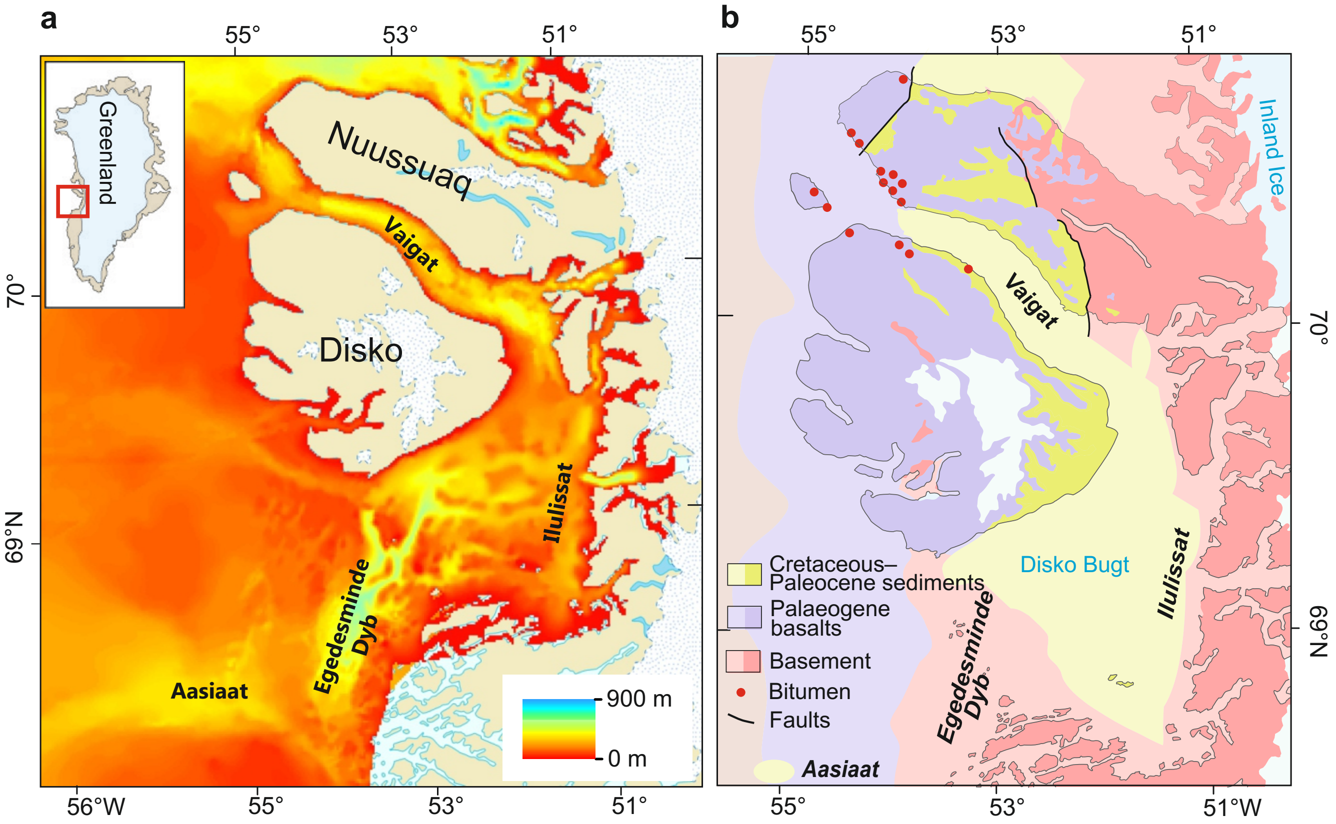
a
55°
53°
51°
70°
69°N
56°W
55°
53°
51°
Greenland
Nuussuaq
Vaigat
Disko
Ilulissat
Egedesminde Dyb
Aasiaat
900 m
0 m
b
55°
53°
51°
70°
69°N
55°
53°
51°W
Inland Ice
Vaigat
Disko Bugt
Ilulissat
Egedesminde Dyb
Aasiaat
Cretaceous–Paleocene sediments
Palaeogene basalts
Basement
Bitumen
Faults

