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Probabilistic assessment of spatial distribution of hydrate methane resources within the economic zone of the Russian Federation of the Black Sea

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Abstract. The results of gas hydrate resources assessment within the Black Sea exclusive economic zone of the Russian Federation by probabilistic-statistical method using the original OHRA (“Oceanic gas Hydrate Resource Assessment”) software are presented. The results of gas hydrate resources assessment in the Black Sea exclusive economic zone of the Russian Federation by probabilistic-statistical method using the original OHRA software are presented. The quantitative assessment performed with data binding to the calculated grid; the specific density of methane resources in gas hydrates is estimated. For the geothermal data account a map of the geothermal gradient of the Black Sea has been compiled. The amount of methane in hydrates is estimated as much as 361.9 trillion with a probability of 5%, 120.5 trillion with a probability of 50%, 36.7 trillion m^3 with a probability of 95%. It has been established that temperature and pressure are the parameters that have the greatest impact on the resource assessment of gas hydrates in the study area. At the sea depths of more than 1,500 m, the resources of P95 are influenced by the mass of methane produced and migrated to the gas hydrate stability zone. The average specific density values of hydrated methane are estimated to be (probability 50%) 1.2 billion, probability 95% – 0.36 billion, probability 5% – 3.59 billion m^3/km^2. The most promising in relation to gas hydrates areas within the Russian exclusive economic zone are the West Black Sea Depression, Sorokin Trough, Tuapse Trough, the Andrusov Ridge, the northern part of the East Black Sea Depression, the northern and the southern parts of the Shatsky Ridge.

Keywords: resource assessments of gas hydrates, the Black Sea, the probabilistic-statistical methods, Monte-Carlo, gas hydrate stability zone

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Introduction

Submarine gas hydrates are natural compounds formed from gas and water at specific temperatures and pressures on the continental slopes of seas and oceans. Gas hydrates have been a promising source of unconventional hydrocarbons of over half a century. In the depths of the water areas, the formation of gas hydrates that form clusters is influenced by a range of factors, including temperature, pressure, and conditions for gas generation and migration (Matveeva, 2018).

The Black Sea is characterized by the widespread occurrence of gas hydrate accumulations. The first suggestion of their existence in the studied water area was made in 1972 by Russian scientists during the cruise of the R/V Moscow University (Efremova, Zhizhchenko, 1974). The first serious studies of the hydrate content of the Black Sea began in 1988 during a joint expedition of the Computing Center of the Siberian Branch of the USSR Academy of Sciences together with VNIIOkeangeologiya during the 21st cruise of the R/V Evpatoria, when hydrate accumulations associated

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with diapiric structures were discovered and studied in detail in the Sorokin Trough (Ginsburg et al., 1990). In 1988–1989, during the Moscow State University expedition on the research vessel Feodosia, hydrates were also documented in the sediments of mud volcanoes in the deep-sea basin of the Black Sea (Konyukhov et al., 1990). The seismic signature of gas hydrates, which is called BSR (Bottom Simulating Reflector), was first identified in the Tuapse Trough in 1985 (Korsakov et al., 1989). The appearance of BSR on seismic profiles is due to differences in acoustic impedance between sediment containing gas hydrates and sediment with gas in pore space (Hyndman, Spence, 1992; Zillmer et al., 2005).

Half a century has passed since the first discovery of gas hydrates, which was marked by a number of findings in gas-fluid discharge centers and mud volcanoes in the central Black Sea region, along the coasts of Georgia and Turkey (Gaynanov et al., 1998; Ivanov et al., 1998; Mazurenko et al., 2002; Shnyukov, 2005; Kruglyakova et al., 2009; and others).

In addition to determining the component and isotopic composition of gas in hydrates (Kruglyakova et al., 1990; Shnyukov et al., 1993; Ginsburg, Soloviev 1994; Byakov, Kruglyakova, 2001), several studies have been conducted to estimate the amount of gas in hydrates throughout the Black Sea using the volumetric method. The first estimates of predicted gas amounted to 40-50 trillion cubic meters (Korsakov et al., 1989). Approximately the same resource estimates (42–49 trillion m^3) were obtained by Bulgarian geologists using the volumetric method (Vassilev, Dimitrov, 2002). A quantitative estimate of methane was made for a section of the Dnieper paleo-delta with an area of 805±20 km^2, delineated using seismic exploration data, was 1.2±0.3 trillion m^3 (Ludmann et al., 2004). The calculations were also carried out using the volumetric method, using the porosity profile from wells and hydrate saturation from seismic data.

All the above quantitative assessments were carried out using a deterministic method. Whereas, in recent decades, probabilistic methods have been widely used for calculating resources and reserves in oil and gas geology. These methods allow considering uncertainties in calculation parameters due to lack of certain data. In most cases, a probabilistic assessment of resource base is carried out in the absence of accurate information or when there is insufficient data. Therefore, data are specified using probability distributions based on collected statistics. The result of the calculation is a range of stochastic (random) models under uncertainty (Khisamov et al., 2018). A shift towards probabilistic statistical assessment is observed not only for traditional hydrocarbons but also for gas hydrates. Thus, the only assessment of methane content in gas hydrates in the Black Sea using the Monte Carlo method was performed in 1D (Merey, Sinayuc, 2016). The initial geological resource values averaged 71.8 trillion cubic meters, with a minimum of 1.7 trillion cubic meters and a maximum of 297.4 trillion cubic meters. These authors also calculated hydrated methane resources separately, considering filtration and capacity properties. They used data from the IMS-METU expedition on the southern shelf and upper slope of the Black Sea in 1988-1989. This assessment reduced the values of the predicted resources of hydrated methane by an average of almost 6 times, to 13.6 trillion cubic meters (the minimum and maximum values were 0.021 trillion cubic meters and 138 trillion cubic meters, respectively), relative to the resources calculated without taking sandiness into account. The calculations were done in 1D, without linking data to a calculation grid, so we can't estimate spatial differentiation of parameters. To identify heterogeneity in density and determine areas with highest densities, it's advisable to do 2D calculations with spatial reference. Previously, no estimates of gas hydrate resources with spatial references based on probabilistic-statistical methods have been done in the Black Sea.

The aim of this work is to forecast the distribution of gas hydrates by area and assess their resource potential within the Russian sector of the Black Sea, based on factual material, using the probabilistic statistical method.

