

Cryogenic gas hydrates on the Arctic shelves: forecast features and resource assessments

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Abstract. The study is dedicated to the features of forecasting and quantitative assessment of methane resources in subsea cryogenic gas hydrates on the Russian Arctic shelf. The work is based on numerical modeling of submarine permafrost and the thermal regime of marine sediments. As a result of the mathematical modeling, equilibrium curves of hydrate formation with variable seawater salinity were constructed. These curves facilitated the determination of the spatial boundaries of cryogenic gas hydrate stability zones. In regions with predicted cryogenic gas hydrate stability zones, potentially hydrate-bearing accumulations were delineated based on Common Depth Point (CDP) seismic data. The amount of methane in four forecasted sub-permafrost gas hydrate accumulations on the Laptev Sea shelf was estimated. The identified accumulations are projected to contain approximately 0.1 trillion cubic meters of methane in hydrate form. According to the regional-scale assessments, up to 9.24 trillion cubic meters of methane, or about 0.3% of the global gas-in-place assessments, may be accumulated on the Russian Arctic shelf

Keywords: cryogenic gas hydrates, resource assessment, submarine permafrost, gas hydrate stability zone, seismic exploration, gas hydrate accumulations

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Introduction

The Arctic continental shelf has become a focal point for both scientific research and resource exploration due to its substantial hydrocarbon potential, including natural gas preserved as cryogenic gas hydrates. Gas hydrates are crystalline compounds that form under low temperatures and elevated pressures when gas molecules, predominantly methane, are encapsulated within a water-ice lattice. These deposits are considered a potential contributor to the hydrocarbon resource base of the Arctic and may even influence the global energy balance (Makogon et al., 2007; Sloan, Koh, 2007).

Two principal models describe hydrate formation. The filtration model associates hydrates with continental slope environments, whereas the cryogenetic model (Ginsburg, Soloviev, 1994) links their occurrence to exogenic cooling during permafrost development (thus

this concept also includes gas hydrates associated with permafrost). On land, this mechanism may transform pre-existing free-gas accumulations into hydrates, although the scale of such transformation remains uncertain (Ginsburg, Soloviev, 1994). A key characteristic of Arctic shelves is the occurrence of cryogenic hydrates in association with subsea relict permafrost. In addition, hydrates may form directly within frozen sediments from gas dissolved in pore waters, independent of prior accumulations (Yakushev, 1989). Relict hydrates may also persist beyond the permafrost zone after its degradation due to the “self-preservation” effect (Chuvillin, Kozlova, 2005).

Cryogenic hydrate accumulations are commonly classified as intrapermafrost, subpermafrost, or relict (post- or epipermafrost) depending on their relation to frozen deposits (Matveeva, Logvina, 2011) (Figure 1). The thickness of the hydrate stability zone is generally proportional to that of the permafrost: the deeper the zero-isotherm, the thicker the stability zone. Cryogenic hydrates usually occur at sub-bottom depths exceeding 100 m, requiring drilling for direct sampling. Shallower occurrences are possible where methane homologues are

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present or where local cryogenic traps generate elevated pressures during permafrost formation.

The study of cryogenic gas hydrates requires an integrated approach to predicting their potential distribution area, commonly referred to as the gas hydrate stability zone (GHSZ). This involves accounting for the paleoclimatic conditions of the Arctic, as well as identifying hydrocarbon traps within this zone. Predictive modeling and resource assessment must incorporate seasonal and annual temperature fluctuations, long-term climate change, and their impacts on the stability of gas hydrate reservoirs and the permafrost system (Ruppel, Kessler, 2017).

A number of features complicate the prediction and assessment of cryogenic submarine hydrates: their association with subsea permafrost and permafrost-related geocryological conditions, the necessity of considering paleoclimate and geothermal factors when modeling the GHSZ, and the challenge of differentiating between frozen and hydrate-bearing strata. Methods for investigating and forecasting cryogenic hydrates include geophysical and geochemical surveys, supported by numerical modeling, which enables evaluation of variations in geological and thermobaric conditions within marine sediments. In addition to their confinement to permafrost zones, cryogenic hydrate accumulations are most likely to occur in basins with thick sedimentary sequences that favor high gas-generation potential. Nevertheless, predictive methods remain limited by multiple factors, including technological constraints on deterministic forecasting and the poor geological

knowledge of Arctic shelves with respect to gas hydrates and permafrost. Therefore, given the current level of understanding of subsea permafrost, the estimation of cryogenic GHSZ extent and properties can only be accomplished through numerical permafrost modeling.

Relict subsea permafrost (RSP) formed on the Eurasian Arctic shelf during the Last Glacial Maximum and persists to the present in a state of progressive degradation across vast areas of the Russian Arctic (Angelopoulos et al., 2019; Osterkamp, 2001). Empirical data on the distribution of frozen deposits, particularly RSP, in the Russian Arctic shelf have been obtained primarily from drilling (Kassens et al., 2001; Rachold et al., 2007; Rokos et al., 2009) and seismic surveys (Hinz et al., 1998; Fütterer, Niessen, 2004; Niessen, 2004; Rekant et al., 2015). However, these data remain insufficient for robust mapping of the cryolithozone – the zone of marine sediments with subzero temperatures – across the extensive Eurasian shelf or for developing reliable models of thermobaric conditions. As a result, numerical modeling remains the primary method for assessing the extent and characteristics of the cryolithozone, as evidenced by numerous studies (Romanovsky et al., 2003; Overduin et al., 2019; Malakhova et al., 2020; Gavrilov et al., 2020).

The aim of this study is to provide a quantitative assessment of methane resources in cryogenic gas hydrates of the Eurasian Arctic shelf as of January 1, 2024. This is achieved through numerical modeling of thermobaric conditions in marine sediments and comparison with the equilibrium conditions of methane