Figure 2

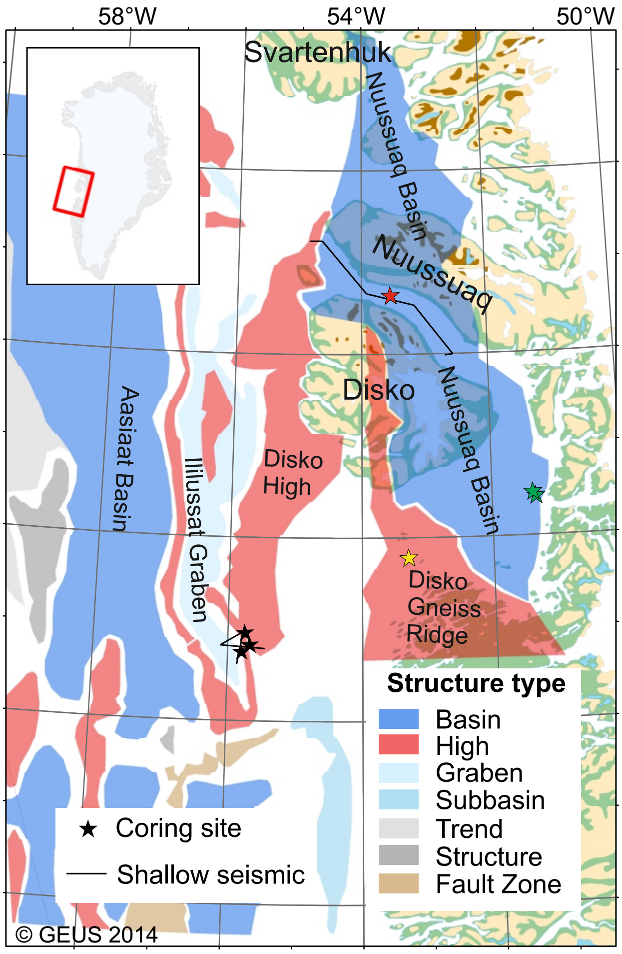
58°W
54°W
50°W
71°N
70°N
69°N
68°N
67°N
Svartenhuk
Nuussuaq Basin
Nuussuaq
Disko
Nuussuaq Basin
Aasiaat Basin
Ilulissat Graben
Disko High
Disko Gneiss Ridge
Structure type
Basin
