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Assessments of resources of gas hydrates and characteristics of hydrate reservoirs of the seas of Russia

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Abstract. The article presents the results of a quantitative assessment of the predicted resources of subaqueous gas hydrates within the exclusive economic zone of Russia and Lake Baikal as of 01.01.2024 at three different levels – global, regional and local. The assessments were carried out using the specific density method based on numerical modeling of the gas hydrate stability zone, its mapping and identification of gas hydrates based on the interpretation of a large volume of digital seismic CDP data and the results of marine sediment sampling. A total of 203 gas hydrate accumulations were identified and taken into account in the exclusive economic zone of the Russian Federation within the Barents, Laptev, East Siberian, Bering, Okhotsk, Japan and Black seas. The total volume of gas hydrate reservoirs in the Russian seas and Lake Baikal is estimated at 520 trillion km^3, where the share of methane in gas hydrates averages just over 10% and the estimated global gas hydrate resource value is more than 147 trillion m^3. Gas hydrate reservoirs in the seas are confined to the interval of subbottom depths from the seabed to 1250 m in the stratigraphic interval from the Holocene to the Oligocene. The largest number of accumulations are confined to the Pliocene sediments. Gas resources in gas hydrate accumulations vary from 0.1 to 6830 billion m^3, corresponding in terms of resource size to traditional gas fields from very small (with reserves of less than 1 billion m^3) to unique (with reserves of more than 300 billion m^3).

Keywords: submarine gas hydrates, gas hydrate reservoirs, gas hydrate accumulations, exclusive economic zone of Russia, Baikal, gas hydrate-bearing provinces, gas hydrate resource assessments, specific density method, local, regional, global gas hydrate estimations

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Introduction

More than half a century has passed since the discovery of natural gas hydrates, yet interest in this phenomenon continues to grow. This is reflected in the promotion of various hypotheses regarding the global impact of natural gas hydrates on Earth's ecosystems, as well as the establishment of numerous gas hydrate international and national R&D. Additionally, there has been an increase in publications and patent activity related to this topic. By 2030–2035, China and the United States plan to start commercial production of hydrate gas[1].

Natural gas hydrates are a type of unconventional hydrocarbon due to their unique physical properties and occurrence. Combustible gases in gas hydrates are found in the subsurface in a solid state associated with water. Therefore, they belong to unconventional types of hydrocarbon sources, unlike unconventional sources such as shale gas and highly viscous oil, where hydrocarbons are found in their traditional state but in unusual geological conditions. In Russia, gas hydrates have not yet been included in the list of commercial hydrocarbon minerals, despite the fact that the geological reserves of combustible gas in the form of solid hydrates are estimated to be twice as large as the resources of conventional gas fields, according to (Pang et al., 2021).

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[1] https://www.precedenceresearch.com/top-companies/gas-hydrates; www.energy.gov/sites/prod/files/2019/07/f65/Gas%20Hydrates%20Roadmap_MHAC.pdf

The current regulatory framework acknowledges the following categories of commercial hydrocarbon minerals: minerals such as oil, free gas, and gases of gas caps, as well as associated useful components such as dissolved gas and gas condensate. The current regulatory framework recognizes the following categories of commercial hydrocarbon resources: minerals such as oil, natural gas, and gas of gas caps, as well as associated useful components such as dissolved gas and gas condensate. Unlike gas hydrates, these types of resources are produced by extracting them from wells using various field development techniques. In order to classify gas hydrates as a mineral resource, it is therefore necessary to determine their potential resource and engage in their extraction.

The experience of the United States in this regard is interesting, where the development of natural gas hydrates has been legalized through government documents such as the Methane Hydrate Research and Development Act of 2000. This act provided for the launching of a research and development program to study gas hydrates with the aim of commercializing them.

In August 2005, the law was revised and extended as part of the Energy Policy Act of 2005. The main customer of the work is the US Department of Energy (DOE), and the goal of the entire Program is to achieve world leadership in the development of this unconventional type of hydrocarbon. Currently, these legislative measures are being implemented in the Alaska North Slope and the Gulf of Mexico, where gas hydrate production tests are being conducted[2].

In addition to addressing technological and legislative aspects of gas hydrate development, it is crucial to estimate the quantity of gas stored in the form of hydrates in prospective hydrate-bearing areas and structures. Therefore, one of the primary objectives of studying natural gas hydrates is to establish their position among other hydrocarbon resources and to justify their significance as a source of energy.

It is noteworthy that the evaluation of the potential of unconventional hydrocarbon resources in offshore areas, including submarine gas hydrates, is a strategic objective for the medium-term perspective, as stipulated in the Maritime Doctrine of the Russian Federation.

In Russia, the assessment of the potential resources of subaquatic gas hydrates has been a subject of traditional research conducted by the All-Russia Research Institute for Geology and Mineral Resourses of the World Ocean (VNIIOkeangeologia). This line of inquiry was initiated by VNIIOkeangeologia in the early 2000s, as evidenced by publications (Soloviev et al., 2000; Soloviev, 2002). Subsequently, based on the findings of field expeditions, further work was undertaken to estimate the resources of specific hydrate accumulations, as documented in publications (Matveeva et al., 2007, 2008, 2010). Additionally, the significance of unconventional hydrocarbon resources, including gas hydrates, is emphasized in studies conducted by VNIIGAZ. This is exemplified by the works (Perlova, 2011; Skorobogatov, 2014). Methodological aspects of resource assessment of gas hydrates are discussed in (Matveeva et al., 2024a), devoted to estimates of the resource potential of gas hydrates in the Russian Arctic seas. However, large-scale quantitative assessment of gas hydrate resources within the exclusive economic zones (EEZ) of the Russian Federation and Lake Baikal was carried out for the first time in the framework of this study under the auspices of Federal Agency for Subsoil Use (Rosnedra). For the first time in more than 25 years, the assessment based on seismic data and modeling of stability conditions has been carried out that has made it possible to substantiate the resources of subaqueous gas hydrates, an unconventional type of fuel that is an integral component of Russia's mineral resources base.

Prior to the commencement of our quantitative investigation, the level of understanding of gas hydrates in the waters of Russia was relatively low. There had been virtually no dedicated expeditionary research on gas hydrates within the EEZ of Russian Federation. Despite the fact that certain water areas had undergone fairly well-documented digital seismic surveys, the data obtained from these investigations required further analysis with a particular focus on the upper part of the sedimentary section, which falls within the gas hydrate stability zone (GHSZ). The exception was the Black Sea and the Okhotsk Sea, where studies of gas hydrates in Russian waters were carried out during international missions (Ivanov et al., 1996; Kenyon et al., 2001; Shoji et al., 2003; Matveeva et al., 2005; et al.). Gas hydrates in sedimentary cores and hydrate-related anomalies have been identified in seismic profiles across the Okhotsk Sea, Black Sea, East Siberian Sea, Laptev Sea, and Bering Sea, primarily during regional geological surveys or oil and gas exploration efforts. However, there has been a lack of systematic research, analysis, and synthesis of geological and geophysical data pertaining to gas hydrate occurrences. Several studies have also focused on calculating the GHSZ based on the thermodynamic characteristics of individual marine areas and the entire Arctic region (Matveeva, Soloviev, 2003; Klitzke et al., 2016; Matveeva et al., 2017; Bogoyavlensky et al., 2018, 2021; Shchur et al., 2021). Even before the use of digital technologies in the late 1990s, GHSZ for all seas of Russia was calculated using nomograms by the VNIIOkeangeologia team, and the results were published as a series of maps as

[2] https://www.energy.gov/fecm/articles/doe-and-international-partners-complete-gas-hydrates-production-testing-alaska-north

part of the atlas (Geology and Mineral Resources of the Shelves of Russia (Atlas), 2004). Characteristics of the conditions of cryogenic hydrate formation associated with the subsea permafrost in the Arctic seas off Russia and their resource estimates are presented in the work (Smirnov et al., 2025).

The aim of this study was to evaluate the geological resources of marine gas hydrates located in the depths of all the waters overall of seas in Russia and Lake Baikal, as well as individual seas, and accumulations of hydrates, and to justify their resource potential using methods and approaches similar to those used in traditional oil and gas geology, based on geological and geophysical studies of gas hydrate reservoir characteristics.

Resource assessment methodology and data used

The work on quantitative assessment of methane in gas hydrates was divided into four stages:

1. Calculation and mapping of the gas hydrate stability zone;
2. Collection and interpretation of seismic and geological data to identify gas hydrate accumulations and create a GIS project;
3. Regional (analogous to Russian resource categories D1+D2) and local (analogous to Russian resource category Dl) estimates of subaqueous gas hydrate resources using the specific density method;
4. Analysis of data on gas hydrate reservoirs and general assessment of geological resources of subaqueous gas hydrates in Russian waters.

Calculation and mapping of the stability zone of gas hydrates generated by filtration

Any predictive models for hydrate stability conditions rely on a comparison between temperature curves and selected equilibrium hydrate formation curves. The gas hydrate stability zone depends on the parameters of pressure (hydrate-forming gas) and temperature. Under these conditions, the gas pressure is determined by hydrostatic pressure, and the temperature curve is derived from geothermal and bottom water temperature data. The salt content of the bottom waters is assumed to be similar to that of the bottom sediments and is considered an inhibitor of hydrate formation.

Forecast mapping of gas hydrate formation conditions involved the creation of a digital cartographic base, the collection of oceanographic data (bathymetry, temperature and salinity data on bottom waters), the analysis of geothermal measurements, and the preparation of geothermal datasets and calculation grids at a resolution of 0.083 × 0.033 degrees for GHSZ mapping in each offshore area. Finally, calculations are made for the thickness of GHSZs.

Due to the fact that the Arctic seas are poorly and fragmentarily studied using geothermal methods, heat flow was estimated based on available data on the geological structure and age of various structural and tectonic elements. For these seas, heat flux values were determined using geothermal zoning based on established correlations between the age of last tectonic-magmatic activity and the magnitude of heat flux, as described by (Bochkarev et al., 2023).