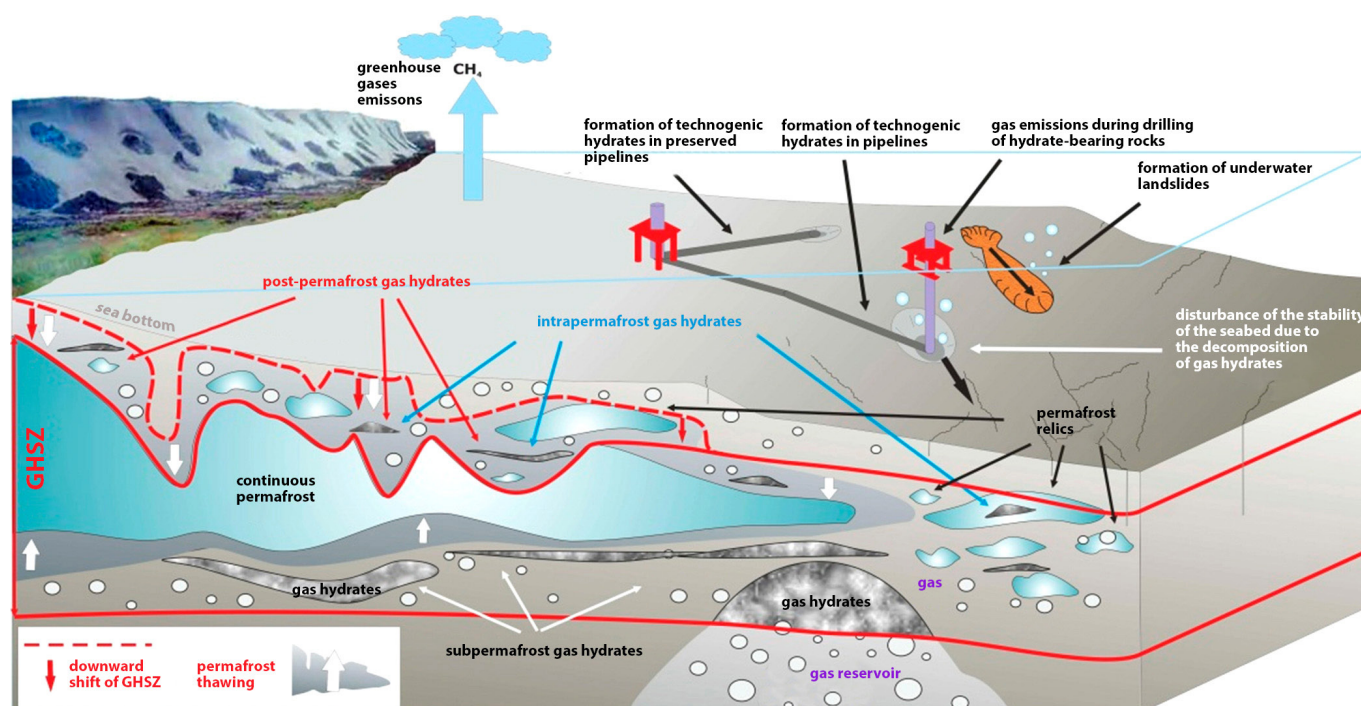


Figure 1. Different genetic types of cryogenic gas hydrates in Arctic shelf basins and potential geohazards related to their presence in submarine deposits, according to (Matveeva, Logvina, 2011)

hydrate stability, which also define the cryolithozone. The work forms part of a broader project on the quantitative evaluation of hydrate resources in Arctic shelf basins, conducted at All-Russia Research Institute for Geology and Mineral Resources of the World Ocean (VNIIOkeangeologia) (St. Petersburg, Russia) between 2021 and 2024 (Matveeva et al., 2023; Matveeva et al., 2024).

Assessment of Cryogenetic Gas Hydrate Resources in the Circumpolar Arctic Outside Russia

Resource assessments of gas hydrates have been conducted since the 1970s and are subject to continuous revision as geological and geophysical knowledge of potentially hydrate-bearing basins improves (Pang et al., 2021; Matveeva et al., 2024).

The most extensively studied onshore region with respect to cryogenetic gas hydrates is the North Slope of Alaska (NSA) (Figure 2). The first comprehensive resource assessment of hydrate-bound gas in the NSA was carried out by the U.S. Geological Survey (USGS) in 1995 as part of a broader evaluation of unconventional hydrocarbons. This assessment included an analysis of the geological conditions favorable for hydrate formation within U.S. jurisdictional areas (Collett, 1995).

The predicted methane hydrate resources were estimated at 16.7 trillion m³, while two major hydrate

accumulations – Eileen and Tarn, located near the Prudhoe Bay oil field – were estimated to contain over 2.8 trillion m³ of gas (Figure 2). Notably, in the Eileen accumulation, hydrates were observed in sandy interbeds beneath the base of RSP (Collett, 1993), whereas in the Tarn accumulation, hydrate-bearing sands were mainly concentrated in the lowermost part of the permafrost section (Collett, 2002).

Subsequently, based on data from the Mount Elbert-1 well (Figure 2) and advances in numerical modeling of hydrocarbon reservoirs (Anderson et al., 2008), the first estimate of technically recoverable methane hydrate resources in sandstone reservoirs of the NSA was provided, amounting to 2.4 trillion m³ (Collett et al., 2008). In 2018, these estimates of recoverable hydrate-bound methane were updated: the revised figure was 1.5 trillion m³. The reduction in estimated resources was primarily attributed to smaller hydrate accumulations identified within the studied formations from additional three-dimensional seismic and well-log data, as well as the application of a reducing factor (down to 0.9) to reflect high uncertainty due to the limited number of drilled wells (Collett, 2019).

Studies focused on cryogenic gas hydrates associated with RSP remain relatively scarce. The two principal works include a regional assessment for the Beaufort-Mackenzie Basin (BMB) (Osadetz, Chen, 2010) and a global estimate of methane contained in cryogenic gas

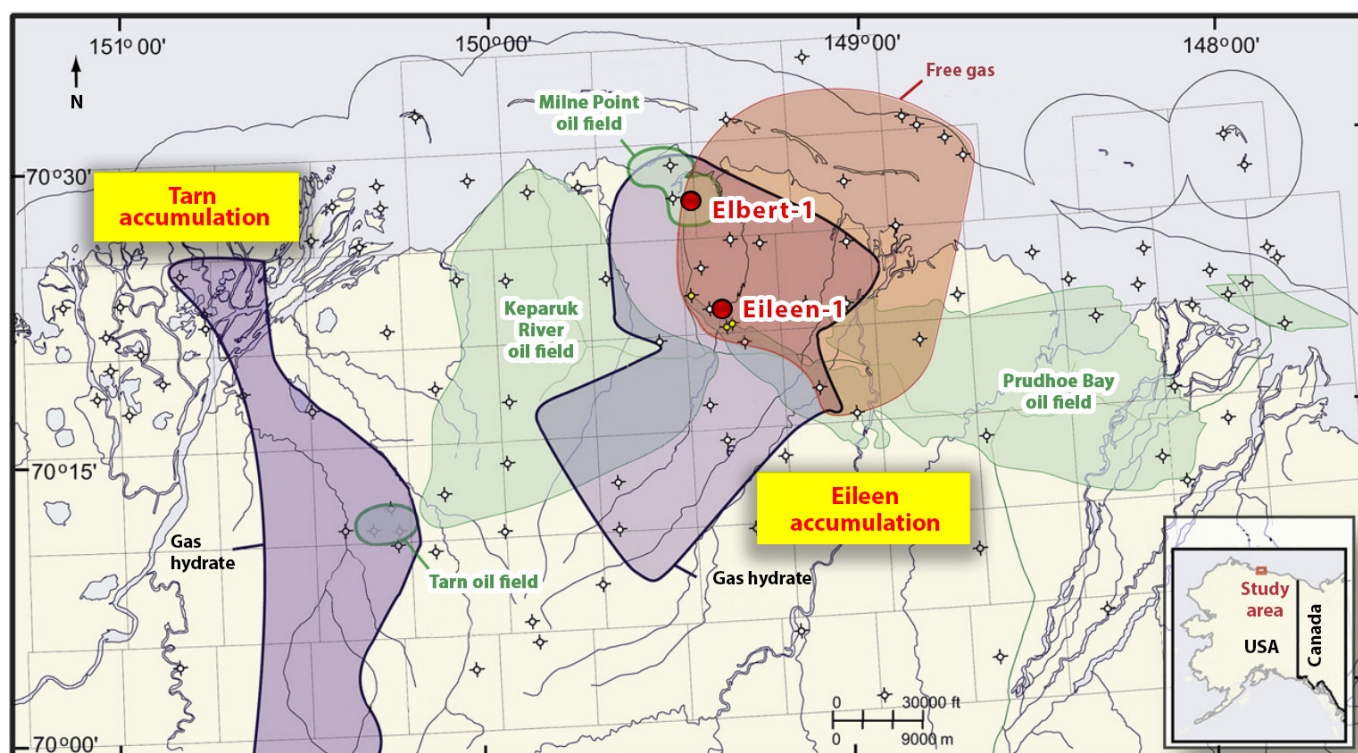


Figure 2. Map of prospective gas hydrate-bearing provinces (purple), oil-bearing provinces (green), and gas-bearing provinces (brown) of the NSA. The Eileen and Tarn gas hydrate accumulations are indicated; both are partly superimposed on the Prudhoe Bay, Kuparuk River, and Milne Point oil fields (Collett, 1993). The locations of research wells Eileen-2 and Mount Elbert-1 are also shown. Modified after (Collett, 2019)

hydrates across the circum-Arctic, encompassing both onshore and offshore permafrost regions (Ruppel, 2015).

