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DANGEROUS GAS-SATURATED OBJECTS ON THE ARCTIC SHELF OF EASTERN SIBERIA, THE FAR EAST (RUSSIA) AND ALASKA (USA)

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For the first time, a comprehensive megaregional analysis of features of potential gas saturation of shallow deposits of the Arctic seas of Eastern Siberia, Chukotka and Alaska was carried out for 2086 objects revealed in CDP seismic sections with a total length of 40 thousand km. It was established that the gas saturation of shallow deposits in the studied areas depended on their tectonic activity on late stages of sedimentation. The highest density of distribution of potentially gas-saturated objects was revealed in the Laptev, Chukchi and Bering seas; in the East Siberian Sea it was 5-6 times lower. Also, in this sea, a minimal share of objects near the bottom (up to 100 m) was observed. The results as a whole confirm low tectonic activity (dislocation) at the late stages of sedimentation in the East Siberian Sea, which concurs with the pattern of the CDP seismic sections. The results can serve as important information for increasing the efficiency and safety of oil and gas exploration in the studied offshore areas.

Keywords: *Arctic, CDP (common depth point) seismic survey, seismic sections, upper part of the section, gas deposits, shallow gas, gas pockets, gas hydrates.*

Introduction

In recent decades, in Russia, as in other leading oil and gas producing countries, more attention has been paid to environmental safety issues in the oil and gas industry, especially in the development of hydrocarbon resources in the areas of the World Ocean. Among the wide range of existing natural and manmade threats, particular problems often occur during well drilling, associated with the gas existence in the upper part of sedimentary cover (depths of up to 500-900 m) [1-11]. Abroad, much attention is paid to the study of the gas content of the upper part of sedimentary cover, and gas accumulations in shallow deposits, sealed by impermeable layers, are most often called shallow gas and/or gas pockets [9; 11]. Due to blowouts, self-ignitions and explosions of shallow gas, many hundreds of drilling rigs on land and in the areas of the World Ocean have been damaged and/or completely destroyed, causing enormous damage to oil and gas fields and the ecosystem of oil and gas producing countries [1-4; 11]. Statistically, about "a third of all blowouts" of gas during drilling occur from shallow deposits [11, p. 362].

The issue of well drilling safety is particularly urgent during development of offshore fields in the Arctic and Subarctic conditions, characterized by a short working season, making it difficult to eliminate the consequences of possible accidents. Uncontrolled gas blowouts have repeatedly occurred during drilling of exploratory wells, including that at the Mikkel Field in the Norwegian Sea in 1985 (the West Vanguard drilling rig), during drilling of the Luninskaya-1 Well in the Barents Sea in 1991 (Shelf-8), during drilling of an engineering-geological well in the Pechora Sea in 1995 (drilling vessel Bavenit), etc. [1-4; 11].

The upper part of sedimentary cover in oil and gas basins is characterized by a wide variety of objects associated with the generation, accumulation and migration of gas of different genesis (mainly methane). Microbial methane is generated directly in shallow deposits, it can form mixtures with methane and other gases from underlying generation zones, including thermogenic methane of deep horizons [12]. Shallow gas might be in free and/or hydrate states [13-17]. Any state of gas poses a threat during drilling operations, but free gas deposits with abnormally high formation pressures pose the greatest threat in the form of instantaneous (impulsive) blowouts – pneumatic exhausts, in most cases accompanied by self-ignition and explosions of gas [3; 4]. The danger of shallow gas-saturated deposits of the Arctic shelf and land for drilling operations is confirmed by the discovery of extensive zones of active gas seeps, forming gas flares on echograms, as well as large craters/pockmarks due to impulsive/explosive degassing [1–4; 10; 11; 18].

The main method for identifying and studying potential gas-saturated objects (hereinafter PGSOs) in the upper part of sedimentary cover is seismic exploration using the common depth point (CDP) method, the efficiency and resolution of which increase with the expansion of the frequency range of recorded waves. A vast volume of archived data of oil and gas exploration CDP seismic covering the Arctic shelf has been accumulated, allowing to study the shallow deposits with minimal costs, excluding the need for organizing new expensive field work. The Arctic shelf of the seas of Eastern Siberia and the Far East of Russia has not been sufficiently studied in terms of geological structure and oil and gas content. In this regard, targeted studies of gas saturation of the shallow deposits can contribute to obtaining new data on geological structure of the region, functioning of regional petroleum systems and identifying possible vertical gas migration paths, which is important for oil and gas exploration. Identifying vertical gas migration paths is also important for environmental and climatological studies. Methane emission into hydrosphere and atmosphere from shallow deposits disrupts the existing gas balance, which can affect global climate change on the Earth [18–20].