Similarly, based on structural and tectonic data from (The International Tectonic Map of the Caspian..., 2001), a geothermal zoning map was created for the Caspian Sea. This allowed us, considering the age of tectonic-magmatic activity, to determine the thermal gradient value of 43.7 mK/m for the Scythian-Turanian Plate, which covers the study area within the Derbent Depression of the Caspian Sea. In cases where geothermal data were available, geothermal zoning was carried out through interpolation, in particular for the Bering Sea, Okhotsk Sea, Japan Sea and Black Sea as well as Lake Baikal, based on actual data from the Global Heat Flow database (http://heatflow.org/). Using the tools provided by ArcGIS, temperature gradients were attributed to corresponding oceanographic nodes in the digital dataset, including information on sea depth and bottom water salinity, and these values were used to calculate the thickness of GHSZ at each node on the grid. The thicknesses of GHSZs were determined using specialized VNIIO_GHSZ software, which was developed in VNIIOkeangeologia (Shchur et al., 2024b), and an improved version of the MAGAS (MArine GAS hydrate) software written in Python, which is also certified (Matveeva et al., 2024b).

Equilibrium temperatures and pressures were computed using the Hydoff program (Sloan, 1998), based on the values of bottom salinity and temperature obtained from an oceanographic dataset compiled from the GLORYS12v1 database (Lellouche et al., 2021). The MAGAS utilizes Hydoff to construct the hydrate formation equilibrium curve, generate a geothermal profile, and calculate GHSZs at every node within a specified computational grid.

To determine the thickness of gas hydrate stability zones (GHSZs) and its mapping, study areas were covered with a grid. At each point on the grid, VNIIO-GHSZ and MAGAS were used to compare temperature and hydrate equilibrium curves for 100% methane at a specific salinity value. Temperature profiles were derived from sea depth data, bottom water temperatures, and geothermal gradient values. Pressure was calculated based on water depth using GEBCO 2020 bathymetric models (available at http://www.gebco.net/). This produced a dataset of GHSZ thickness values and their base depths at each grid point. These data were then used to create 2D (for GHSZ's thickness) or 3D (for GHSZ's top and base) maps of GHS Z distributions using ArcGIS 10.4 software.

The obtained GHSZ thickness values were spatially interpolated using the Spatial Analyst tool available in the ArcGIS 10.4. A natural neighborhood was chosen as the method of interpolation, with a resolution increase of the raster up to 0.005×0.005 pixels.

Using the tools of ArcGIS 10.4, an area where methane hydrate stability conditions exists has been delineated. Further mapping has been carried out in a manner similar to that described in (Shchur et al., 2021).

The calculations and mapping of GHSZ have been conducted within the exclusive economic zones of Russia, encompassing the Barents, Kara, Laptev, East Siberian, Chukchi, Bering, Japan, Black, Caspian seas and the Sea of Okhotsk. In Lake Baikal, the mapping of GHSZ was carried out in accordance with the methodology described in (Shchur et al., 2024a).

Sedimentary cover thickness within potentially gas-hydrate-bearing water areas and gas sources

A prerequisite for the formation of gas in subsurface environments is the presence of a substantial concentration of organic matter within sediments, accompanied by a relatively rapid sedimentation rate. This combination facilitates the production of biochemical methane within the upper part of the sedimentary section. Moreover, when sedimentary layers exhibit a substantial thickness, the potential for the generation of thermogenic gas becomes evident (Trotsyuk, 1982).

Based on this premise, it is possible to categorize potentially non-hydrate bearing regions as those where the quantity of gas within the sediments is insufficient for the formation of hydrates. In other words, these are water areas where conditions conducive to gas generation and accumulation are not present. These offshore areas with thickness of sediments does not surpassed 500 meters, as the sulfate reduction zone that hinders methanogenesis typically extends to approximately this depth.

Conversely, all other offshore areas where the prevailing thermobaric conditions favor the formation of gas hydrates should be regarded as potentially hydrate-bearing ones. Based on our observations, it appears that accumulations of gas hydrates of filtration origin are not confined to areas with a sedimentary cover of less than 500 metres thick. It is important to note that the origin of the hydrate-forming gas has not been taken into account in the calculations, which were based on the assumption that gas hydrates can form from any type of gas (biogenic, thermogenic, or a combination thereof) that filters towards the seabed or is generated in situ within the gas hydrate stability zone. The primary geological factor determining the conditions for gas generation is the thickness of the sedimentary cover, which contributes to the abundance of organic matter.

In order to delineate potential offshore Gas Hydrate Prone Areas (GHPAs), we excluded regions with a sediment thickness of 500 meters or less from the overall area under consideration.

The Arctic seas were zoned based on the thickness of their sedimentary deposits, as described by (Poselov et al., 2012). The Far Eastern seas were divided according to the "Map of oil and gas potential..." (Margulis et al., 2012), while the Sea of Japan was subdivided based on maps of sediment thickness by (Karnaukh, Karp, 2002). The Black Sea was also divided using maps of sedimentation thickness by (Glumov et al., 2004, 2014), while other offshore areas were zoned using data on potential gas hydrates, as presented in (Geology and Mineral Resources of the Shelves of Russia (Atlas), 2005). Baikal was zoned according to data on total sedimentation, as provided by (Geomorphology of Lake Baikal..., 1994). Raster data on sedimentation was digitized and assigned to each point using ArcGIS for spatial analysis and mapping.

Geological and geophysical data on gas hydrate accumulations

Based on the diverse conditions of their formation, marine accumulations of gas hydrates can be categorized into two main groups: 'cryogenic', which are localized in the cryolithozone within sedimentary layers with remnants of submerged relic permafrost, and those formed through upward infiltration of gas towards the seabed within the gas hydrate stability zone – 'filterogenetic' (Ginsburg, Soloviev, 1990).

Within the category of filterogenetic hydrates, there are two distinct types based on their mode of formation. The *deep-seated type* is formed under conditions of dissipated fluid infiltration, occurring at significant depths below the seabed ranging from tens to hundreds of meters and spanning extensive areas. The key objective in detecting these hydrate accumulations is identifying the hydrate-induced anomalous seismic horizon known as the BSR (Bottom Simulating Reflector), which mimics the reflection of the seafloor. The BSR is a seismic reflection boundary that arises due to the acoustic impedance contrast between hydrate-bearing sediments and the underlying, gas-saturated deposits. Consequently, on the one hand, the BSR serves as an indication of the presence of filterogenetic gas hydrate accumulations. On the other hand, it corresponds to the base of the gas hydrate stability zone, marking the transition point between the free and hydrate phases of gas.

In addition to the BSR, velocity-amplitude anomalies of the VAMP (Velocity-AMPlitude feature) type are observed in the GHSZ in association with gas hydrates (Ginsburg, Soloviev, 1994; Barth et al., 2004).

The formation of *shallow-seated accumulations of gas hydrates* occurs under conditions of concentrated gas flows, either near the sea floor or directly on it, in areas where hydrocarbons are discharged. These accumulations are primarily associated with free gas seeps, pockmarks, and mud volcanoes, which can be detected through seismic anomalies indicating the presence of substantial amounts of gas within the sediment. When such anomalies occur within the GHSZ, they are likely indicative of the presence of gas hydrate accumulations. To quantify these types of accumulations, data from original core samples from gas hydrate accumulations in the Sea of Okhotsk were utilized, as well as data on mud volcanic breccias from the Black Sea and published data.

A total of 240,812 km^2 of CDP (common depth point) data were collected and subsequently reinterpreted with the aim of conducting a comprehensive assessment of gas hydrates. The objective of this reanalysis was to detect anomalies such as BSRs and VAMPs in the seismic data, which are direct indicators of gas hydrate accumulations resulting from the presence of solid hydrates within sediments and free gas beneath them. This type of work has not been systematically conducted in Russian offshore areas, except for occasional findings during interpretation of CDP data for other purposes. In addition, over 200 publications on the Black Sea, Japan Sea, Okhotsk Sea, Bering Sea and Laptev Sea have been analyzed. Approximately 90 of these publications provide information on BSRs, resulting in the cataloguing of more than 100 seismic sections with BSR fragments.

In the Black Sea, 28 locations with BSRs were identified based on data from 26 seismic profiles, as well as additional data on gas hydrate samples. Of these 28 sites, eight are located within Russia's EEZ, specifically in the paleo delta of the Dnieper River and Tuapse Trough.

The methodology of resource assessments

The methodology employed for assessing resources involves the application of a specific density approach, as meticulously detailed in the work (Matveeva et al. , 2024a). This method relies on empirical observations of increasing density patterns in conventional gas reserves within the structural components of oil and gas geological zones, categorized into megaprovincial, provincial, regional, district, and deposit levels, with specific density ranges assigned to each category (Nazarov, 1989). Consequently, the average density of gas reserves within gas deposit surpasses their corresponding averages in megaprovinces by a factor of 124.

The applicability of this method is predicated on the fact that gas hydrates, like other types of hydrocarbons, are localized in specific accumulations and can be subject to oil and gas geological zonation. Additionally, it is based on the assumption that the amount of gas in hydrates per unit area follows the same pattern as the density of free gas reserves.

This method relies on analyzing the most reliable measurements of specific gas content per unit area from well-studied gas hydrate accumulations in the Ocean. Matveeva with colleagues (Matveeva et al., 2024a) found an average value of $1.2 \cdot 10^9$ m^3/km^2 for the specific hydrate gas content in a gas hydrate accumulation, with a range from 0.01 to $7.4 \cdot 10^3$ m^3/km^2. This average further used for regional quantitative assessments.

In comparison to the work of (Matveeva et al., 2024a), several modifications have been implemented in this research. A zoning process was conducted, resulting in the identification of promising and well-established gas-hydrate-bearing areas and sites. The dimensions of the designated zoning components were multiplied by dilution coefficients derived from the study of (Matveeva et al., 2024a).

Multiplying the mean specific gas content (q_{loc}) in designated zoning elements by the area of GHA (Gas Hydrate Accumulation) considering the 'dilution' factor for regions and provinces yields the desired regional methane content in gas hydrates (Q_{reg}) analogous to resource estimates for Russian categories D1+D2 and the overall value of hydrate gas reserves across all water areas in Russia (Q_{glob}).

