THE FACULTY OF SCIENCE AND TECHNOLOGY

DEPARTMENT OF GEOLOGY

Role of subsea permafrost and gas hydrate in postglacial Arctic methane releases

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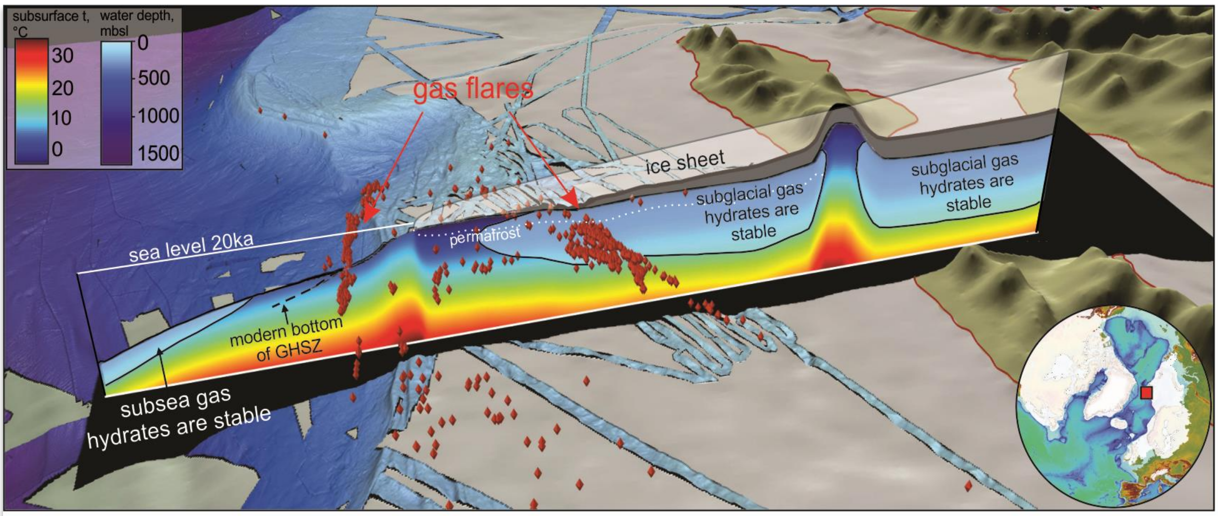
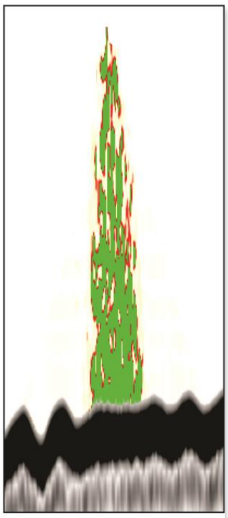
A dissertation for the degree of Philosophiae Doctor – September 2015





Preface

This doctoral thesis was carried out in the Department of Geology in The Arctic University of Norway, Tromsø, from September 2012 to September 2015. The research was a part of CAGE - Centre for Arctic Gas Hydrate, Environment and Climate funded by the Norwegian research council (grant 223259). During my PhD I was also funded by the Statoil fellowship through the Arctic University of Norway. The comprehensive data from the Russian Kara Sea used in this thesis came from The All-Russia Scientific Institute for Geology and Mineral Resources of the Ocean “VNIIOkeangeologia named after I.S. Gramberg”. The field research in the Kara Sea was funded by the Federal Subsoil Resources Management Agency of Russia (object 70–113: “Regional geologic-geophysical explorations at Yamal sector of the South Kara Sea shelf”).

The doctoral thesis includes research within two geographically-remote regions – South Kara Sea and West Svalbard margin. However, they bear particular resemblance, expressed in the extensive seafloor gas discharge, and thus present an attractive subject for climate-related greenhouse gas research. Within the three years of scientific research I took part in five cruises. Two cruises, conducted by VNIIOkeangeologia in the South Kara Sea in 2012 and 2013 provided essential high-resolution seismic, hydrologic and marine organic and gas geochemical data from offshore Yamal Peninsula. These data were used both independently for permafrost mapping during the first phase of my PhD and for a ground truthing the subsequent permafrost modeling, leading to three papers. I also participated in three cruises on RV Helmer Hanssen offshore Svalbard conducted by CAGE at the Department of Geology UiT in 2012 and 2014. These interdisciplinary cruises broadened my marine field experience and resulted in one manuscript. Tentative and final results of my PhD research were presented during 10 international scientific conferences and workshops in the form of oral and poster presentations. Public dissemination of my research results included publications in a number of online and printed media resources, collaboration with the geological section of Tromsø city museum and cooperation with the digital production company ARTGAL in the UK. During my PhD I accomplished several training courses on geographic information systems (ArcGIS, Fledermaus) and seismic software (Petrel, Charisma), which allowed for a more efficient presenting of my observations and modeling of scientific results.

My thesis comprises an introduction and four articles revealing peculiarities of shallow subsea permafrost and subglacial gas hydrate systems from the last ice age (20 ka to the present). The research emphasizes feasible distinctions between these systems as sea level rose, offshore permafrost started to thaw and ice sheets melted. As a consequence, shallow seafloor gas escape from the South Kara Sea via the Barents Sea to the Svalbard margin became active.

Acknowledgements

To start with, I would like to thank my scientific advisors, who made it possible for me to get my dissertation started and completed. First of all, I would like to express my sincere gratitude to Prof. Jürgen Mienert, who supervised me during the three years of my doctoral study. His efficiency and enthusiasm in scientific research always admired me, his timely criticism, which I apparently deserved more of, educated me. His sense of humor and comprehensive support inspired and guided me through my work. It is an honour to be his student. I would also like to thank Prof. Georgy Cherkashov, who supervised me during my master study and provided support during doctoral research. Particularly, I thank Dr. Pavel Rekant, who first introduced me to marine geoscience many years ago, and became not just a tutor for me, but also a good friend. Dr. Boris Vanstein, who showed me the peculiarities of applied geoscience and put a lot of effort in organizing field work, particularly included in this dissertation. These people are greatly responsible both for my growth as a specialist and development as a person.

I am grateful to Assoc. Prof. Stefan Buenz for organizing two of the three UiT cruises I took part in, and for our fruitful scientific (and sometimes not very) discussions. I would also like to thank Prof. Joel Jonson, Dr. Monica Winsborrow for proof-reading my work, as well as Prof. Karin Andreassen, Prof. Alun Hubbard, Prof. Giuliana Panieri, Dr. Matthias Forwick, Dr. Tatiana Matveeva and others, who shared their expertise and experience.

I would like to thank my colleagues, who helped to develop and mature our scientific papers – my co-authors and friends Pavel Serov, Sunil Vadakkepuliyambatta, Peter Semenov and particularly Andrew Smith, who helped me a lot during the first stages of my PhD in Tromsø. I very much appreciate our young academic community in Tromsø, and want to thank all of my friends here for such a colorful and exciting time, shared hours of scientific discussions, skiing, mountaineering, having fun and enjoying life – Alexey, Anna, Giacomo, Calvin, Mariana, Kate, Diana, Carly, Julia, Andreia, Noortje, Sarah, Andrea, Simone, Kamila, Emmelie, Pær, Henry, Kari, Friederike, Eythor, Peter and others. I owe special thanks to Alexandros, Mohamed, Emilia, Sunny and Sandra for being perfect office mates, having coped with me and the permanent chaos on my desk.

Many thanks to Margrethe Lindquist, Inger Solheim and Kai Mortensen for their tough administrative work, and Maja Sojtaric for her help in the promotion of our scientific results.

I owe an immeasurable gratitude to those who I left in Russia but have always felt their everlasting support – my parents, sister, friends and my favorite city Saint-Petersburg. My biggest acknowledgement goes to my wife Daria, who is always with me and continuously inspires, overcomes, shares, sustains, supports and loves.

