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PROSPECTS OF GAS HYDRATE PRESENCE IN THE CHUKCHI SEA

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The purpose of this study is to forecast the scale and distribution character of gas hydrate stability zone in the Chukchi Sea under simulated natural conditions and basing on these results to estimate resource potential of gas hydrates within this area. Three types of stability zone have been identified. A forecast map of gas hydrate environment and potentially gas hydrate-bearing water areas in the Chukchi Sea has been plotted to a scale of 1:5 000 000. Mapping of gas hydrate stability zone allowed to give a justified forecast based on currently available data on geologic, fluid dynamic, cryogenic, geothermal and pressure-temperature conditions of gas hydrate formation in the Chukchi Sea. It is the first forecast of such kind that focuses on formation conditions for hydrates of various types and compositions in the Arctic seas offshore Russia. Potential amount of gas, stored beneath the Chukchi Sea in the form of hydrates, is estimated based on mapping of their stability zone and falls into the interval of $7\cdot10^{11}$-$11.8\cdot10^{13}$ m^3.

Keywords: Chukchi Sea, gas hydrates, methane, hydrocarbon gases, gas hydrate stability zone, potentially gas hydrate-bearing water areas, resources

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Introduction. In the recent years many studies have been dedicated to gas hydrates of the Arctic seas [13]. Gas hydrates are solid crystalline compounds composed of water and gas under relatively high pressure and low temperature; under such conditions water molecules form hydrogen bounded lattice structures with gas molecules inside, trapped by van der Waals forces. Naturally hydrates usually form cubic crystallographic structures of types I and II, differing by their ratio of large and small cages of the water lattice. Those cages that better fit the size of gas molecules get filled first. Hydrocarbon gas hydrates are a solid phase of conventional natural gas (usually pure methane or a mixture of methane, ethane and carbon dioxide) bounded by water molecules. Gas hydrates form under specific thermodynamic, geologic and fluid dynamic conditions. Inside they contain a highly concentrated gas, which means that even decomposition of the smallest hydrate volume will release substantial quantities of hydrocarbons. This explains why hydrates are regarded as a promising source of energy. Submarine hydrates are distinguished by their occurrence in the form of certain geologic bodies (accumulations) similar to ore deposits. Other than that hydrate accumulations should be regarded from the positions of petroleum geology, taking into account specific pressure and temperature conditions of their formation.

Submarine gas hydrates can form during sedimentation, diagenesis, cooling of existing deposits of natural gas and gas-saturated groundwater and their upward infiltration. In most cases, formation of gas hydrates in submarine environments takes place through gas transportation to the hydrate formation zone in the filtration flow (filtrogenic hydrates). Apart from that, Arctic shelf basins with a thick sedimentary cover are expected to have cryogenic hydrate accumulations associated with relict submarine permafrost [3].

Up until now there have been no reports of gas hydrate recovery in the marine sediments of the Russian Arctic. On the one hand, insufficient knowledge of the Arctic Ocean due to its geographic location in high latitudes (negative temperatures, seasonal and permanent ice cover, lack of developed infrastructure etc.) poses certain difficulties in gas hydrate research. On the other hand, it is exactly low temperatures and the presence of relict submarine permafrost that create opportunities for hydrate formation, not only in deep-sea areas but also in shallow shelf seas [4, 5, 12, 14, 16]. Up to date, the scale of gas hydrate formation in the shallow seas of the Arctic shelf remains an open question.

Problem statement. Gas hydrate formation can only occur in certain areas or intervals of the sedimentary or water column, known as gas hydrate stability zone (GHSZ). Above or below this zone gas either dissolves in the water or remains in a free state. GHSZ is primarily characterized by thickness and distribution. Basins with favourable pressure, temperature and geologic conditions for hydrate formation (and/or conservation) are regarded as potentially gas hydrate-bearing water areas, all the remaining areas are classified as hydrate-free [5].

The Chukchi Sea is situated in the Arctic shelf with an average depth of 40-60 m; however it has some sea banks with water depth of up to 13 m. An isobath of 1500 m bounds the maximal depth of the sea, but this deep-water zone only occupies a small sector in the northern part of the sea. According to forecasts, stability zone for filtrogenic hydrates had to occur in this limited deep-sea area in the northern part of the sea [8]. An analysis of depths distribution shows that during climatic cooling and associated regressions, reaching up to 100 m, the shelf was subaerially exposed, and ice-bonded permafrost zone (later reflooded) must have formed in the sediments [7]. It is essentially this zone that has been associated with favourable conditions for methane hydrate formation. Hence, up to the time of this study the hydrate-bearing potential of the Chukchi Sea has been considered negligible. However, improved methods of GHSZ mapping, analysis of factors that control submarine hydrate formation, and study on hydrocarbon gases in the near-bottom sediments [18] suggest that gas hydrates could form even in the shallow water-areas of the Chukchi Sea.