In the calculations by Ruppel (2015), it was conservatively assumed that hydrates may accumulate beneath 10% of the Arctic petroleum basins underlain by RSP. The hydrate-bearing interval was assigned a thickness of 50 m within the GHSZ, porosity of 50%, and hydrate saturation of 5%. The volume of hydrate-bound gas in RSP settings was estimated by multiplying the area of RSP within petroleum basins by the assumed hydrate-bearing thickness, porosity, and hydrate saturation.

The resource assessment of gas hydrates in the BMB (Figure 3) was based on well-log data from 203 boreholes drilled onshore and in the nearshore zone, using both deterministic and probabilistic modeling approaches (Osadetz, Chen, 2010). Well-log analysis provided intervals of hydrate occurrence and allowed estimation of hydrate saturation. Of the 203 studied wells, only 122 encountered gas hydrates. In their assessment (Osadetz, Chen, 2010) applied Archie's method to calculate hydrate saturation from resistivity logs, and incorporated a structural element density map – accounting for faults and fold zones that facilitate hydrocarbon migration – to refine estimates of gas migration pathways.

In the study (Osadetz, Chen, 2010), hydrate accumulations were assumed to be confined within a radius of 565 m around wells that encountered gas hydrates, with hydrate saturation considered uniform across the surrounding area. Based on this approach, estimates of hydrate-bound methane volume per unit area (specific density within accumulations, q_i) in the BMB were classified into three categories of recoverable resources:

1. “Rich” accumulations, where q_i exceeds 1.0×10^9 m^3/km^2 (observed in wells Mallik L-38 and Adgo P-25);
2. “Intermediate” accumulations, with q_i values ranging from 1.0×10^8 to 1.0×10^9 m^3/km^2 (12 wells);
3. “Lean” (depleted) accumulations, where q_i is less than 1.0×10^8 m^3/km^2 (105 wells and associated areas).

The majority of accumulations (~86%) were classified as “lean,” while only a limited number of wells and adjacent areas indicated high specific densities.

On the Eurasian Arctic shelf, gas hydrates have not yet been confirmed by drilling, and no data on hydrate saturation are available. Consequently, published studies from the BMB remain the only source for predictive resource assessments, as they provide essential information on hydrate saturation and resource densities per unit area. The BMB is also considered a relevant analogue due to geological similarities with the Laptev Sea, where widespread RSP development is likewise anticipated (Smirnov et al., 2024a).

Materials and Methods

Methodology for modeling the gas hydrate stability zone

To address the problem of modeling and mapping the cryolithozone and cryogenic GHSZ, a software suite for numerical simulation of thermobaric conditions in marine sediments was developed: PEGAS (Permafrost GAs hydrate Stability forecast) (Smirnov et al., 2024b).

The model underlying the PEGAS suite is based on the solution of the one-dimensional, non-stationary heat conduction equation using an implicit finite-difference scheme with a through-counting method:

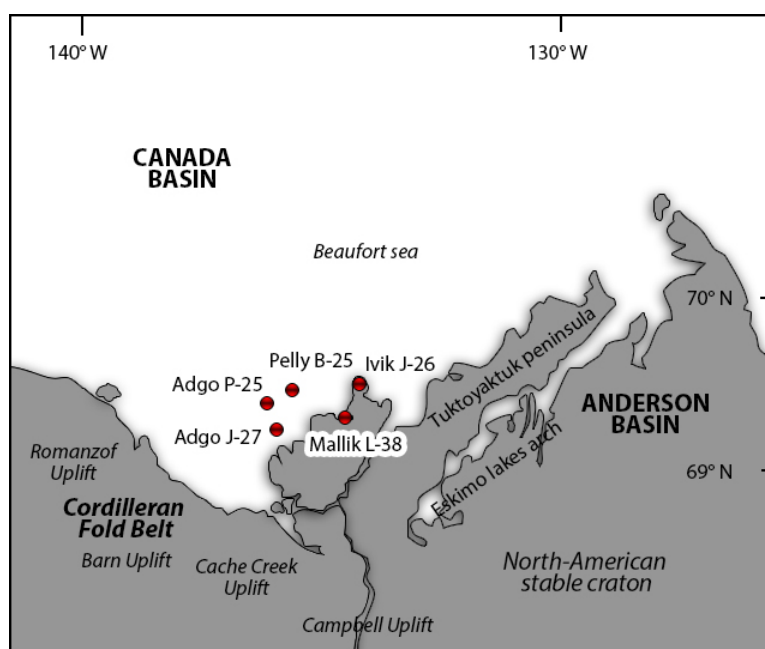


Figure 3. Map of the Beaufort-Mackenzie Basin showing major wells and structural elements, modified after (Osadetz, Chen, 2010). Wells are shown as red circles.

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left(\lambda_e \frac{\partial T}{\partial z} \right),$$

where ρ is the density of marine sediments, C is the specific heat capacity of marine sediments, and λ_e is the effective thermal conductivity of the sediments. The depth of the computational domain (Z_{max}) is 10,000 m, with a vertical discretization step of 1 m. The model time step is 10^9 s. A detailed description of the model is provided in (Smirnov et al., 2024a).

When modeling the thermal regime of marine sediments at a regional scale, it is important to recognize the large number of physical processes and parameters that cannot be fully accounted for. As shown by calculations in (Smirnov et al., 2024a), marine sediments represent a highly inertial dynamic system, requiring precise calibration of boundary conditions and thermophysical parameters to obtain reliable results. Analysis of modeling results for wells in Buor-Khaya Bay (Chuvilin et al., 2021) indicates discrepancies between observed and predicted temperatures (Figure 4). The main causes of these discrepancies include: inaccurate specification of temperature and salinity at the upper boundary due to interpolation from reanalysis archives instead of *in situ* measurements; omission of seasonal variations in temperature and salinity at the top of the computational domain; uncertainties in the selection of thermophysical parameters; and methodological inaccuracies in describing the water–ice phase transition, particularly the inappropriate choice of the unfrozen water curve.

