LOCALIZATION OF ZONES OF ENDOGENOUS INFLUENCE IN AREAS WITH HIGH GAS SATURATION LEVELS BASED ON MAGNETIC FIELD ANOMALIES

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Abstract. Based on the interpretation of the Earth's magnetic field anomalies and gravity anomalies, the structure of the Arctic lithosphere in areas of increased gas saturation of bottom sediments has been studied. The analysis of density and magnetic sections has shown that the lithosphere in the zones of methane fluxes and gas hydrates is characterized by the presence of thermo-fault that remove fluid flows from the Earth crust and mantle. In areas of aquatories where, according to geochemical studies, methane outputs of deep genesis have been confirmed for the first time, the trajectories of fluid flows coming from a depth of the Earth crust and mantle have been traced on petrophysical sections. The study of the influence of the endogenous fluid-dynamic factor make it possible to optimize the choice of safe shipping routes along the Northern Sea Route in the fields of methane emissions.

Keywords: *Arctic, magnetic anomalies, endogenous factors, gas seeps*

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1. INTRODUCTION

Thanks to the implementation of the national project "Modernization," which includes the development of the Northern Sea Route (NSR), a logistics system for the Northern Sea Transport Corridor (NSTC) is being created.

The formation of a direct route for the NSTC transport and logistics system, connecting the northwestern regions of Russia with the Far East, creates the shortest sea route, allowing for increased connectivity within Russia and providing an impulse connecting Asian markets with North Atlantic and European ones. To implement this plan, it is necessary to ensure safe year-round navigation along the NSR, which is a priority for the logistics of the country's energy potential.

The East Siberian Arctic shelf is at the center of active research due to gas emissions and detection of elevated methane concentrations in the atmosphere and hydrosphere, recorded during numerous expeditions on the Arctic sea shelves [Baranov et al, 2020; Shakhova et al., 2010; Shakhova et al., 2015; Bogoyavlensky et al., 2018]. It is concerning that some of the discovered gas-explosive objects are located near the NSR routes [Bogoyavlensky and Kishankov, 2020].

The purpose of this work is to study the specific structure of the lithosphere in the Arctic shelf seas in areas of increased gas saturation of bottom sediments, gas deposits, massive methane emissions, and "flare-type" gas manifestations in the Barents, Laptev, East Siberian, and Chukchi seas using analysis of lithospheric magnetic anomalies.

In zones of increased gas saturation, the influence of endogenous natural factors creates risks to safe navigation and disrupts logistical shipping operations along the NSR routes.

Research results from the East Siberian Arctic shelf show abnormally high concentrations of dissolved CH_4. CH_4 flows to the seabed were caused mainly by permafrost integrity violations; the flow passed through identified migration pathways, as well as through taliks and fault polynyas, the width of which can reach tens of kilometers [Shakhova et al., 2010].

The main source of ice information is satellite remote sensing data, which detect zones of ice cover degradation [Yulin et al., 2019].

Satellite measurements of the Earth's magnetic field (EMF) allow assessment of the deep structure of the lithosphere [Petrova et al., 2020; Petrova et al., 2022a; Kharitonov et al., 2004].

To identify lithospheric features that have a destructive effect on ice cover formation, ground-based magnetic data of the EMF module were used [Kopytenko and Petrova, 2016; Kopytenko and Petrova, 2020]. Magnetic and density sections were constructed along profile systems crossing zones of accelerated ice melting. Density sections are constructed based on gravity anomalies [Bonvalot et al., 2012].

Analysis of satellite observations of seasonal changes in Arctic ice thickness from 2007 to 2024 showed that both the area of the ice cover and its thickness are changing. Fluid flows from the depths of the Earth's crust and mantle rise through thermofluid-processed channels and emerge through through-taliks, thinning the ice, forming thawed patches and leads, which contributes to ice destruction. The conducted research allows understanding possible causes of localization of ice melting areas.

Joint analysis of satellite monitoring data on ice cover thickness with petrophysical sections of the Earth's crust confirmed that over the past decades, the endogenous fluid dynamic factor has played an important role in the formation of the ice regime in the Arctic Ocean waters [Petrova et al., 2022; Petrova et al., 2022; Petrova et al., 2020; Kopytenko et al., 2020; Petrova et al., 2020a; Petrova et al., 2022a].

Research has shown that ice cover melting is most actively manifested above the outlets of ascending fluid flows from deep-focus lenses of fluid layers of the Earth's crust and mantle [Petrova et al., 2020]. Fluid layers and channels of thermoactive faults are visualized in magnetic and density sections as weakened zones with low magnetization and reduced density properties [Petrova et al., 2020; Petrova and Kopytenko, 2019].