For the first time, the authors carried out large volumes of such studies (about 49 thousand km of seismic lines) in 2014–2023 for the areas of the Sea of Okhotsk [21], the shelf of Eastern Siberia, the Far East (Russia) [22–27] and Alaska (USA) [28].

The paper objective was a comprehensive analysis of the results of a number of studies previously completed by the authors with the aim to investigate gas content of the shallow deposits of the shelf zones of the Arctic region of Russia and the USA, including the Laptev, East Siberian, Chukchi, Beaufort and Bering Seas [22–28], in order to identify megaregional patterns in the spatial and depth distribution of potentially gas-saturated objects in shallow deposits, as well as their distribution by horizontal size.

Materials and method of the research

In CDP seismic sections, PGSOs are revealed by certain dynamic and kinematic features, which are given in the digital indexation adopted in the studies of the authors [22-28]:

1) abrupt local increase in the amplitude of reflections (bright spot) above the PGSO;

2) inversion of reflection phases (polarity change);

3) pull-down of the seismic horizons under the PGO, caused by a decrease in values of propagation velocity of waves in gas-saturated deposits (kinematic distortions);

4) decrease in the frequencies of recorded waves due to anomalous absorption of high-frequency components;

5) presence of an "acoustic shadow zone" - deterioration in tracing seismic horizons under the PGO (reduced reflection amplitudes);

6) presence of flat seismic horizons (flat spot), corresponding to reflected waves from a possible gas-water contact.

In CDP seismic sections, gas migration zones (gas chimney) are also identified in the form of sub-vertical disturbances of seismic horizons, usually associated with faults.

An evidence of gas hydrate (GH) deposits in seismic sections is a bottom simulating reflector (BSR), indicating the base of the GH stability zone, under which gas is in a free state [1; 11; 13-17]. A BSR horizon is determined by the following features: conformity to the surface of the seafloor, intersection of layering of the sedimentary cover (clearly visible on the continental slope), reverse polarity of reflected waves.

Results of the research and discussion

To identify PGSOs in the Laptev and East Siberian seas, an analysis of the archived CDP seismic sections of JSC MAGE acquired in 2005-2016 in the volume of 17.68 thousand km was performed (Table 1), the location of seismic lines is shown in Fig. 1 [15; 22; 25-27]. The study of PGSOs in the Chukchi, Beaufort and Bering seas was carried out using the CDP seismic sections of the US Geological Survey (USGS) in