Geological overview

The Black Sea region is located between two mountain ranges: the Crimean-Caucasus to the northeast and the Pontides to the south. From a structural and tectonic perspective, the area within Russia's Exclusive Economic Zone (EEZ) can be divided into the following regions: the southern Scythian Platform, which encompasses the, Stormovoy Graben, Karkinit-Sivash system troughs, Kalamat-Novoselov Uplift system, Alma Depression, and Marginal Monocline. Additionally, there are the northern parts of the West Black Sea and East Black Sea, separated by the Andrusov-Archangelsk Ridge. Between the East Black Sea and the fold-and-thrust belt of the Greater Caucasus is the Shatsky Ridge, along with two marginal Oligocene and Neogene depressions: the Tuapse and Sorokin Troughs, the Pallas Uplift, and the Crimean and Caucasus Orogeny (Glumov et al., 2014) (Figure 1). The formation of the current structural framework of the region has been influenced by various geological processes, including rifting, back-arc spreading, and tectonic compression. These events occurred during the Middle Eocene, leading to the opening and subsidence of the Western and Eastern Black Sea basins. Uncompensated bending of the foredeep regions (forming the Maikop formation, predominantly composed of clay) and gravitational tectonic activity (including syn-sedimentary slumping)

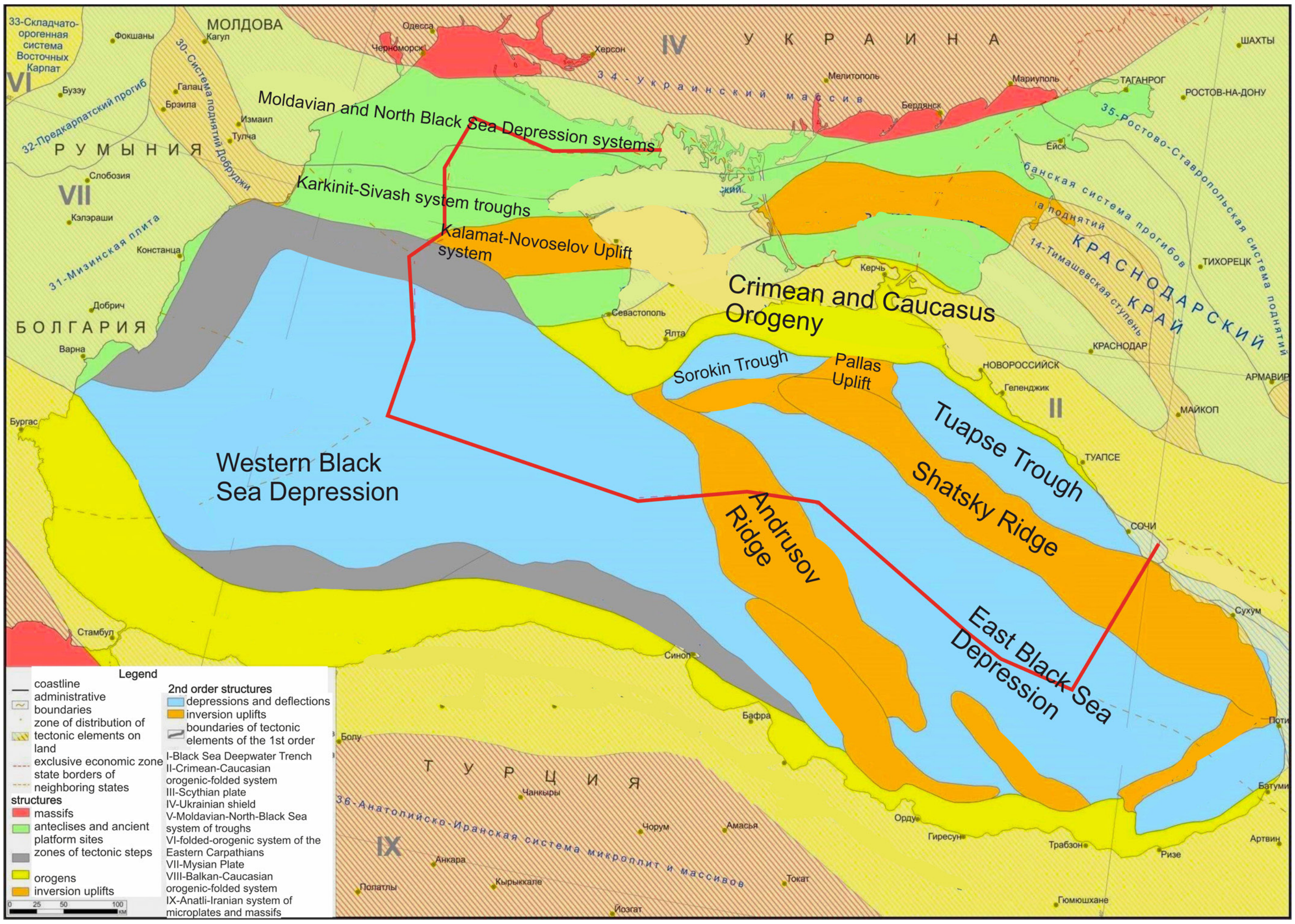

Figure 1. Scheme of the tectonic structure of the Black Sea from (Suslova, Stupakova, 2020) based on data from (Glumov et al., 2014); red line – border of the EEZ of the Russian Federation

occurred as a result of these processes. Additionally, dislocations were created due to diapirism and mud volcanic activity (Glumov et al., 2014; Afonasenkov et al., 2007; Gerasimov et al., 2008). These events created favorable conditions for the formation and migration of hydrocarbons, which facilitated their upward movement into the gas hydrate stability zone, both as free phases and within mud volcanic fluid.

Hydrocarbon Systems of the Black Sea Region

Source rocks are widely distributed in the Jurassic-Lower Cretaceous and Paleogene-Miocene periods (Glumov et al., 2014). In the Western Black Sea region, the major source rocks include clayey deposits from the Lower Cretaceous period, the lower portion of the Maikop Formation, and the Middle-Upper Miocene period. In the Eastern Black Sea, they include Lower-Middle Jurassic clay and mudstone, Aptian-Albian mudstone, Middle Eocene claystone and clayey marl, as well as Oligocene clay and mudstone deposits (lower Maikop) (Afonasenkov et al., 2007).

Clastic reservoir rocks, such as sands, sandstones, and siltstones, are most commonly found in the Eocene and Neogene sequences, as well as the Jurassic and Cretaceous periods. Carbonate reservoir rocks, including karstified and fractured dolomite limestones and reef carbonates, occupy a relatively narrow stratigraphic range, spanning the Jurassic, Cretaceous, and some of the Paleogene periods (Afonasenkov et al., 2007; Glumov et al., 2014).

Regional seals layers are typically represented by clay-rich units within the Maikop sequence, as well as clay- and carbonate-rich deposits in the Miocene and Pliocene epochs (Afonasenko et al. 2007; Glumova et al., 2014).

