Polarforschung 68: 221 - 225, 1998 (erschienen 2000)

Temporal Variability of Subsea Permafrost and Gas Hydrate Occurrences as Function of Climate Change in the Laptev Sea, Siberia

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THEME 12: Gashydrates and Permafrost, Onshore and Offshore

Summary: Reflection- and refraction seismic surveys of the Laptev Sea shelf have revealed the existence of 300-800 m thick subsea permafrost today. Its development is apparently associated with marine regressions during the maxima of the last cold stages. Numerical modelling of permafrost aggradation and degradation suggest the continued presence of subsea permafrost throughout the last two cycles of warm and cold stages despite regionally varying and at places elevated heat flow from depth in this area of active tectonic movements. During warm stages the subsea permafrost acquires a nearly isothermal state. The stability field of the gas hydrate zone expands to near the surface during cold stages. Its upper boundary receeds rapidly to greater depth with the advent of a warm stage. An additional complicating factor in this scenario is the development of a probably meandering river system (fed by the Lena River and other rivers) across the shelf during times of marine regression. The rivers thaw partially or completely the underlying permafrost due to their high thermal capacity. Taliks, having developed in this way, may open pathways for gas migration from greater depth. The apparent lack of taliks observable today points to refreezing of freshwater sediments during marine transgressions under the influence of cold marine bottom waters, whose temperatures today are known to range between -1.5 °C to -2.4 °C.

INTRODUCTION

The 10-100 m shallow waters of the Laptev Sea recede from the shelf area whenever sea levels drop worldwide during cold stages. As a consequence of the then perennial cold conditions - mean annual temperatures of -10 °C to -20 °C prevail - thick permafrost develops under the former sea bed. Theoretically, the permafrost should eventually degrade with each marine transgression associated with the re-occurrence of warm stages. However, even today, the ~-2 °C cold bottom waters of the Laptev Sea are too cold to allow permafrost degradation to any great extent.

The occurrence of submarine permafrost in the Laptev Sea (SOLOVIEV et al. 1987, KASSENS et al. 1994, Hinz et al. 1998, DELISLE 1998b) presents a number of unique problems, some of which this paper attempts to contribute to:

- variability of the subaereal/subsea permafrost as function of climate and heat flow from depth,
- variability of the temperature field of the subsea permafrost during times of marine transgression,
- the role of newly developing arms of the Lena River across dry-fallen portions of the shelf and geothermal conditions during cold stages in the shelf sediments, and
- changes in thickness of a suspected gas hydrate layer.

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Manuscript received 13 January 1999, accepted 15 June 1999

Mathematical simulation of permafrost growth and degradation

The accurate description of the heat exchange at moving phase change boundaries of permafrost layers is the key element in the numerical simulation of permafrost growth and degradation. The principal approach chosen here is based on the small scale discretization of the space, through which the permafrost boundary will migrate. The mathematical approach chosen here is described in more detail in DELISLE (1998a). The temperature field of the space containing the permafrost zone is calculated using the equations (1) and (2):

$$dT/dt = \lambda/\rho c \; \mathrm{div}\,(\mathrm{grad}\, T) \qquad (1)$$

$$\lambda(dT_1/dz - dT_2/dz) = L\, I_c\, dZ/dt \qquad (2)$$

with

λ	= thermal conductivity	(W/mK)
ρ	= density of rock	(kg/m^3)
c	= specific heat capacity of rock	(Ws/kgK)
L	= latent heat	(Ws/kg)
I_c	= amount of ice per m^3 sediment	(kg/m^3)
dZ/dt	= rate of movement of phase change boundary	($m\ s^{-1}$)
t	= time	(s)
T	= temperature	(K)
dT_1/dz	= temperature gradient out of the element containing the phase change boundary	
dT_2/dz	= temperature gradient into the element containing the phase change boundary	

Equation (2) describes the rate by which latent heat is lost or gained by each element containing the phase change boundary. The time dependent change of the temperature field is calculated by an explicite finite difference scheme. Equation (2) can be used for the calculation of the thermal behaviour of permafrost layers and gas hydrate layers alike, if for each medium the appropriate value for latent heat is incorporated. In 2-D calculations, the heat flow through the lateral boundaries of the element containing the phase change boundary must be considered in addition.

For simplicity, the temperature at the soil surface is equated with the mean annual air temperature (T_{mean}) at the Earth's surface according to the applied climatic curve. The annual fluctuation of the soil temperatures within the uppermost meters (active layer) is not considered.