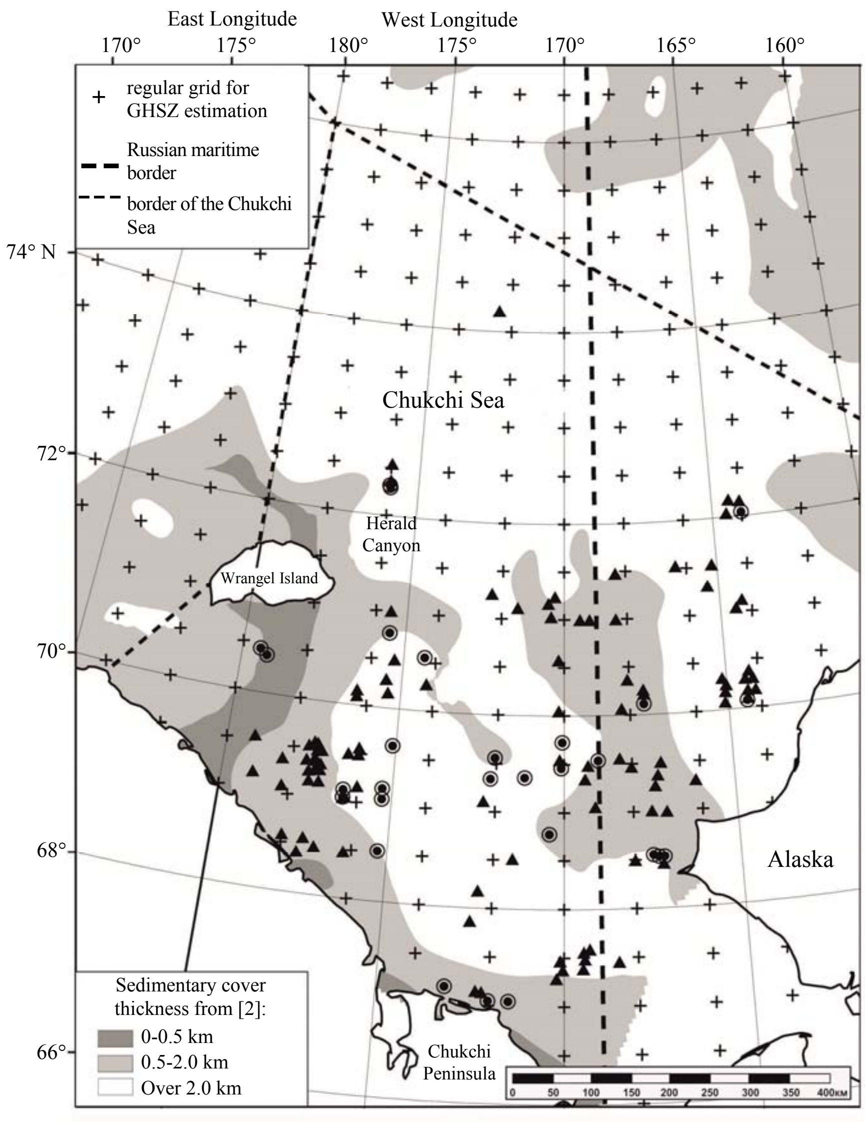

Fig.1. Study area discussed in this article with location of sampling stations according to sediment gas composition:
pure methane – circles; methane with homologues – triangles

The aim of this study is to forecast the scale and distribution character of GHSZ in the sedimentary cover of the Chukchi Sea under simulated physical and geologic conditions and basing on these results to estimate resource potential of gas hydrates within this area.

Materials and methods. The study area is limited by geographical boundaries of the Chukchi Sea and occupies the area of approximately 600 000 km^2. In order to define conditions of gas hydrate stability, the entire area was covered with a regular grid of 150 points with longitudinal distance 2° and latitudinal distance 0.5° (Fig.1). For each point of the grid water depth was calculated using data from [20]; average annual bottom temperature and salinity were taken from [1], geothermal

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gradient values – from [3]. The calculations were carried out for the water depth interval of 1 500 m.

The calculation of stability zone thickness has been performed in proprietary VNIIO_GHSZ program, which allows to match temperature (and/or geothermal gradient) and pressure values in a particular point of the grid with a selected *P-T* equilibrium curve. Equilibrium curves of gas hydrate formation (Fig.2) have been calculated using [17]. Correlation has been assessed for every meter of sub-bottom depth. GHSZ mapping and its differentiation in terms of thickness in 100 m increments have been carried out in ArcGIS v.10.4 using geostatistical IDW (Inverse Distance to a Power) interpolation, which was selected as a method of constructing the grid function.

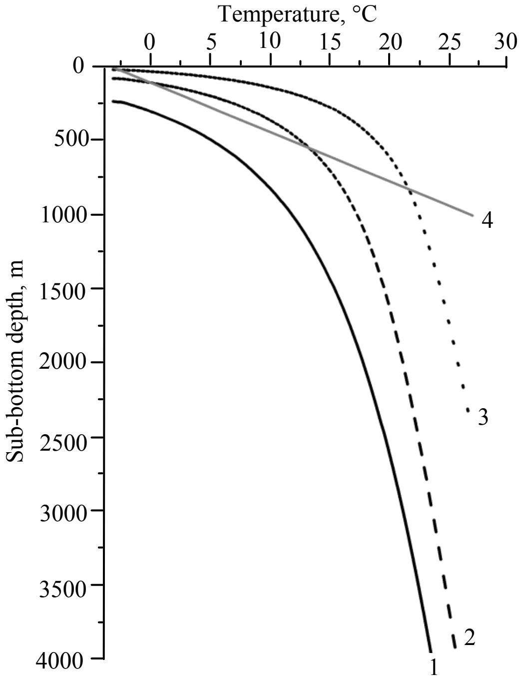

Fig.2. Equilibrium curves calculated for the systems:
1 – «*hydrate – water + methane* (*100* %) +*NaCl solution* (*3.5* %)»;
2 – «*hydrate – water + methane* (*95.997* %), *ethane*(*1.879* %), *propane* (*2.115* %), *butane* (*0.009* %) + *NaCl solution* (*3.5* %)»;
3 – «*hydrate – water + methane* (*60.6* %), *ethane* (*9.1* %), *propane* (*30.3* %) (according to data from station 25, R/V «Maksimov» 1981)+ *salinity*(‰)»;
4 – temperature profile with the gradient of 3 °C/100 m