For local estimates, specific values of gas hydrate density in accumulations were also obtained by calculating averages based on actual data on hydrate content (% from the core volume) in shallow-seated accumulations (q_{loc1}, Table 1), and hydrate saturation (% of pore space volume) in deep-seated accumulations (q_{loc2}, Table 2). The Q_l values, which are similar to resources of Russian category Dl, are obtained by multiplying the area of corresponding hydrate accumulation by average value of q_{loc1} or q_{loc2}.

The gas hydrate reservoirs in the Russian EEZ have been characterized based on a comprehensive analysis of data, encompassing both model simulations of GHSZ and zoning based on sediment thickness, as well as assessments of the potential gas hydrate content. Additionally, geological, geophysical, and seismic-stratigraphic data related to gas hydrates have been considered.

Results and Discussion

Forecast Mapping of Gas Hydrate Formation Conditions

Oceanographic and geothermal data are used to model the GHSZ, along with data on sediment thickness. This allows us to map offshore GHPAs (gas hydrate prone areas) within the EEZ of the Russian Federation and Lake Baikal.

#	Area	Gas hydrate manifestation Comment	Specific gas content per unit area (q_{loc1}), billion m^3/km^2,	Reference
1	South Caspian	Buzdag mud volcano; within the mud volcanic (MV) structure	0.4	(Soloviev, 2002)
2	Norwegian Sea	Haakon Mosby mud volcano; within the MV structure	0.3	(Ginsburg et al., 1999)
3	Mediterranean Sea	Milano mud volcano; within the MV structure	0.4	authors' assessment based on data (De Lange and Brumsack, 1998)
4	Sakhalin slope, Sea of Okhotsk	gas seep; within the seep structure	0.8	(Soloviev, 2002)
5	Gulf of Cadiz	Captain Arutyunov mud volcano; within the MV structure	0.5	(Matveeva et al., 2008)
6	Gulf of Cadiz	Ginsburg mud volcano; within the MV structure	0.01	(Matveeva et al., 2008)
7	Gulf of Cadiz	Bonjardim mud volcano; within the MV structure	$1.8 \cdot 10^9$	(Matveeva et al., 2008)
8	Sakhalin slope, Sea of Okhots	Obzhirov gas seep; within the seep structure	0.5	authors' assessment
9	Sakhalin slope, Sea of Okhots	CHAOS gas seep; within the seep structure	0.8	authors' assessment
10	Sorokin Trough, Black Sea	Dvurechensky mud volcano; within the MV structure	7.4	(Bohrmann et al., 2003; Bohrmann, 2011; Feseker et al., 2009; Wagner-Friedrichs et al., 2007; Geological Processes in the Mediterranean…, 2001)
11	Sorokin Trough, Black Sea	Sevastopol mud volcano; within the MV structure	4.6	authors' assessment based on data (Bohrmann et al., 2003; Bohrmann, 2011; Feseker et al., 2009; Wagner-Friedrichs et al., 2007; Geological Processes in the Mediterranean…, 2001)
According to 11 reliable definitions, the specific gas content per unit area		Average	1.6 m^3/km^2	
		Maximum	7.4 m^3/km^2	
		Minimal	0.01 m^3/km^2	

Table 1. Results of the assessment of specific gas content in shallow-seated gas hydrate accumulations in areas with focused fluid discharge

#	Area	Gas hydrate manifestation / Comment	Specific gas content per unit area (q_{loc2}), billion m^3/km^2,	Reference
1	Peruvian Trench	Site 685, 112 Leg ODP	0.4	authors' assessment based on data (Suess et al., 1988)
2	Central American Trench	Site 570, 84 Leg DSDP	1.4	(Mathews and von Huene, 1985) with changes
3	Offshore Vancouver Island	Site 889 Leg, 146 ODP	0.5	(Collett, 1995)
4	Bering Sea	within VAMPs	0.7	(Scholl and Hart, 1993)
5	Blake Outer Ridge, NE Atlantic	Site 994, 164 Leg ODP; according to logging data	0.7	(Collett, Ladd, 2000)
6	Blake Outer Ridge, NE Atlantic	Site 995, 164 Leg ODP; according to logging data	1.3	(Collett, Ladd, 2000)
7	Blake Outer Ridge, NE Atlantic	Site 997, 164 Leg ODP; according to logging data	1.4	(Collett, Ladd, 2000)
8	Blake Outer Ridge, NE Atlantic	on an area of 26000 $км^2$; within BSR	0.4	authors' assessment
9	Nankai Trough, Japan Sea	within BSR; on an area of 324 $км^2$; according to logging data and basin modelling	1.3	authors' assessment based on data (Taladay et al., 2017)
10	Nyegga, Vøring Plateau	within BSR, on an area of 2254 $км^2$ according to seismic data, drilling and basin modeling	0.3	(Senger et al., 2010)
11	Terribon Basin, Gulf of Mexico	gas hydrate accumulation in the Lower Pleistocene trap (Q_{loc}=4.4·10^9m)	1.2 (in sandy reservoirs) 0.3 (in clay reservoirs)	(Frye et al., 2012)
12	Andaman Sea	within BSR on an area of 25 $км^2$ according to logging and seismic data; the thickness of the hydrate layer is 30 m; hydrate saturation according to logging data is 30%; Q_{loc} = 1/4·10^{10} m^3	0.6	authors' assessment based on data (Prakash, 2017)
13	Japan Sea	Ulleung Basin within BSR on an area of 7629 $км^2$	1.4	authors' assessment based on data (Ryu et al., 2013)
14	Bering Sea	by seismic velocities; within VAMPs	0.6	authors' assessment based on data (Scholl and Hart, 1993; Barth et al., 2004).
According to 11 reliable definitions, the specific gas content per unit area		Average Maximum Minimal	0.83 m^3/km^2 1.4 m^3/km^2 0.3 m^3/km^2	

Table 2. The results of the assessment of specific gas content in deep-seated gas hydrate accumulations formed under conditions of dissipated fluid filtration

The total area of the EEZ is 7,136.7 km², and the total area of GHPAs is 2,394 km². Therefore, approximately 34% of the EEZ area is characterized by favorable thermobaric conditions for the formation of natural gas hydrates, according to the filtration model. The largest areas of GHPAs are found in the Sea of Okhotsk and Bering Sea (Figure 1A and 1B), due to their large areas and extensive continental slopes, as well as in the three Arctic seas – the Barents, Kara, and Laptev – where the conditions for gas hydrate stability are associated with the continental shelf edge and continental slope. Lake Baikal holds a unique position as the sole freshwater reservoir on the planet, characterized by its thermobaric, geological, and fluid-dynamic attributes, which create the ideal conditions for the formation of gas hydrates. These conditions are further enhanced by the presence of increased seismic activity in the rift zone, as reported in (Matveeva et al., 2003; Khlystov et al., 2022).

The GHPA for hydrate of filtration genesis in the Russian Arctic shelf is estimated at 920,000 km², accounting for 21.5% of the total EEZ of the Russian Federation.

The Far Eastern seas are characterized by the most widespread occurence of GHPA. The share of GHPA from the EEZ in these seas varies from 47% in the Sea of Okhotsk to 63% in the Sea of Japan. The largest areas of GHPA, reaching 740 thousand km², are mapped in the Sea of Okhotsk. In the Bering Sea, the GHPA covers 418 thousand km², which is almost 2 times less than that of the Sea of Okhotsk. The proportion of offshore areas with thermobaric conditions unfavorable for the formation of gas hydrates in the Sea of Okhotsk is associated with extensive shelves. In addition, for all the Far Eastern seas, the proportion of areas with the absence of the amount of gas necessary for hydrate formation is noticeable (6.5–8.9%).

Regional estimates of the gas hydrate content in subaqueous hydrates (similar to Russian categories D1+D2)

The results of calculations of methane content in gas hydrates in the offshore areas within the exclusive economic zone of the Russian Federation and Lake Baikal as of January 1, 2024 using the specific density method are shown in Figure 2 and Table 3.

The Bering Sea has the greatest gas hydrate potential (41.8 trillion m³), exceeding the resources of the Laptev Sea and the Sea of Okhotsk (27.2 and 28.6 trillion m³, respectively) by 1.5 times. This is due to large areas of GHPA and a significant volume of gas hydrate reservoirs. The high potential of these seas is also supported by numerous discoveries of gas hydrates (see below). Regional estimates for the Black Sea (10.2 trillion m³) and Lake Baikal (1.6 billion m³) using this approach