High
Graben
Subbasin
Trend
Structure
Fault Zone
Coring site
Shallow seismic
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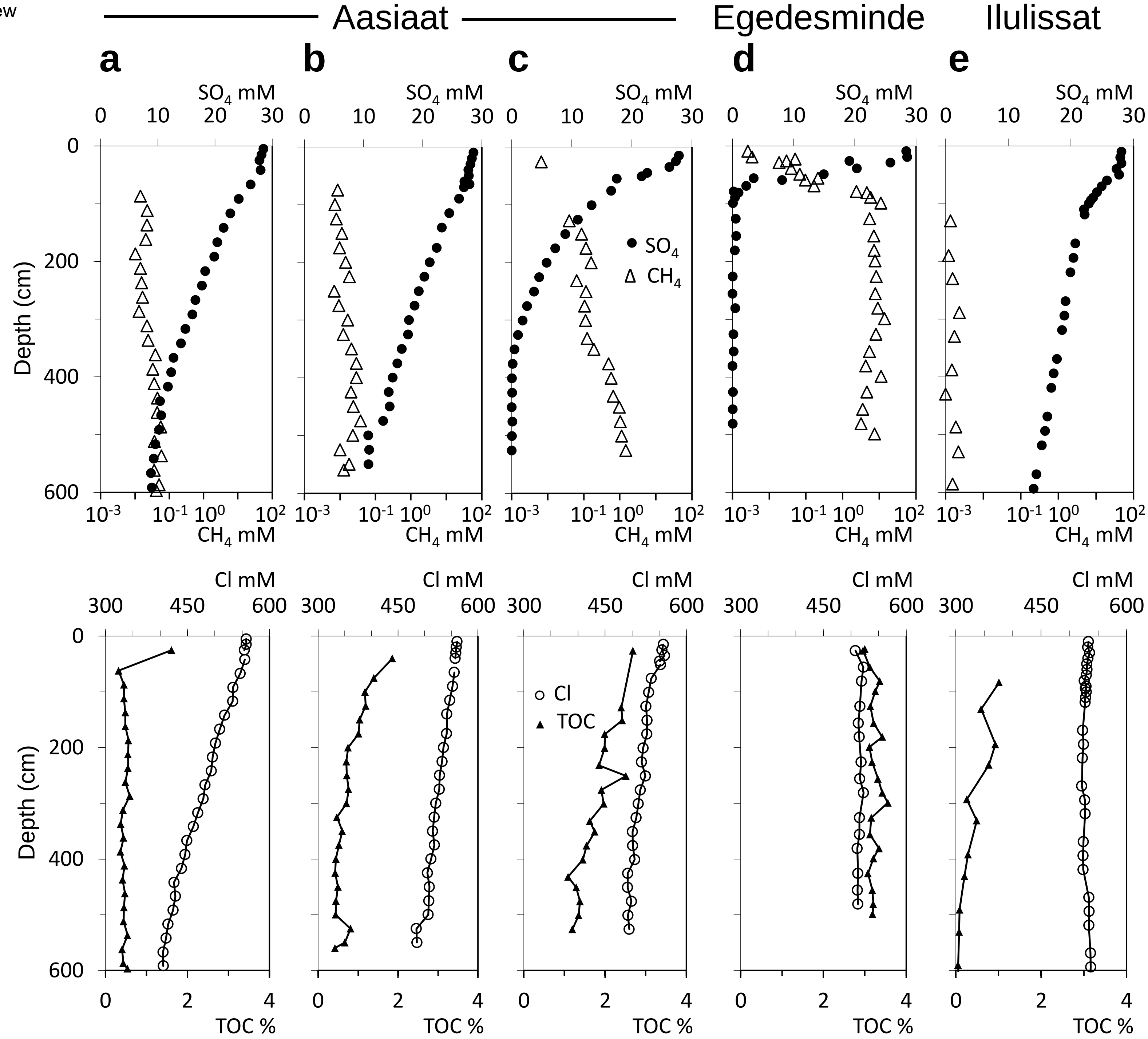
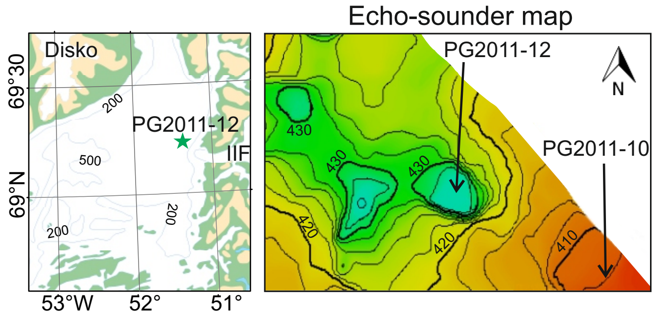
Figure3 new