Apart from regular grid points, data from 143 stations recovering near-bottom sediments (typically no more than 1 m of subbottom depths), which had been used in the analysis of hydrocarbon gas composition, were used in this study (see Fig.1). This provided an opportunity for significant extension of the regular grid. The dataset included results of gas compositional analysis, obtained in VNIIOkeangeologia expeditions in 1976-1988 and Russian-American Long Term Census of the Arctic (RUSALCA) expeditions in 2004, 2009 and 2012 [15, 18]. These data have been used to plot equilibrium curves and to forecast potential composition of hydrate-forming gas.

Results and discussions. Assessment of pressure and temperature conditions from the viewpoint of hydrate formation includes GHSZ mapping and evaluation of its thickness, whereas consideration of geologic criteria allows to estimate possibilities of generation and transportation of the potential hydrate-forming gas, as well as to forecast formation of hydrates with different compositions.

One of the critical formal *geologic criteria*, which defines the possibility of submarine hydrate formation, is the thickness of sedimentary cover. Hydrate-bearing zones (similar to oil- and gas-bearing zones for the conventional hydrocarbons) are always associated with thick sedimentary covers, because essential conditions of gas accumulation include significant amounts of organic matter and high sedimentation rate, which in its own turn leads to generation of biochemical methane and prevents it from dissipation. Moreover, thick sedimentary cover facilitates formation of natural gas through catagenesis. With this in mind, areas that do not possess sufficient amounts of gas are considered hydrate-free (even if they are located within stability zone), as they do not meet conditions for gas generation and accumulation [5]. Previously in publications [3, 9] basing on deep-sea drilling logs it was established that minimal sediment thickness should not be lower than 500 m – in the opposite case sedimentary cover is likely to be located above sulfate reduction zone and does not support accumulation of biochemical methane, whereas maximal amount of juvenile methane is much lower than its solubility limit in interstitial water. Optimal thickness that provides for generation of both biochemical and thermogenic gas, is believed to be 2 km.

From the viewpoint of geology, the study area is located in the continental margin of Laptev, East Siberian and Chukchi seas. It contains two major basins – South Chukchi Basin (primarily Cretaceous-Cenozoic) and North Chukchi Basin (primarily Paleo-Mesozoic), divided by the structural Wrangel-Herald Uplift. South Chukchi Basin has sediment thickness of 2-4 km and is composed of multitudinal echelon deeps, separated by linear swells. The latter can be regarded as potential structural traps associated with Cretaceous and Paleogene gas-source rocks [6, 19]. Maximal thickness of the North Chukchi Basin sediment fill reaches 22 km. The sedimentary cover of the dividing swells is less than 1 km [21].

In order to rule out regions with low hydrocarbon potential, the Chukchi Sea was subdivided into regions according to sedimentary cover thickness using data from [2]. The resulting map contains hydrate-free areas (with sediment thickness below 0.5 km) and the most promising regions with sediment thickness of 2 km and more (Fig.1). Most area of the Chukchi Sea (70 % of the area is characterized by sediment thickness over 2 km, 95 % – over 0.5 km) is characterized by sufficient thickness of the sedimentary cover to provide favourable conditions for gas generation and consequently for gas hydrate formation. Significant thickness of the sedimentary cover and high hydrocarbon potential of the Chukchi Sea allow to predict generation of thermogenic gases (including methane homologues) and their consequent migration toward the seafloor through the weak zones and faults.

Stability zone of filtrogenic gas hydrates. *P-T conditions* of gas hydrate stability are defined by the pressure (*P*) of the hydrate-forming gas and temperature (*T*). The former parameter is usually replaced with external pressure (hydrostatic or water depth).

Hydrostatic pressure has been calculated using the water depth data from IBCAO (The International Bathymetric Chart of the Arctic Ocean) [20].

In order to identify GHSZ parameters, time variations and annual mean of temperature and salinity values of near-bottom waters in the Chukchi Sea from hydrological records by Arctic and Antarctic Research Institute (AARI) [1] have been used. Maps of water temperature and salinity [1] demonstrate the distribution of long-time average annual values, estimated in AARI using the database of thermohaline characteristics (DBTC) for the Arctic Ocean. DBTC contains data collected during expeditions from the period of 1900 to 2014. To calculate the average values, these data have been interpolated into the nodes of the regular 50×50 km grid for summer (August – September) and winter (February – May) periods. According to findings, the temperature of near-bottom waters in the Chukchi Sea (near the coast of Alaska) varies from –1,8 to 0 °C in winter and from –1,4 to 6 °C in summer.