In terms of fluid type, most of the discovered fields in the Black Sea contain gas. Exceptions to this include the Istria area in the Romanian sector and the Taman Trough area, where oil deposits have been identified (Grushevskaya et al., 2022). Commercial gas production has been established from the terrigenous Maikop Formation deposits, carbonate-terigenous Middle Miocene deposits, and gas-condensate carbonate reservoirs in the Lower Paleocene Golitsynskoye, Yuzhno-Golitsinsky, Shmidtsky, Arkhangelsky, and Shtormovsky fields (Grushevskaya et al., 2022). Gas accumulations can be found in both structural and stratigraphic traps, with the largest being associated with Pliocene-Quaternary deltaic complexes (Leonchik et al., 2015).

The high gas content of Cenozoic sediments in the Black Sea suggests that there are geological conditions conducive to the formation of gas hydrates under favorable thermobaric conditions. Potential areas for such formations include the continental slope, submarine fans, landslide zones, and areas of diapirism. This is supported by the discovery of gas hydrate deposits within the Danube, Dnieper, Sorokin and Tuapse fans and in deep-water regions of the central Black Sea. These hydrates are associated with Maikopian-aged mud volcanic breccias.

Methodology and Data Used

Computational Grid. The study utilized a computational grid with a spatial resolution of 0.083 degrees by 0.083 in the EEZ of the Russian Federation within the Black Sea. This grid covered an area of approximately 137,000 square km and consisted of 2,217 individual grid points (Figure 2). The size of each grid cell ranged from approximately 61 to 64 square kilometers.

To estimate the methane resources within gas hydrates, a custom software solution was utilized: the "Oceanic Gas Hydrate Resource Assessment Software Package for Probabilistic-Statistical Estimation of Methane in Gas Hydrates" (OHRA) (Matveeva et al., 2024b), with the author's modifications. The core functionality of this software is to determine, for each grid cell, two parameters: (1) the volume of methane that can completely saturate the gas hydrate reservoir, and (2) the amount of methane generated and transported into the Gas Hydrate Stability Zone (GHSZ). These parameters are then compared and the lower value is selected as the final estimate, as the ultimate methane quantity cannot exceed either the physical capacity of the reservoir or the amount of gas generated.

The calculation parameters and data used to describe their change over the area were set for each point on the calculation grid using the following constants: bathymetry (seafloor depth, which determines the pressure required for hydrate stability), bottom water temperature, geothermal gradient, bottom water salinity, total sedimentary cover thickness, and thicknesses of stratigraphic units for the western part of the study area and the Shatsky Ridge. Parameters with limited data density were determined stochastically for each realization using the Monte Carlo method, based on assigned probability density functions derived from compiled statistics. These parameters include the proportion of high-permeability deposits, the porosity coefficient, hydrate saturation (the volume of pore space occupied by hydrates), total organic carbon (TOC) content, the sedimentary cover thickness for the East Black Sea Basin and the thickness of the Tuapse Trough.

The quantitative assessment incorporated the following key elements: GHSZ, volume of methane required to saturate the hydrate reservoir, methane generation and migration, actual data from direct and indirect indicators of gas hydrate presence, measurements and analysis results.

The GHSZ was calculated using the following input parameters for each cell: area, bathymetry, salinity, temperature of the bottom water, and geothermal gradient. The bathymetric data was derived from the GEBCO 2023[1] grid, which provides information on the depths of the seafloor in the study area. These depths range from 2200 m, with an average of 1,393 m. Multi-year average (1993–2020) bottom water temperatures and salinities at the grid nodes were obtained from the GLORYS12V physical oceanographic model developed by the Copernicus Marine Service (Lellouche et al., 2021). The average temperature and salinity of the bottom in this area were found to be 9.2 °C and 21.8 ‰, respectively. OHRA software typically uses geothermal gradients in the form of probability density functions. However, for this study, adjustments were made to the way this parameter was treated in the calculations.

Actual Data. A geothermal data array was compiled for the calculations based on materials from the global heat flow database (Fuchs, Norden, 2021). Using the obtained statistics, a map of the geothermal gradient distribution for the Black Sea was constructed (Figure 3), and each point of the computational grid was assigned a geothermal gradient value according to this map.

The volume of methane that can fully saturate the gas hydrate formation was determined in a series of steps. The effective volume and pore volume were derived sequentially from the total volume of the gas hydrate zone (V_{GHSZ}) by multiplying it with the fraction of highly permeable deposits and the porosity factor. The distribution function for the proportion of high-permeability rock types (sandstones, limestones, and siltstones) has been derived from statistical analysis of published results from the interpretation of geophysical well data from 12 wells. The porosity coefficients for these high-permeability rocks were obtained from neutron-gamma logging data collected from the wells (Grushevskaya et al., 2022) (Table 1, Figure 2). For the Quaternary rock interval, which is not characterized by well data, average porosity values have been assigned based on bottom seismic data (Zillmer et al., 2005).

[1]GEBCO (2023), Bathymetric map of the world's oceans, http://www.gebco.net/data_and_products/gridded_Bathymetry Data/