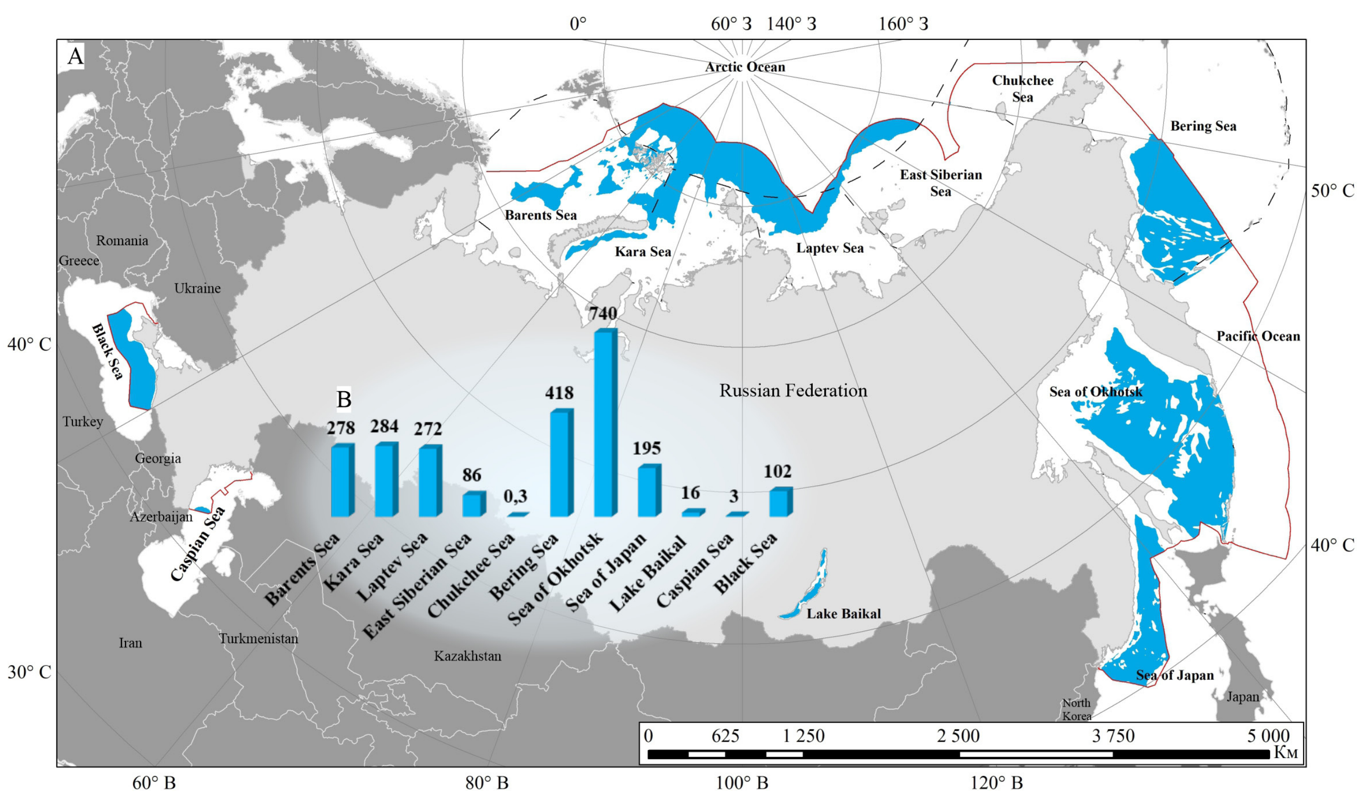

Figure 1. A. Offshore gas hydrate prone areas (GHPAs) in the exclusive economic zone of the Russian Federation, including Lake Baikal, within GHSZ with a sediment thickness exceeding 500 meters – blue fill. The EEZ boundary is represented by a solid red line, while the geographical boundaries of the seas are indicated by a black dotted line. B. Histogram of the distribution of gas hydrate prone areas by the corresponding sea (thousands of square kilometers).

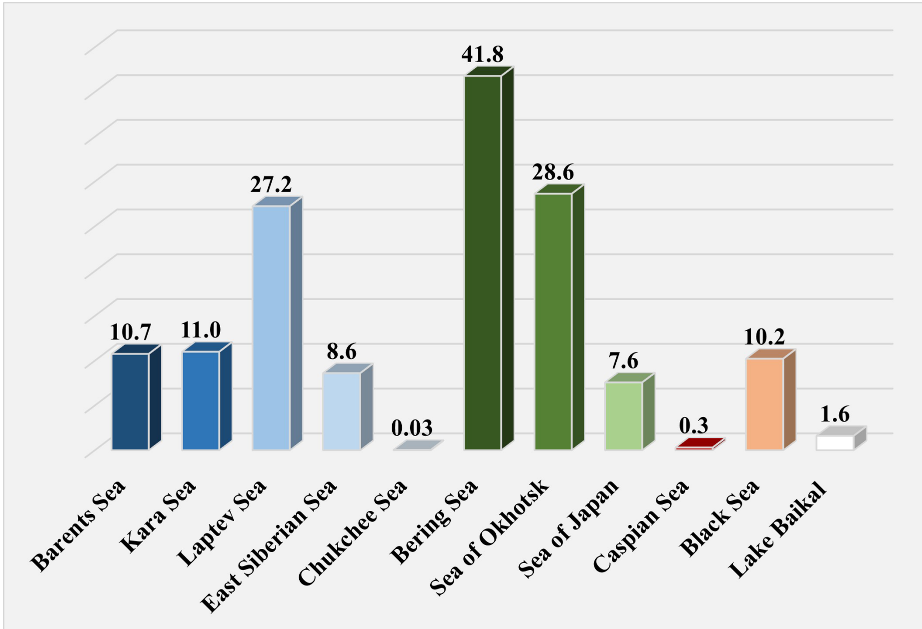

Figure 2. Regional estimates of the gas hydrate content in subaqueous hydrates (similar to Russian categories D1+D2), trillion m^3

appear to be underestimated as both areas have many gas hydrate discoveries.

In accordance with the size of the GHPA and their proximity to certain elements of the oil and gas geological zoning of the continental shelf, the Black and Caspian seas, and the prospects for detecting accumulations of gas hydrates, the following elements are identified (Table 3): Okhotsk and Japan seas gas-hydrate provinces, Barents and Kara prospective gas-hydrate provinces; gas-hydrate-bearing regions – Bering, Laptev, Eastern Arctic, Black seas; prospective gas-hydrate-bearing regions – Chukchi Sea and Central Caspian. Lake Baikal was allocated to a separate Baikal gas-hydrate-bearing region. Among them, the provinces of the Okhotsk Sea and Japan Sea, as well as Bering, Laptev, Black Seas and Baikal are characterized by numerous gas hydrate accumulations. The Sea of Japan and the Eastern Arctic GHPAs are still insufficiently studied, although they are characterized by accumulations of gas hydrates. The remaining provinces and regions have been classified as 'prospective', where there are either no direct signs of hydrates or they occur sporadically.

The gas hydrates in the offshore areas of Russia: geological and seismic data

As a result of the reinterpretation of digital seismic sections, total 14,540 km of BSRs were identified. All identified BSR are hydrate-induced, as they are located within the stability zone for methane hydrates. They have a reversed polarity to reflections from the seafloor and cross sedimentary strata. They are also characterized by blanking above the BSR. In the EEZ of Russia, gas hydrates were recovered from sediments of gas seeps and mud volcanic breccias in the Okhotsk, Japan and Black seas. Based on the comprehensive analysis of geological and geophysical data on gas hydrate occurrences, a comprehensive database of filtration in origin gas hydrate accumulations has been established as of January 1, 2024. This database encompasses information on a total of 203 hydrate accumulations.

Furthermore, in addition to the numerous BSRs, anomalies of VAMP type (Velocity AMPlitude features on the seismic records) are prevalent in the Bering Sea. These anomalies also serve as indicators of the presence of gas hydrate deposits. Similar single anomalies have been identified in the Barents Sea and the Black Sea as well.

Arctic seas. The Laptev Sea is one of the most promising among Arctic seas for gas hydrates offshore Russia. In this area, BSRs have been identified on numerous seismic profiles. This allows us to identify a large accumulation of gas hydrates and several smaller ones (Figure 3). Figure 3 (a fragment from seismic profile number 2) shows a typical seismic profile with a discontinuous BSR and a prominent blanking zone above it, indicating hydrate-bearing sediments.

In the Barents Sea, CDP data was analyzed in the St. Anna Trough and areas located north of Novaya Zemlya and south of Franz Josef Land, as these areas are characterized by a high density of seismic data. A gas hydrate accumulation has been identified within the VAMP anomaly in the Barents Sea, with a range of 2 km wide at the margins, and a depth of between 115 and 105 meters below sea floor (mbsf), and 65 mbsf in the central part of the underlying gas chimney. A pockmark is located above an anomaly, indicating active discharge of gas-saturated fluids from the below.

The Kara Sea is mostly characterized by the presence of a submarine cryolithozone. No unambiguous seismic signs of gas hydrates of filtration origin have been found here, but generally, the Kara Sea is characterized by numerous hydrocarbon seeps and corresponding anomalies on seismic profiles.

In the East Siberian Sea, in the Vilkitsky Trough, a hydrate-induced BSR was identified with gas discharge structures, identified by gas chimneys (Figure 3, fragment of seismic section 3). The anomaly (Figure 3) located on the continental slope at a sea depth of 1,800–2,100 meters. The BSR depth varies from 370 to 395 mbsf. The main features of the BSR are clearly visible in the section: reverse polarity relative to the seafloor, subparallel to the sea bed, and intersection with sedimentary stratification. The insets in circles show the polarity of signals reflecting from the seabed and from the BSR. The length of the anomaly is 18 km.

The Far Eastern seas. The Bering Sea exhibits a diverse array of seismic signatures associated with gas hydrates. 79 BSR on 76 seismic lines are revealed here, with 64 within the Russian EEZ, encompassing regions such as the continental slope, the Aleutian Basin, and the slopes of the Shirshov Ridge (Figure 4A). Gas chimneys traverse through these BSRs in weak zones, as shown in Figure 4A (fragments of seismic sections 1 and 2). Additionally, double BSRs (DBSR) have been identified. A distinctive feature of the Bering Sea is the abundance of VAMPs amplitude-velocity anomalies (Figure 4, fragment 3). These hydrate-induced anomalies are characterized by an increased signal frequency above the anomaly and a decreased frequency below it, as well

Study area	Unit of oil and gas geological zoning	Dilution ratio	Area of GHPA, thousand km^2	Volume of the gas hydrate reservoir, trillion m^3	Amount of methane in gas hydrates (Q_{reg}), trillion m^3	Share of methane hydrate in the total volume of the hydrate reservoir,%
Barents Sea	Barents prospective gas hydrate province	31^{-1}	278	64	10.7	6.8
Kara Sea	Kara prospective gas hydrate province	31^{-1}	284	79	11.0	8.7
Laptev Sea	Laptev gas hydrate-bearing region	12^{-1}	272	91	27.2	24.8
East Siberian Sea	Eastern Arctic gas hydrate-bearing region	12^{-1}	86	27	8.6	2.3
Chukchi Sea	Chukchi Sea prospective gas hydrate-bearing region	12^{-1}	0.3	0.02	0.03	0.0
Bering Sea	Bering Sea gas hydrate-bearing region	12^{-1}	418	114	41.8	47.7
Sea of Okhotsk	Okhotsk gas hydrate province	31^{-1}	740	85	28.6	24.3
Sea of Japan	Japan Sea gas hydrate province	31^{-1}	195	31	7.6	2.4
Caspian Sea	Central Caspian prospective gas hydrate-bearing region	12^{-1}	3	0.2	0.3	0.001
Black Sea	Black Sea gas hydrate region	12^{-1}	102	27	10.2	2.8
Lake Baikal	Baikal gas hydrate-bearing region	12^{-1}	16	2	1.6	0.03