List of articles:

Article 1: Alexey Portnov, Andrew J. Smith, Jürgen Mienert, Georgy Cherkashov, Pavel Rekant, Peter Semenov, Pavel Serov, Boris Vanshtein (2013). **Offshore permafrost decay and massive seabed methane escape in water depths > 20 m at the South Kara Sea shelf.** *Geophysical Research Letters*, VOL. 40, 1–6, doi:10.1002/grl.50735.

Article 2: Alexey Portnov, Jürgen Mienert, Pavel Serov (2014). **Modeling the evolution of climate-sensitive Arctic subsea permafrost in regions of extensive gas expulsion at the West Yamal shelf.** *Journal of geophysical research: Biogeosciences*, 119, 2082–2094, doi:10.1002/2014JG002685.

Article 3: Pavel Serov, Alexey Portnov, Jürgen Mienert, Peter Semenov, Polina Ilatovskaya. **Methane release from pingo-like features across the South Kara Sea shelf, an area of thawing offshore permafrost.** *Journal of geophysical research: Earth surface*, in review.

Article 4: Alexey Portnov, Sunil Vadakkepulyambatta, Jürgen Mienert, Alun Hubbard. **Ice-sheet driven methane storage and release in the Arctic.** Submitted to *Nature Geoscience*.

Table of contents:

Introduction

Scope

This thesis concentrates on thawing relict subsea permafrost and shallow gas hydrate that govern Arctic submarine seafloor gas discharge from the last glacial maximum (LGM) until today. The study area covers two climate sensitive Arctic regions – the West Yamal Shelf in the South Kara Sea (study area 1), and the West Svalbard Margin which is influenced by the northward flowing warm NW-Spitsbergen Current (study area 2). This research embraces three themes which are of considerable interest:

1. Scientific interest. The research provides information on the current distribution of relict subsea permafrost and subpermafrost gas hydrates in one of the key Arctic shallow sea regions – South Kara Sea. It shows potential dynamics of permafrost evolution related to temperature fluctuations and eustatic sea level change in an area located just ~100 kilometers westward from the recently discovered giant craters onshore Yamal Peninsula [*Bogoyavlenskiy*, 2014a; b; *Moskvitch*, 2014]. Of specific interest is offshore permafrost melting and the issue of former subglacial gas hydrate dissociation in the shallow waters offshore West Svalbard which are associated with extensive seafloor gas discharge. Numerous presently inactive pockmark fields, discovered on the seafloor offshore and in the fjords of Svalbard are seen as finger-prints of deglaciation. Both regions can significantly contribute to a more comprehensive understanding of the post-glacial evolution of the pan-Arctic region.
2. Geological-engineering interest. Permafrost and enclosed pressurized gas are critical factors for various kinds of geological risks during engineering activity onshore and offshore [*Rokos*, 2008]. Prediction of potential geo-hazards in the area of active oil and gas exploration in the shallow South Kara Sea must include permafrost mapping and modeling. Shallow subpermafrost gas hydrates and pingo-like features also present significant risks related to potential blowout events during drilling operations.
3. Climate change interest. After carbon dioxide methane is the second most important greenhouse gas on Earth, as much as 25 times more potent than CO_2 [*IPCC*, 2014]. It is still disputable how much of the methane released from marine sediments reaches the atmosphere. However, emissions from the shallow water regions have obviously more potential to reach the atmosphere than gas escaping

from the deep-water regions. Recent methane input from melting permafrost to the atmosphere across the East Siberian Sea shelf is estimated to 17 Tg year^{-1} [*Shakhova et al.*, 2013]. Expressed in carbon dioxide equivalent, it is roughly 1/19 part of total anthropogenic methane pollution over one year, a significant contribution from just a single Arctic region.

General setting

Arctic shallow shelf regions are potentially capable of storing, capping and releasing significant amounts of methane. Definitions of the most important components in this Arctic system are given as follows:

- *Permafrost* is defined as a frozen ground that remains at or below 0°C for 2 or more years [*Osterkamp*, 2001]. However, due to saline pore water in sediments, permafrost may be cryotic (<0 °C) but unfrozen. Ice-bearing permafrost is studied by the authors within the current research.
- *Relict subsea permafrost* is former terrestrial permafrost, which has been flooded during a transgression cycle. It can be widespread throughout the shallow Arctic shelves [*Ruppel*, 2015](Figures 1,2).
- *Gas hydrate* is a crystalline ice-like substance, comprising molecules of gas in a cage-like ice structure. Gas hydrates are stable within the gas hydrate stability zone (GHSZ) at low-temperatures and high-pressures, that are reached in cold water in water depths >300 m [*Sloan*, 1998]. However, gas hydrates may also be stable under the shallow shelves, confined to the lower permafrost unit due to the reduced subsurface temperatures (*subpermafrost gas hydrates*)[*Ruppel*, 2015]. These hydrate-bearing systems are likely to exist today under the relicts of shallow water permafrost that seals large parts of the Arctic shelves (Figure 1).
- *Subglacial gas hydrates* could have developed during the LGM under high pressure conditions below the Barents-Kara Ice Sheet. In the present-day environment such subglacial gas hydrates can theoretically exist only under the glaciated margins of Greenland and Antarctica [*Wadham et al.*, 2012].

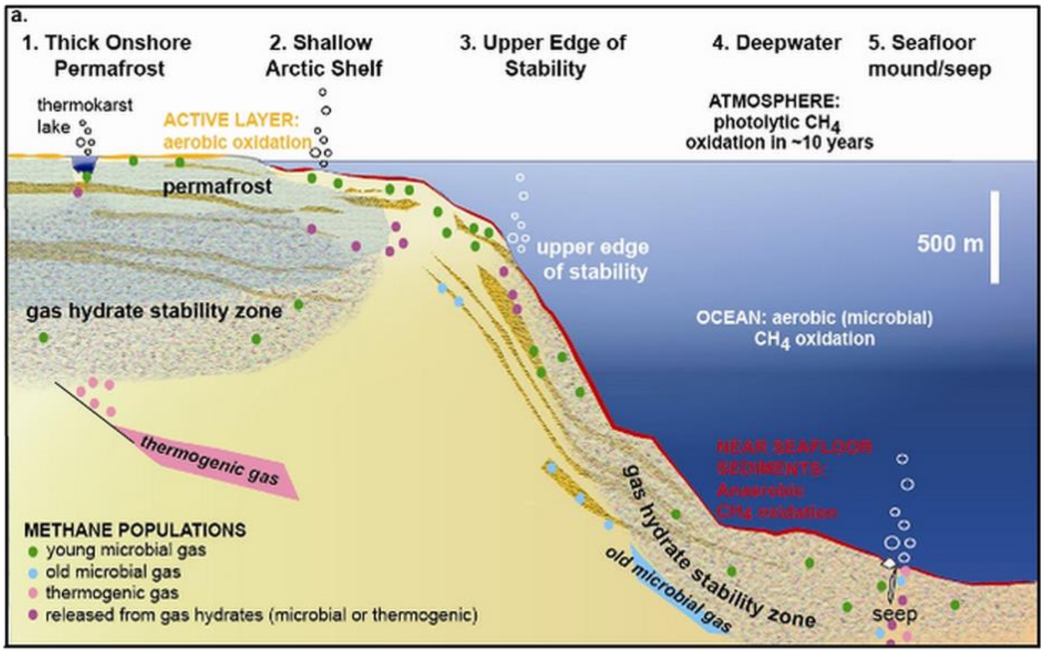


Figure 1: Schematic cross-section, showing interrelation between relict subsea permafrost and subpermafrost gas hydrate stability zone within the Arctic shelves. [*Ruppel*, 2011]