The phase change boundary for ice in sediments was set at 0 °C. The actual temperature of sediment freezing depends on the composition of the sediments and can be depressed to negative values (NIXON 1985). We assume that the top layers of the Laptev Sea shelf were built predominantly by freshwater deposits during the last cold stages, in which the Lena river did presumably distribute its sedimentary load via numerous side arms across the shelf. The actual phase change boundary in the marine environment today might be slightly below 0 °C. The bottom waters of today with temperatures between -1.5 °C to -2.4 °C are, however, apparently too low to degrade the top of the submarine permafrost. Repeated sampling of top sediments with a gravity corer by BGR in 1997 resulted in core lengths of only decimeters. In several cases, interstitial ice was observed at the bottom of only dm-long cores (e.g. at 77° 04.1'N, 126° 11.6'E).

A uniform thermal conductivity of 2.2 W m^{-1} K^{-1} is assumed for the frozen and unfrozen underground, corresponding to slightly compacted silty to sandy sediments (see i.e. KAPPELMEYER & HAENEL 1974). A uniform water content of 20 % in the sediments is assumed to participate in the phase change. An additional, but small content of water will remain unfrozen in permafrost depending on the type of sediment (NIXON 1985).

THE MODELS

Permafrost thickness as function of climate and terrestrial heat flow

The model is formulated in the same way as previously presented by DELISLE (1998b). The model incorporates a climate curve for the last 160,000 years which was adapted and modified from a paper by MAXIMOVA & ROMANOVSKY (1988). The curve was modified for the time periods of 125-70 Ka and 8-0 Ka before present. During these time periods, complete flooding of the shelf area by the Laptev Sea with a water temperature of -1.5 °C at the sea floor (assumed as the mean annual temperature of the sea water) is assumed. These time periods are equivalent to a massive warming of the top of the permafrost layer by the incursion of sea water. The chosen time periods of flooding events of the shelfs are admittedly to some extent of speculative nature. The onset of subaerial conditions depends on the onset of large scale glaciation in the Northern hemisphere as the cause for the worldwide lowering of the sea level.

The model was run with assuming subsequently six different terrestrial heat flow values ranging from 40 mW m^{-2} in steps of 10 mW m^{-2} to 90 mW m^{-2}. The resulting variation in permafrost thickness as function of climate and basal heat flow was calculated. The results are shown in Figure 1.