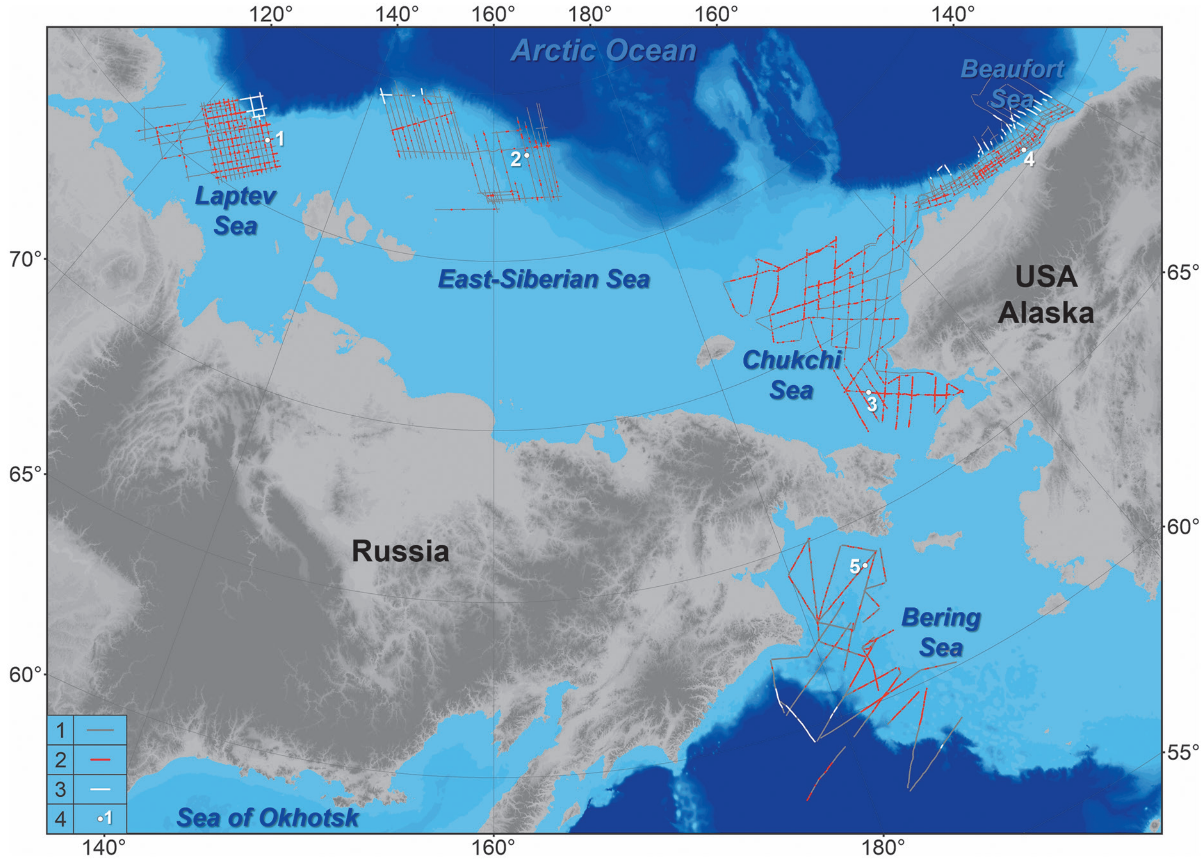

Fig. 1. Location map of seismic lines (1) with marked potentially gas-saturated objects (PGSOs) (2), gas hydrates (3) and positions of the PGSO fragments (4) shown in Fig. 2.

Table 1. Volumes of analyzed seismic lines and characteristics of potentially gas-saturated objects (PGSOs)

Sea	Total length of seismic lines, km	Number of the revealed PGSOs	Average interval between the PGSOs, km	Share of the PGSOs, shallower than 100 m, %	The longest PGSOs, km
Laptev	7810	550	14.2	66.5	More than 7
East Siberian	8200	129	63.6	31.8	More than 7
Chukchi	9500	782	12.1	57.5	More than 7
Beaufort	8440	184	22.0	66.8	4—4,5
Bering	5900	441	13.4	49.0	5—5,5
Total	*39850*	*2086*	*19.1*	*57.3*	*More than 7*

the volume of 23.84 thousand km (see Table 1, Fig. 1), which are in public access (https://walrus.wr.usgs.gov/namss/) [23; 24; 28].

Fig. 2 shows fragments of CDP seismic sections for the five studied offshore areas with clearly visible anomalous objects (heterogeneities) in shallow deposits, indicating the presence of PGSOs. A common feature for all five PGSOs is their multi-layer structure, which is found in most PGSOs. All five PGSOs are clearly distinguished by the five features listed above (1-5). The sixth feature (flat spot) is not clearly visible, which is connected with insufficiently high frequencies of seismic waves, small horizontal sizes of PGSOs (1-2.5 km) and their amplitude/height. On all seismic reflecting horizons below the PGSOs, pull-downs are clearly observed due to a decrease in the propagation velocities of seismic waves (feature 3), which can cause strong distortions into the structural imaging of target horizons at great depths (if there is no detail analysis and consideration of velocities in the PGSO zone).