Temperature distribution of near-bottom water is closely related to its mineralization. As a rule, the water mineralization corresponds to the salinity of interstitial water of the bottom sediments and, therefore, in the calculations of equilibrium conditions for gas hydrate formation they are considered equal. In GHSZ estimations respective nodes of the grid were assigned values of temperature and salinity, averaged across the summer and winter hydrological seasons. The interval of accepted near-bottom temperatures was from –1.5 to 1.0 °C, salinity – from 32.5 to 35 ‰. Salinity across the entire northern part of the basin was close to 35 ‰.

The procedure described above applies to 2D GHSZ mapping. 3D mapping proves to be a more challenging task, as it requires data on subsoil thermal conditions. Information about the temperature field of the Arctic submarine sediments is very scarce and unevenly distributed. For the western part of the Arctic Ocean (shelf of the Barents and Kara seas) there are available estimations of the heat flow – either from temperature variations in oil and gas prospecting wells, or from subbottom thermographs. By contrast, thermal conditions in the eastern part of the Arctic shelf are practically unexplored. In this case the forecasting of heat flow distribution and geothermal gradient is carried out using long span extrapolations, shallow-depth temperature measurements, as well as indirect data on thermal conditions and known correlations between the heat flow and the age of geologic structures. The fullest picture of geothermal fields in the

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Arctic Ocean is given by Soloviev et al. [3], who specify variations of the heat flow in the eastern part of the Arctic shelf (from 40 mW/m^2 in the north to 60 mW/m^2 in the south). According to [3], geothermal gradient calculations for the Beaufort Sea from the same work (results of temperature measurements and estimates of geothermal gradient based on observations of the Bottom Simulated Reflector - seismic horizon, which corresponds to lower limit of the GHSZ) and the most frequent gradient values for Arctic oil and gas provinces, the most reasonable value of geothermal gradient for this study appears to equal 3 °C/100 m.

Basing on analysis of the abovementioned materials, we estimated resource potential of gas hydrates in the Chukchi Sea by means of calculating GHSZ thickness and mapping of the stability zone. The first step was to identify formation conditions for pure methane hydrates. For this purpose an equilibrium curve for the system «*hydrate – water + methane* (*100* %) + *NaCl solution* (*3.5* %)» has been calculated for the entire mapped area on the assumption of 35 ‰ salinity (Fig.2). For each point of the regular grid (see Fig.1) with particular values of temperature and geothermal gradient of 3 °C/100 m GHSZ thickness has been calculated and its distribution has been mapped (Fig.3, A). It has been established that under given parameters stability zone of methane hydrates is bounded coastwardly by a 290-m isobaths, so that with minor exceptions almost the entire area of the Chukchi Sea should be classified as hydrate-free due to unfavourable pressure and temperature conditions.

One more *geologic criterion,* which must be taken into account when assessing submarine hydrate-forming conditions, is the composition of hydrate-forming gas – with the temperatures being equal, «heavier» composition of hydrocarbon gas (in terms of molar mass) requires lower equilibrium pressure for hydrate formation. Hence, when hydrate forms from a gas mixture, the first component to transform into hydrate phase is the one with the greatest molar mass. For hydrocarbon gases, hydrate transformation ascends in the following order: methane – ethane – propane [17]. Based on this fact, an assumption has been made that *P-T* conditions of the Chukchi Sea, being unfavourable for pure methane hydrates, may turn out favourable for the mixture of methane and its homologues. In order to test this hypothesis, information on the composition of potential hydrate-forming gas, as well as data on its distribution patterns in the sediments of the study area was required.

Works [10, 18] contain some data on gases in the near-bottom sediments of the Chukchi Sea, but they were not considered in respect to hydrate formation. This paper offers an analysis of all available data on the molecular composition of sediment gases, obtained by coring in the Chukchi Sea (see Fig.1). In total, 240 gas samples have been examined, 185 of them contained methane homologues in the gas mixture. Statistically it has been identified that geochemical background of the study area is characterized by methane concentrations up to 0.05 cm^3/kg and homologue concentrations up to 0.001 cm^3/kg. Around one third of the samples have anomalously high gas content as compared to the background level. Maximal concentrations reached 34.6 cm^3/kg for methane and 0.02 cm^3/kg for its homologues. The proportion of hydrocarbon gases in the samples is highly volatile: methane 60.6-99.9 %, ethane 0-16.7 %, propane 0-30.3 %, butane 0-0.96 %. Evidently, the content of methane homologues in the Chukchi Sea sediments varies in a wide range and reaches significant values. Obtained information reflects both background levels of hydrocarbon gases, generated in shallow sediments during biochemical decomposition of the organic matter, and anomalous values, caused by ascending gas migration from the deep sediment strata (even without isotope data on $C/(C_2 + C_3)$ ratio, an assumption can be made that a gas with such composition has a migration origin). Thus, a 2D analysis of hydrocarbon gas distribution in the Chukchi Sea sediments allowed to identify approximate location of gas seepage sites. All of them occur at depths 40-80 m and are situated in the central part of the study area (triangles in Fig.1).