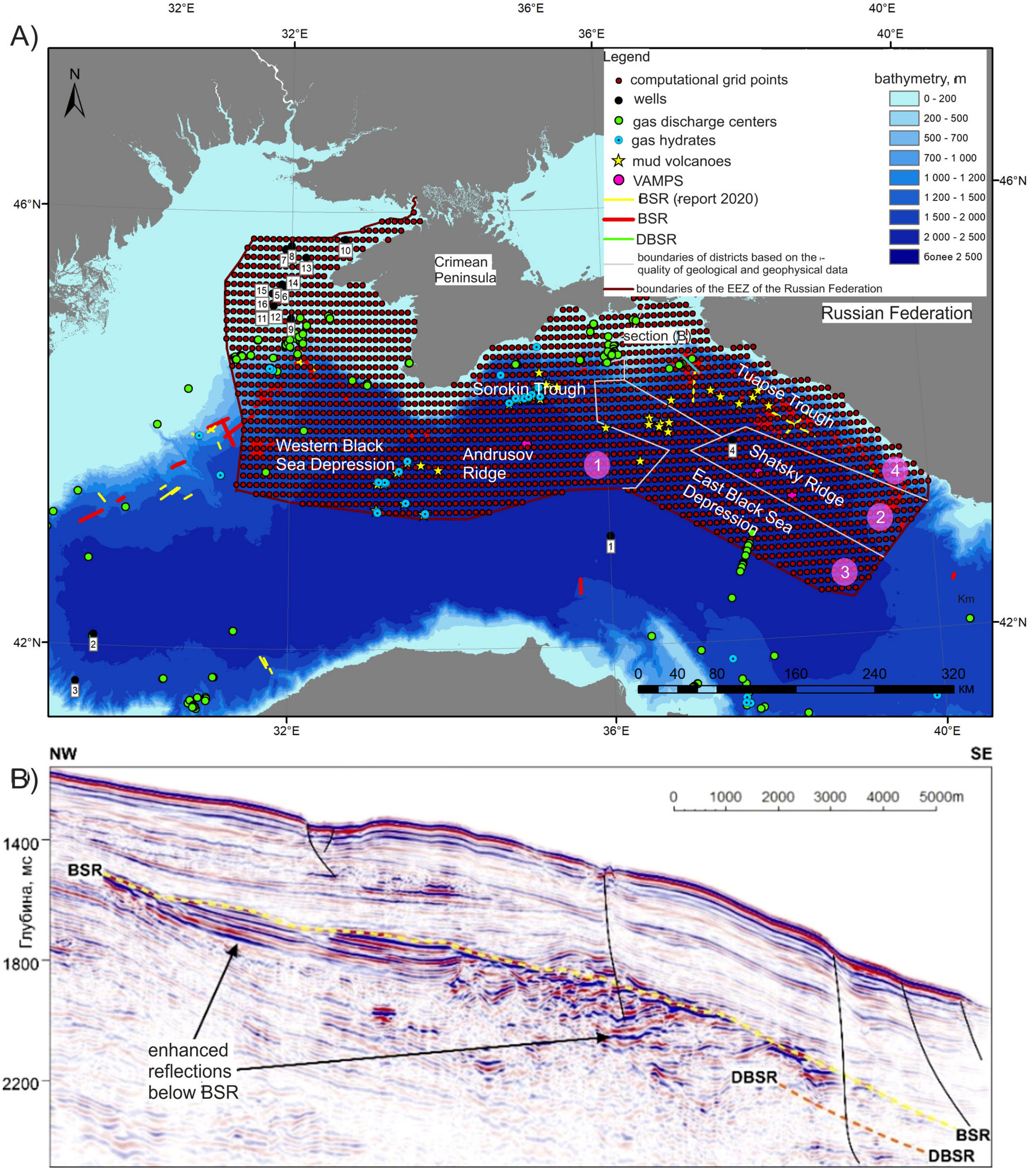

Figure 2. (A) The calculated grid in the study area and identified gas- and hydrate-induced anomalies (Matveeva et al., 2024c), Wells: 1 – 379, 2 – 380, 3 – 381 (Anders et al., 1978; Calvert et al., 1978; Morosanu, 2012), 4 – Maria-1 (Proshlyakov et al., 2018), 5 – Arkhangelskaya-1, 6 – Arkhangelskaya-2, 7 – Golitsyna-21, 8 – Golitsyna-3, 9 – Ilyichevskaya-2, 10 – Karkinitskaya-1, 11 – Selskogo-40, 12 – Fedorovskaya-1, 13 – Shmidta-8, 14 – Shtilevaya-2, 15 – Shtormovaya-2, 16 – Shtormovaya-4 (Grushevskaya et al., 2022), (B) an example of BSR on the KT9810 seismic section in the Tuapse Trough area

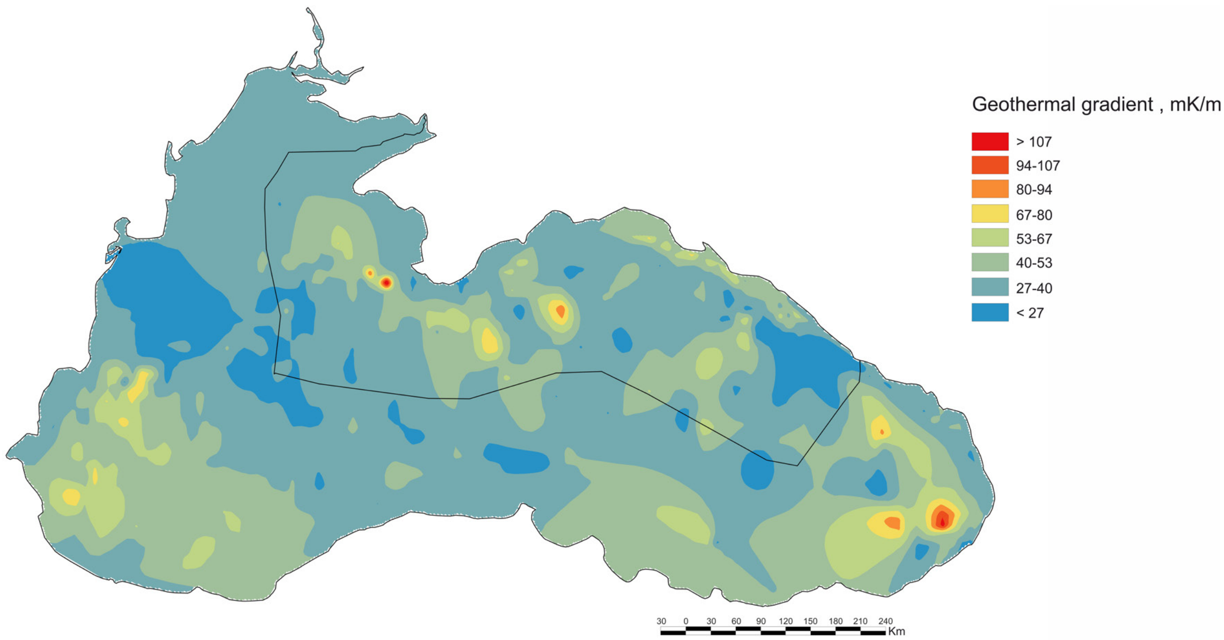

Figure 3. Geothermal gradient in the Black Sea area

Countable parameters with low data density	Statistical parameters		
	Min	Mean	Max
Share of high-permeability deposits, unit fraction	0.09	0.12	0.45
Porosity, unit fraction	0.25	0.40	0.58
Gas hydrate saturation, unit fraction	0.28	0.38	0.48
Total organic carbon, %	0.35	1.11	4.52

Table 1. Input parameters with low data density

Hydrate saturation has been used as a measure of the concentration of gas hydrates in the rock, and this value is only applicable to high-permeable rocks; calculations have not been performed for clay deposits due to their low hydrate saturation (Boswell et al., 2016) and low permeability. In the final stage, the volume obtained was multiplied by the amount of methane that could fill gas hydrates under normal conditions.

The accounting for methane production was based on the following data: total organic carbon (TOC), limit of organic carbon conversion to hydrocarbons, thickness of the sedimentary cover and each stratigraphic layer, and duration of sedimentation. In this study, we only considered the production of biogenic gas, i.e., the conversion of organic matter to biogenic methane through the action of methanogenic archaea.