Aasiaat
Egedesminde
Ilulissat
a
b
c
d
e
SO4 mM
0
10
20
30
Depth (cm)
0
200
400
600
10-3
10-1
100
102
CH4 mM
SO4
CH4
Cl mM
300
450
600
Cl
TOC
0
2
4
TOC %

Figure 4



Echo-sounder map
Disko
69°30
69°N
200
500
200
200
PG2011-12
IIF
53°W
52°
51°
PG2011-12
PG2011-10
N
430
430
430
420
420
410

Figure 5

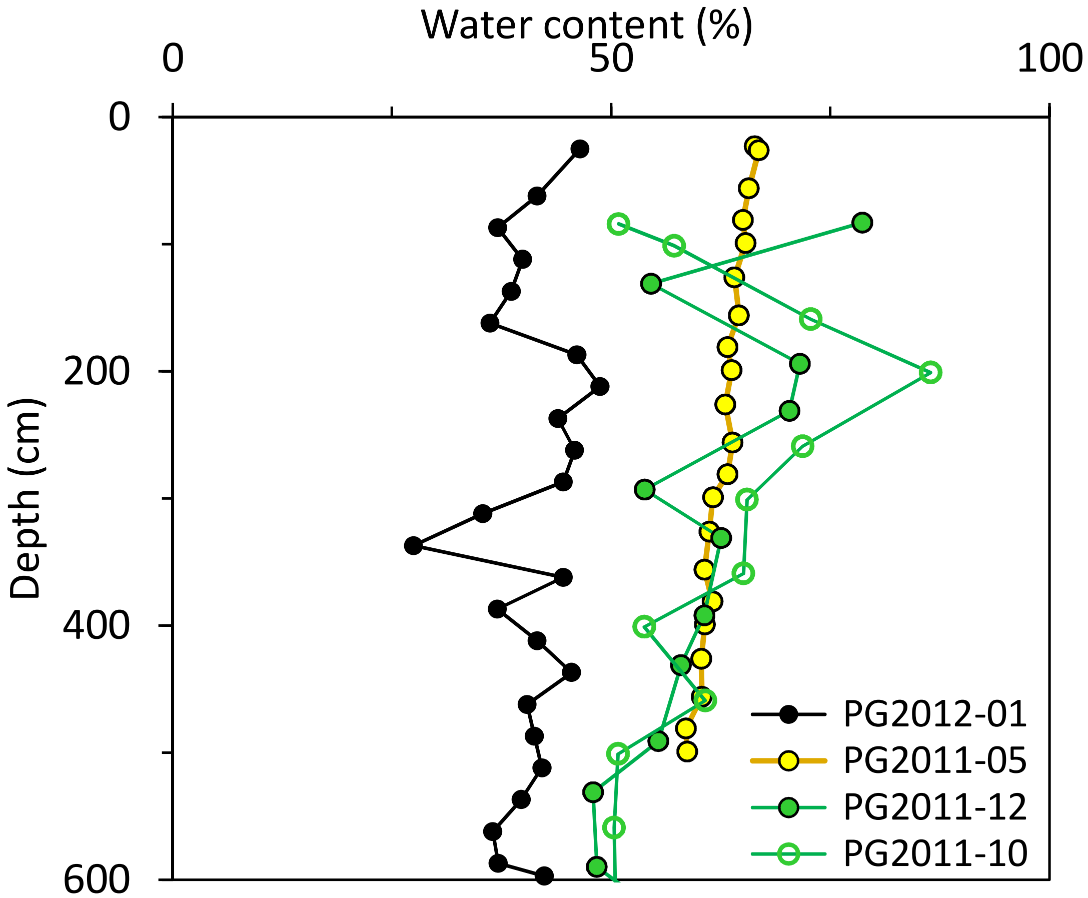
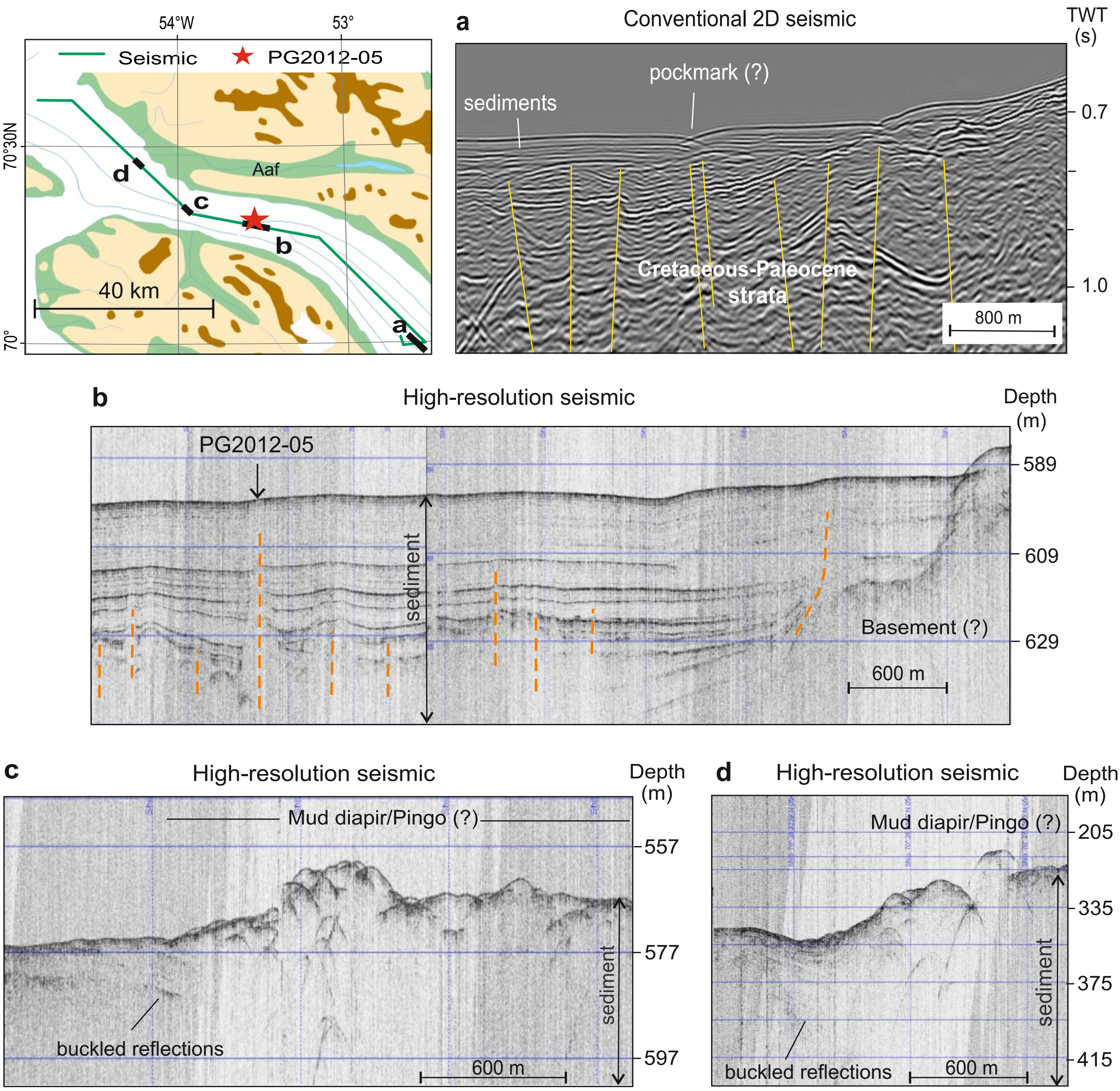