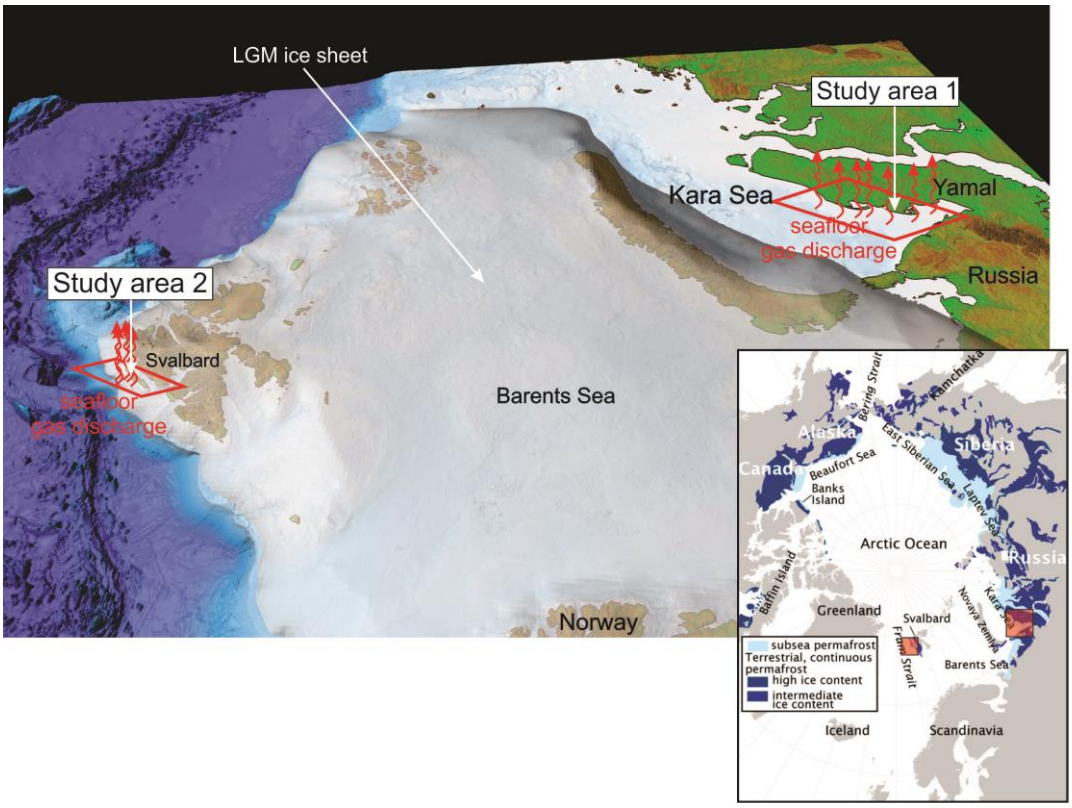


Figure 2: Location of the study areas relatively to the LGM ice sheet. Spatial distribution of diverse permafrost complexes in the Arctic [*Ruppel*, 2015] are shown in the lower right box.

During the LGM (~25-20 Ka) the global sea level dropped as much as 120-130 meters below the present sea level, exposing large shelf areas all over the world [*Fleming et al.*, 1998]. Extensive regions across the Arctic, including the whole Barents Sea and western Kara Sea, were covered with a roughly 2-3 km thick ice sheet [*Svendsen et al.*, 2004], creating a significant pressure on the area below. Beyond the ice sheet margins the Arctic shelves were exposed to deep freezing under subaerial conditions and low annual ground temperatures, dropping to as much as -20 °C [*Pavlidis et al.*, 1998; *Taylor*, 1991]. The two regions which are a focus of this research experienced very different environmental conditions during the LGM, which predetermined diverse scenarios of their subsequent evolution (Figure 2).

Evolution of relict subsea permafrost (Study area 1)

The South Kara Sea shelf comprises a deep petroleum province of 7-10 km thick Mesozoic and upper Cenozoic rocks which is a seaward extension of the West Siberian plate formations [*Stupakova*, 2011]. According to ice sheet reconstructions significant parts of the South Kara Sea, including West Yamal shelf in the east, were not glaciated during the LGM [*Polyak et al.*, 2008]. These conditions led to the development of a several hundred meter thick permafrost, extending out to the present ~120 m isobaths which constrained the LGM marine limit [*Rekant and Vasiliev*, 2011]. This thick permafrost layer was later inundated during the Late Pleistocene-Holocene transgression, forming subsea permafrost. Attempts to define the current extent of permafrost in the South Kara Sea were initially based on drilling data, which documented relict and modern permafrost in water depths up to 115 m offshore, although the majority of permafrost was found to be in wells with water depths <20 m [*GEOS*, 1997]. Some of the drilling sites offshore Kharasavey showed abrupt submerging of the subseabed permafrost surface in 5-7 m water depth. It can be suggested that the presence of the open taliks (local areas of thawed deposits within the permafrost)[*Rekant and Vasiliev*, 2011] developed in terrestrial conditions during the LGM, or in a marine environment under increasing nearshore water temperatures during the Holocene climatic optimum.

Permafrost exhibits significantly higher seismic velocities than non-frozen sediments. Ranging from ~2.5 to ~4.3 km s^{-1} (depending on the ice saturation)[*Brothers et al.*, 2012], permafrost velocities cause a high reflection coefficient at the interface between frozen and unfrozen sediments. As a result, the acoustic impedance contrast appears as a high-amplitude reflection on seismic data. This effect was utilized by *Rekant and Vasiliev* [2011] who mapped permafrost using the strong reflection in high-resolution seismic data. Based on this study, the approximate limit of the permafrost in the South Kara Sea is the 60 m isobaths. Extensive research on the physical and acoustic properties of permafrost from offshore South Kara and Pechora Seas was carried out by JSC "AMIGE" [*Bondarev et al.*, 1999; *Bondarev et al.*, 2002; *Rokos and Tarasov*, 2007; *Rokos et al.*, 2009]. This work indicated an abundance of subsea permafrost based on drilling and high-resolution seismic data, and showed its widespread relation to shallow gas accumulations.

Brothers et al. [2012] employed an alternative method to map subsea permafrost based on identification of elevated seismic velocities (>2.3 km s^{-1}) from pre-stack multichannel seismic data, which has been shown to be diagnostic of ice-bearing subsea permafrost in the U.S. Beaufort Sea. Her study showed that permafrost doesn't extend further than 30 km offshore and is generally limited by ~20 m isobaths. *Overduin et al.* [2012] used apparent electric resistivity to register the upper surface of ice-bonded permafrost in nearshore regions (<5 m water depths) of the Alaskan Beaufort Sea shelf. This study showed that ice-bearing sediments with higher resistivity occur in the bottom-fast ice zone (<2 m water depth). In greater depths, the permafrost surface abruptly submerge to at least 12 m below the seafloor.

Continuous permafrost is mostly or completely impermeable for gas [*Shakhova et al.*, 2010; *Yakushev*, 2009]. Thus it can trap methane, produced by bacteria (archaea), which reside in anaerobic deposits comprising the sedimentary cover (Figure 1). This genetic type of methane is called microbial [*Whiticar*, 1999; *Whiticar et al.*, 1986]. Similarly permafrost can seal thermogenic methane, migrating upward along faults and weak zones from deeper hydrocarbon accumulations (e.g petroleum sources.) [*Abrams*, 2005]. In permafrost-free areas with active fluid flow, or intensive bacterial methanogenesis gas bubbles may reach the seafloor and generate "gas flares" in the water column. Gas flare is a commonly accepted term for a hydroacoustic anomaly, appearing on the echosounder or high-frequency chirp records in response to gas bubbles [*Veloso et al.*, 2015]. Released from the seabed, gas bubbles change the physical properties of water. The signal backscattered from the bubbles appears on the echo sounder record as a distinct hydro-acoustic anomaly. Potentially the higher-frequency record is aimed to detect the bubbles of smaller size. The methodology of detection and analyzing hydro-acoustic anomalies from the single-beam echo sounder data and distinguishing between gas bubbles and fish schools is widely used and described in the literature, e.g. [*Granin et al.*, 2012; *Nikolovska et al.*, 2008; *Veloso et al.*, 2015; *Weber et al.*, 2014].