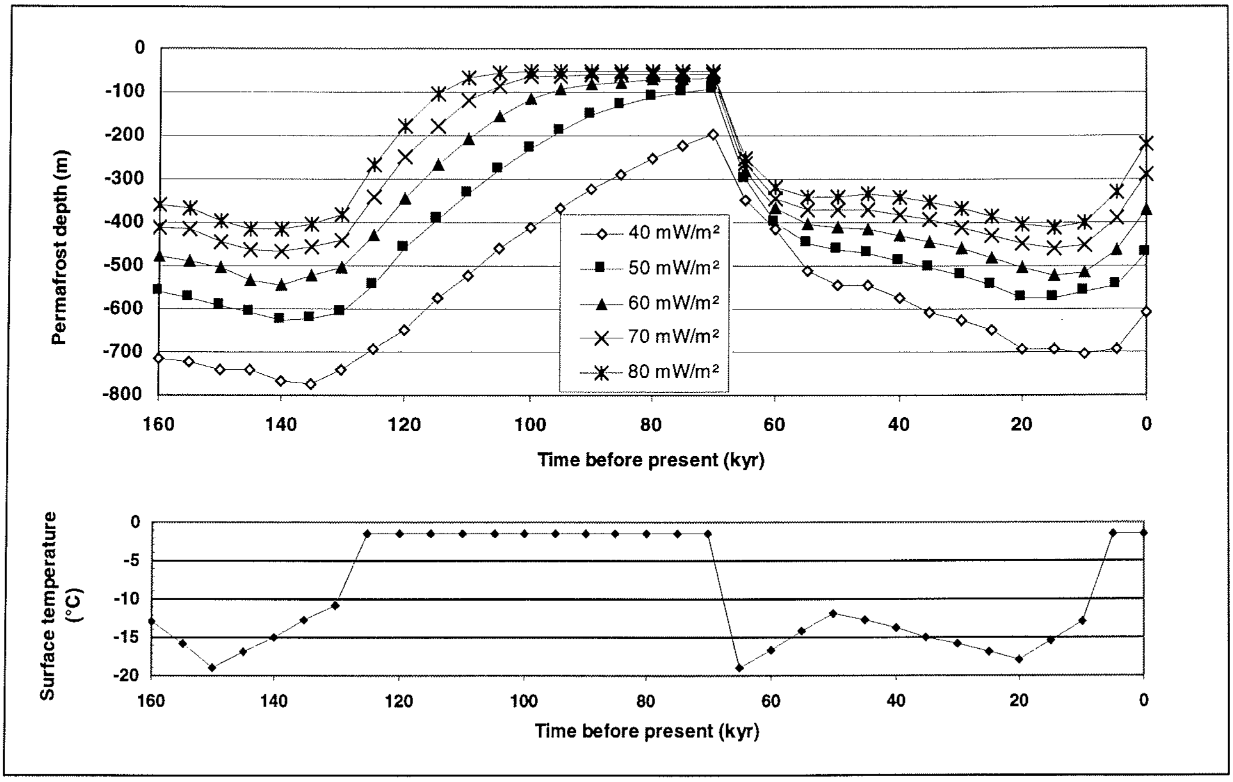

Fig. 1: Numerical simulation of permafrost thickness in the Laptev Sea as function of climate and terrestrial heat flow (top). Assumed climatic course in the Laptev Sea region during the last 160,000 years. Mean annual surface temperature (sea bottom) at times of marine transgression is assumed at -1.5 °C (bottom).

Previous studies by BGR (HINZ et al. 1998) suggest an about 300 m thick submarine permafrost to rest atop the currently extending continental crust under the central Laptev Sea and a likely permafrost thickness of up to 800 m in the vicinity of Kotel´ny Island. As the numerical result clearly demonstrates, a permafrost thickness of 300 m can be best explained by assuming a current heat flow value of 70 mW m^{-2} and likewise, 800 m thick permafrost by the presence of terrestrial heat flow values of 35-40 mW m^{-2} typical for old continental shields.

This result implies a transition from low heat flow values (old shield material) to high heat flow (continental crust under extension) to exist along an E-W-profile from Kotel'ny Island towards the center of the Laptev Sea about 150 km to the west.

Thermal effect of marine transgressions on the permafrost temperature field

The degradation of permafrost after the marine transgression forces near 0 °C-temperatures on the upper boundary of the permafrost zone. This process was analysed on the basis of the following model: An area with the mean annual temperature of initially –17 °C at the surface is invaded by seawater with a mean annual temperature of -1.5 °C. The regional heat flow from depth in the area is 70 mW m^{-2}, equivalent to an initial permafrost thickness of 534 m. The mean thermal conductivity of the sediments is 2.2 W m^{-1} K^{-1} and the pore water porosity (frozen and unfrozen) is 20 %.