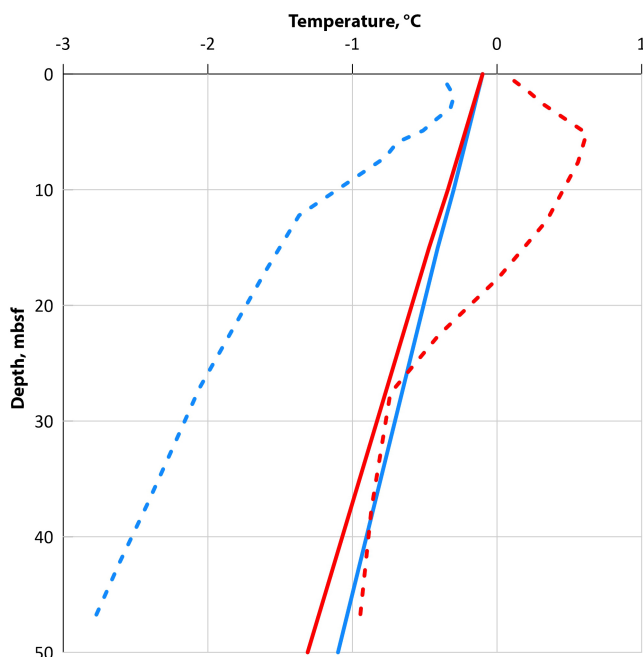


Figure 4. Simulation results (Smirnov et al., 2024a) and well temperature measurements from Buor-Khaya Bay (Chuvilin et al., 2021). Red – well 4D-12, blue – well 1D-14; solid lines represent model predictions, dashed lines correspond to observed temperatures.

However, it should be noted that achieving temperature profiles closely matching “real” values is inherently challenging due to the complexity of specifying the upper boundary condition (Kneier, 2018). Overall, the modeling results are considered adequate for representing the underlying physical processes. As demonstrated in (Smirnov et al., 2024a), the influence of the upper boundary condition diminishes with depth, and short-term temperature fluctuations at the top have negligible effect on the GHSZ. This justifies the use of the described methodology at a regional scale for preliminary resource assessments.

Since the main factors controlling the properties of the GHSZ, including its thickness and spatial extent, are temperature and pressure – as is the case for the cryolithozone – the thermal fields computed by the PEGAS system form the basis for subsequent modeling of the cryogenic-type GHSZ.

The equilibrium curve for methane hydrate is derived from experimental data or constructed using empirical correlations. A general form of such an approximation for aqueous systems can be expressed as in (Moricidis et al., 2003):

$$\ln(P_D) = \sum_{n=0}^5 a_n (T + T_D)^n,$$

where P_D is the equilibrium pressure (MPa), T and T_D are the equilibrium temperature and its deviation due to the salinity of the medium, respectively, and a_n are empirical constants.

Similar regression-based correlations are implemented in the freely available CSMHYD Hydooff software (Sloan, 1998), which allows calculation of the hydrate formation equilibrium pressure for a given temperature.

To automate data input into Hydooff, as well as output processing and preparation for subsequent mapping, a Python-based software suite named MAGAS (MARine GAS hydrate) was developed (Matveeva et al., 2024). MAGAS interacts with Hydooff in the background using subprocesses, enabling automated data input from imported arrays containing the required geothermal gradient values. Background interaction with Hydooff is performed via the Popen class from the Python subprocess library.

In addition to computing the equilibrium curve, MAGAS can generate geothermal profiles at grid nodes using the thermal gradient and bottom water temperature, or analyze existing profiles. At each grid node, the gas GHSZ is calculated based on the intersection with the computed equilibrium curves. The output is a dataset containing GHSZ thickness and the sub-bottom depth of its lower boundary at each grid point. These data can be used to create two-dimensional (thickness) or three-dimensional (top and base positions) maps of GHSZ distribution in any GIS.

This background automation method for calculating hydrate equilibrium curves has been applied in previous studies, e.g. (Matveeva et al., 2023). A key advantage of MAGAS over simpler approaches is its ability to calculate equilibrium curves for gases of arbitrary composition using Hydooff, enabling parametric studies that account for natural gas composition. An example of calculated curves for different gas compositions is shown in Figure 5, illustrating that the least favorable conditions for GHSZ formation correspond to increased methane content in the gas mixture and higher salinity of the hydrate-forming water.

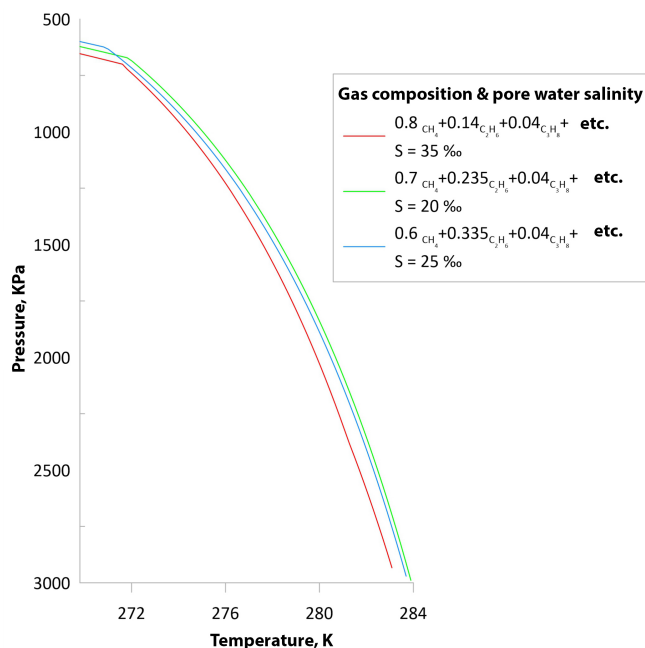


Figure 5. Equilibrium curves for different compositions of hydrate-forming gas and water salinity, calculated using background automation of Hydooff. S – salinity of the hydrate-forming water, ‰.

Resource Assessment Methodology

To estimate the amount of methane in cryogenic gas hydrates, the specific density method described in (Matveeva et al., 2024) was applied. This method involves extending an empirically established pattern to hierarchically ranked hydrate-bearing objects, where each object – from petroleum province to individual accumulation – has a defined range of specific gas content per unit area. Generally, lower-ranked objects exhibit higher characteristic specific densities. Knowing the specific densities of resources and the corresponding areas of potentially hydrate-bearing basins, regions, or accumulations, the amount of methane Q is calculated according to the methodology of (Matveeva et al., 2024):

$$Q_i = q_i \cdot S_i,$$

where S_i is the area of the corresponding petroleum-geological unit, and q_i – is the specific gas content per unit area for that unit. This allows determination

of the total gas content (Q_i) in the gas hydrates of the corresponding i -th spatial unit.

As a reference for determining the specific resource density in a gas hydrate accumulation, data from the BMB were used (Osadetz, Chen, 2010), the only study providing estimates of specific density q_i in permafrost-associated accumulations over an area of 58,550 km². The total methane volume in the BMB accumulations, calculated using the deterministic approach (Q_{BMB} was estimated at 8.82×10^{12} m³, representing the sum across 112 individual accumulations. Based on these data, the average specific density q_i for the BMB accumulations was 1.51×10^3 m³/km². When scaling from individual accumulations to the province level, following the empirically established pattern of decreasing gas resource density from accumulation to province (Matveeva et al., 2024), q_i is reduced by a factor of 31, i.e. $q_r = 1.5 \times 10^8 : 31 = 4.87 \times 10^6$ m³/km².