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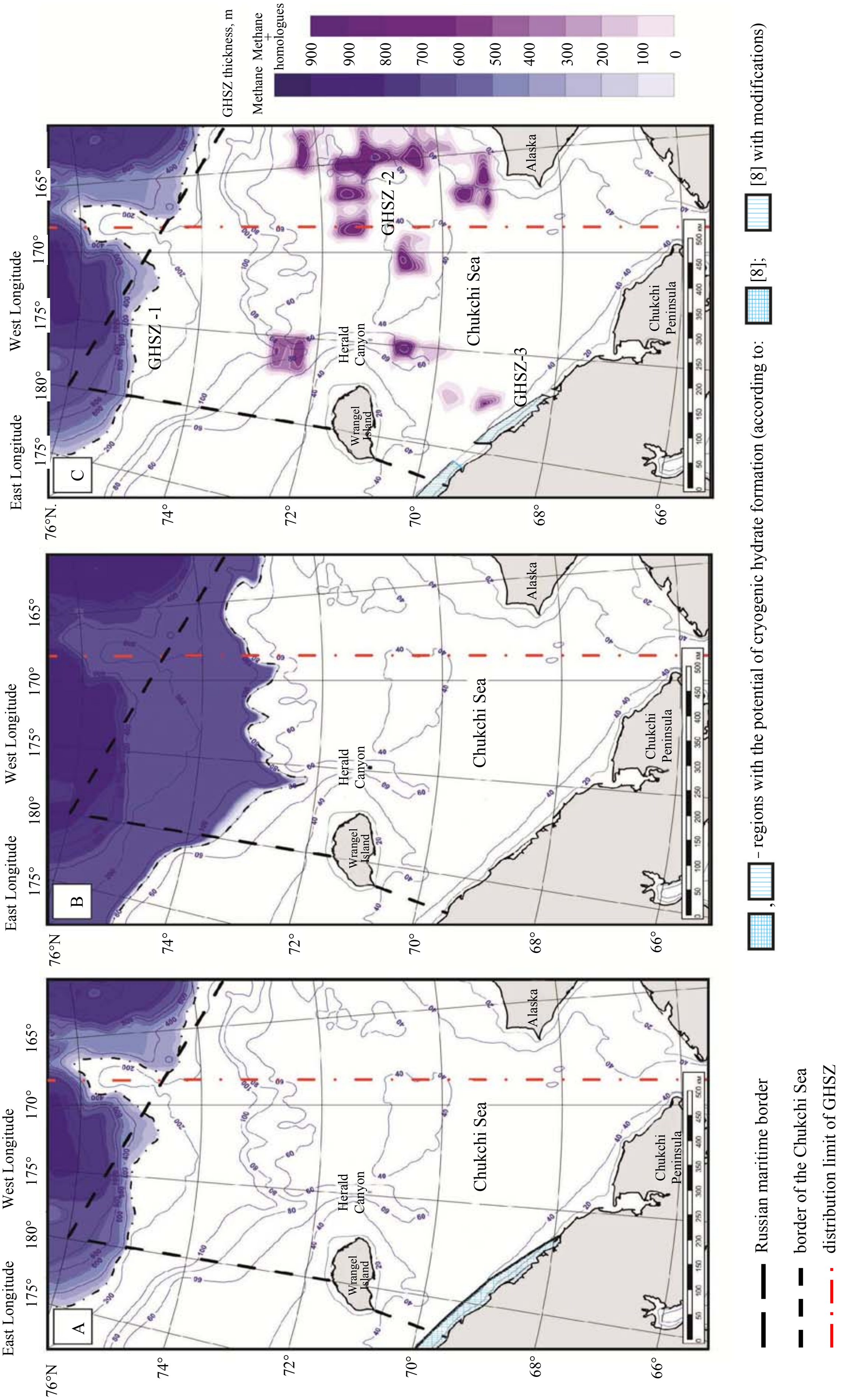

Fig. 3. Forecast maps of gas hydrate–bearing areas in the Chukchi Sea: A – GHSZ for pure methane; B – GHSZ for gas mixture (composition of the hydrate-forming gas averaged across all the samples); C – resulting map for different types of GHSZ

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It should be mentioned that the composition of hydrate-forming gas is the key factor responsible for the resulting hydrate structure and its formation conditions. It has been identified that the ratio between the sizes of «guest» gas and «host» water molecules defines equilibrium *P-T* conditions: lower *T* means higher equilibrium *P*. Methane forms hydrates at higher pressure than other gases, and adding only 1 % of propane to the mixture reduces equilibrium pressure by 42 %. In general, the same is true for ethane. Natural gases with propane and isobutene content higher than 0.3 % form hydrates with a cubic structure II.

Due to high volatility of molecular composition, the average proportion of hydrocarbon gases in the gas mixture has been determined statistically: methane 95.997 %, propane 2.115 % and butane 0.009 %. Later this proportion has been used as a composition of potential hydrate-forming gas in subsequent assessment of GHSZ parameters (Fig.3, B). Temperature, pressure, salinity and geothermal gradient were the same as described earlier, the equilibrium curve has been calculated for the system «*hydrate – water + methane* (*95.997* %), *ethane* (*1.879* %), *propane* (*2.115* %), *butane* (*0.009* %)+ *NaCl solution* (*3.5* %)» (see Fig.2). GHSZ calculations were performed for the regular grid. It turned out that stability zone for mixed-gas filtrogenic hydrates is bounded coastwardly by an 80-m isobaths. As seen from Fig.3, B, a 5 % change in molecular composition of the hydrate-forming gas significantly broadens the stability zone and increases its volume. However, extrapolation of this hypothetical hydrated gas composition across the entire study area would not be justified.