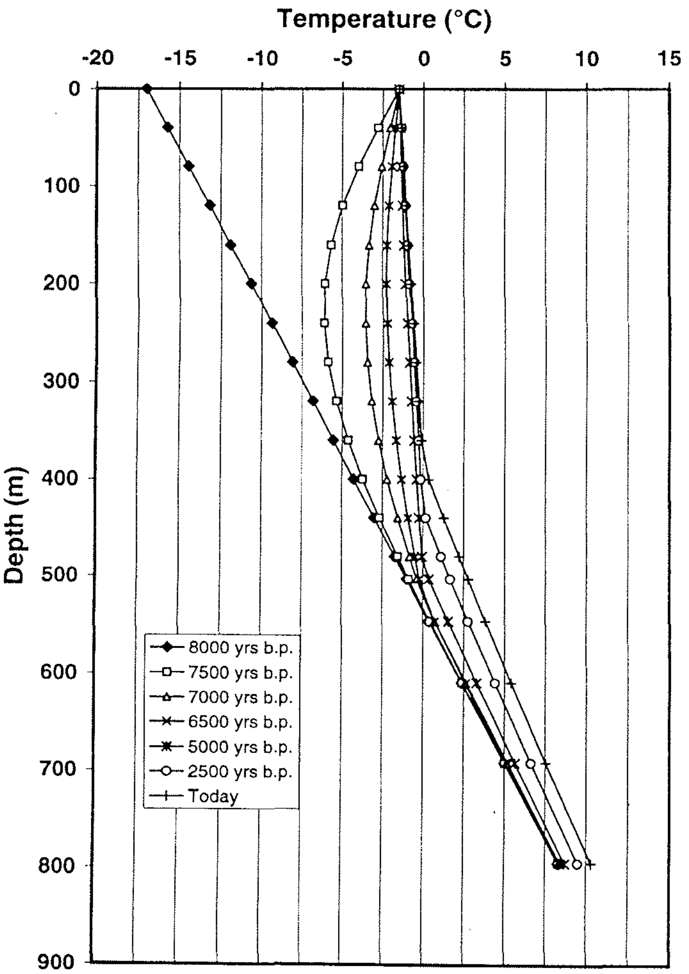

Fig. 2: Permafrost degradation after a marine transgression 8000 years ago. Shown is the changing temperature field as function of depth and time developing toward an isothermal state today.

The numerical calculation of the evolving temperature field within and below the permafrost layer after the marine transgression suggests a evolution to practically isothermal conditions within ~3000 years (Fig. 2). The further degradation of permafrost now depends critically on the melting point of the frozen fluids within the sediments. The fact that the submarine permafrost today, typically exposed to bottom water temperatures of less than -1.5 °C, reaches frequently to within 1 dm of the seabed, points to a low salinity content of the frozen sediments.

Thermal effects of rivers on the permafrost layer

The Lena River discharges currently its waters across a large deltaic complex into the Laptev Sea. During times of marine regressions, its waters are forced to form new river beds directed to the northwards retreating coastline. These river arms will shift back and forth with time across the shelf area. Running fresh water, in particular during summer time, has sufficiently heat stored to act as a perennial heat source capable to degrade underlying permafrost. The same is true for lakes, which have not frozen down to their base in winter.

With respect to rivers, a 2-D numerical analysis was attempted to estimate the time scale necessary to completely degrade permafrost under a newly formed river bed. A scenario in an area with the following characteristics was chosen:

- mean annual temperature of –14 °C at t=0
- regional heat flow = 60 mW m^{-2}
- pore water porosity of the shelf sediments = 20 %
- thermal conductivity of sediment = 2.2 W m^{-1} K^{-1}
- fully developed permafrost (initial thickness = 513 m)

and a climate deteriorating at a rate of -0.5 °C per 1000 years is invaded by four river arms of width 500 m, 1000 m 3000 m and 200 m over a profile length of 13 km. The position of the rivers relative to each other is shown in Figure 3. The mean annual temperature of the bottom waters of the rivers is +2 °C. Calculated was the time necessary to completely degrade the permafrost under the river beds. The analyzed scenario is of highly idealized nature and is only intended to offer approximate values for the sought for quantity.

As Figure 3 shows, the 200 m and 500 m wide rivers are unable to degrade the underlying permafrost within 6000 years. The 1000 m wide river requires slightly over 6000 years, the 3000 m wide river about 3000 years.