Article 1 describes an extensive front of gas flares in the water column offshore West Yamal Peninsula and explains processes related to their origin, including subsea permafrost evolution. The gas flare front is generally limited by the 20 m isobaths, and absent in the near shore shallow water corridor. A continuous permafrost layer may be a major factor governing the seafloor gas discharge in the study area. This study presents an alternative and new approach for defining the distribution of subsea permafrost in addition to previously used high-resolution seismic, conventional multichannel seismic and geo-electric methods.

Modeling of permafrost evolution

Permafrost modeling is an effective tool defining the current state of subsea permafrost sealing, and its evolution during the past, including its spatial extent, inner temperature distribution and location of the upper and lower boundaries. Modeling applied for the East Siberian Russian Arctic Seas, e.g. [*Romanovskii et al.*, 2005], or Canadian Oceanic Margins [*Majorowicz et al.*, 2013] generally showed a complex permafrost evolution, dependent on changes in the lower and upper boundary conditions in space and time. Sea level lowstand during the LGM provoked generation of a massive terrestrial permafrost layer, which in places reached 800-1000 m thickness. Such thick permafrost maintained an anomalously low subsurface temperature, contributing to favorable pressure-temperature conditions for GHSZ. Figure 3 shows positions of modeled temperature geotherms in the upper sediment cover relative to the theoretical curve for the hydrate phase boundary. Points of intersection between this curve and temperature geotherms define the depths of upper and lower GHSZ boundaries. In other words, GHSZ can exist under the long-standing ground temperatures <5 °C, applying the heat flow (60 mW m^{-2}) and conductivity of the sediments (3.4 and 2.1 W $m^{-1}K^{-1}$ for frozen and thawed sediments respectively) as for the Beaufort Mackenzie Basin [*Majorowicz et al.*, 2012]. Under these conditions potent intra- and subpermafrost GHSZ can expand to several hundred meters, reaching substantial subsurface depth of ~900 m (Figure 3).

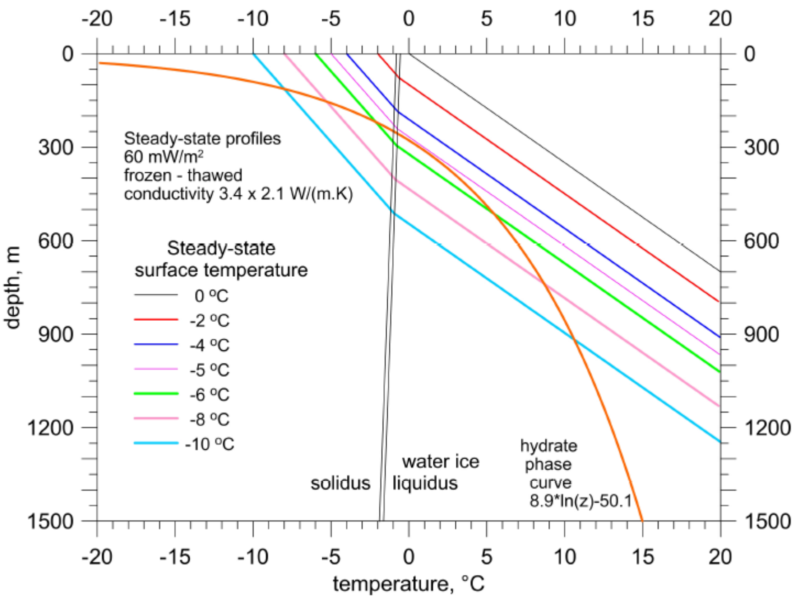


Figure 3: Modelled steady-state temperature profiles within the terrestrial permafrost in the Beaufort Mackenzie Basin relatively to the gas hydrate phase curve [*Majorowicz et al.*, 2012].

Reconstructions for the South Kara Sea and northern Yamal showed ground temperatures as low as -15 - -18 °C during the LGM. Subsequent inundation, which started ~20 Ka, has caused a temperature increase on the upper boundary of former terrestrial permafrost (e.g. by 15 °C according to *Shakhova et al.* [2010]). It resulted in a gradual leveling of the intra-permafrost temperature profile from the top, under the relatively warm bottom water temperature, and from the bottom due to the geothermal heat flux. Diminishing subpermafrost GHSZ provoked release of methane from the dissociating gas hydrates. To date, relict subsea permafrost has thawed under the deeper parts of the Arctic shelves, however large quantities of permafrost still underlie shallower shelf regions, which maintain favorable conditions for preserving gas hydrates [*Romanovskii et al.*, 2005; *Ruppel*, 2011].

The problem of state of matter transformation within a medium, i.e. freezing and thawing is believed to have been first explored by the Austrian physicist Joseph Stefan [*Stefan*, 1891]. The problem involves analysis of the water-ice phase boundary behavior under certain boundary conditions. The complexity of the problem is determined by heat transfer processes on the boundary between the frozen and unfrozen medium and its thermophysical properties. Generalized mathematical solution of this problem may be utilized for a wide range of tasks, including freezing and melting of the ground [*Sharbatyan*, 1974]. Implemented for permafrost modeling, it implies an infinite homogeneous medium with constant temperature conditions at its upper boundary and constant geothermal heat flux. The processes of permafrost aggradation and degradation are described by the Stefan's equations for thermal conductivity, under the changing upper boundary conditions, simulating transition from cold subaerial to relatively warm subsea conditions. Based on these equations, Article 2 presents modeling results of permafrost evolution offshore the West Yamal Shelf, introducing it as a highly-dynamic system. The model predicts present day subsea permafrost with its maximal thickness nearshore, tapering seaward. A lack of quality-controlled input data from the West Yamal Shelf (e.g. thermal conductivity and density of the sediments, or salinity of the pore water), and uncertain boundary conditions (temperature gradient measurements and paleo bottom water temperatures), required comprehensive sensitivity analysis, which eventually may be used as an individual tool for tentative estimations of thickness vs time scenarios of permafrost evolution across other Arctic shelves. Various modeling modifications show maximum (~390 m thick and limited to 100 m isobaths) and minimal (~120 m thick and limited to 17 m isobaths) present day scenarios. However the most plausible scenario for the West Yamal shelf shows permafrost with maximal nearshore thickness ~250m, tapering seaward and terminating at ~20 m isobaths.

Pingo-like features

Pingo-like features (PLFs) are conical mounds, discovered in permafrost and hydrate-bearing regions onshore and offshore across the Arctic [*Grosse and Jones*, 2011; *Mackay*, 1998; *Paull et al.*, 2007; *Rokos*, 2008; *Shearer et al.*, 1971; *Walker et al.*, 1985]. More than 11000 terrestrial pingos are predicted to exist at present in polar regions [*Grosse and Jones*, 2011]. PLFs reported from northern Asia, US and Canadian Arctic permafrost regions are circular build-ups reaching up to several hundred meters in diameter, comprising an ice core. Recently discovered deep craters onshore Yamal peninsula are <50 m wide and <50 m deep depressions and it is believed that they have formed as a result of collapsed PLF. Original uncollapsed PLFs are still recognizable on satellite images, acquired earlier in 2013 [*Bogoyavlenskiy*, 2014a; b]. Recently more PLFs and craters have been found in adjacent areas. The authors suggest that the PLF origin may be related to pressurized intra-permafrost shallow gas pockets accumulating at the top of deep-rooted fluid flow systems connected to gas chimneys. Destabilization of this system can provoke a severe gas blowout, leading to the formation of the observed craters [*Bogoyavlenskiy*, 2014b].