Water content (%)
0
50
100
0
200
400
600
Depth (cm)
PG2012-01
PG2011-05
PG2011-12
PG2011-10

Figure 6



54°W
53°
Seismic
PG2012-05
70°30N
70°
Aaf
d
c
b
a
40 km
a
Conventional 2D seismic
TWT
(s)
pockmark (?)
sediments
0.7
1.0
Cretaceous-Paleocene
strata
800 m
b
High-resolution seismic
Depth
(m)
PG2012-05
589
609
629
sediment
Basement (?)
600 m
c
High-resolution seismic
Depth
(m)
Mud diapir/Pingo (?)
557
577
597
sediment
buckled reflections
600 m
d
High-resolution seismic
Depth
(m)
Mud diapir/Pingo (?)
205
335
375
415
sediment
buckled reflections
600 m

Figure 7

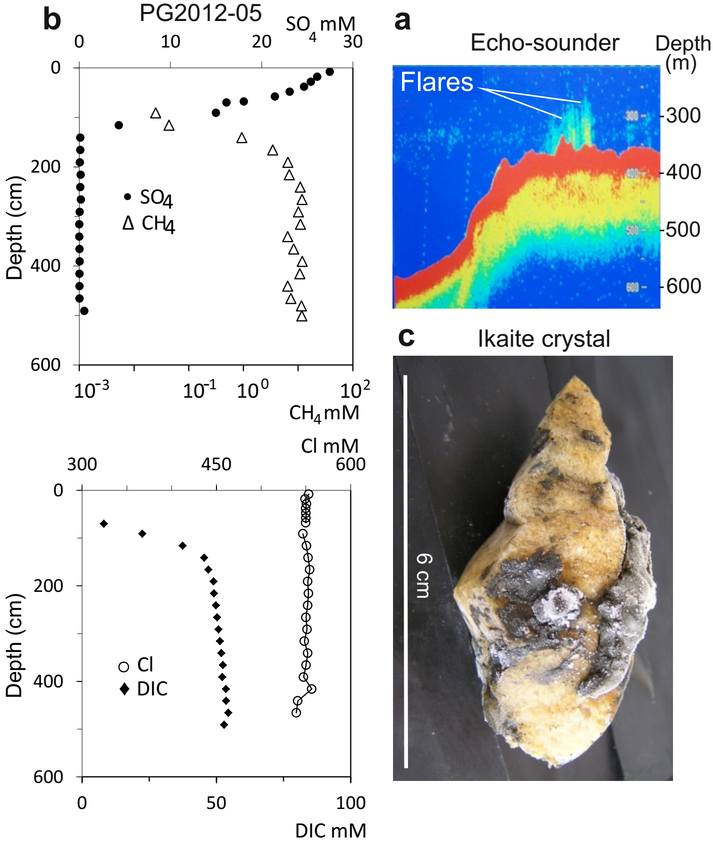

b
PG2012-05
SO4 mM
0
10
20
30
0
200
400
600
Depth (cm)
SO4
CH4
10-3
10-1
10^0
10^2
CH4 mM
Cl mM
300
450
600
0
200
400
600
Depth (cm)
Cl
DIC
0
50
100
DIC mM
a
Echo-sounder
Depth (m)
Flares
300
400
500
600
c
Ikaite crystal
6 cm