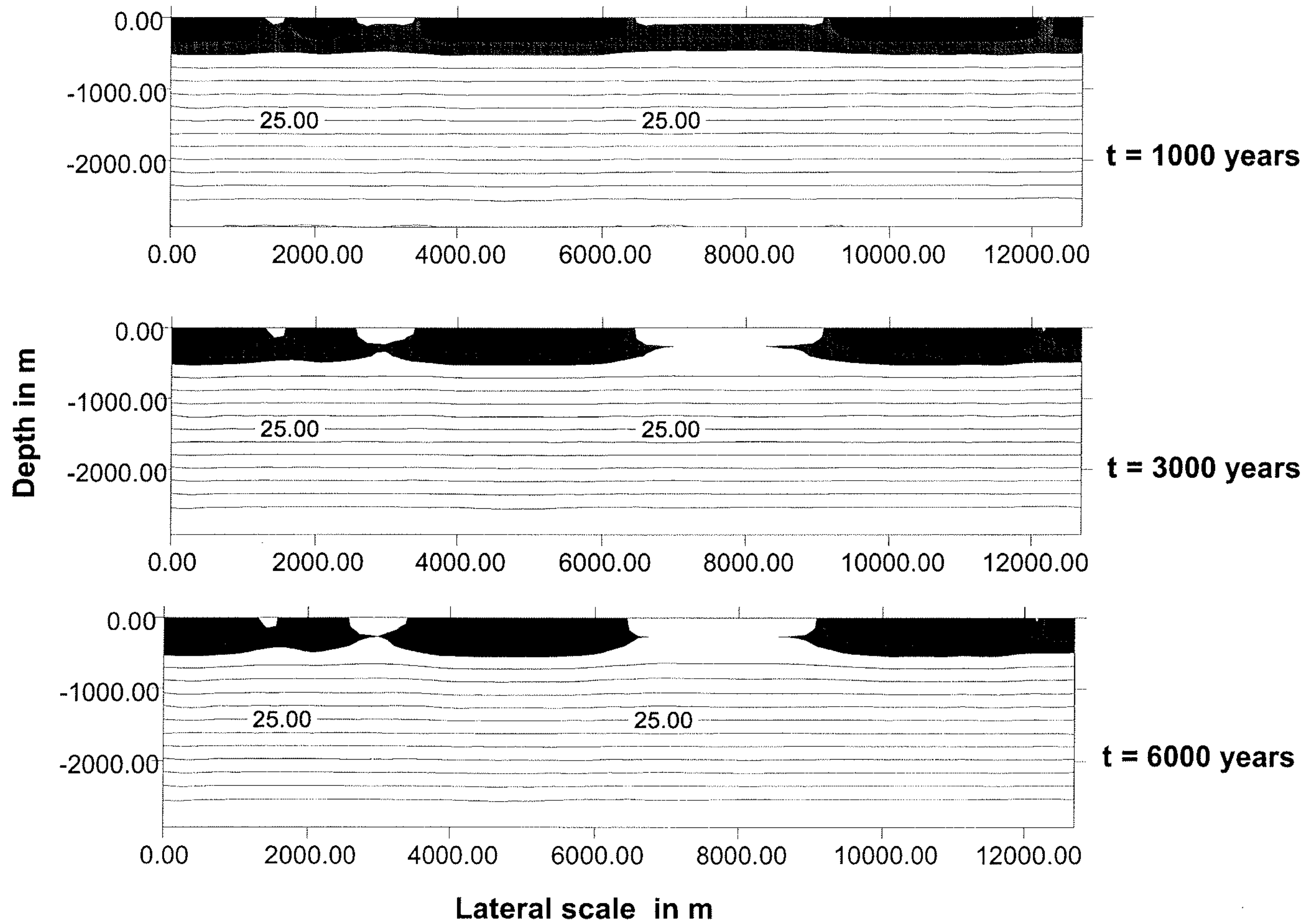

Fig. 3: Thermal influence of rivers on underlying permafrost. Only broad rivers are able with their large and perennial heat content in the river water to melt the underlying permafrost. For boundary conditions see text.

Expansion and contraction of the gas hydrate stability field

The depth extent, of where gas hydrates are within their stability field, expands by several 100 m during the peak of the cold stage and shrinks again during warm stages.To visualize the course of this process, a vertical sedimentary column is considered, on whose surface a climatic course is imposed. The climatic course is assumed as in the first model above (see also Fig. 1 bottom). A value of 60 mW m^{-2} was chosen for the regional terrestrial heat flow. Gas hydrates potentially develop, whenever rock temperatures drop below the gas hydrate stability curve. The mathematical functions describing the stability field of methane as function of temperature and pressure were taken from Collett (1993). A moderate value of 0.3 x 10^8 Ws m^{-3} equivalent to about only 8 % filling of pore space by gas hydrates, was chosen as mean value for the liberation / uptake of latent heat during gas hydrate formation / degradation.

The upper boundary of the gas hydrate zone lies in general cleary well within the permafrost zone, as a comparison of Figures 1 with 4 shows. Only in times of marine regressions the upper boundary of the gas hydrate zone migrates potentially below the lower boundary of the permafrost zone. The timing of the crossover depends critically on the regional heat flow. Given high heat flow, the crossover occurs early on after the marine transgression, given low heat flow, it takes several ten thousand years, before a potential crossover is within reach. After crossover, a sandwich-type situation exists with a subsea permafrost layer on top, an unfrozen layer in between and a gas hydrate layer below.

The lower boundary of the gas hydrate zone moves, given above boundary conditions, from a maximum value of 1140 m depth up to 648 m depth (at 65 ka before present; see Fig. 4).

Serve subsea permafrost and the gas hydrate zone as caprocks of gas reservoirs?

The crustal extension of the crust of the Laptev Sea shelf resulted in complex horst and graben structures, in which km-thick sedimentary basins are embedded. The geochemical analysis of sea bottom sediments points to the evolution of thermogenic gases at depth. The question to what extent these gases held back by subsea permafrost and gas hydrate zones can be answered only qualitatively by the above analysis.