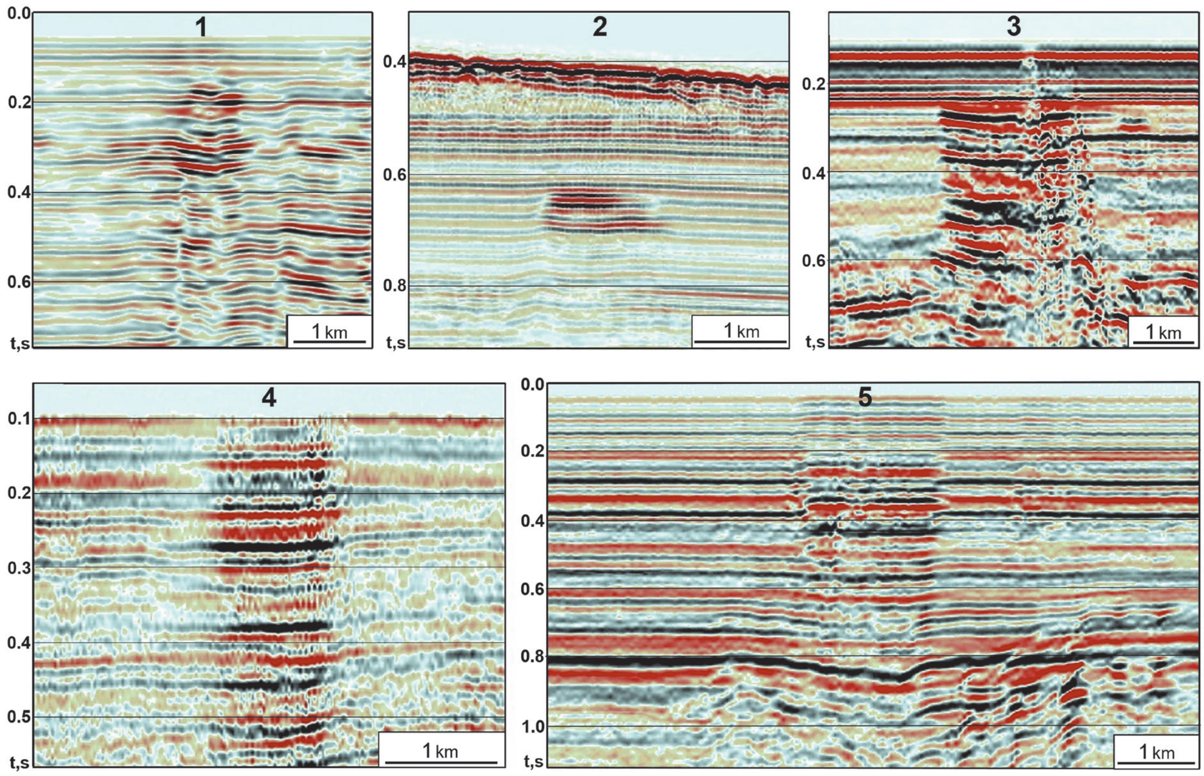

Fig. 2. Fragments of CDP seismic sections with potentially gas-saturated objects (PGSOs) in the Laptev (1), East Siberian (2), Chukchi (3), Beaufort (4) and Bering (5) seas (location of PGSOs on the map is shown in Fig. 1)

Here are described some features of the five PGSOs shown in Fig. 2. The smallest number of PGSOs (2-3) is observed in the example for the East Siberian Sea (Fig. 2.2), with the upper part of the PGSO located at the maximum (over 200 m) depth from the seafloor compared to other examples. In the bottom sediments of the section in the Chukchi Sea (Fig. 2.3), a degassing channel with a possible pockmark (crater) in the bottom relief is observed, while due to feature 3, the deep seismic horizons (over 0.7 s) are completely destroyed. In the Bering Sea, the most pronounced PGSOs (the highest gas saturation) with a length of about 2 km are observed at depths of about 200-450 m (0.2-0.45 s), with PGSOs also present near the bottom (up to 100 m), and a heave mound is visible in the seafloor relief.

Laptev Sea

For the Laptev Sea, seismic sections of JSC MAGE were analyzed within the base network of seismic lines acquired in 2005-2009, covering the central and southwestern parts of the area with a total length of about 7810 km (see Fig. 1) [22]. A total of 550 PGSOs were identified during the analysis (Table 1, Fig. 3). As a result of the analysis of their features it was established that most of them are up to 2.5 km in size (86.5%), while less than 0.5 km in size – 33.9%. With an average interval of 14.2 km between PGSOs, their highest density was found in the Central Laptev region (11.2 km). Most of the objects (82.6%) have an upper gas saturation boundary at depths of up to 200 m, and the maximum number of them (66.5%) is located near the bottom (up to 100 m). The obtained model of the depth distribution of gas-saturated objects is presumably associated with a large number of faults - potential channels for gas migration in the sedimentary cover, most of which reach the seafloor and are expressed in its relief in form of steps [29; 30].