Multiplying the average specific gas content by the area of the hydrate-bearing province (i.e., the GHSZ of a given basin) yields the regional estimate of methane in cryogenic gas hydrates of the studied Arctic seas (Q_{reg}) and the total estimate for all Russian Arctic shelf seas (Q_{ARC}).

Resource Estimates of Cryogenic Gas Hydrates on the Russian Arctic Shelf

Cryogenic gas hydrate stability zone

The cryogenic gas hydrate stability zone includes gas hydrates associated with permafrost, as well as gas hydrates occurring within the unfrozen sections of the cryolithozone. The cryogenic gas hydrate stability zone (GHSZ) was calculated based on data from (Smirnov et al., 2024a) for 100% CH₄ curves and varying bottom-water salinities (Figure 6). The cryogenic GHSZ exhibits extensive distribution across the entire Eurasian Arctic shelf. According to our forecasts, the maximum thickness of the GHSZ is located east of the Novosibirsk Islands, reaching 1,417 m. Beyond the New Siberian Islands, the GHSZ controlled by the cryolithozone is widely distributed in the northwest of the Kara Sea (southwest of Severnaya Zemlya), along the coast of the Taymyr Peninsula, at the entrance to the Khatanga Bay, and in the coastal zone between Khatanga Bay and the Lena River delta.

The influence of temperature and bottom-water salinity is evident through characteristic hydrological effects (Figure 6), for example, in the formation of a “meander-like” pattern – persistent vortices of relatively warm water west of Wrangel Island – caused by two thermohaline intrusions: freshwater discharge from the Lena River delta and inflow of warm saline waters through the Bering Strait. The combination of low-salinity waters and elevated temperatures in the delta leads to the formation of an anomalous shallow zone

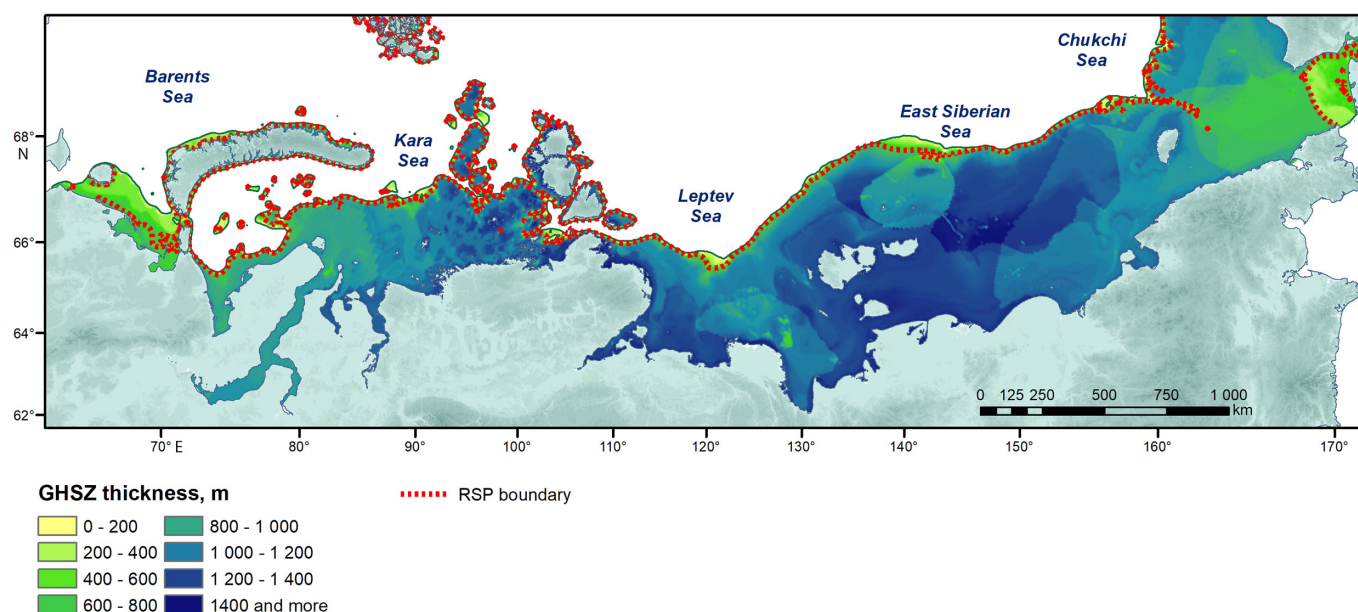


Figure 6. Distribution of the cryogenic gas hydrate stability zone

with reduced GHSZ thickness (800–1,000 m, with minimum values down to 200–400 m in certain areas). The intrusion of Pacific waters through the Bering Strait contributes to GHSZ degradation, reducing its thickness in the central Chukchi Sea to about 200 m.

In the Bering Strait, comparison of cryolithozone modeling results (Smirnov et al., 2024a) with the present study indicates that cryogenic GHSZ persists in areas with fully degraded modeled RSP. It is evident that this “post-cryogenic” GHSZ is preserved due to the high thermal inertia of marine sediments as a system, as well as additional hydrostatic pressure at the upper boundary resulting from sea transgression. A similar pattern is observed in the Pechora Sea.

Prospective resources at the local/object scale (Russian classification D_1)

Within the framework of identifying gas hydrate accumulations, using the methodology described in (Matveeva et al., 2023) for the Kara Sea shelf, a number of hydrocarbon traps within the GHSZ were delineated. Among them, four potentially hydrate-bearing targets were outlined in the Laptev and Kara Seas (Figure 7).

The size of gas hydrate accumulations depends on the type of hydrocarbon traps to which they are associated. The smallest accumulations are found in tectonically shielded traps, with an average size of approximately 2 km. Larger extents on seismic sections are observed for structural dome and stratigraphic traps, with average sizes of about 8 km and 12 km, respectively. Using intersections of seismic profiles, the external outlines of the predicted sub-permafrost gas hydrate accumulations associated with traps located within the cryogenic-type GHSZ were constructed (Figure 8).

Local-scale resource estimates of methane in the predicted cryogenic gas hydrate accumulations (sites) on the Laptev Sea shelf (Figure 9) were performed by multiplying the area of the local accumulations by the specific density q_r .

As shown in Figure 9, the amount of methane in the gas hydrates is directly proportional to the accumulation area, reflecting the methodology used for the calculation. The largest volumes of hydrate-bound methane are observed in sites 1 and 4, which are similar in magnitude.

Prospective resources at the basin/province scale (Russian classification D_1+D_2)

For regional assessments of gas hydrate potential in the Russian Arctic shelf seas, each basin (within the GHSZ) was treated as a separate gas hydrate-bearing province and evaluated individually (Figure 10). One of the critically important parameters in gas hydrate resource assessment is the gas-generating potential of marine sediments, which is determined by the thickness of the sedimentary cover, with a minimum threshold of 500 m. This threshold is based on the approximate depth of the sulfate-reduction zone, which inhibits methanogenesis. Accordingly, for regional assessments, areas with a sedimentary cover less than 500 m were excluded from calculations (Poselov et al., 2012) (Figure 10).

The resulting regional estimates (Q_r) are directly proportional to the area of the potentially hydrate-bearing provinces, reflecting the calculation methodology using a constant specific resource density (Figure 11). The largest Q_r is observed for the East Siberian Sea ($3.45 \times 10^{12} \text{ m}^3$), followed at a considerable distance by the Kara Sea ($2.37 \times 10^{12} \text{ m}^3$).