The study area was divided into four regions based on the quality of geological and geophysical data: (1) the western part of Russia's Exclusive Economic Zone, based on data from (Grushevskaya et al., 2022), (2) Shatsky Ridge, data from (Proshlyakova et al., 2018), (3) Eastern Black Sea Basin, and (4) Tuapse Trough, based on stratigraphic sections (Meisner, Tugolessova, 2004) (Figure 2). Stratigraphically, eight lithological units were identified: Quaternary, Upper Miocene, Pliocene, Maikopian, Eocene, Paleocene, Upper Cretaceous, and Lower Cretaceous-Upper Jurassic. For regions 1 and 2, values for the thickness of each lithological unit were assigned to each grid point, and the total thickness of the sediment cover was calculated by summing the thicknesses of all considered units. For regions 3 and 4, the thickness of the sediment cover was derived from a probability distribution based on data from the strata using Monte Carlo simulation.

A single probability density function for total organic carbon (TOC) was created based on all samples from the Pleistocene and Paleocene deposits using 144 measurements (Proshlyakov et al., 2018; Anders et al., 1978; Calvert et al., 1979; Morosanu, 2002) (Table 1).

It was determined that the kerogen from these deposits is of type 2 and type 3, indicating a mixed composition of humic and sapropelic materials and the potential to produce both oil and gas. The average conversion limit for organic carbon to hydrocarbons was found to be 437 milligrams per gram, and the composition of gas forming hydrates was assumed to be 100 percent methane.

In order to account for the migration of methane into the GHSZ, actual data on both direct and indirect indicators of hydrate presence, as well as indicators of gas migration, were utilized. This included the interpretation of seismic data, the location of mud volcanoes and diapiric structures, areas of gas seepage, and the positions of sampling stations for gas hydrates. Direct seismic indicators of gas hydrates include seismic boundaries related to gas hydrates BSR (Bottom Simulating Reflector), and velocity-amplitude anomalies of the VAMP (Velocity Amplitude Modelling) type. For each grid point, a migration coefficient is assigned, with a value of "1" if the grid point falls within a buffer zone around mud volcanic structures, hydrocarbon seepages, and gas hydrate sampling stations, as well as any accumulations identified on seismic sections by BSR and VAMP. If a grid point does not lie within this zone, the methane migration parameter for that point is assigned a value based on the high-permeability content of the rock.

The study utilized the results of the analysis of seismic data collected along profiles (Matveeva, 2024c). These data revealed a widespread distribution of hydrocarbon seeps and hydrate-related features (Figure 2). These features are associated with the following regional geomorphological structures: the West Black Sea basin, the Shatsky and Andrusov ridges, and the Tuapse and Sorokin troughs.

Based on these data, one thousand simulations were generated for each grid point. This allowed us to estimate the predicted resources with probabilities of 5%, 50%, and 95%.

Results and Discussion

Assessment of Methane Resources in the Russian Black Sea Sector. Based on calculations performed for all possible scenarios, the estimated area of gas hydrate accumulation in the Russian exclusive economic zone in the Black Sea is 76%. This represents 104,000 square km. The results were compared with previous estimates of gas hydrate resources using probabilistic statistical techniques. There have been few studies published on the topic of submarine gas hydrate resource assessment in the literature to date. For comparative purposes, we selected previously published estimates of methane resources in the entire Black Sea region (30,000 km²), the Gulf of Mexico (458,000 km²) and the Barents Sea (278,000 km²).

The estimated methane resources within gas hydrates in the study area amount to 120.5 trillion cubic meters with a 50% probability (P50), which is 1.7 times greater than the hydrate methane resource (P5) of the entire Black Sea aquatic area (71.8 trillion cubic meters) (Merey, Sinayuc, 2016). This exceeds the average estimate of methane from filtration gas hydrates in the Barents Sea by a factor of 16, calculated using a probabilistic-statistical approach (Matveeva et al., 2023), and is 5.1 times lower than the average hydrated methane value in the Gulf of Mexico, also calculated using probabilistic statistical techniques (Preliminary Evaluation..., 2008).

The methane resources in gas hydrates, with a 95% probability, amounted to 36.7 trillion m³, which is 21.1 times greater than the total amount of hydrate methane for the entire Black Sea (1.7 trillion cubic meters) (Merey, Sinayuc, 2016). These values are 8.7 times smaller than the minimum estimate for gas hydrate in the Gulf of Mexico (Preliminary Evaluation..., 2008).

The methane resources in gas hydrates with a probability of 5% (P5) amounted to 361.9 trillion cubic meters, which exceeds by 1.2 times the methane resources of hydrates in the entire Black Sea area (297.4 trillion cubic meters) from the study (Merey, Sinayuc, 2016). These values are 2.7 times smaller than the maximum estimate of gas hydrate methane in the Gulf of Mexico (Preliminary Evaluation..., 2008) (Figure 4).

The obtained quantitative estimates for hydrate methane inside the Russian Exclusive Economic Zone in the Black Sea exceed the resource potential of gas hydrates methane in the Barents Sea, estimated using a similar method with OHRA, but they are lower than the amount of gas hydrated methane in the gulf of Mexico – one of the most promising areas for developing deepwater gas fields in USA.

Assessment of the Influence of Input Parameters on Calculation Results. A study was conducted to assess the impact of input parameters on calculation results. The aim was to determine the effect of the parameters used in the calculation of the volume of a gas hydrate reservoir, as well as the volume of methane generated and migrated. The primary correlation between the amount of gas hydrates and temperature parameters (geothermal gradient) and hydrostatic pressure has been observed. As the geothermal gradient decreases, the P50 value of gas hydrates increases exponentially. Similarly, as sea depth (pressure) increases at constant geothermal gradient values, the P50 quantity of gas hydrates also increases. A zone with seafloor depths between 2,000 and 2,200 meters within the Shatsky and Andrusov ridges has been identified, which deviates from this general trend. In this zone, the relationship between the geothermal gradient and P50 of gas hydrates aligns with average bathymetric values (Figure 5). This phenomenon is likely due to high bottom seawater salinity and/or elevated bottom water temperatures, both of which reduce the amount of hydrate formation.