The faults in the Laptev Sea were formed in the Late Cretaceous-Paleocene during crustal extension and became active in the Late Miocene-Pleistocene [31]. Extension stresses are transmitted to the Laptev Sea shelf from the adjacent Gakkel Ridge, an active spreading zone; the Laptev Sea area is currently characterized by high seismicity [1; 32]. The crust extension setting is a favorable factor for intensive vertical gas migration, and the thick sedimentary cover (up to 12-16 km) indicates the possibility of generating large volumes of thermogenic hydrocarbons. The obtained distribution also indicates the presence of seals of varying levels of integrity in a number of locations in the uppermost (bottom) deposits (depths up to 100 m), not disturbed by faults. In the Central Laptev region, the authors have juxtaposed the identified shallow PGSOs with previously discovered gas seeps [18; 30] and deep faults identified in the seismic sections of MAGE [22]. As a result, a clear association of seeps with deep

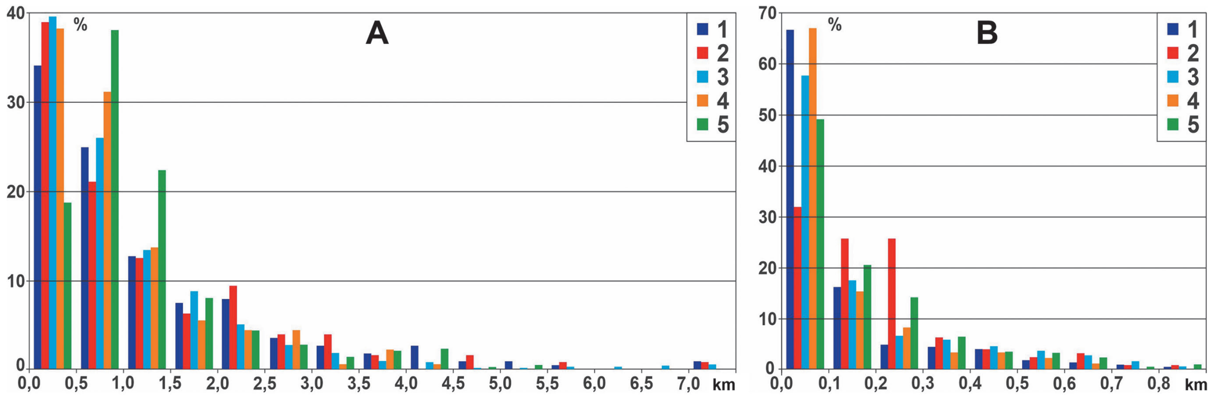

Fig. 3. Shared distribution of potentially gas-saturated objects in the section upper part by horizontal dimentions (A) and by depths of the gas saturation upper boundaries (B) in the Laptev (1), East Siberian (2), Chukchi (3), Beaufort (4), Bering (5) seas

faults, which are the Earth degassing channels, has been established.

On seismic sections of the six seismic lines crossing the continental slope of the Laptev Sea, the BSR horizon has been identified for the first time, indicating the possible presence of GHs (see Fig. 1) [27].

East Siberian Sea

For the East Siberian Sea, CDP seismic sections of MAGE have been used, acquired along seismic lines in the northwestern part of the area in 2011-2012 and 2016, with a total length of about 8200 km. As a result of the analysis, a total of 129 PGSOs have been identified [25; 26] (see Fig. 1). Concerning the distribution of the identified anomalous objects, it has been established that the majority of PGSOs (83.0%) have upper gas saturation boundaries at depths of up to 300 m from the seabed, however, only 31.8% are located shallower than 100 m (see Fig. 3 and Table 1). Most of the PGSOs are up to 2.5 km in size (87.6%), with 38.8% of the PGOs being less than 500 m. When analyzing seismic sections of the East Siberian Sea, a relatively small number of faults reaching the seafloor have been revealed. In the East Siberian Sea, there have been no intense tectonic movements since the Late Miocene [31], which results in a lesser dislocation of the upper part of the sedimentary cover and a lower intensity of vertical gas migration to the near-surface deposits.

On three seismic sections in the upper part of the continental slope sedimentary cover, a BSR reflecting horizon has been identified (see Fig. 1), which is associated with potential GH deposits [25; 26].