The thickness of the gas hydrate zone varied in above model between more than 200 m to 1000 m. Gas migration through the zone is most likely at the end of long periods of marine trans-

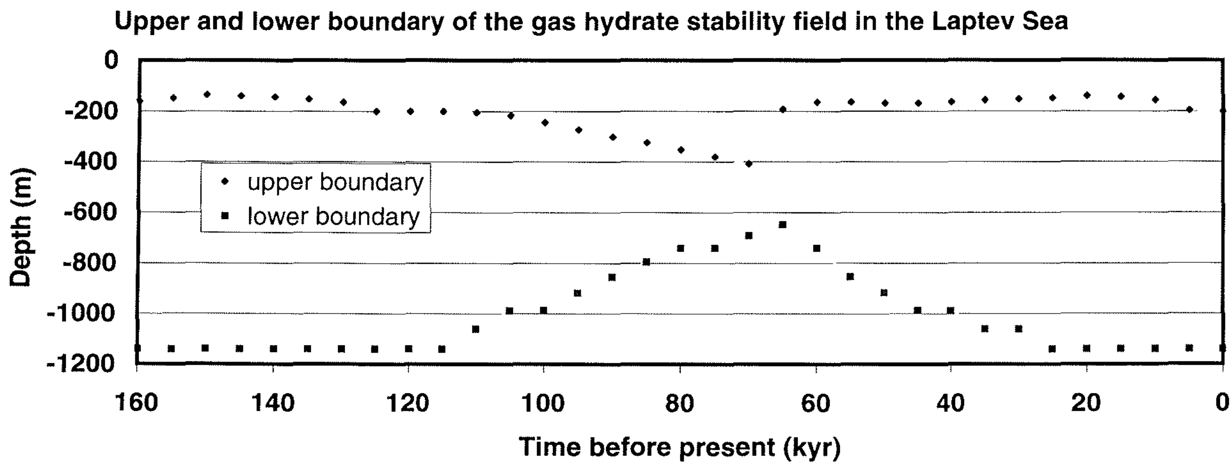

Fig. 4: Changing thickness of the gas hydrate stability zone assuming the same climatic course as in Figure 1. Please note the massive thinning of the gas hydrate zone as consequence of a long time marine transgression.

gression, equivalent to thin subsea permafrost and strongly reduced gas hydrate thickness. The calculated thickness of the gas hydrate stability zone for today on the order of almost 1000 m argues strongly against massive gas diffusion from below. The great uncertainty in the case of the Laptev Sea is the role of the numerous crustal faults, which usually bound the sedimentary basins. They serve potentially as perennially open pathways for gas migration.

The subsea permafrost is a weaker potential caprock. His maximum attainable thickness, even in areas of low heat flow, is less than that of the gas hydrate zone. In addition, in times of marine regression, the development of taliks caused by the thermal effect of large rivers running across the shelf opens potential pathways for gas migration. In addition, during times of marine transgression, the subsea permafrost reduces in thickness and develops nearly isothermal conditions close to the melting point. Therefore, the potential for open pathways for gas migration is much greater than in the case of the gas hydrate zone.

Nevertheless, the numerical results suggest that both, subsea permafrost and the gas hydrate zone, most likely existed continuously during the last 10^5, probably the last million years as separate entities with oscillating thickness as function of the climatic course. The potential for gas reservoir development or gas retention at depth is therefore in this region much greater than in relation to non-arctic regions.

CONCLUDING REMARKS

The above scenarios were developed on the basis of numerical simulations and need to be checked by field work. Of critical importance is a better understanding of the exact climatic course during the last climatic cycles. Talik formation in times of marine regression is an important and unsolved question. The last BGR-cruises to the Laptev Sea were unable to find firm evidence for the presence of taliks today. Do taliks refreeze after marine transgressions due to cold bottom waters? Do the large Siberian rivers disperse via a large number of river arms across the shelf area with the consequence of subdued melting of the underlying permafrost? Finally, the formation mechanism of pock marks at the sea bottom, which by some authors are interpreted as consequence of massive outflow of gases or fluids is not well understood. The above models do not point to a particular time period, in which due to changes in thickness of the permafrost or gas hydrate zone a particular massive discharge of free or dissolved gas is made likely.

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