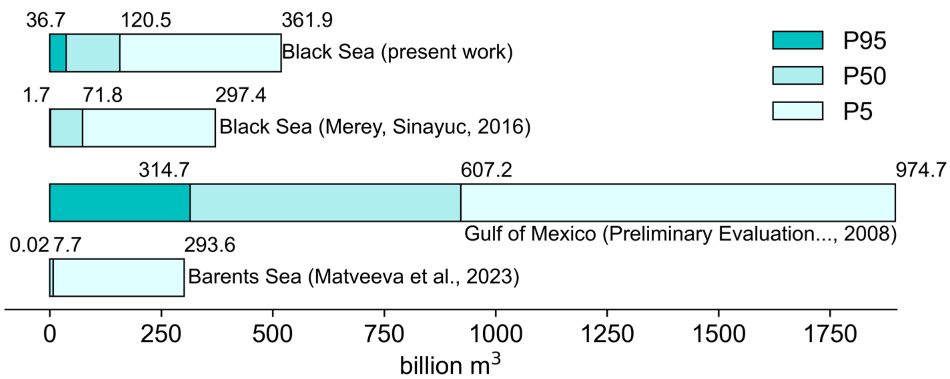

Figure 4. The ratio of predicted gas hydrate in Russia sector of the Black Sea, the entire Black Sea area (Merey, Sinayuc, 2016), the Barents Sea (Matveeva et al., 2023) and the Gulf of Mexico (Preliminary Evaluation…, 2008)

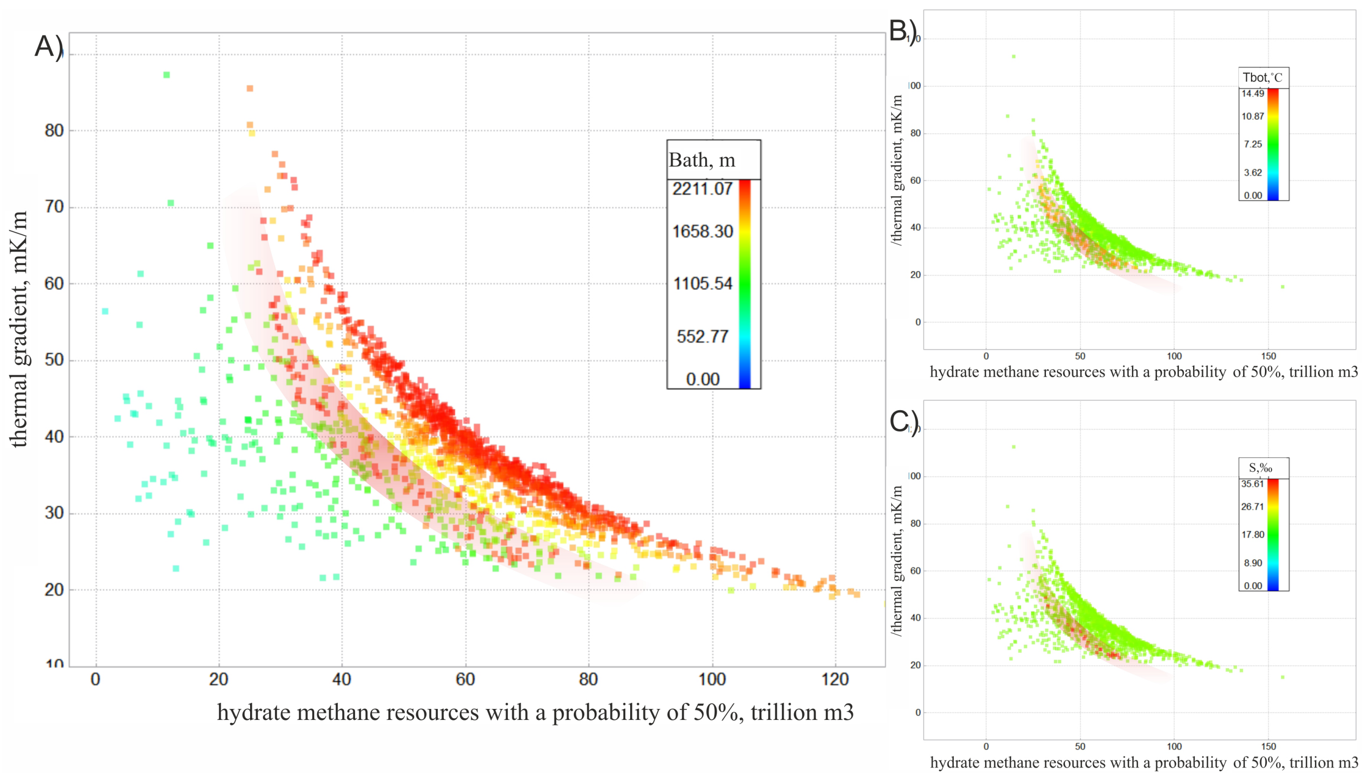

Figure 5. Graphs of the dependence of the amount of hydrate methane with probability of 50% on the thermal gradient, the color of the points corresponds to the scale of parameters: A) bathymetry, B) bottom temperature, C) salinity; the red zone – anomalous values, outside the general dependence

The strong correlation between the amount of P50 gas hydrates and certain parameters (bathymetry, geothermal gradient, salinity, and bottom temperature) indicates a significant impact of the gas hydrate reservoir volume on quantitative assessments of gas hydrate resources. Similar dependencies are observed for P5 and P95 methane hydrate quantities. However, starting at depths of 1500 meters, P95 quantitative estimates no longer correlate with P50 and P5, suggesting the influence of additional calculation parameters on methane hydrate quantity (Figure 6).

To identify the controlling factors, separate calculations were carried out: (1) determining the volume of methane that could completely saturate the gas hydrate reservoir with a 95% probability (P95), and (2) estimating the volume of methane produced and migrated into the gas hydrate stability zone (GHSZ) with a 95% probability (P95). The difference between the final P95 volumes for each scenario was then determined. The analysis of the obtained data showed that, at locations with significant water depths, the minimum hydrate methane amount (P95) was predominantly determined by scenario (2). This indicates a significant influence from input parameters such as the thickness of the overlying sedimentary cover and Total Organic Carbon (TOC) content.

Specific Density of Predicted Methane Resources in Gas Hydrates. Comparison with Previous Studies. As noted in the study (Matveeva et al., 2024a), since different methods, approaches, and areas are used in gas hydrate assessments by various authors, a comparison of specific densities of gas hydrates is considered the most appropriate approach. To compare our estimates of resources with the results of previous studies in the Black Sea, we calculated specific densities for P5, P50 and P95.

The average density of the predicted resources for the baseline case (P50) estimated by the probabilistic-statistical method is 1.2 billion m³/km². This value is almost 2.5 times higher than the calculated resource density for an average estimate of methane in gas hydrates (0.45 billion m³/ km²) for the entire Black Sea water area from the study (Merey, Sinayuc, 2016), and is comparable to the average density in the Gulf of Mexico (1.29 thousand m³/km²) (Preliminary Evaluation..., 2008) (Figure 7).

The average prediction of resources for P95 is 0.36 trillion m³/km², which corresponds with the data obtained by Turkish geologists on the minimum estimate of methane resources in Black Sea hydrates – 0. 31 trillion m³/m³ (Merey, Sinayuc, 2016). This value is approximately two times smaller than the minimum estimated hydrate density methane in the Gulf of Mexico (0.67 trillion m³/ m²) (Figure 7).

For the resource base case (P5), the average methane density is 3.59 billion m³/km², which is 1.3 times smaller than the specific density for the maximum methane resource value (4.6 billion m³/km²) across the entire Black Sea aquatic area (Merey, Sinayuc, 2016). However, this value is 1.7 times larger than the density of the maximum estimate of hydrate methane in the Gulf of Mexico (2.08 trillion m³/km²) (Figure 7).