Chukchi Sea

The base data on the Chukchi Sea included seismic sections of USGS, acquired in 1978-1980 in both the Russian and American sectors of the area, with a total length of about 9,500 km. A total of 782 PGSOs have been identified as a result of the analysis [24] (see Fig. 1). It has been established that the majority of objects have an upper gas saturation boundary at depths of up to 200 m from the seafloor (74.9%), and this boundary is located extremely close to the seafloor (up to 100 m) for 57.5% of all objects (see Fig. 3 and Table 1). Most of the objects have a horizontal size of up to 2 km along the seismic lines (87.2%), and 39.4% of the objects – up to 500 m. The high gas saturation of the shallow deposits of the Chukchi Sea shelf can be explained by the presence of numerous faults, the main conduits of vertical gas migration, some of which come close to the surface of the sedimentary cover. Rifting occurred in the Jurassic, presumably, faults were activated in the Cenozoic. There is evidence of fault formation in the Quaternary [33]. The high oil and gas potential of the most submerged area of the shelf - the North Chukchi Depression - is predicted by analogy with the adjacent basin of the North Slope of Alaska, where fields have been discovered both on land and offshore [34].

Beaufort Sea

The data on the Beaufort Sea included sections of USGS acquired in 1977 and 1982 in the American sector of the area with a total length of 8440 m. A total of 184 PGSOs have been identified [28] (Fig. 2). As a result of the analysis of distribution of the identified PGSOs, it has been established that most of them in the Beaufort Sea (82.6%) are characterized by length of up to 1.5 km along the seismic lines. The maximum number of PGOs is concentrated in the interval of minimum sizes less than 500 m - 38%. In terms of the depth of upper boundaries, PGSOs are mainly shallower 200 m (82.1%), and the maximum number is concentrated in the interval of 0-100 m (66.8%). The fact that the largest number of PGSOs is confined to near-surface deposits can be explained by the presence of faults reaching the Quaternary deposits. The Beaufort Sea shelf is part of the Alaska North Slope basin, where deposits in a wide stratigraphic interval from the Carboniferous to the Cenozoic have varying oil and gas potential [34].

The oil and gas potential of the Alaska North Slope is confirmed by discovered fields, including the large Prudhoe Bay and Kuparuk River fields on the northern coast of Alaska, as well as Endicott and others on the shelf.

On 22 seismic sections crossing the continental slope of the Beaufort Sea, a BSR reflecting horizon indicating possible GHs has been identified (see Fig. 1). The obtained results are consistent with the data of previous studies [35; 36]. At the same time, there is direct evidence of the existence of GHs in the Beaufort Sea based on drilling data [37].

Bering Sea

For the Bering Sea, USGS sections acquired in 1977, 1980 and 1982 in the northwestern part of the water area, both in the Russian and American sectors, with a total length of about 5900 km were used. A total of 441 PGSOs have been identified, mainly in the shallow-water (up to 100 m) zone [23] (Fig. 2). As a result of the analysis of distribution of the identified PGSOs, it has been established that 86.2% of them are related to the depths of upper boundaries of gas saturation up to 300 m, and the maximum number reaches depths of less than 100 m (50.6%). 87.3% of PGSOs are less than 2 km in size, the maximum number is characterized by sizes of 500-1000 m (38.2%). The high concentration of gas hydrocarbons in near-surface deposits, as in the seas considered above, may be due to the distribution of faults in the upper part of sedimentary cover – channels for gas migration from deep deposits. In the Anadyr basin, active tectonic movements took place in the Cenozoic, which caused the dislocation of the near-surface deposits and active migration of hydrocarbons along faults [38]. There are no discovered fields on the shelf, but there are a number of discoveries on land that confirm the hydrocarbon potential of the region.

In the Aleutian Basin, 14 PGSOs have been identified at great depths of 500–700 m, which can be explained by the sealing of free gas by GH deposits existing at high pressures of the water column. Also, in four sections crossing the continental slope of the Bering Sea and the Aleutian Basin, a BSR horizon has been identified, indicating the potential presence of GHs. It should be noted that GHs were previously predicted in this region [39; 40].