Table 3: Results of regional estimates of the amount of methane in filtrational in origin gas hydrates in Russian offshore areas

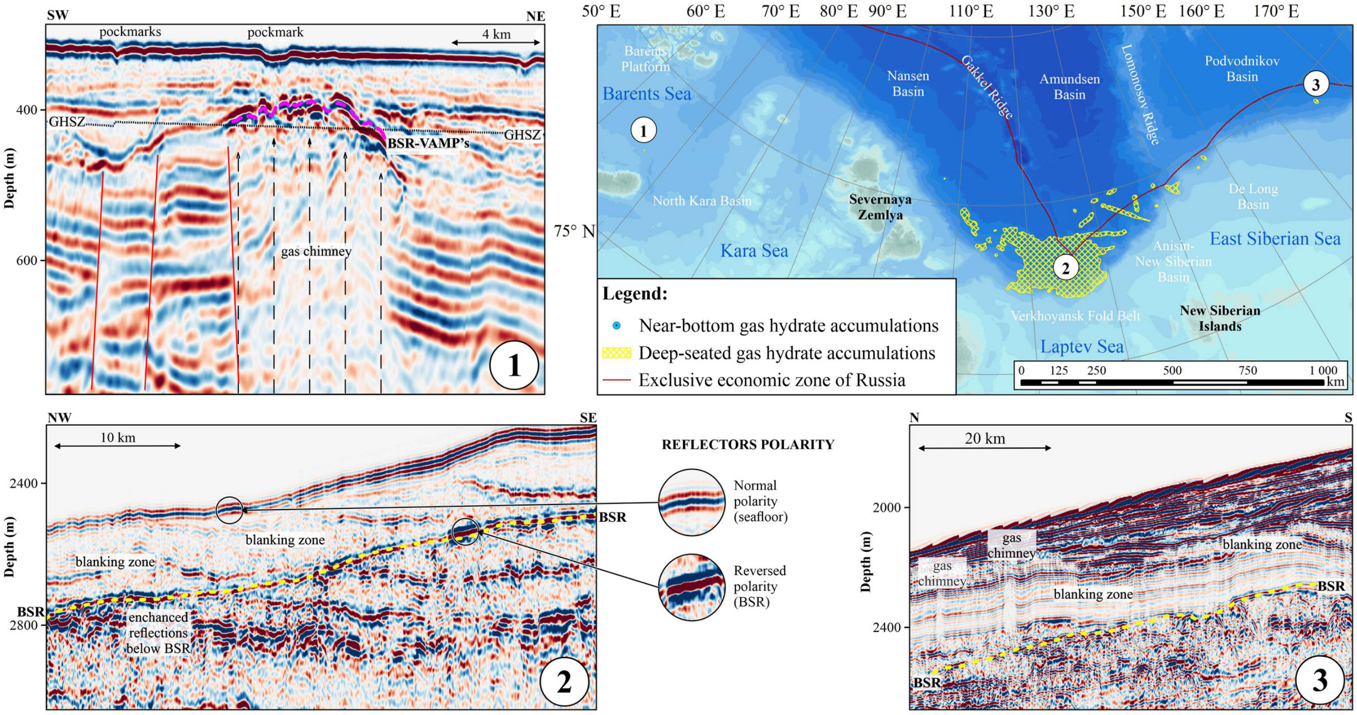

Figure 3. Accumulation of filtration originated gas hydrates in the seas of the Russian Arctic. The numbers in circles represent the position of hydrate-related anomalies on seismic sections.

as by pull-up effect. They also have a distinctive shape that resembles an inverted saucer (Figure 3, fragment 1 and Figure 4, fragment 3). The area of VAMP distribution is confined to the central part of the sea. Ten sites with VAMPs have been mapped on seismic lines located outside the Russian EEZ (Figure 4A). The spatial distribution of VAMPs is determined by the topography of the basement - they are confined to uplifts. Supply channels in the form of bending horizons (pull ups) can be traced down hundreds of meters to basement rocks. The diameters of upper parts of structures reach 4 km. Based on this seismic data, several accumulations of gas hydrates have been identified (Figure 4A).

In the Sea of Okhotsk, Bottom Simulating Reflectors were detected on the northeastern slope of Sakhalin Island and in the western Paramushir Island. They were also identified in the Deryugin and Tinro depressions, as well as on the southern slope of the Academy of Sciences uplift and in Terpeniya Bay. This is illustrated in Figure 4B, a fragment of seismic section 4.

The BSR stands out clearly on the continental shelf of the Sakhalin, where it appears as an inverted-polarity horizon that intersects sedimentary strata. The subbottom depth of the BSR increases with increasing water depth. Seismic data reveals enhanced reflections below the BSR, with sediment cover further complicated by various tectonic disturbances. Wave patterns in the Deryugin region appear chaotic, possibly due to high gas saturation in sediments. In some cases, the BSR shows upward bending in local areas, indicating concentrated upward migration of hydrocarbons. The BSR clearly stands out on the continental slope in the Prisahalinskaya Flexure. It appears as an inverted polarity horizon that intersects with sedimentary layers and its depth increases with increasing water depths. Seismic data reveals enhanced reflections below the BSR, where sediments are complicated by various tectonic disturbances.

Numerous accumulations of gas hydrates in the Sea of Okhotsk are associated with gas seeps (Figure 4B – blue dots). Gas hydrates were recovered at four well-studied sites in association with gas seeps: off Paramushir Island at water depths of about 800 meters; on the western slope of the Deryugin Depression, northeast of Sakhalin, at sea depths between 390 and 700 meters; and on the southeastern Sakhalin slope near Terpeniya Bay. Twenty-three locations where gas hydrate was recovered by core sampling are shown on Figure 5A. Numerous hydrate-bearing seepages were discovered on Sakhalin's continental shelf and slope at sea depths ranging from 390 to 1500 meters. They were reliably recorded by echo sounders. A feature of hydrate occurrences associated with free gas seepage is the lenticular-bedded structure of hydrate-bearing sediments, resulting from water segregation due to diffusing gas.

In the Sea of Japan, numerous BSR observations are known outside the Russian EEZ – 52 off the coast of Korea, 58 in the Joetsu Basin, and five in the area of the Okushiri Ridge (off the coast of Japan). In the Russian sector, a single BSR has been identified in the southern part of the Tatar Strait at subbottom depths ranging from 100 to 260 m at sea depths of 1200–1500 m (Figure 4B). Gas hydrates have been recovered in Russian waters

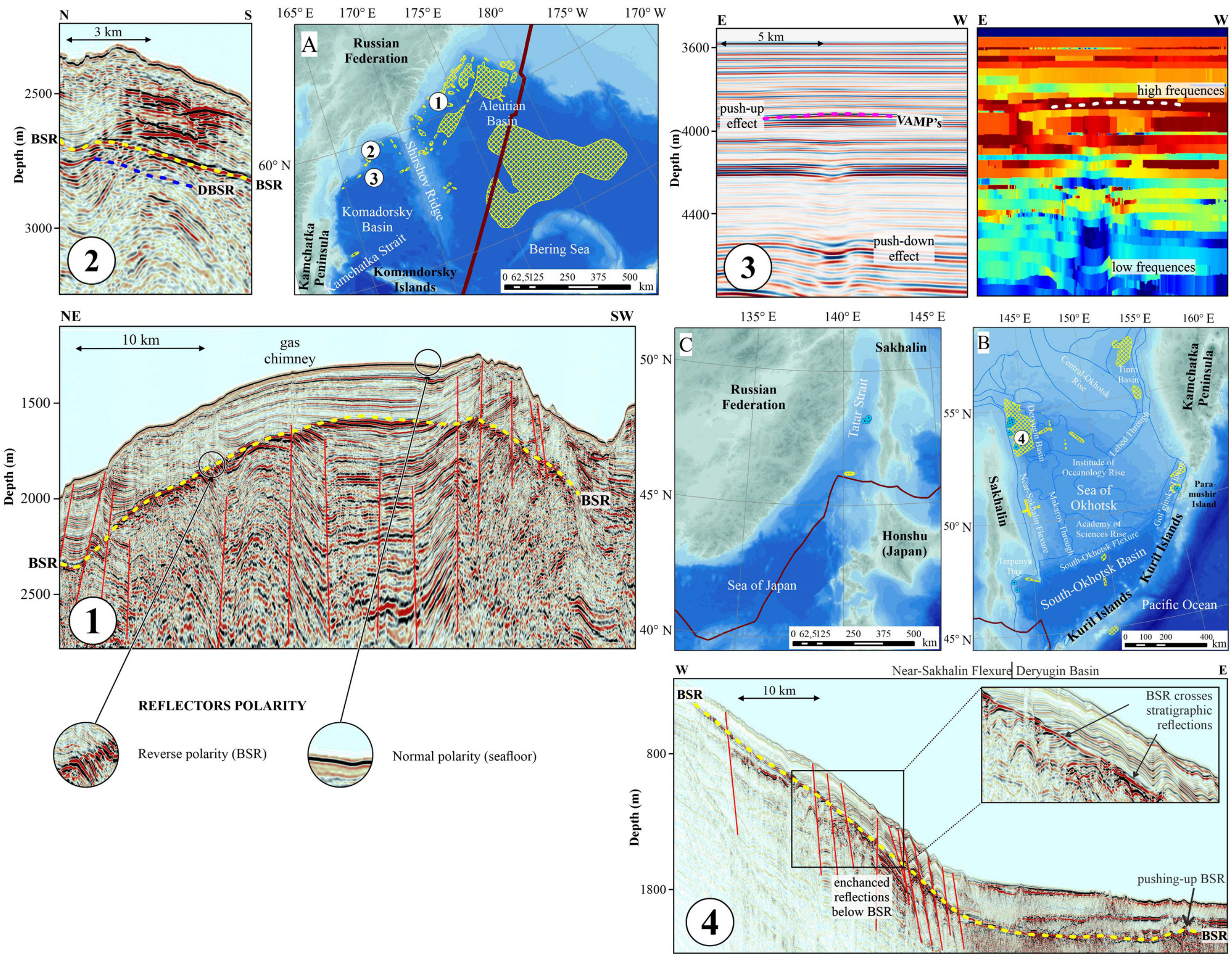

Figure 4. Accumulation of filtration originated in the Far Eastern Seas off Russia; numbers in circles represent positions of hydrate-related anomalies on seismic sections. Symbols are shown in Figure 3.

within gas seeps in the Tatar Strait and on the eastern slopes of the Tatar Trench.