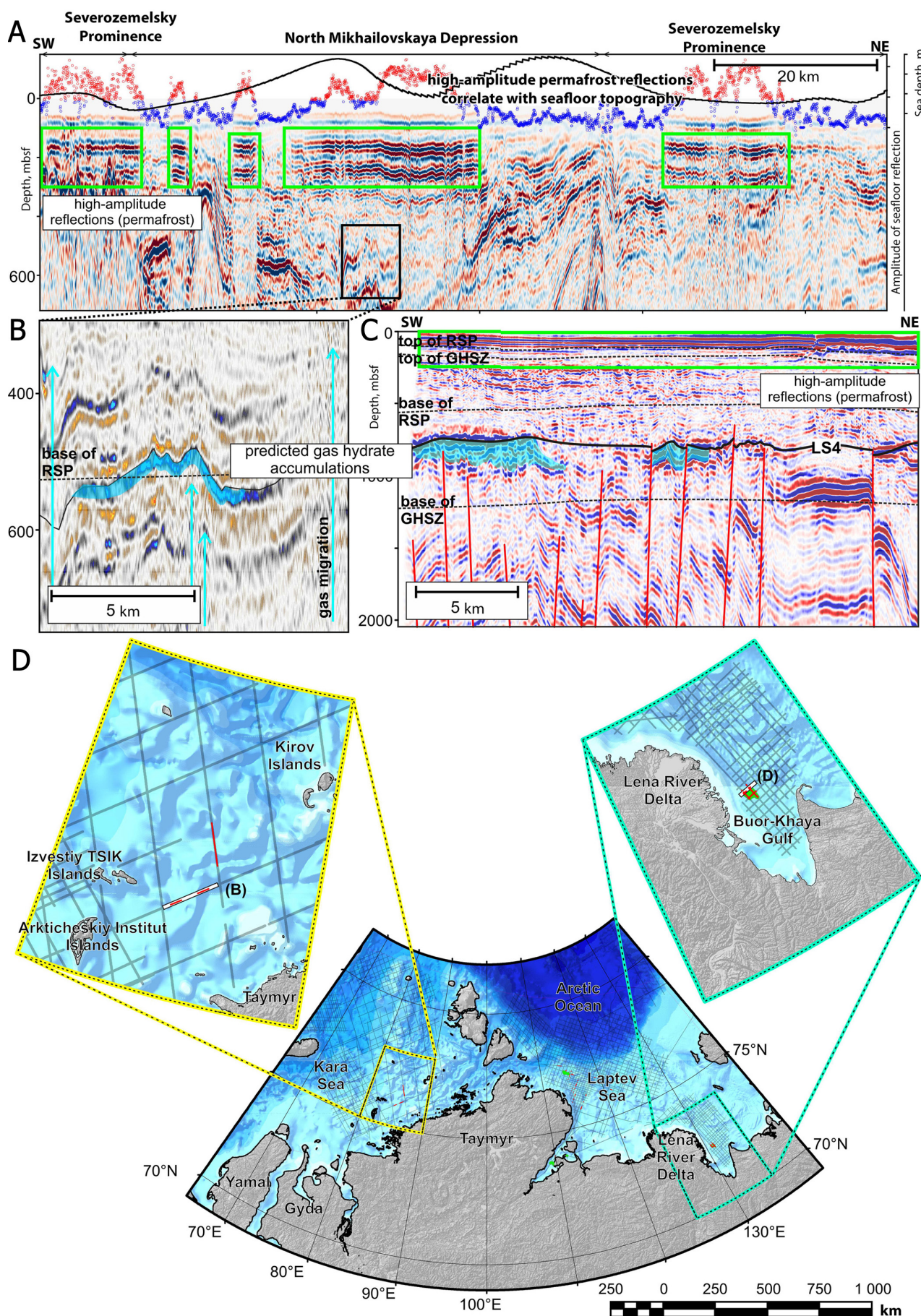


Figure 7. Examples of subsurface hydrocarbon traps in the GHSZ (predicted accumulations of gas hydrates): A – on the seismic section in the Kara Sea; B and C – on fragments of seismic sections in the Laptev Sea. High-amplitude reflections caused by permafrost are marked with green frames, and the amplitude of reflections from the bottom is a black line on graph A. D – the position of fragments of seismic profiles is marked with a red dotted line, the contours of traps are green.

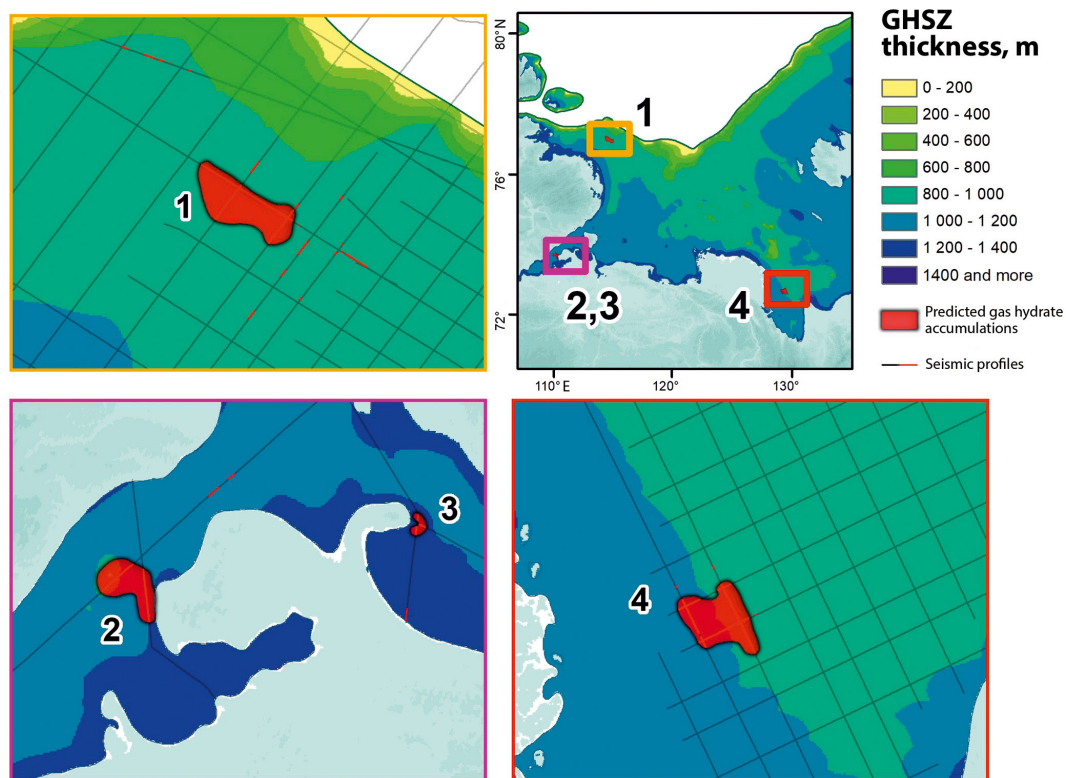


Figure 8. Predicted gas hydrate-bearing structures (sub-permafrost accumulations) in the shelf zone of the Laptev: 1 – “Taymyr-North”, 2 – “Khatanga-1”, 3 – “Khatanga-2”, 4 – “Buor-Khaya”