Summarizing discussion of the results for all areas

The most frequently PGSOs are located in the Bering, Chukchi seas and in the central part of the Laptev Sea (on average, every 11.4-14.2 km, see Table 1), and the least densely (63.6 km) – in the East Siberian Sea. The differences in the obtained density of PGSO distribution in the studied seas can be due to lithological heterogeneities of the shallow deposits in the corresponding regions, affecting the distribution of reservoirs and seals. The studied region of the East Siberian Sea (north of the De Long High) is characterized by a smaller thickness of the sedimentary cover and a smaller number of faults reaching the bottom sediments and, consequently, less intense vertical migration.

The general pattern of distribution of the PGSOs by horizontal size may indicate the predominantly small sizes of natural reservoirs in the shallow deposits of the studied seas: from 55% to 70% of PGSOs have lengths of up to 1 km (Fig. 3A), although the sizes of individual accumulations in the seas of Eastern Siberia and Chukotka exceed 7 km, which may be of interest for prospecting and exploration (Fig. 3A).

General pattern of the distribution of PGSOs by depths for the Laptev, Chukchi, and Beaufort seas is the prevalence (57.5–66.5%) of objects with the upper boundary of gas saturation at depths of up to 100 m from the seafloor (Fig. 3B). This may be associated with intense tectonic movements in the corresponding regions at the stage of accumulation of shallow deposits, which resulted in formation or activation of faults that conduct gas to the near-bottom sediments. In the Bering Sea, about half of the PGSOs (49.0%) reach the depth of 100 m. In the East Siberian Sea, there is a quieter sedimentation regime that began in the late Miocene, which results in a smaller number of faults reaching the shallow deposits and, consequently, a lower concentration of PGSOs in them, formed by gas migrating along the faults (only 31.8%). However, subvertical gas migration along faults, together with the generation of biogenic gas in situ, also seems to be a key factor in the distribution of PGSOs in the East Siberian Sea, which is expressed by the concentration of most of them at depths of 100–300 m from the seafloor (51.2%).

Position of the fragments of the seismic sections with identified BSR horizons in all the studied offshore areas is consistent with the zone favorable for formation and existence of GHs, determined for the Arctic Ocean and adjacent offshore areas in publication [16] based on an analysis of the extensive database of near-bottom water temperatures of NOAA World Ocean Database 13 (WOD13) [41].

Conclusion

In the course of megaregional studies, the potential gas content of shallow deposits of the northern seas of Eastern Siberia and the Russian Far East, as well as the Beaufort Sea on the shelf of Alaska (USA) has been studied. As a result of the interpretation of CDP seismic sections with a total length of about 40 thousand km along the Laptev, East Siberian, Chukchi, Beaufort and Bering seas, a total of 2086 anomalies of seismic record have been identified, indicating the presence of PGSOs in the upper part of sedimentary cover.

The created models of distribution of PGSOs in shallow deposits showed that the identified objects predominantly have the upper boundary of the predicted gas saturation at depths of up to 300 m from the seabed (81.5-90.2%) and are characterized by linear sizes of up to 2-2.5 km (86.5-92.4%). The predominant distribution of PGSOs in the near-surface deposits is explained by both generation of microbial gas in situ and subvertical migration of gas along faults from the deposits located lower in the sedimentary cover. The relationship between the distribution of gas-saturated objects in shallow deposits and migration along faults indicates a highly probable presence of hydrocarbons in deposits, which are currently predicted to be highly promising for oil and gas based on the existing geological and geophysical information [1; 31; 34; 42; 43]. It has been established that gas saturation of near-surface deposits in the studied regions depends on their tectonic activity at the late stages of sedimentation.

The results can serve as important information for increasing the efficiency and safety of drilling deep oil and gas exploration wells in the studied offshore areas. Studying and mapping the distribution of gas-saturated objects in shallow deposits is necessary for selecting optimal drilling locations, preventing gas blowouts that can lead to serious emergency and even disastrous situations. Perhaps, in the future, some of the identified PGSOs will be of independent interest for fulfilling the energy needs of nearby settlements and industrial facilities on the coast, as it is already under way on the shelf of the Gulf of Mexico in the USA and the North Sea (Netherlands) [44].

On the continental slope of the Laptev, East Siberian, Beaufort, and Bering seas, a BSR reflecting horizon has been identified in CDP seismic sections, indicating the probable presence of GHs. The area of distribution of the BSR horizon is consistent with the zone of favorable thermobaric conditions for stable existence of methane hydrates, determined in [16].

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