South Seas. The sedimentary basins of the Black Sea are characterized by thick ‘young’ sedimentary cover. They are also characterized by clay diapirism, active mud volcanism, discharge of fluids (water and gas) along fault zones, and the presence of large sediment fans and landslide structures. In the Black Sea, gas hydrates are associated with clay diapirs, mud volcanoes and gas seeps. They have been observed at sea depths ranging from 700 to 2,000 m, both in mud breccias, as small scattered inclusions and large massive lumps and nodules, and in deformed silty-clay sediments on the periphery of diapirs, in the form of separate plates. Total data on 64 geological sampling stations were collected in the Black Sea where gas hydrate were observed in sediment cores. Some of these stations are located within the Russian EEZ (Figure 5A).

Numerous gas hydrate-related anomalies were identified and mapped in the Black Sea: BSR (Figure 5A, fragments of seismic sections 1 and 3), DBSR, and VAMP (Figure 5A, fragment of seismic section 2). Under the VAMP, there is a “drawdown”-type anomaly – a pull-up effect due to high gas saturation. A large number of discontinuous faults are observed throughout the Shatsky Rise, which serve as fluid conduits that reach up to the GHSZ. Many bright spots and pulls up are associated with these faults. The total length of all identified gas hydrate induced anomalies was 1483 km. These anomalies are observed at sea depths of 800–2100 meters, and their subsurface depths vary from 130 to 600 m.

In the deep-water part of the Southern depression of the Caspian Sea, there are known accumulations of gas hydrates associated with mud volcanoes, with water depths of about 490 meters. However, there is no evidence of gas hydrates within the Russian EEZ. The Russian sector of the sea is characterized by a lack of study and a small area covered by potential gas hydrate-bearing areas, as shown in Figure 5B.

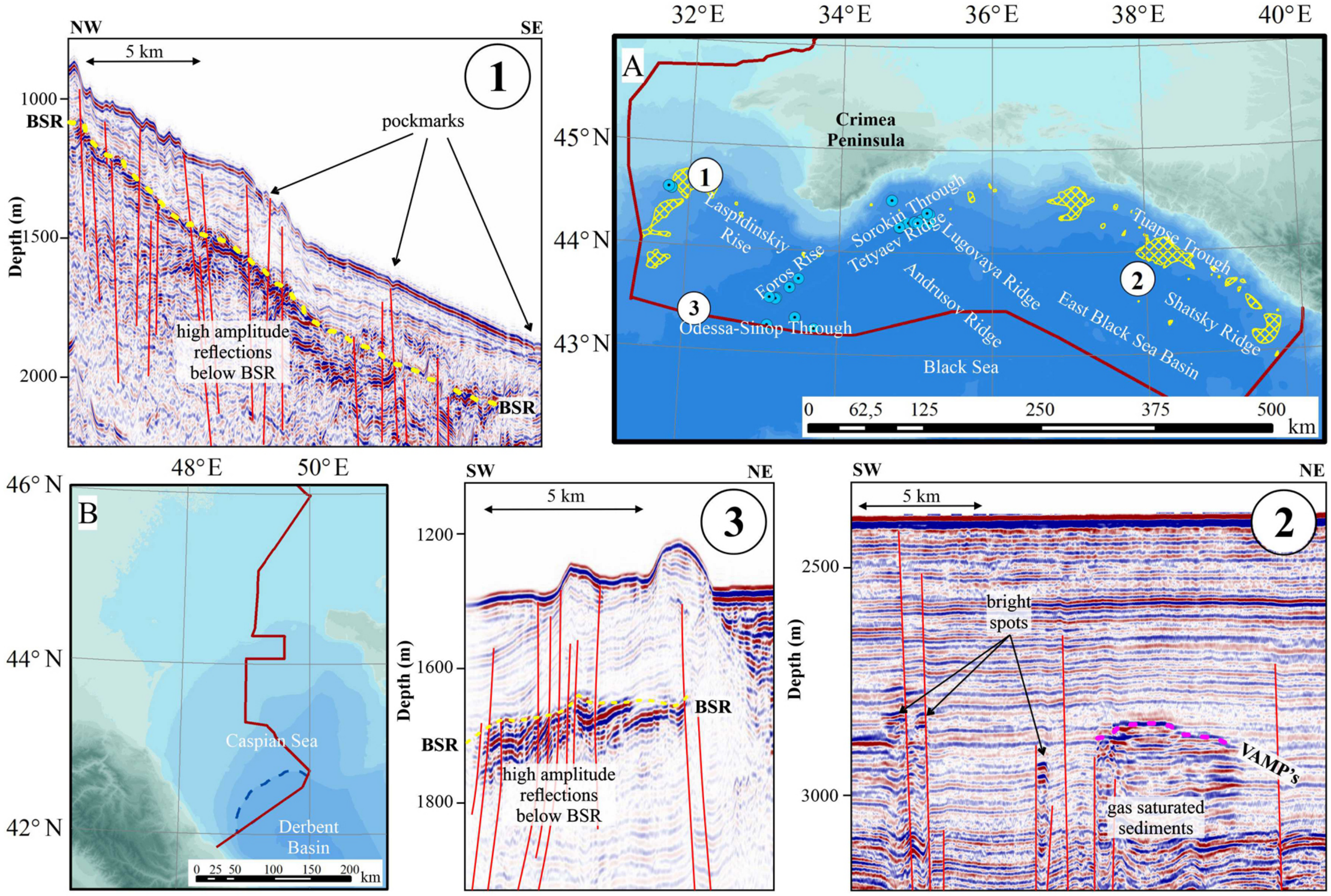

Figure 5. Accumulation of filtration originated in the Russian sector of the Black Sea (A), and the boundary of GHPA in the EEZ of Russia in the Caspian Sea (B). The numbers in circles represent the position of hydrate-related anomalies on fragments of seismic profiles. The symbols used are shown in Figure 3.

Local estimates of the amount of methane in subaqueous accumulations of gas hydrates (analogous to the Russian Dl category)

Since the first detailed studies of submarine accumulations of gas hydrates, estimates of their resources based on direct observations of hydrates in cores and their indirect signs have been of great interest, as most adequate resource assessments should be based on data on gas hydrate saturation, the size and shape of accumulations and reservoirs. To perform local estimates of methane content in specific gas hydrate accumulations, the following data is necessary: thermobaric conditions inside the accumulations, gas hydrate saturation, data on heat flow from subsurface, information about shape and size of the accumulation (mainly from seismic or sonar surveys), type of accumulation (shallow- or deep-seated, filtration in origin or cryogenic). Thus, the methodology for local estimates of the amount of methane in gas hydrate accumulations is determined by the type of accumulation and available geological information on a particular occurrence. First, this information includes seismic data, evidences, as well as data from geothermal measurements in from coring and drilling. There are no accumulations with a full set of required data offshore Russia; about a dozen GHAs relatively well studied. All of these are shallow-seated and confined to gas discharge areas. These types of accumulations can be localized using hydroacoustic studies and CTD studies of the water column. They are controlled by morphology of hydrocarbon discharge structure and can be easily sampled using coring and characterized by geothermal data. Thus, with the current degree of study, the specific density method seems to be quite adequate for local gas hydrate estimates. Gas hydrate accumulations of this type have been mapped and resources were evaluated in the Black Sea and the Sea of Okhotsk.

A total of 26 shallow-seated gas hydrate accumulations Black Sea and the Sea of Okhotsk were taken into account in the quantitative assessment. The shape and size of the structures controlling the fluid discharge were determined for these accumulations. An analysis of specific gas content in 11 studied accumulations showed that it ranged from 0.01 to 7.4 billion m^3 per km^2 (Table 2), with an average value of q_{loc1} of 1.6 m^3/km^2. This value was multiplied by the area of each accumulation to obtain the Q_l value. Gas resources in the form of methane hydrates vary from 0.1 to 13 billion m^3 in these accumulations, and the total amount of methane is estimated at 69 billion m^3 for all 26 accumulations studied. Estimates of projected gas amounts in identified accumulations range between 0.5 and 14 billion m^3.

Gas hydrate accumulations formed under conditions of dispersed fluid infiltration in Russian waters have not been detected by drilling as of January 1, 2024. The exception is the report (Petrovskaya et al., 1989), which describes the discovery of gas hydrates in the deep water part of the Bering Sea at sea depths of 2110 m and subbottom depths of 610 m in Miocene terrigenous deposits. A gas-hydrate horizon 10 to 15 m thick was identified there, but there is no information available on the size or hydrate saturation of this accumulation.

For the quantitative assessment, analysis of published works was performed on the most well-studied accumulations of subaquatic gas hydrates of the Ocean with established values of gas hydrate density based on data from drilling or seismic velocities analysis (Table 3). The results from 14 measurements of hydrate saturation in deep-seated accumulations and hydrate-bearing areas allowed us to calculate the specific content of hydrated gas per unit area, ranging from 0.3 billion m^3/km^2 to 1.4 billion m^3/km^2 with an average value of q_{loc2} of 0.83 billion m^3/km^2, which was then used in further calculations. Areas of GHAs were calculated based on seismic data – distribution of BSRs (143 GHAs) and VAMPs (31 GHAs). In general, accumulations associated with VAMPs are characterized by both smaller sizes and fewer resources – the maximum estimate of 6,012 billion m^3 is calculated for the large GHA associated with the entire area occupied by the VAMP anomalies in the central part of the Aleutian Basin (Figure 4A). The total amount of methane in deep-seated gas hydrates (Q_1) varies over a wide range, from 0.03 to 6829 billion m^3. This variation is due to the size of the gas-hydrate structures studied and the quality of the seismic data used to identify accumulations. Some structures are only intersected by one seismic profile, and as the grid of profiles becomes denser, the size of these accumulations will increase.