The difference in the specific density of methane resources in gas hydrates calculated by Turkish geologists for the entire Black Sea area and by the authors of this article is due to different calculation methods. In 1D assessments (Merey, Sinayuc, 2016) the thickness of GHSZ was generated randomly and the parameter was assigned to the entire area of the Black Sea without considering area differentiation. In this work, a 2D calculation is performed: methane resource values were calculated for each point on a computational grid, and comparable values for P50 and higher values

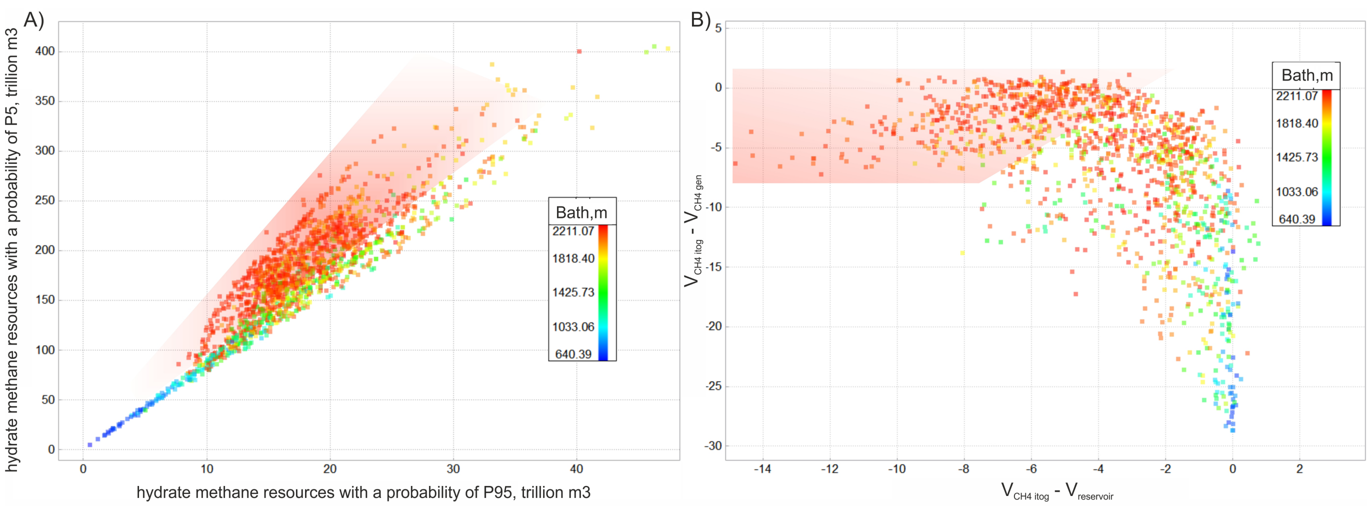

Figure 6. Graphs of the dependence of: A) the amount of hydrate methane with probability of 95% and 5%, B) the difference between the total volume of methane converted into gas hydrate with probability of 95% and the volume of the gas hydrate reservoir with probability of 95% and the difference between the total volume of methane converted into gas hydrate with probability of 95% and the volume of methane produced and migrated to the ZSGG with probability of 95%; the red zone – the area in which the resource assessment is related to the volume of produced and migrated methane

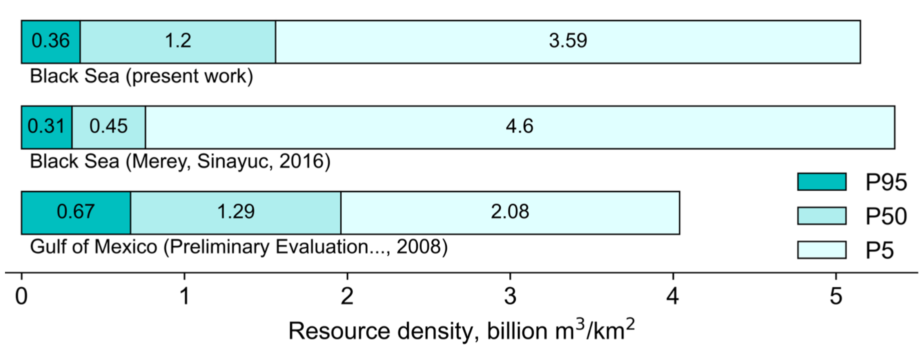

Figure 7. Comparison of average densities of predicted resources of the Russian sector of the Black Sea and of the entire Black Sea (Merey, Sinayuc, 2016) and of the Gulf of Mexico (Preliminary Evalution…, 2008)

for specific methane density in Black Sea gas hydrates compared with those in the Gulf of Mexico indicate greater potential resources in the US area, which exceeds it by 4.4 times due to the larger area covered by hydrate distributions.

On the obtained maps of predicted resource densities (Figure 8), areas most promising for gas hydrates were identified in all scenarios: the West Black Sea Basin, the Sorokin Trough, Tuapse Trough and Andrusov Ridge, as well as the northern part of the East Black Sea basin and the northern and southern parts of Shatsky ridge. These areas corresponded to the locations of gas hydrate discoveries in the Black Sea and gas hydrate related seismic boundaries (BSRs) and the positions of mud volcanoes.

Conclusion

This study presents the results of a quantitative assessment of predicted methane resources in gas hydrates within the Russian sector of the Black Sea, conducted using a probabilistic-statistical methodology.

The quantitative assessment employed original software OHRA, and incorporated the following input parameters: sea depth, bottom water temperature, salinity, geothermal gradient, reservoir properties of the gas hydrate stability zone, parameters characterizing gas generation potential (sedimentary cover thickness, individual stratigraphic unit thicknesses, deposition time, total organic carbon content, and limiting values of organic carbon conversion to hydrocarbons), parameters reflecting migration characteristics (data on geophysical anomalies, mud volcanoes, gas seepage sites, gas hydrate sampling locations), and a map of geothermal gradient distribution across the Black Sea.

The primary correlation between calculated hydrate volumes and geothermal gradient values is observed, but at depths exceeding 1500 meters, the P95 quantitative estimate is influenced by sediment cover thickness and total organic carbon content. Probabilistic-statistical assessments yield predicted methane accumulations within gas hydrates in the Russian sector of the Black Sea: 361.9 trillion cubic meters at a probability of 5%, 120.5 trillion cubic meters with a probability of P50, and 36.7 trillion cubic meters for P95.

A comparative analysis of resource estimates conducted using similar methods for different marine areas, including the Black Sea, Gulf of Mexico, and Barents Sea, has been performed.