The formation mechanism of the offshore PLFs still remains elusive. The first of two dominating hypothesis infers that the ice core of the PLF may develop in terrestrial conditions during glacial stadials due to temporal fresh water supply [*Shearer et al.*, 1971]. An alternative scenario infers that PLFs could have formed in submarine conditions [*Bondarev et al.*, 2002; *Paull et al.*, 2007] as a reaction to the upward migration of pressurized gas below permafrost. Thus today's PLFs may indicate ongoing fluid flow, dissociation of gas hydrate (e.g. in the Beaufort Sea, described by *Paull et al.* [2007]), or pressurized intra-permafrost gas accumulation (e.g. in the Pechora Sea, described by *Rokos* [2008]). PLFs may constitute a geohazard, such as evidenced by *Bondarev et al.* [2002] when a drilling operation was forced to abort due to massive gas blowouts as a result of drilling a PLF in the Pechora Sea. The event deactivated the hydroacoustic positioning system of the drilling vessel and temporarily disabled the engines. Article 3 describes two PLFs discovered during the summer cruises 2012 and 2013 in the South Kara Sea, and speculates about their origin and their relation to permafrost and gas hydrates.

Ice sheet margin and GHSZ dynamics (Study area 2)

The West Svalbard Margin, as one of the most extensively studied regions in the Arctic, represents a natural laboratory for the study of ice sheet and GHSZ dynamics. The study area is located on the continental margin of the Eurasian plate some ~70 km eastward from the ultra-slow (~10 mm yr^{-1} total spreading rate) mid-ocean ridge system, e.g. [*Crane et al.*, 2001; *Engen et al.*, 2008; *Faleide et al.*, 2008]. The West Svalbard Margin represents the eastern side of the only existing deep-water gateway to the Arctic – Fram Strait, which opened ~11.2-13.7 Ma [*Engen et al.*, 2008; *Jakobsson et al.*, 2007; *Winkler et al.*, 2002]. The total thickness of the sediment cover in the area varies but reaches ~5 km at the lower continental slope [*Amundsen et al.*, 2011; *Forwick et al.*, 2009; *Ritzmann and Jokat*, 2003].

Contrary to the South Kara Sea, the West Svalbard shelf was covered with an ice sheet during the LGM, extending to the shelf break [*Hormes et al.*, 2013; *Ottesen et al.*, 2007]. Past ice ages have left significant footprints in the form of glacial sedimentary sequences, resulting in several hundred meter thick glacial deposits, the oldest of which are dated as ~2.7 Ma [*Mattingsdal et al.*, 2014]. Various indications of gas saturation in the sediments, including enhanced seismic reflections, gas chimneys, acoustic turbidity, are seen on high-resolution seismic data, defining a dynamic fluid flow in the study area (Figure 4) [*Hustoft et al.*, 2009; *Rajan et al.*, 2012; *Sarkar et al.*, 2012; *Vanneste et al.*, 2005].

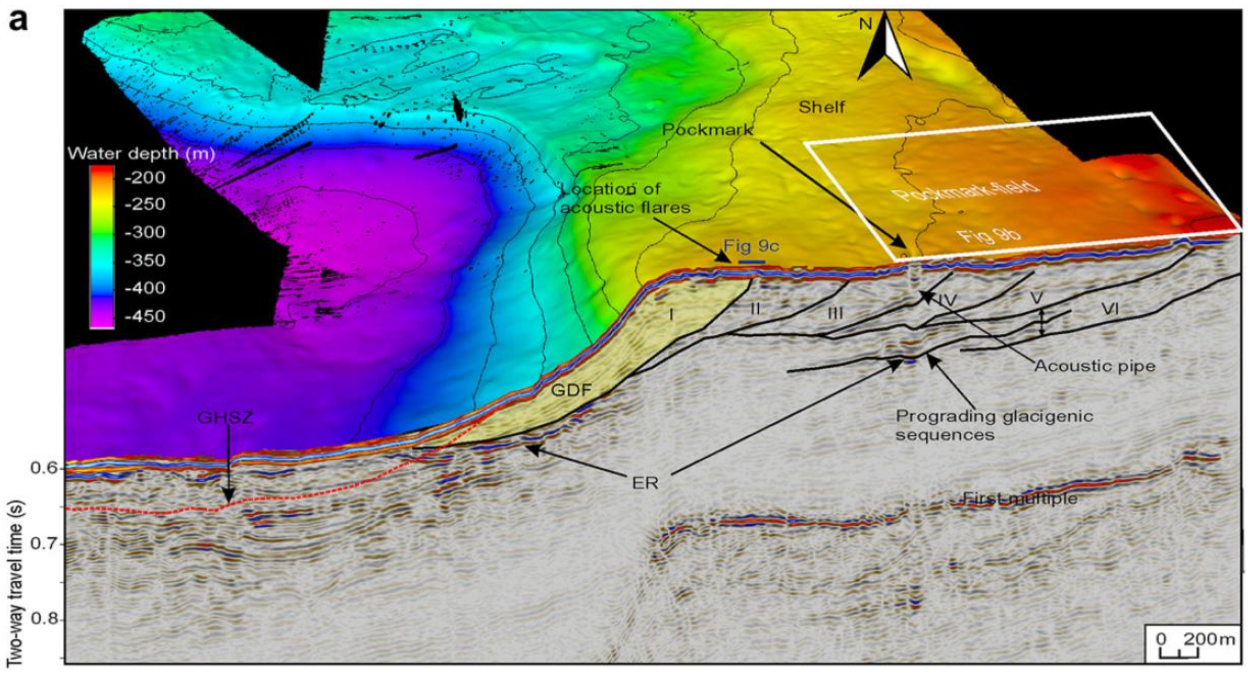


Figure 4: West Svalbard shelf and upper continental slope, showing subseabed glacigenic sequences and enhanced seismic reflections, pockmark fields and gas flares in the water column [*Rajan et al.*, 2012].

Pockmarks and gas flares

Rounded craters (pockmarks) indicate seabed expression caused by advective vertical fluid flow through sediments [*Hovland and Judd*, 1988]. Pockmarks may or may not release gas bubbles to the water column, indicating episodic fluid flow activity, or times of inactivity with no bubbles.

Numerous pockmark fields, discovered on the Norwegian-Barents-Svalbard margin are attributed to shallow gas reservoirs, thawing of relict subsea permafrost, modern dissociation of gas hydrates, or alternatively post-LGM dissociation of former subglacial gas hydrate, e.g. [*Damm et al.*, 2005; *Forsberg et al.*, 2007; *Hovland*, 1992; *Mienert et al.*, 1998; *Sahling et al.*, 2014]. Gas hydrates have been repeatedly reported from deeper water areas based on the presence of bottom-simulating reflector and seismic velocity analysis along the West Svalbard continental slope [*Hustoft et al.*, 2009; *Vanneste et al.*, 2005]. Geological sampling across the Vestnesa Ridge has revealed patches of gas hydrates in sediment cores [*Fisher et al.*, 2011; *Hustoft et al.*, 2009; *Panieri et al.*, 2014], where pockmarks indicate discharge of biogenic and thermogenic gas in the water column [*Smith et al.*, 2014]. The seafloor of fjords can be characterized by abundant pockmark fields, perforating the shallow shelf areas [*Forwick et al.*, 2009; *Ottesen et al.*, 2007; *Srikumar et al.*, 2014]. 546 of 1304 individual pockmarks, mapped in Isfjorden are confined to thrust faults, suggesting focused fluid flow migration [*Srikumar et al.*, 2014]. The pockmarks may have been generated after the deglaciation of the area, i.e. at ~11.3 ka, estimated for Grønfjorden pockmarks (southernmost branch of Isfjorden) [*Forwick et al.*, 2009] which is similar to the age of ~11 ka, estimated for the pockmarks from the Norwegian Channel [*Forsberg et al.*, 2007].