The resource assessment included the results of analyzing CDP data, gas hydrate-bearing cores, and published papers and reports on submarine gas hydrate accumulations. This led to the creation of a database on submarine gas hydrate accumulation offshore Russia, including estimates of hydrated methane resources in these accumulations.

Projected Q_1 resources, analogous to the Russian Dl category, have been estimated for 203 submarine filtrational-type accumulations identified within the EEZ of the Russian Federation. The total volume of methane in hydrates of the studied accumulations classified as D_1 is approximately 120 trillion m^3. The distribution of methane resources in gas hydrate accumulations by offshore ware areas is shown in Figure 6A. Each diagram of the sea indicates the number of accumulations discovered (colored numbers) and the total amount of methane in those hydrate accumulations (black numbers). Resources in the largest deep-seated accumulations are comparable in rank to reserves in large conventional gas fields (those GHAs numbered more than 40) and unique conventional gas fields (more than 30 GHAs). Unique and large gas hydrate accumulations have been identified in Laptev and Bering seas, and the Sea of Okhotsk. Resources of shallow-seated gas hydrate accumulations associated with fluid discharge areas are comparable in rank to very small, small and medium-size conventional gas field reserves (Figue 6B).

Gas hydrate reservoirs of the Russian seas

Since the key condition for the existence of hydrates in marine sediments is the presence of a zone of their stability – a part of the lithosphere in which previously formed hydrates can exist in a stable condition,

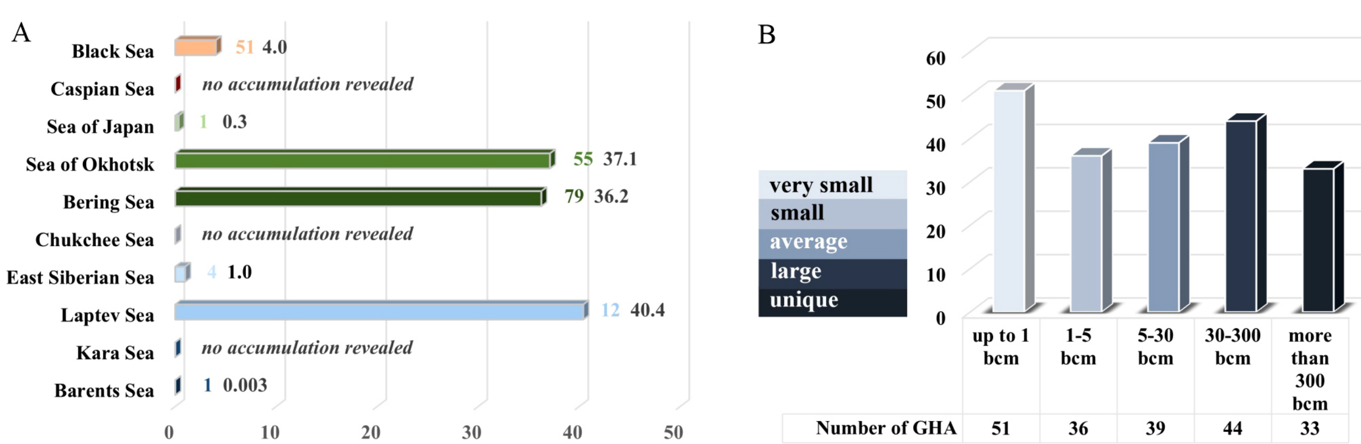

Figure 6. Histograms of the distribution of (A) the total local estimates of Q_1 (analogous to the Russian Dl category) for the predicted amount of methane in gas hydrate accumulations of filtration origin in Russian waters (black numbers, trillion m^3); colored numbers opposite the bars indicate the number of identified accumulations; and (B) a ranking of gas hydrate accumulations based on their resource, analogous to the ranking of conventional gas deposits by reserves.

the practical task of supraregional forecasting of gas hydrate conditions is to map the stability zone of gas hydrates and calculate its thickness. The thickness of the gas hydrate stability zone of filtration origin, together with information on the thickness of the sedimentary cover within its boundaries, as well as data on BSR and seismic-stratigraphic data, allows us to characterize gas hydrate reservoirs. That is, i.e. to obtain information about their vertical variability, their association with specific morphological structures on the shelf, continental slope, and foot, as well as about the age of sediments containing the gas hydrates (Figure 7).

Let us focus on the concept of 'gas hydrate reservoir', which is used in our study and distinguishes potentially gas hydrate-bearing sediments from those characteristic of conventional gas fields. This was discussed earlier by (Matveeva, 2018). We will compare this concept to the term 'natural reservoir' introduced by I.O. Brod (1951) as a 'natural receptacle for oil, gas and water inside which there is circulation of fluids'. The shape of the reservoir (collector) depends on its relationship with surrounding impermeable rocks (caps).

Gas hydrate reservoirs exhibit a series of distinctive features when compared to conventional hydrocarbon reservoirs. Unlike conventional reservoirs, they do not require the impermeable seals. Instead, they are characterized by the existence of fluid-conducting zones inside. The role of a trap in the context of a gas hydrate reservoir is played by the gas hydrate formation zone, which is the interval in the sedimentary section where the solubility of methane matches or exceeds its solubility limit at specific temperatures and pressures. In essence, a gas hydrate reservoir can be defined as a spatially limited interval within a sedimentary sequence that is conducive to the accumulation of significant amounts of natural gas sufficient to saturate the pore water in equilibrium with gas hydrates and to the formation and long-term preservation of these hydrates (Figure 7).

These hydrate reservoirs are not bounded by material barriers, like those that are typical of conventional oil and gas reservoirs. Instead, they are limited by physical, temperature and chemical fields. These conditions determine the shape of the gas hydrate stability zone and they depend on the permeability of the sediments, which allows gas and water to move into the zone.

In contrast, in the presence of impermeable layers below the stability zone, hydrate formation is unlikely to occur due to a lack of sufficient gas to saturate the pore waters. Additionally, although hydrate formation depends on the grain size distribution of sediment and is most likely to occur in sediments with good reservoir properties, it can also happen in fine-grained clay deposits which are not usually considered as collectors.

A gas hydrate reservoir is characterized by the type of sediments containing hydrates, their age and conditions of accumulation, infiltration conditions (e.g., ascending, dissipated, concentrated flows of gas and water), the type of hydrate manifestation, capacity, deposition, and hydrodynamic conditions, as well as thermobaric conditions.

Based on the data on the depth of the BSR and shallow sampling, gas hydrate reservoirs in the Russian seas are generally found in Cenozoic sediments. These sediments can be divided into two main intervals: the upper

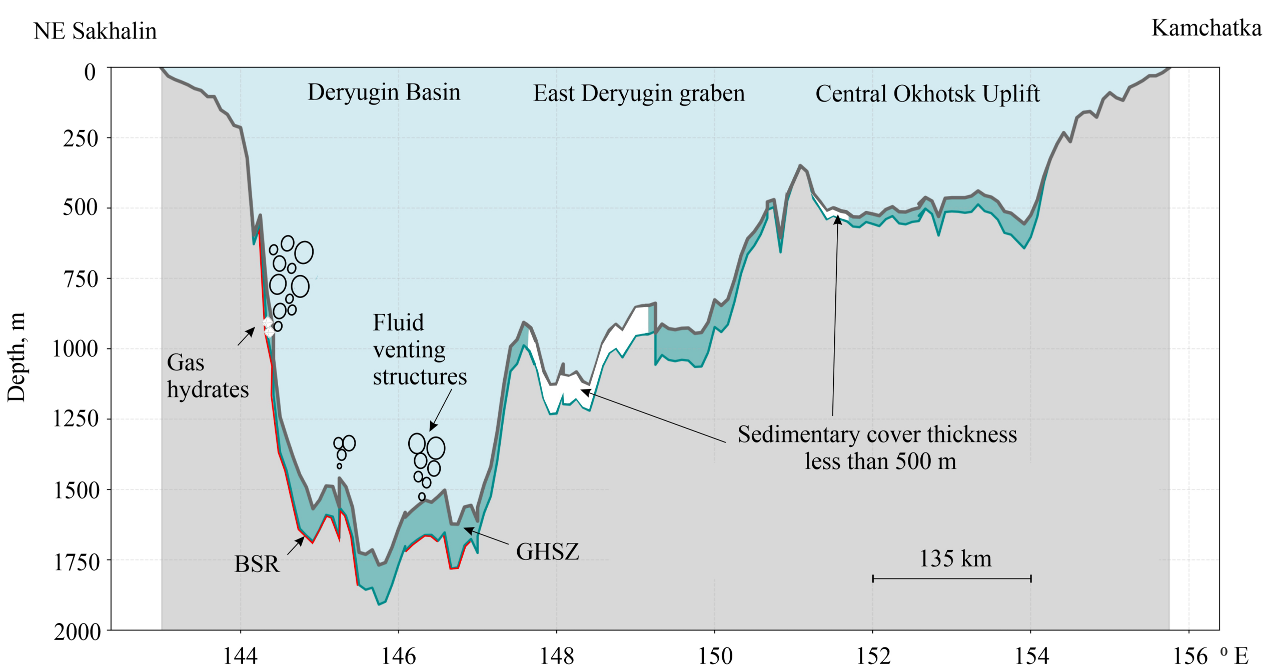

Figure 7. A schematic section along the Sakhalin-Kamchatka SW profile through a gas hydrate reservoir in the Sea of Okhotsk. The green line shows the GHSZ. The red line is base of a GHA with a prominent BSR. White diamonds represent the location of shallow-seated accumulations of gas hydrates at gas seeps.

(Holocene) and lower (Pleistocene-Oligocene). In the upper interval, shallow-seated accumulations of gas hydrates are found at depth of about up to 50 mbsf (Figure 8).

Here, under conditions of focused discharge of hydrocarbons, maximum overcooling and filtration pressure are achieved. This leads to maximum oversaturation of pore waters with gas and precipitation of its excess in the form of hydrates. The accumulations of hydrate forming in the upper interval are small and confined to the Holocene age.