In order to get the closest approximation to hydrate-forming conditions of the Chukchi Sea, at the next stage of research the grid was modified by adding sampling points to the regular grid. For each new point of the extended grid individual equilibrium curve for the system «*hydrate – water + methane + homologues + salinity* (‰)» has been calculated basing on measured composition of the gas mixture and taking into account regional variations of seawater salinity and near-bottom temperatures. An example of such curve is presented in Fig.2 (curve 3). In the nodes of grid with unknown actual composition of hydrate-forming gas, assessment of GHSZ parameters has been performed for the regular grid using equilibrium curve «*hydrate – water + methane* (*100* %) + *NaCl solution* (*3.5* %)». These calculations allow to state that under given parameters the shelf of the Chukchi Sea has favourable conditions for mixed-type hydrate formation starting from a 40-m depth. It should be noted that the stability zone was especially thick (100-750 m) in the proximity of 22 out of 143 sampling stations. Thus, by adding points of actual measurements to the regular grid and modifying the calculation procedure, reliability of the GHSZ forecast was significantly improved.

Stability zone of cryogenic gas hydrates. The study of hydrate-forming conditions in the Arctic shelf would be incomplete without cryogenic hydrates. GHSZ distribution should correspond to the area of relict permafrost, and the top of the stability zone can be associated with the upper limit (intra-permafrost hydrates) or lower limit (sub-permafrost hydrates) of the cryolithozone [7].The upper and lower limits of the stability zone itself, i.e. its thickness, can only be determined through direct or indirect observations during permafrost drilling. The data presented above indicates that thermal pattern and mineralization of bottom waters in the Chukchi Sea enable conservation of bottom sediments in seasonal or permanent frozen state. However, only a small coastal area, associated with a relict permafrost zone, predicted in [7] and characterized by maximal thickness of 50-100 m, has the potential of gas hydrate presence (see Fig.1). Taking into account conditions of gas generation, a part of this zone (Fig.1) should be considered as hydrate-free due to insufficient thickness (below 0.5 km) of the sedimentary cover. This being said, the area of cryogenic gas hydrates stability zone distribution reaches approximately 5 700 km^2 (Fig.3, C). According to [8], its thickness amounts to 200-400 m.

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Thus, an integrated approach to forecasting hydrate-forming conditions in the Chukchi Sea based on geologic, permafrost, pressure and temperature criteria and composition of the hydrate-forming gas allowed to identify three types of stability zone (Fig.3, B): GHSZ-1 – filtrogenic hydrates, mostly pure methane composition, cubic crystalline structure I; GHSZ-2 – filtrogenic hydrates of mixed composition, cubic crystalline structure II; GHSZ-3 – cryogenic hydrates, methane composition, cubic crystalline structure I. GHSZ mapping served as a base of subsequent resource estimations, discussed below.

Assessment of gas hydrate resources in the Chukchi Sea. One critical task of gas hydrate research is to assess the scale of hydrate formation and amounts of gas stored in the subsoil in the form of hydrates. GHSZ mapping is one method to estimate gas hydrate resources, and in the absence of direct observations of gas hydrates in the Russian Arctic it proves to be the only feasible option.

Resource estimates of gas hydrates can be divided into local (Q_L) – for separate accumulations, regional (Q_R) – for hydrate-bearing regions or provinces, and global (Q_G) – for the entire World Ocean. Overall regional estimate for the Chukchi Sea (Q_R) must comprise regional estimates of gas amounts in filtrogenic hydrates of methane (Q_{R1}) and mixed composition (Q_{R2}) and cryogenic hydrates (Q_{R3})

According to [9], amount of gas captured by hydrates can be calculated using formula $Q = qS$, where q – gas content per unit area, m^3/km^2, subdivided into local q_L, regional q_R and global q_G; S –potentially hydrate-bearing water area, km^2.

If one knows q_R and respective hydrate-bearing area S_R, it is possible to estimate target values. As for the areas, in our case they correspond to three types of stability zone, presented in Fig.3, C (see Table). The gas content per unit area in each stability zone is much harder to asses due to the absence of field data. Analysis of published estimates and their methodology for the World Ocean and Arctic Ocean allowed to apply an individual approach to the selection of q_R values.

Following the algorithm described in [9], in case there is no reliable data it is acceptable to use the average value of gas content per unit area $q_L = 6.5 \cdot 10^8$ m^3/km^2, calculated across 16 thoroughly studied hydrate accumulations. In order to adjust the value of q_L to regional estimates, q_R can be calculated as $6.5 \cdot 10^8 : 40 = 1.6 \cdot 10^7$ m^3/km^2 basing on the assumption that average density of gas resources in hydrate accumulations q_L exceeds the same value in potentially hydrate-bearing areas q_R by factor of 40, because resource density of hydrate accumulations has the same distribution as that of conventional gas fields [9]. Multiplying $1.6 \cdot 10^7$ m^3/km^2 by the area of potentially hydrate-bearing areas produces the target estimate. Values of Q_{R1} and Q_{R3}, calculated for methane hydrates with this method, are presented in the Table under Scenario 1.