Figure8 new

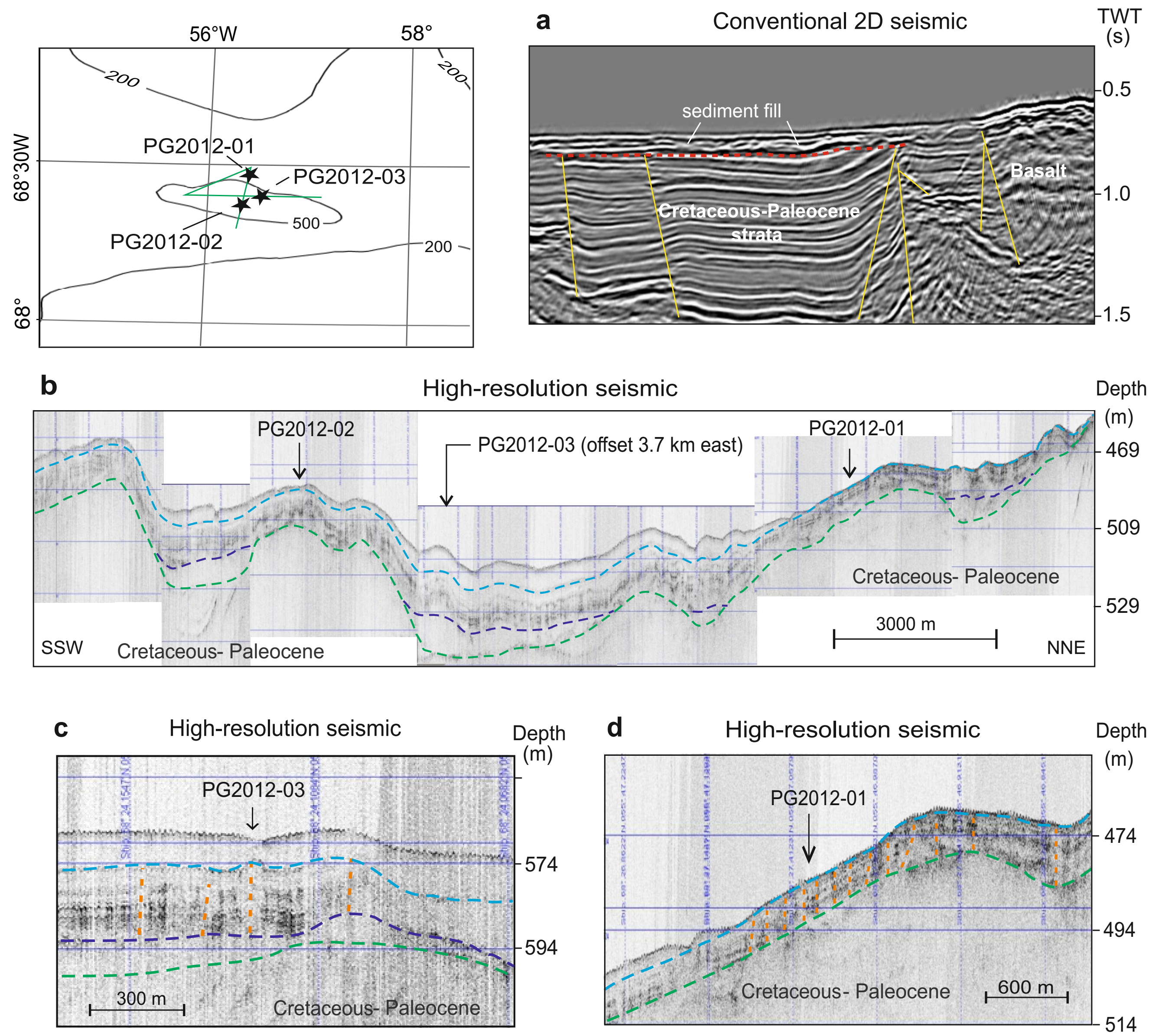
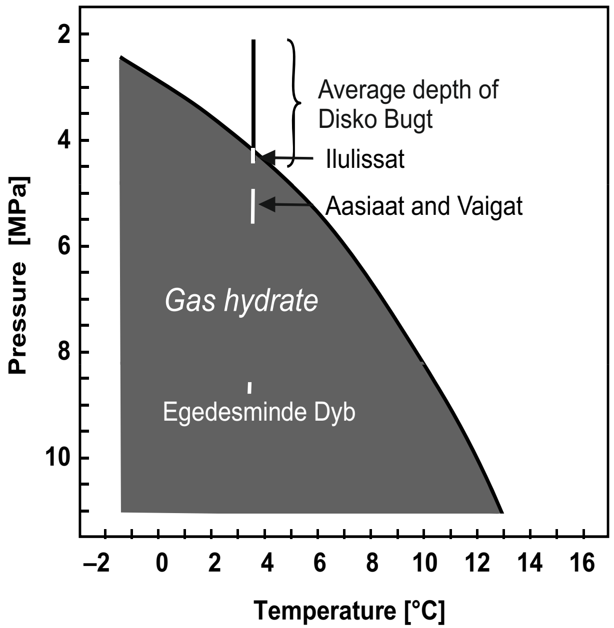

56°W
58°
68°30'W
68°
200
500
PG2012-01
PG2012-03
PG2012-02
a
Conventional 2D seismic
TWT (s)
0.5
1.0
1.5
sediment fill
Cretaceous-Paleocene strata
Basalt
b
High-resolution seismic
Depth (m)
469
509
529
PG2012-02
PG2012-03 (offset 3.7 km east)
PG2012-01
SSW
Cretaceous- Paleocene
Cretaceous- Paleocene
3000 m
NNE
c
High-resolution seismic
Depth (m)
PG2012-03
574
594
300 m
Cretaceous- Paleocene
d
High-resolution seismic
Depth (m)
PG2012-01
474
494
514
Cretaceous- Paleocene
600 m

Figure 9


Average depth of
Disko Bugt
Ilulissat
Aasiaat and Vaigat
Gas hydrate
Egedesminde Dyb
Pressure [MPa]
2
4
6
8
10
–2
0
2
4
6
8
10
12
14
16
Temperature [°C]