For the first time, spatial distribution maps of methane specific densities in hydrates have been obtained for the study area, ranging from 0.03 to 3.2 billion m³ / km² in the base case scenario, with an average specific density of 1.2 billion / km². The areas with the highest resource density within the Russian Exclusive Economic Zone include the West Black Sea Basin, the Sorokin Trough, the Tuapse Trough and the Andrusov Ridge. In addition, there are also northern parts of the East Black Sea basin and the northern and southern parts of the Shatsky ridge.

A comparison of the specific densities of the predicted methane gas hydrate resources was carried out for the Russian Exclusive Economic Zone of the Black Sea, the entire Black Sea area, and the Gulf of Mexico. The comparable values of the average specific densities of hydrate methane in the Black Sea and the Gulf of Mexico, obtained by a probabilistic-statistical method, indicate that the greater resource potential of the Gulf of Mexico is associated with its larger Gas Hydrate Stability Zone area.

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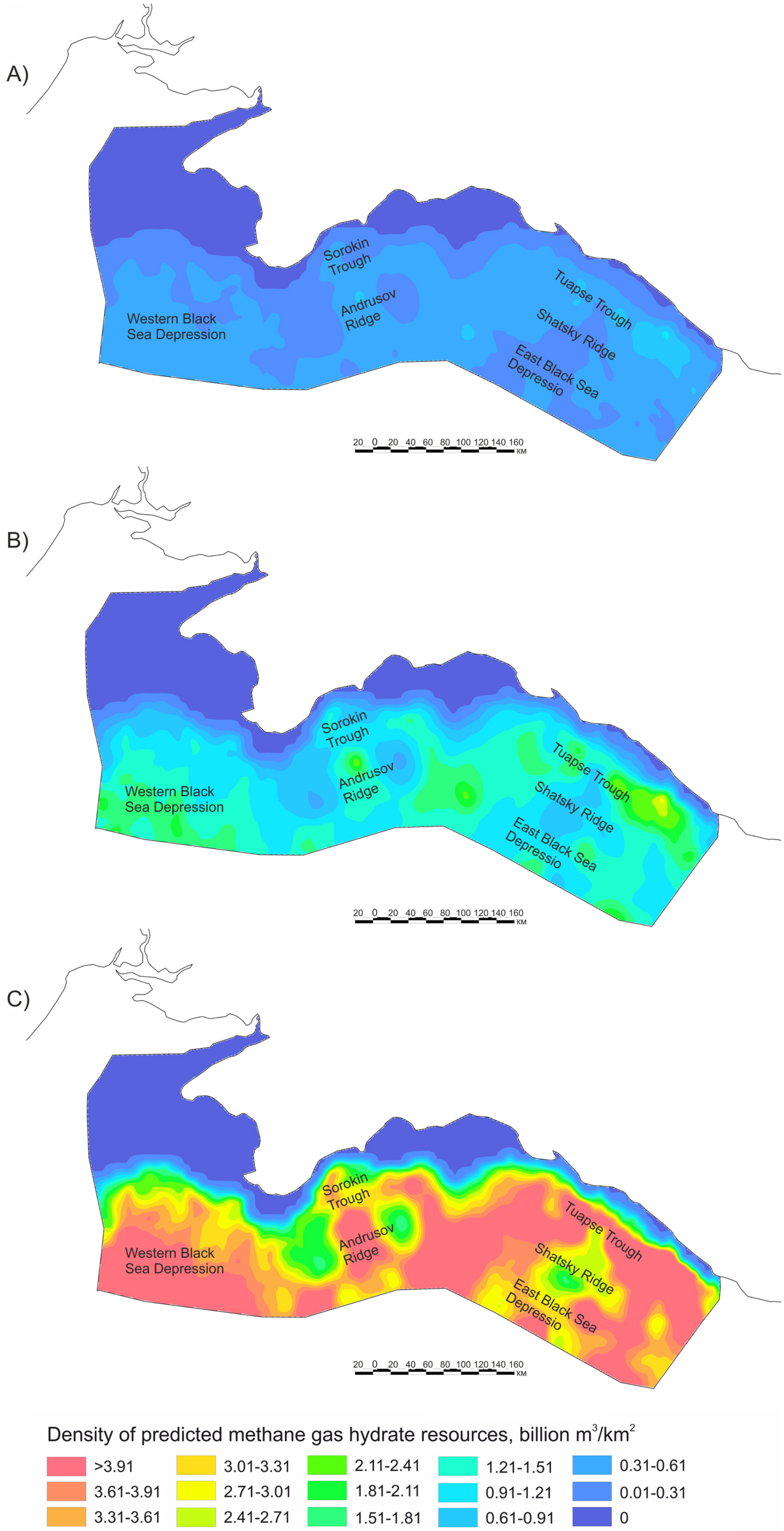

Figure 8. Density of predicted methane gas hydrate resources calculated by the Monte-Carlo method with a probability of: A) 95%, B) 50%, C) 5%

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Вероятностная оценка пространственного распределения ресурсов метана в газовых гидратах в российском секторе Черного моря

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Впервые выполнена оценка количества метана в газовых гидратах российского сектора Черного моря на основе вероятностно-статистического метода в пределах исключительной экономической зоны Российской Федерации с использованием оригинального программного обеспечения «Программный комплекс для оценки количества газа в газовых гидратах вероятностно-статистическим методом «Oceanic gas Hydrate Resource Assessment» (OHRA)». Приведены результаты количественной оценки с привязкой данных к расчетной сетке для рассматриваемой акватории, оценена пространственная дифференциация плотности ресурсов метана газовых гидратов. Представлена карта геотермического районирования Черного моря. Количество метана в гидратах оценено величиной 361.9 трлн м^3 с вероятностью 5%, 120.5 трлн м^3 с вероятностью 50%, 36.7 трлн м^3 с вероятностью 95%. Установлено, что температура и давление – входные параметры, которые оказывают наибольшее влияние на оценку ресурсов метана газовых гидратов. При глубинах более 1500 м на ресурсы P95 оказывает влияние масса метана, произведенного и мигрировавшего в зону стабильности газовых гидратов. Средние величины плотности прогнозируемых ресурсов гидратного метана при базовом варианте (P50) вероятно-статистическим методом составляют 1.2 млрд м^3/км^2, при варианте P95 – 0.36 млрд м^3/км^2, при варианте P5 – 3.59 млрд м^3/км^2. Наиболее перспективными в отношении газовых гидратов морфоструктурами являются Западно-Черноморская впадина, прогиб Сорокина, Туапсинский прогиб, вал Андрусова, северная часть Восточно-Черноморской впадины, северная и южная части вала Шатского.

Ключевые слова: газовые гидраты, метан, ресурсные оценки, Черное море, вероятносто-статистические методы, Монте-Карло, зона стабильности газовых гидратов

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