An analysis of data on well-studied accumulations in the Ocean has shown that, with a much smaller size of gas hydrate-bearing structures, the maximum specific density of hydrated methane in shallow-seated accumulations is 5 times greater than this value for deep-seated ones (Tables 2 and 3). At the same time, the minimum specific density in deep-seated accumulations is about 30 times higher than that in those formed at fluid discharge sites. This is apparently due to the particularity of gas hydrates in shallow occurrences, where overcooling of pore waters and their oversaturation with methane leads to maximum pressure formation of hydrates, resulting in high specific resource densities.

Deep-seated accumulations of hydrates form in the gas hydrate reservoirs of the lower interval at subbottom depths ranging from 250 to 1200 meters. Most studied accumulations of this type are confined to terrigenous Pliocene deposits, which are almost twice as common as Miocene or Pleistocene ones.

In this study, we define a gas hydrate reservoir as the volume of sediments within the GHSZ that is characterized by a thickness of more than 500 meters and contains accumulations of gas hydrates. The elements of a gas hydrate reservoir are GHSZ, the gas hydrate formation zone, sediments containing hydrates with their inherent lithological properties and the hydrate manifestation themselves, which are characterized by certain geometries and hydrate saturations.

The volumes of gas hydrate reservoirs in the studied water areas vary widely (0.02–114 trillion m^3). The largest volumes are found in the Bering and Laptev seas and the Sea of Okhotsk (114.91 and 85.37 trillion m^3 respectively (Table 3 and Figure 2). At the same time, the volume of the gas hydrate reservoir in the Bering Sea is 3.7 times larger than in the Sea of Japan and 1.3 times larger than the Sea of Okhotsk. This is due to both the larger area of the Bering Sea itself and greater average thickness of gas hydrate stability zone within its limits. The total volume of gas hydrate reservoirs in Russian offshore areas is estimated at more than 520 billion m^3 (excluding cryogenic hydrates on Arctic shelves).

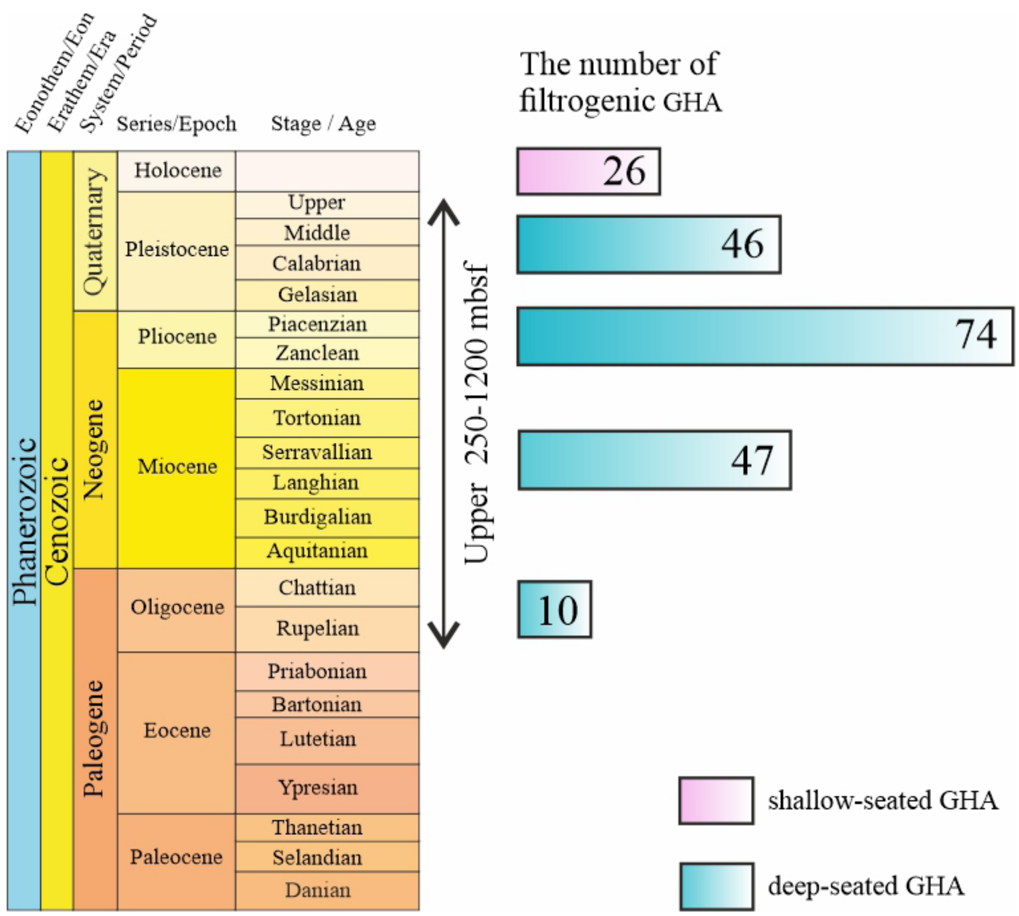

Figure 8. Stratigraphic confinement of gas hydrate reservoirs of filtration origin. The arrows show the lower interval of the gas hydrate reservoir, to which deep-seated accumulations of hydrates are confined.

The proportion of methane from gas hydrates, which accounts for the volume of gas hydrate reservoirs in each unit of oil and gas geological zoning, is calculated. The largest amounts of gas hydrates and their shares in the volumes of sedimentary deposits are predicted in the reservoirs of the Bering, Okhotsk, and Laptev seas, amounting to 47.7%, 24.8%, and 27.3% respectively.

Conclusions

The paper presents the results of a quantitative assessment of subaqueous gas hydrates of filtration origin within the exclusive economic zones of Russia and Lake Baikal as of January 1, 2024. The assessment was conducted at three different levels: national (for Russia as a whole), regional (for specific offshore areas) and local (for individual gas hydrate accumulations studied).

The studies conducted have made it possible to characterize, for the first time, the resource potential of underwater gas hydrates in Russian waters with a sufficient degree of reliability and detail. The work on identifying and mapping gas hydrate accumulations based on seismic data has greatly increased our knowledge about gas hydrates of the Russian seas and allowed us to substantiate their resources.

Another significant finding from the quantitative assessment was the geological division of the areas with potential for hydrate formation and the identification of new promising regions. These include the hydrate-bearing areas of the Barents and Laptev seas, (along with the previously known Okhotsk gas hydrate-bearing province), whose potential had been previously estimated qualitatively and therefore underestimated.

Several unique gas hydrate accumulations have been identified in the Bering, Okhotsk, and Laptev seas that require further investigation.

The definition of a 'gas hydrate reservoir' term is provided, and changes in its thickness in Russian waters are calculated, with the stratigraphic association of gas hydrates being determined mainly with Pleistocene-Miocene sediments. For the first time, the volume of gas hydrate reservoirs in all Russian offshore areas has been estimated, reaching 520 trillion m^3, and the share of gas hydrate resources within it has been averaged at 10%.

The amount of methane in gas hydrates formed through filtration in Russian waters at a regional level (Q_{reg}, analogous to the Russian D1+D2 category) is estimated to be 147 trillion m^3, and the total resource of individual accumulations (sumQ_l, analogous to the Dl category in Russia) amounts to approximately 120 trillion m^3. The largest contribution to the total resources of these individual accumulations comes from deep-seated gas hydrate deposits. Despite the possibility of there being many more shallow-seated accumulations that have not been accounted for, if their number were to increase by an order of magnitude, it would still not significantly affect the overall resource potential of gas hydrates due to their low resource value.

The results obtained turned out to be of the same order of magnitude as in the estimation by (Walsh et al., 2009). In this estimation, 112 trillion m³ of methane hydrates are accumulated in reservoirs with good filtration and capacity properties (apparently not differentiated between marine and continental) at the territories of the former Soviet Union.

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IN RUSSIAN

Оценки ресурсов фильтрогенных газовых гидратов и характеристика гидратных резервуаров морей России

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В статье представлены результаты количественной оценки прогнозируемых ресурсов субаквальных газовых гидратов в пределах исключительной экономической зоны России и на озере Байкал по состоянию на 01.01.2024 г. на трех различных уровнях: общем – для всех акваторий России, региональном – в пределах отдельных акваторий, и локальном – в конкретных скоплениях. Оценки выполнялись по методу удельных плотностей на основе численного моделирования зоны стабильности газовых гидратов, ее картирования и выявления газовых гидратов на основе интерпретации большого объема данных цифровой сейсморазведки МОВ ОГТ и результатов грунтового опробования морских отложений. В исключительной экономической зоне Российской Федерации выявлено и учтено 203 скопления газовых гидратов в морях Баренцевом, Лаптевых, Восточно-Сибирском, Беринговом, Охотском, Японском и Черном. Обосновано понятие «газогидратный резервуар». Суммарный объем газогидратных резервуаров российских морей и озера Байкал оценен величиной 520 трлн км^3, доля метана газовых гидратов в объеме газогидратного резервуара в среднем превышает 10% и оценивается величиной глобальных ресурсов газовых гидратов 147,6 трлн м^3. Наибольшим ресурсным потенциалом газовых гидратов характеризуются моря Берингово, Лаптевых, Охотское. Высокий газогидратный потенциал характеризует и российский сектор Черного моря. Газогидратные резервуары в морях приурочены к интервалу поддонных глубин от морского дна до 1200 м в стратиграфическом интервале от голоцена до олигоцена. Наибольшее количество скоплений приурочено к плиоценовым отложениям. Ресурсы газа в скоплениях газовых гидратов варьируют от 0,05 до 3719 млрд м^3, соответствуя по рангу традиционным газовым месторождениям от очень мелких (с запасами менее 1 млрд м^3) до уникальных (с запасами более 300 млрд м^3).

Ключевые слова: субмаринные газовые гидраты, газогидратные резервуары, скопления газовых гидратов, исключительная экономическая зона России, Байкал, газогидратоносные провинции, оценки ресурсов газовых гидратов, метод удельных плотностей, количество метана, локальные, региональные, глобальные оценки газовых гидратов

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