Longstanding widespread seafloor discharge of gas bubbles into the water column offshore Prins Karls Foreland (PKF) was repeatedly reported since their first discovery in 2008 [*Berndt et al.*, 2014; *Ferré et al.*, 2012; *Westbrook et al.*, 2009]. Single- and multibeam echosounder investigations of the area by different research vessels have recorded more than 1000 solitary active gas plumes over the last decade (Figure 5). Gas flares may be roughly divided into shallow-water (80-130 m) and deep-water (380-420 m) assemblages. The majority of deeper gas flares line up along the bottom of GHSZ pinch out area on the seabed in water depth of ~396 m. Therefore, present-day decomposition of gas hydrate is the preferred theory for the gas release, though no gas hydrates have been documented from this water depth [*Berndt et al.*, 2014; *Sahling et al.*, 2014; *Westbrook et al.*, 2009]. Shallow water gas flares, extending far beyond the modern GHSZ theoretically cannot be caused by gas hydrate dissociation. *Sahling et al.* [2014] have suggested that gas may leak from melting subsea permafrost, or alternatively it may migrate along the deep-seated Hornsund fault zone [*Damm et al.*, 2005].

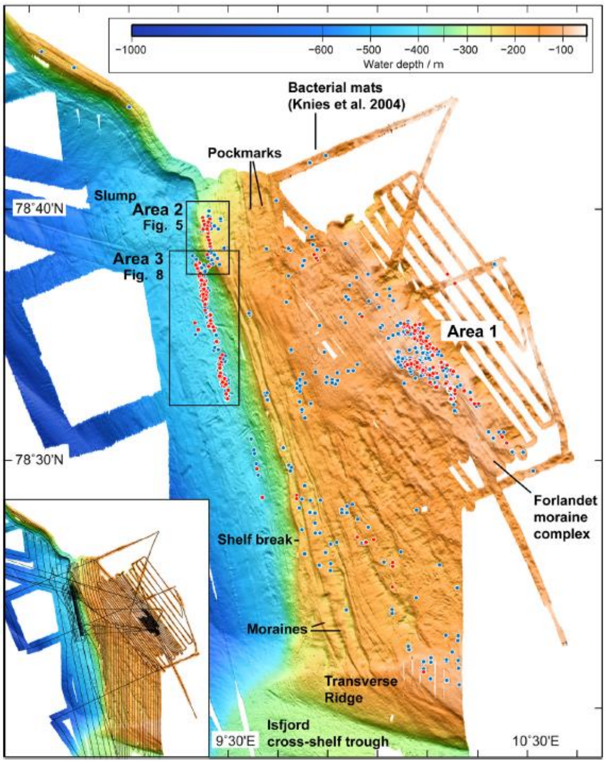


Figure 5: Red and blue dots indicate solitary shallow- and deep-water gas flares observed on the seafloor offshore West Svalbard over the last years [*Sahling et al.*, 2014].

Shallow water gas discharge offshore PKF, has been annually monitored over the last 8 years and is undoubtedly continuous. Attempts have been made to quantify the initial amount of gas (predominantly methane), leaving the upper sediments into the water column [*Gentz et al.*, 2014; *Greinert et al.*, 2012]. Natural methane escape from the seabed, through the water column, is of special interest for the climate-change research community [*IPCC*, 2014].

LGM ice sheet extent and its control on gas hydrate and fluid flow

Current research introduces one important mechanism which could have switched on shallow water fluid flow systems. Here we refer to the late Weichselian ice sheet, which covered large parts of the West Svalbard shelf during the LGM (Figures 2, 6). Various research results document the maximum extent of the grounded ice sheet in our study area, towards the shelf break (~150 m water depth) [*Hormes et al.*, 2013; *Landvik et al.*, 2005; *Ottesen et al.*, 2007]. Ancient marine limits and ^{10}Be exposure dating of glacial erratics on PKF have helped to constrain glacial isostatic loading (~105 m for PKF and ~128 m for western Spitsbergen margin) and minimal ice sheet elevation (~473 m for

PKF) [*Andersson et al.*, 1999; *Forman*, 1990; *Landvik et al.*, 2013]. A ~120 m sea level drop during the LGM should have controlled the depth of the subsea GHSZ pinch-out on the continental slope. At the same time, high pressure from the ice sheets on land and negative temperatures at the base of an ice sheet could have generated subglacial GHSZ beneath the present shelf, west of PKF. Article 4 represents a compilation of observations and integrates a comprehensive dataset including ice sheet and subsea/subglacial GHSZ modeling along a transect from West Spitsbergen, across the shelf, to the continental slope. Ice sheet configurations and glacial-isostatic rebound from marine and land observations have been incorporated into an empirical steady state model. Modeling output shows that not only subglacial and subsea GHSZ existed during the LGM but also an upper margin window for methane release. The GHSZ subsurface thickness, exceeding 800 m below Forlandsundet, decreased westward, where it abruptly tapered out under the modern Forlandet moraine complex. Compared to the subglacial GHSZ, the subsea GHSZ was considerably thinner, reaching a maximal thickness of ~160 m under the most submerged western segment of the study area. Since ~20 ka the area has undergone continuous deglaciation, triggering dissociation of subglacial gas hydrates. The process is envisioned as a potential mechanism for pockmark formations offshore West Svalbard in postglacial times.

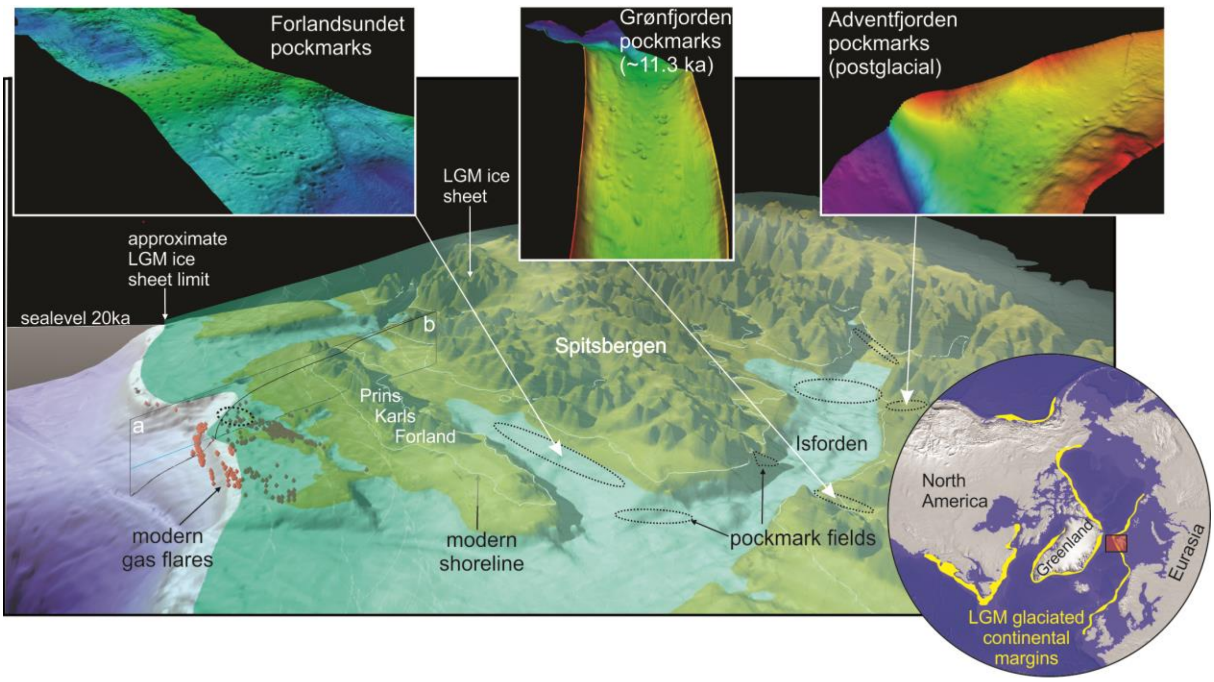


Figure 6: Distribution of gas flares (red) and pockmark fields (dotted ovals) in relation to the modelled West Svalbard ice sheet margin and fjords (Figure 3 from Article 4 of this thesis).