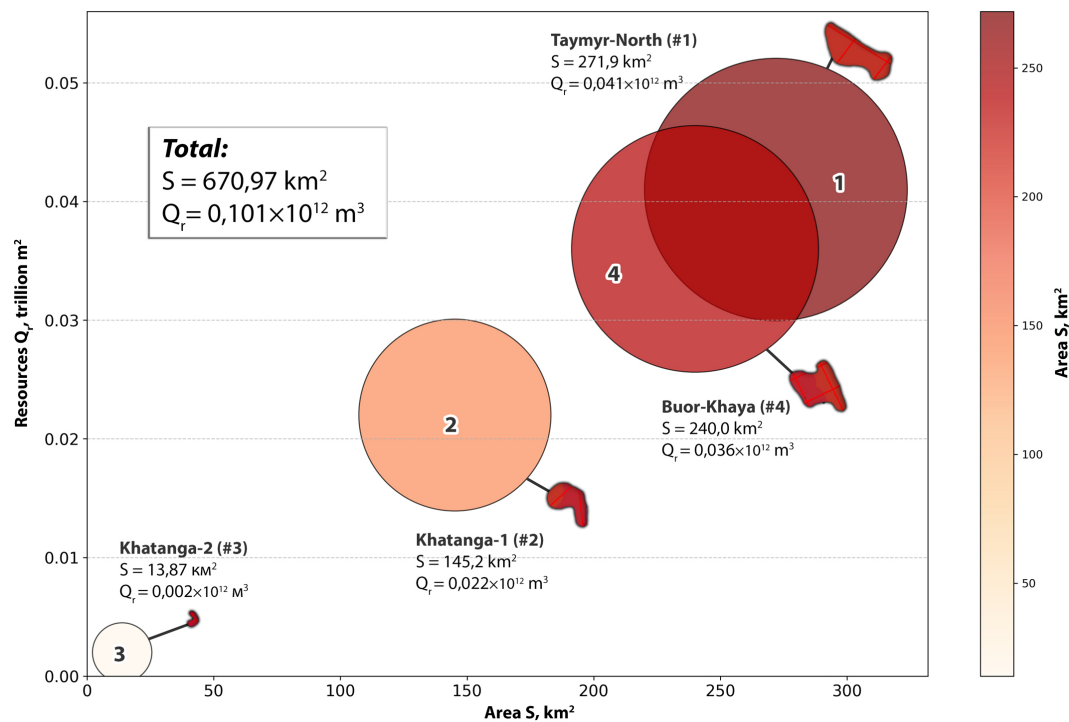


Figure 9. Methane content in cryogenic gas hydrate accumulations of the Laptev Sea (circle size indicates the area of the accumulation). The numbering of the accumulations corresponds to Figure 8.

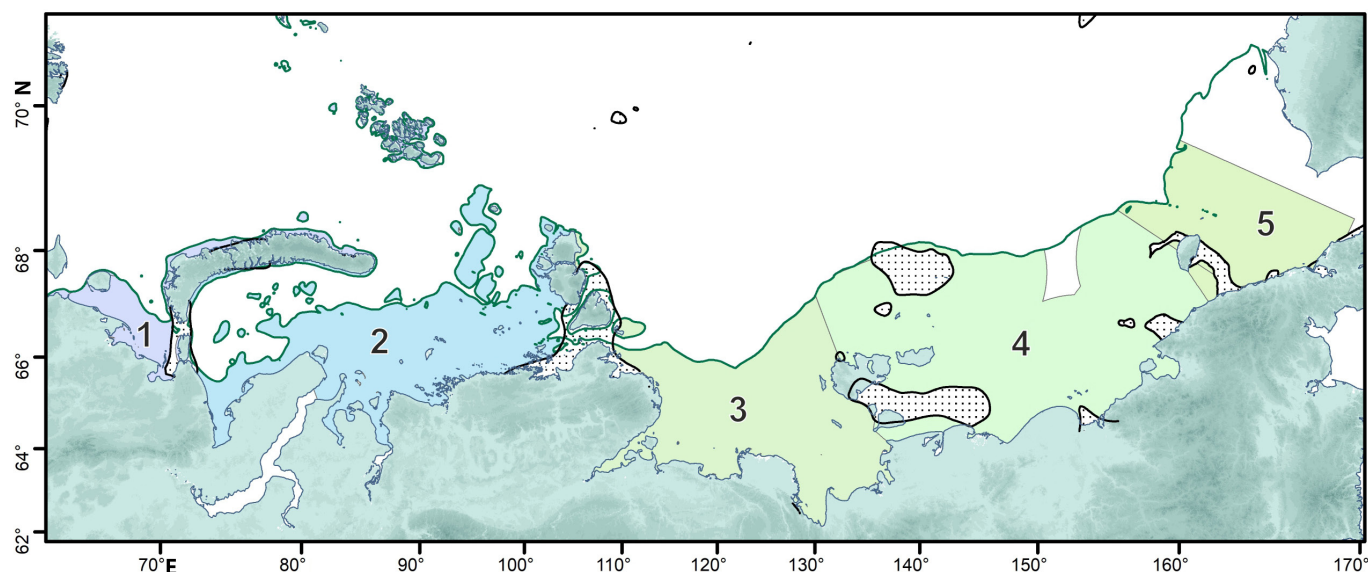


Figure 10. Potential gas hydrate-bearing provinces: 1 – Barents Sea, 2 – Kara Sea, 3 – Laptev Sea, 4 – East Siberian Sea, 5 – Chukchi Sea; areas with a thin sedimentary cover, according to (Poselov et al., 2012), are marked with black dots. The green line indicates the boundary of the cryogenic-type GHSZ.