Another possible approach to resource estimation is based on the assessments of the U.S. Geological Survey [11]. Using geological statistics (with no regard for actual data on hydrate observations and extrapolating calculated parameters across the entire potentially hydrate-bearing area), gas resources have been estimated for nine submarine areas located in the U.S. exclusive economic zone, including the Gulf of Alaska, Beaufort and Bering seas. Methane content per unit area q_R for the abovementioned regions has been calculated by V.A. Soloviev [9] using data from [11]. Thus, for the Gulf of Alaska, whose P-T conditions are the closest to those of the study area, q_R equals $2.7 \cdot 10^9$ m^3/km^2. The value for Beaufort and Bering seas is of the same order of magnitude (3.8 and $2 \cdot 10^9$ m^3/km^2), which basically means that data from the Gulf of Alaska can be used in the calculations of Q_{R1} and Q_{R3} for methane hydrates with the proviso that the results are likely to be overestimated due to the use of statistical method (see Table, Scenario 2).

Described procedure applies to methane hydrates. It is harder to estimate q value for the hydrates of mixed composition. The calculation of GHSZ-2 (Fig.3, C) has been carried out for the hydrates of cubic structure II. Hence, all q_R values were divided by 2.95, the least value of gas expansion factor for such structure (5.75:17·164), where 5.75 and 17 – hydrate numbers for structures I and II respectively, 164 – methane expansion factor (see Table).

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Gas resources in hydrates of the Chukchi Sea

GHSZ / Q_R	Potentially hydrate-bearing area S, km^2	Scenario 1		Scenario 2	
		q_R, m^3/km^2	In-place gas hydrate resources Q_R, m^3	q_R, m^3/km^2	In-place gas hydrate resources Q_R, m^3
GHSZ-1/Q_{R1}	20000	$1.6\cdot10^7$ (from [9])	$3.20\cdot10^{11}$	$2.7\cdot10^9$ (from [11])	$5.40\cdot10^{13}$
GHSZ-2/Q_{R2}	54000	$5.4\cdot10^6$	$2.93\cdot10^{11}$	$0.9\cdot10^9$	$4.86\cdot10^{13}$
GHSZ-3/Q_{R3}	5700	$1.6\cdot10^7$ (from [9])	$0.91\cdot10^{11}$	$2.7\cdot10^9$ (from [11])	$1.54\cdot10^{13}$
Total	79700	–	$7.0\cdot10^{11}$	–	$11.8\cdot10^{13}$

As seen in the Table, Q_R results based on q_R value for the Gulf of Alaska is by three orders of magnitude higher than those obtained with the measured gas content. These evaluations can be regarded as maximal and minimal estimations of the study area.

Conclusions. In this study using integrated approach the potential of gas hydrate presence in the Chukchi Sea was estimated by means of assessing parameters of the stability zone and its mapping in ArcGIS software. A forecast map of potential hydrate-bearing areas of the Chukchi Sea has been plotted to a scale of 1:5 000 000. Our results demonstrated that even shallow areas of the Chukchi Sea shelf (from 40 m and deeper) are characterized by the presence of stability zones of structure II gas hydrates.

2D analysis of hydrocarbon gas distribution in the Chukchi Sea sediments allowed to identify approximate location of thermogenic gas seepage sites at 40-80 m depth in the central part of the study area.

Three types of gas hydrate stability zone have been specified: filtrogenic GHSZ of pure methane (1) and mixed composition (2), characterized by cubic structures I and II respectively, and cryogenic methane hydrate stability zone (3), characterized by cubic structure I.

Mapping of gas hydrate stability zone allowed to obtain a justified forecast of its distribution, based on available data on pressure, temperature, geologic, fluid dynamic, permafrost and geothermal conditions in the Chukchi Sea. Total area of hydrate stability zone (regardless of origin and composition) amounts to 80 000 km^2, which is more than 13 % of the overall area of the Sea.

Potential in-place gas resources, captured by hydrates in the Chukchi Sea, have been estimated to lie between $7\cdot10^{11}$ and $11.8\cdot10^{13}$ m^3 depending on the calculation method.

REFERENCES

1. Atlas of Hydrometeorological and Ice Conditions in the Russian Arctic Seas: Compilation of Library Materials and Expedition Results by OOO «Arctic Research Center of Shelf Development» in 2012-2014 / Ed. by V.A.Pavlova et al. Moscow: ZAO «Izdatel'stvo «Neftyanoe khozyaistvo», 2015, p. 128 (in Russian).

2. Poselov V.A., Zholondz S.M., Trukhalev A.I., Kos'ko M.K., Poselova L.G., Butsenko V.V., Pavlenkin A.D., Verba V.V., Kim B.I. Map of Sedimentary Cover Thickness in the Arctic Ocean. Geologo-geofizicheskie kharakteristiki litosfery Arkticheskogo regiona. St. Petersburg: VNIIOkeangeologiya. 2012. Vol. 233. Iss. 8, p. 8-14 (in Russian).

3. Soloviev V.A., Ginsburg G.D., Telepnev E.V., Mikhalyuk Yu.N. Cryogeothermics and Natural Gas Hydrates within the Interior of the Arctic Ocean. Leningrad: PGO «Sevmorgeologiya», 1987, p. 150 (in Russian).