South Kara Sea versus West Svalbard Margin

The two studied regions both exhibit similar processes of extensive modern gas discharge from the seafloor. Based on the observations, both regions show leakage of gas that occurs continuously over at least several years. At the present time a gas flare front exists in water depths >20 m within an area of ~7500 km^2 over the West Yamal Shelf. The West Svalbard gas flares show more than 1000 single flares, which occur in the water depths from ~80 to ~410 m over an area of ~1000 km^2. However, more than 900 currently inactive pockmarks have been observed on the shelf and within the fjords, indicating that gas could have been leaking over a significantly larger area in the past. In both study areas the process of seafloor gas discharge seems to have been controlled by major environmental changes following the LGM, including ice sheet retreat, temperature increases and eustatic sea level rise. However, local mechanisms, which ultimately triggered the gas discharge in each particular region, have been different.

At the West Yamal Shelf methane is released from thawing subsea permafrost, trapped during the LGM inside or beneath the inundated former terrestrial permafrost. Elevated methane concentrations were measured in the bottom water at depths >20 m, which approximately confines the seaward extent of continuous permafrost in this area. Modeling predicts up to 250 m thick permafrost, still underlying shallow water shelf regions off West Yamal peninsula.

At the West Svalbard shelf and continental margin gas leakage has been controlled by the LGM ice sheet. High pressure and low temperature led to subglacial permafrost and an increase in the gas hydrate stability zone. This created a solid impermeable cover, restricting surface gas discharge. Post-LGM ice sheet retreat initiated thawing of permafrost and potential dissociation of gas hydrates, releasing the methane stored in the previously stable subglacial system. Gradual shoreward ice sheet retreat may explain widespread orientations of pockmark fields, discovered all the way from the shelf break to the inner fjords. Some of these pockmarks in the fjords were previously dated and show an age consistent with the major period of deglaciation along the West Svalbard margin.

Summary of articles

Article 1:

Alexey Portnov, Andrew J. Smith, Jürgen Mienert, Georgy Cherkashov, Pavel Rekant, Peter Semenov, Pavel Serov, Boris Vanshtein (2013). **Offshore permafrost decay and massive seabed methane escape in water depths > 20 m at the South Kara Sea shelf.** *Geophysical Research Letters*, VOL. 40, 1–6, doi:10.1002/grl.50735.

In Article 1 we studied the West-Yamal Shelf in the Kara Sea, offshore Western Russia. And present new high-resolution seismic data and gas geochemical data from 2012 cruises operated by I.S. Gramberg VNIIOkeangeologia. In the high-resolution seismic data (2-16 kHz), we found extensive acoustic anomalies in the water column, which we interpreted to be gas (bubble) flares rising from the seafloor. These anomalies were widespread throughout the study area, but seemed to be limited to water depths > 20 meters below sea level. In one case, we observed a focused, gas-seepage site in ~6 m water depth that reached close to the sea surface. This seepage site, however, was not detected during subsequent passes over the area. It is somewhat speculative to explain why the majority of hydroacoustic anomalies are limited to the 20 m isobaths. Based on borehole information we favour that permafrost is still present below the seafloor at shallower depths providing an impermeable layer through which gas and other fluids cannot migrate.

We also detected acoustically transparent zones in sediments in the upper 2-5 meters below seafloor. We interpret these acoustic anomalies to be caused by the presence of gas. They were widespread throughout the study area and occurred in water depths ranging from 0-60 meters below sea level. The presence of these acoustic anomalies in the subseabed show no connection to the distribution of acoustic anomalies detected in the water column. Geochemical analysis of pore water samples from sediment cores reveals that acoustically transparent zones have methane concentrations that are elevated if compared to none-transparent zones. In addition to the more widespread and disperse acoustically transparent zones, we discovered two prominent transparent mounds that are 1.5-2 km wide and 10-15 meters high above the seafloor. These mounds are surrounded by layered sediments. Study of these remarkable seafloor features provided targets for further research in the near future.

Article 2:

Alexey Portnov, Jurgen Mienert, Pavel Serov (2014). **Modeling the evolution of climate-sensitive Arctic subsea permafrost in regions of extensive gas expulsion at the West Yamal shelf.** *Journal of geophysical research: Biogeosciences*, 119, 2082–2094, doi:10.1002/2014JG002685

Modeling of the permafrost at the West Yamal shelf allowed describing its evolution from the Late Pleistocene to Holocene. During the previous work we detected extensive emissions of free gas into the water column at the boundary between today's shallow water permafrost and deeper water discontinuous or none-permafrost areas. The gas expulsions formed seismic and hydro-acoustic anomalies on the high-resolution seismic records across this boundary. We suggested that in water depths <20m continuous ice-bearing permafrost plays a major role as a seal through which gas can not migrate. **In Article 2** we integrate1D modeling results of relict permafrost distributions with these field data from the South Kara Sea. Modeling results suggest a highly-dynamic permafrost system that directly responds to even minor variations of lower and upper boundary conditions, e.g. heat flux from below and/or bottom water temperature changes from above. We present several scenarios of permafrost evolution and show that potentially minimal modern extent of the permafrost at the West Yamal shelf is limited by ~17 m isobaths, whereas maximal probable extent coincides with ~100 m isobaths. The model also predicts seaward tapering of relict permafrost with its maximal thickness 275-390 m near the shore line. We present a detailed sensitivity analysis, which defines the ranges of modeling results depending on changes of input parameters (e.g. geothermal heat flux, bottom water temperature, porosity of the sediments). The modeling results relate well to corresponding field data, providing crucial information about the modern permafrost conditions, current location of the upper and lower permafrost boundaries and its possible impact on both the hydrosphere and atmosphere in a warming Arctic.

Article 3:

Pavel Serov, Alexey Portnov, Jurgen Mienert, Peter Semenov, Polina Ilatovskaya. **Methane release from pingo-like features across the South Kara Sea shelf, an area of thawing offshore permafrost.** *Journal of geophysical research: Earth surface*, in review.

We used high-resolution seismic data, acquired during the cruise of I.S. Gramberg VNIIOkeangeologia at the West Yamal Shelf in 2012 to describe distinct circular mounds with a height of ~5-9 m above the seafloor. These features bear striking resemblance to the pingo-like features that have been studied on the Beaufort Shelf, e.g. [*Paull et al.*, 2011; *Shearer et al.*, 1971], and Pechora Sea [*Rokos et al.*, 2009]**.** Each mound presents an acoustically transparent unit, bounded by sections of layered sedimentary reflections on their flanks. These data served to select gravity coring sites to sample and geochemically analyze the sediments at the flanks, crests and areas adjacent to the mounds.