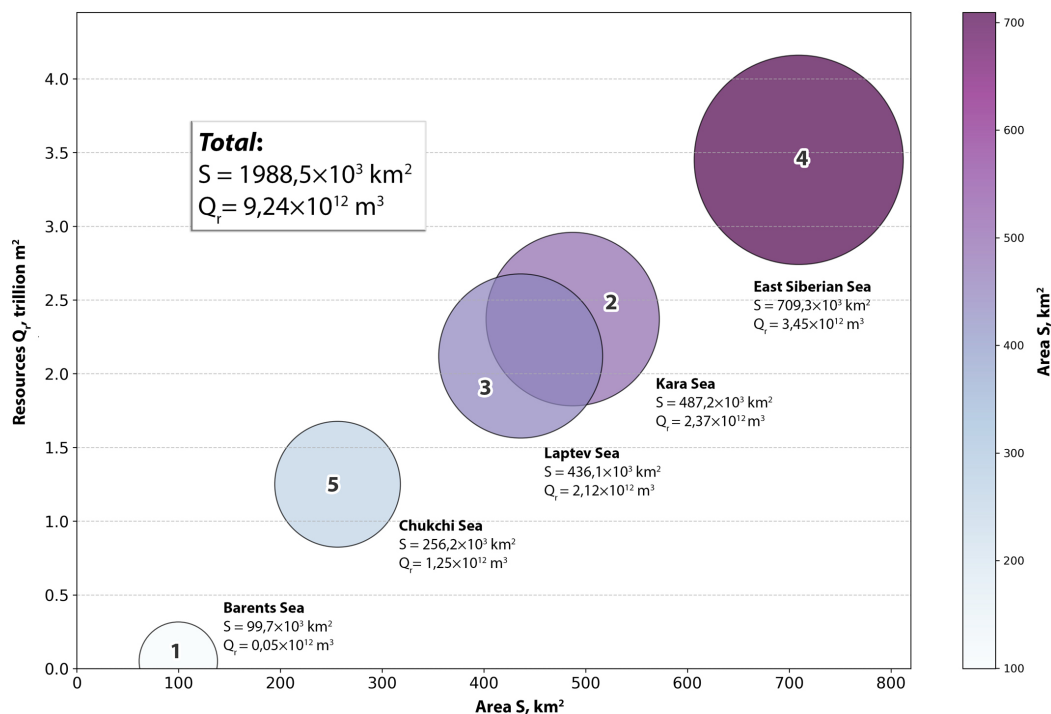


Figure 11. Regional estimates of methane resources and areas of the cryogenic-type GHSZ. The numbering of the accumulations corresponds to Figure 10.

Discussion

An analysis of studies on quantitative assessments of submarine cryogenic gas hydrates in the Arctic revealed a limited number of such works. In the domestic literature, notable studies include article by E. V. Perlova; however, these focus on filtration-type submarine gas hydrates and terrestrial cryogenic hydrates (Perlova, 2019) and do not consider the gas hydrate pool addressed in the present paper. In (Matveeva et al., 2024), using a similar specific-density methodology, a cumulative

assessment as of January 1, 2020, was provided for both filtration-type and cryogenic gas hydrates of the Arctic seas, with emphasis on the features and methodological approaches for quantitative evaluation of filtration-genesis gas hydrates. The present work provides, for the first time, the features and specifics of calculations for the cryogenic GHSZ and methane content, with the quantitative assessment updated to January 1, 2024.

The predicted amount of methane in cryogenic gas hydrates on the Eurasian Arctic shelf, with a total area of

the cryolithozone-controlled GHSZ of $1,988.5 \times 10^3 \text{ km}^2$, is estimated in this study at $9.24 \times 10^{12} \text{ m}^3$, assuming a specific density of $4.87 \times 10^6 \text{ m}^3/\text{km}^2$. The area covered by RSP, within which cryogenic submarine gas hydrates are expected to occur according to (Ruppel, 2015), is $508 \times 10^3 \text{ km}^2$, approximately 10% of the total assessed area. Following the methodology of (Matveeva et al., 2024), this area accumulates about $2.55 \times 10^{12} \text{ m}^3$ of CH_4 in hydrate form, assuming a specific density q_r of $5.01 \times 10^6 \text{ m}^3/\text{km}^2$. Both assessments q_r yield values that are extremely close. The differences between the studies lie in the assessed areas and the methodological approach.

Local resource estimates indicate a total gas content of $0.101 \times 10^{12} \text{ m}^3$ across four predicted cryogenic gas hydrate accumulations out of 83 localized in the Laptev Sea. Multiplying the average content Q_i of the four objects ($0.025 \times 10^{12} \text{ m}^3$) by the total number of localized accumulations (83) provides an estimate of $\sim 2.075 \times 10^{12} \text{ m}^3$, which is consistent with the regional assessment results for the Laptev Sea ($2.12 \times 10^{12} \text{ m}^3$).

Conclusion

This paper presents an approach for regional and local resource assessments of submarine cryogenic gas hydrates using the specific-density method based on numerical modeling of thermal conductivity in marine sediments.

The main features of cryogenic gas hydrates relevant to their assessment are highlighted: the association of the gas hydrate stability zone (GHSZ) with the cryolithozone, and the limited geological knowledge of the shelf, which precludes the evaluation of Russian C2-category resources. This necessitates modeling the thermobaric conditions of marine sediments, predicting the spatial distribution of the cryolithozone, and performing resource assessments based on statistical patterns and trends established in petroleum geology or from better-studied gas hydrate regions.

A methodology for background automation of equilibrium curve calculations is presented, allowing the use of the known software Hydoff to determine GHSZ boundaries.

According to numerical modeling, the greatest thicknesses of the cryogenic-type GHSZ are predicted for the Laptev and East Siberian Seas, while the smallest are found in the Pechora and Chukchi Seas. Comparison of GHSZ and cryolithozone areas indicates regions where the cryolithozone has fully degraded, but due to the high inertia of marine sediments as a system, a “post-cryogenic” GHSZ may still form, which has been accounted for in the resource assessments.

Regional-level calculations indicate that the volume of methane in cryogenically generated hydrates on the Eurasian shelf of Russia is $9.24 \times 10^{12} \text{ m}^3$. Given that the total volume of cryogenic methane hydrates across the

Arctic, including terrestrial permafrost, is slightly less than 1% of the global geological gas reserves (Ruppel, 2015), it can be inferred that approximately 0.3% of global gas reserves are accumulated in submarine gas hydrates on the Russian Arctic shelf.

Seismic surveys have identified four potential gas hydrate-bearing structures on the Laptev Sea shelf, associated with the cryolithozone. Based on this localization, local quantitative assessments of gas hydrate accumulations on the Eurasian Arctic shelf were performed for the first time. The total CH_4 content in the four predicted accumulations is estimated at $0.101 \times 10^{12} \text{ m}^3$.

Further refinement of resource assessments is possible through the development of advanced numerical modeling techniques and incorporation of additional paleogeographic factors. Obtaining new local estimates will require additional field data, primarily hydrate saturation values and well GIS data from permafrost-exposed cores.

In conclusion, comprehensive studies of cryogenic gas hydrates on Arctic shelves require further research aimed at improving forecasting methodologies and resource assessment techniques, taking into account dynamic climatic changes and the evolution of the cryolithozone and GHSZ within shelf areas.

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Криогенные газовые гидраты на арктических шельфах – особенности прогноза и ресурсные оценки

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Работа посвящена особенностям прогнозирования и количественной оценки ресурсов метана в субаквальных криогенных газовых гидратах на шельфе российской Арктики. Основу работы составляет численное моделирование субаквальной криолитозоны и температурного режима морских отложений. В ходе математического моделирования были построены равновесные кривые гидратообразования с переменной соленостью морской воды, позволившие определить пространственное положение границ зоны стабильности газовых гидратов (ЗСГГ) криогенного типа. В районах прогнозируемой ЗСГГ по данным МОВ ОГТ оконтурены потенциально гидратоносные скопления. Оценено количество метана в четырех прогнозируемых подмерзлотных газогидратных скоплениях на шельфе моря Лаптевых. В выявленных скоплениях может содержаться порядка

0,1 трлн м³ метана в форме гидрата. Согласно выполненным оценкам регионального масштаба, на шельфе российской Арктики может быть аккумуляровано до 9,24 трлн м³ метана или около 0,3% от общемировых геологических запасов газа в форме газовых гидратов.

Ключевые слова: криогенные газовые гидраты, ресурсные оценки, подводная мерзлота, субмаринные многолетнемерзлые породы, численное моделирование, зона стабильности газовых гидратов, сейсморазведка, скопления газовых гидратов

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