4. Matveeva T.V., Logvina E.A. Gas Hydrates of the Arctic Basins: Risk Factor or Potential Resource? *Rossiiskie polyarnye issledovaniya*. 2011. N 2 (4), p. 19-21 (in Russian).

5. Matveeva T.V. Methodology and Stage-by-Stage Approach for the Exploration of Potentially Gas Hydrate-Bearing Water Areas and Hydrate Accumulations. *Nedropol'zovanie XXI vek*. 2014. N 3 (47), p. 74-79 (in Russian).

6. Orudzheva D.S, Obukhov A.N., Agapitov D.D. Prospects of Oil and gas Offshore Exploration in the Chukchi Sea. *Geologiya nefti i gaza*. 1999. N 3/4, p. 28-33 (in Russian).

7. Soloviev V.A., Telepnev E.V. Russian Arctic Seas. Sheet 3-10. Submarine Permafrost Area. Forecast of Distribution. Geology and Mineral Resources of the Russian Shelf areas (atlas). Red. M.N. Alekseev. Moscow, Scientific World. 2004.

8. Soloviev V.A., Ginsburg G.D. Russian Arctic Seas. Sheet 1-32. Gas Hydrate Environmentsand Potential Gas Hydrate Water Areas. Geology and Mineral Resources of the Russian Shelf areas (atlas). Red. M.N. Alekseev. Moscow, Scientific World. 2004.

9. Soloviev V.A. Global Estimates of Gas Content in Submarine Gas Hydrate Accumulations. *Russian Geology and Gophysics*. 2002. Vol. 43: N 7, p. 609-624.

10. Yashin D.S., Kim B.I. Geochemical Features of Oil and Gas Potential in the Eastern Arctic Shelf of Russia. *Geologiyaneftiigaza*. 2007. N 4, p. 25-29 (in Russian).

11. Collett T.S. Gas Hydrate Resources of the United States. D.L.Gautier et al (eds); National assessment of United States oil and gas resources on CD-ROM. U.S. Geological Survey Digital Data Series 30. 1995.

12. Collett T.S., Lewis R.E., Winters W.J., Lee M.W., Rose K.K., Boswell R.M. Downhole Well Log and Core Montages from the Mount Elbert Gas Hydrate Stratigraphic Test Well, Alaska North Slope. *Marine and Petroleum Geolog*y. 2011. Vol.28, p. 561-577. DOI: 10.1016/j.marpetgeo.2010.03.016.

13. Shakhova N., Semiletov I., Leifer I., Sergienko V., Salyuk A., Kosmach D., Chernykh D., Stubbs Ch., Nicolsky D., Tumskoy V., Gustafsson Ö. Ebullition and Storm-Induced Methane Release from the East-Siberian Arctic Shelf. *Nature Geoscience* 7.2013, p. 64-70.DOI: 10.1038/ngeo2007.

14. Kvenvolden K.A., Ginsburg G.D., Soloviev V.A. Worldwide Distribution of Subaquatic Gas Hydrates. *Geo-Marine Letters*. 1993. Vol. 13.Iss. 1, p. 32-40. DOI: 10.1007/BF01204390.

15. Savvichev A.S., Rusanov I.I., Pimenov N.V., Zakharova E.E., Veslopolova E.F., Lein A.Yu., Crane K., Ivanov M.V. Microbial Processes of the Carbon and Sulfur Cycles in the Chukchi Sea. *Microbiology*. 2007. Vol. 76. Iss. 5, p. 603-613. DOI: 10.1134/S0026261707050141.

16. Portnov A., Mienert J., Serov P. Modeling the Evolution of Climate-Sensitive Arctic Subsea Permafrost in Regions of Extensive Gas Expulsion at the West Yamal Shelf. *Journal of geophysical research*: *Biogeosciences*. 2014. Vol. 119, p. 2082-2094. DOI: 10.1002/2014JG002685.

17. Sloan E.D., Koh C.A. Clathrate Hydrates of Natural Gases. 3rd Edition. CRC Press: Taylor & Francis Group, 2008, p. 752. DOI: 10.1201/9781420008494.

18. Matveeva T.V., Savvichev A.S., Semenova A.A., Logvina E.A., Kolesnik A.N., Bosin A.A. Source, Origin, and Spatial Distribution of Shallow Sediment Methane in the Chukchi Sea. *Oceanography*. 2015. Vol. 28. N 3, p. 202-217. DOI: 10.5670/oceanog.2015.66.

19. Malyshev N.A., Obmetko V.V., Borodulin A.A., Barinova E.M., Ikhsanov B.I. Tectonics of the Sedimentary Basins in the Russian Sector of the Chukchi Sea. Proceedings of the International Conference on Arctic Margins VI (ICAM VI).Fairbanks, Alaska, May 2011, University of Alaska Fairbanks.2011, p. 203-209.

20. The International Bathymetric Chart of the Arctic Ocean (IBCAO) [Electronic Resource]. Date of access: http://www.gebco.net/data_and_products/printable_maps/ibcao_map/ (Reference date: 17.04.2017).

21. Vinogradov V.A., Gusev E.A., Lopatin B.G. Structure of the Russian Eastern Arctic Shelf. Proceedings of the Fourth International Conference on Arctic Margirs ICAM IV, September 30th-October 3rd 2003, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada. 2006, p. 90-98.

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