Article 3 presents sediment core analysis obtained from two pingo-like features in the South Kara Sea. The analysis show elevated methane concentrations (up to ~120000 ppm) at PLF 2 and methane concentrations generally lower than the background at PLF 1. Hydrocarbon gas analysis demonstrate a well pronounced microbial gas signature, expressed in low wet gas fraction, δ13CCH4 values ranging from -55,1‰ to -88,0‰ and δDCH4 values varying from -175‰ to -246‰. Studies of n-alkanes and isoprenoids do not indicate any presence of migrated thermogenic hydrocarbons. As a result fluid discharge from deeper hydrocarbon reservoirs may be absent. Low content of total organic carbon restricts extensive methane generation in anoxic sediments. High methane concentrations at PLF 2 are seen as a result of production and migration of microbial gas.

We integrated the results of geochemical and geophysical studies with our modeling of permafrost evolution at the West Yamal Shelf. The South Kara Sea pingo-like features occur within an area of discontinuous relict subsea permafrost, providing a possible scenario for their build-up mechanism. We suggest the scenario in which pingo-like features form as a direct consequence of extrusion of frozen sediments, governed by the release of over-pressured subpermafrost methane accumulations.

Article 4:

Alexey Portnov, Sunil Vadakkepulyambatta, Jurgen Mienert, Alun Hubbard. **Ice-sheet driven methane storage and release in the Arctic.** Submitted to *Nature Geoscience.*

Our study integrates observations and modeling to document the effects of the interplay between Last Glacial Maximum ice sheet extent, glacio-isostatic loading, eustatic sea level change and ocean water mass variability on the stability of an Arctic gas hydrate reservoir. **In Article 4** we model the variability and reaction of the gas hydrate stability zone in one of the most climate sensitive regions, NW-Svalbard. Based on the existing field observations of fluid flow release distribution, we model the impact of the Last Glacial Maximum ice sheet and the rapid alteration of ground temperature regimes induced by the transition from subglacial to subsea environmental conditions. We implement these data in an empirical steady-state gas hydrate stability zone modeling for the Last Glacial Maximum. Finally, we use recently reprocessed multi-beam and existing single-beam echosounder data to provide a case for the potential relationship between offshore gas discharge and glacial as well as postglacial GHSZ evolution.

Based on The Last Glacial Maximum steady-state model, the gas hydrate stability zone subsurface thickness, exceeding 700 m below Forlandsundet, decreased westward, where it abruptly tapered out under the modern Forlandet moraine complex. The model predicts an area of "no gas hydrate stability zone" west of Prince-Karls Foreland, caused by a reduced ice-sheet thickness and thus insufficient pressure at the ground surface. The model shows that not only subglacial gas hydrate stability zone existed during the Last Glacial Maximum but also an upper margin window for continuous methane release.

The West Svalbard margin is not only a part of an extended chain of glaciated Arctic margins, but also have similarities to the US east formerly glaciated margins where today thousands of active gas flares exist. Thus the understanding of the dynamic processes of natural greenhouse gas release when coming out of the ice age is crucial because it demonstrates the potential impacts we can have from ice sheet melting of Greenland and Antarctica in a future global warming scenario.

Future research

Creation of a time-dependent numerical model of the NW-Svalbard and Barents Sea ice sheet retreat seems to be one of the most consequent developments of our steady-state scenario. The ice sheet dynamics will apparently allow defining the evolution of subglacial permafrost and gas hydrate stability and its decreases throughout the post-LGM period. The response time span under a changing surface temperature and pressure condition is one of the crucial parameters, required to determine the rate and timing of the decomposing GHSZ and permafrost for example off West Svalbard. The subsea fluid flow system, which was very likely activated by the retreating ice sheet, and is still actively leaking gas, may be fueled by extensive deeper gas reservoirs below.

Field observations, including water column studies may discover new fields of gas flares, where no gas flare search has been previously carried out. Potential ^{14}C and $\delta^{13}C$ analysis of carbonate crusts from pockmarks, dating of sediment core sections, coupled with high-resolution 3D seismic-stratigraphic reconstructions may allow to improve the model.

Further permafrost and gas hydrate research in the South Kara Sea can be focused on new hydro-acoustic surveys and drilling, including single-beam and multibeam echosounding and high-resolution seismic data acquisition in the western segment of the South Kara Sea. Sediment and water sampling at potential pockmark/PLF structures is essential for gas geochemical and sedimentological analysis. We envision that the deep-water (<400 m) East-Novozemelsky Trough, which underlay the eastern edge of the Barents-Kara LGM ice sheet, and relatively shallow (40-70 m) rises at the eastern flank of the trough are among the first priority sites for further studies of Kara Sea permafrost and gas hydrate systems. Personal conversations with the representatives of the oil and gas companies, operating within the Prinovozemelsky 1 and 2 licensed blocks in the South Kara Sea, showed a high scientific value of this study area for understanding the coupling between permafrost and gas hydrates. Unfortunately, in the foreseeable future this region seems to be inaccessible for the scientific community due to new regulations, which prohibit publishing any data from these licensed areas. Therefore, research activities in the South Kara Sea can be more recommended for academic research.

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Appendix

Conferences, workshops and meetings

2015 ICAM, Trondheim, Norway. Oral report: "Arctic greenhouse gas methane storage during LGM and its release across a formerly glaciated polar margin".

2015 AMGG workshop, Tromsø, Norway. Oral report: "Massive methane release from the formerly glaciated western Svalbard margin".

2015 EGU, Vienna. Oral report: "Climate-sensitive subsea permafrost and related gas expulsions on the South Kara Sea shelf. Field studies and modeling results".

2014 United international conference "Minerals of the ocean-7 and deep sea minerals and mining-4", Saint-Petersburg, Russia. Oral report at Gas Hydrate section.

2014 AMGG workshop, Tromsø, Norway. Oral report: "Modeled evolution of subsea permafrost associated with extensive gas escape offshore the West Yamal shelf".

2014 INTSOK - 12th annual Russian-Norwegian Oil and Gas Conference. Participant. Tromsø, Norway.

2013 AGU, San Francisco, USA. Poster: "Fluid-flow dynamics in association with subsea permafrost and possible gas hydrates in the Kara Sea".

2013 3PArctic Conference, Stavanger, Norway. "The polar petroleum potential conference and exhibition". Oral talk and poster: "Fluid-flow dynamics in association with subsea permafrost and possible gas hydrates in the Kara Sea".

2013 AMGG workshop, Tromsø, Norway. **"**Offshore permafrost decay and massive seabed methane escape in water depths >20 m at the South Kara Sea shelf**"**.

2013 PERGAMON workshop, Helsinki, Finland. "Subsea permafrost, gas seeps and gas hydrates in the Arctic: available data and perspective projects". Oral report: "New HRS data indicating interaction of gas migration processes and subsea permafrost at West Yamal shelf (Kara Sea)".

2012 United international conference "Minerals of the ocean-6 and deep sea minerals and mining-3", Saint-Petersburg, Russia. Oral report

Cruises

2014, October. Norwegian Sea, West Svalbard Margin (Scientific cruise of University of Tromsø and Centre for Arctic Gas Hydrate Environment and Climate. Hydro-acoustic, 2D seismic and geological investigations in the areas of active gas plumes).

2014, June. Norwegian Sea, West Svalbard Margin (Scientific cruise of University of Tromsø and Centre for Arctic Gas Hydrate Environment and Climate. Hydro-acoustic, 2D seismic and geological investigations in the areas of intensive gas plumes).

2013, August. Kara Sea (Supervisor in Rosneft and ExxonMobil joint project. Acoustic survey at the potential oil and gas fields)

2012, August. Kara Sea, West Yamal Shelf (Complex gas-geochemical and high-resolution seismic survey)

2012, June. Norwegian and Barents Sea (Scientific cruise of University of Tromsø, seismic survey 3D)