The structure of the lithosphere in natural hydrocarbon degassing zones has certain features reflected in geophysical fields. For example, this is shown in the work [Kharitonov, 2022], where comprehensive studies were conducted to examine degassing heterogeneities in the upper layers of the lithosphere, based on satellite measurements of magnetic and gravitational fields, taking into account heat flow data.

In the zones of potential gas hydrates accumulation [Bogoyavlensky et al., 2018; Shakhova et al., 2019] in the Arctic seas, areas influenced by fluid dynamic factors have been identified. Migration pathways of fluid flows from the Earth's crust and mantle that destroy the ice cover are visualized on petrophysical cross-sections as channels with reduced magnetic and density properties. This allowed for the prediction of areas with the highest probability of emergencies of deep origin in gas hydrate development zones in the NSR water area [Petrova et al., 2022a]. Taking into account the fluid dynamic influence on the ice regime makes it possible to optimize the location of safe transport and logistics routes for year-round navigation.

Satellite information has important practical significance for operational monitoring of gas seep emergence sites on the Arctic shelf. This paper presents the results of studying the deep lithosphere structure of the Russian Arctic seas in areas with high gas saturation levels in bottom sediments, where gas can exist both in free and hydrate states [Shakhova et al., 2010; Shakhova et al., 2015; Shakhova et al., 2019; Bogoyavlensky and Bogoyavlensky, 2021; Wallmann et al., 2018; Andreassen et al., 2020; Serov et al., 2023; Sokolov et al., 2023; Bogoyavlensky et al., 2022; Bondur and Kuznetsova, 2015; Bogoyavlensky et al., 2021a; Bogoyavlensky et al., 2023].

As a result of interpreting magnetic anomalies and gravity anomalies in the Barents, East Siberian, Chukchi, and Laptev Seas, methane discharge pathways have been identified. Gas flows emerging through open taliks have endogenous genesis and are confined to disjunctive disturbances. In the exit zones of subvertical deep faults, where deep fluid circulation occurs, an increased geothermal flow is possible.

The activation of gas seeps (flares) can create a powerful influx of deep thermogenic gas along faults and systems of subvertical fractures, which contributes to the expansion of through taliks and the formation of large areas of thawed waters. The size of the flare depends on the depth from which the gas comes and under what reservoir pressure, which is reflected in the trajectory of the thermofluid channel.

When methane reaches the lower boundary of sea ice, it undergoes intensive oxidation with heat release. This leads to changes in the rheological and strength characteristics of ice, causing acceleration of crack formation, polynya, and lead formation processes.

In the southeastern part of the Barents Sea, the fast-ice edge Pechora polynya is observed; to the northwest of Novaya Zemlya, the West Novaya Zemlya polynya regularly forms; in the Kara Sea, the Amderma, Yamal, Ob-Yenisei, and West Severnaya Zemlya polynyas are distinguished. In the Laptev Sea, a system of fast-ice edge polynyas forms: East Severnaya Zemlya, Taimyr, Lena, and Novosibirsk. The latter is located north of the New Siberian Islands, occupying in some years vast areas of two seas – the Laptev and East Siberian [Atlas..., 2019].

In the present work, to determine the causes of the Great Siberian polynya formation [Atlas..., 2019], petrophysical cross-sections were constructed and its lithosphere was studied. This polynya represents a continuous line of open water and young ice that systematically forms beyond the outer edge of the fast ice in the water area from Bolshoy Begichev Island in the Laptev Sea to the Medvezhyi Islands in the East Siberian Sea.

Analysis of magnetic and density cross-sections of the lithosphere in gas flare activation zones demonstrates the features of thermofluid channel trajectories, areas of their outlets to the bottom surface, depth and location of fluid system lenses, which allows for the prediction of potentially dangerous zones of deep origin caused by the movement of fluid flows.

2. BRIEF INFORMATION ABOUT THE RESEARCH AREA

In the area of the Russian Arctic shelf, considerable experience has been accumulated in identifying and mapping hazardous geological objects using hydroacoustic methods. Methane concentrations in the Arctic atmosphere are the highest on the planet. Gas flares are gas emanations in the form of bubbles rising from the bottom, forming stable areas of increased concentration in the water column. Gas flares have been recorded in many regions of the World Ocean, including the Arctic shelf [Sergienko et al., 2012].

In the works [Shakhova et al., 2010; Shakhova et al., 2015; Shakhova et al., 2019; Bogoyavlensky and Bogoyavlensky, 2021; Wallmann et al., 2018; Andreassen et al., 2020; Serov et al., 2023; Sokolov et al., 2023; Bogoyavlensky et al., 2022; Bondur and Kuznetsova, 2015; Bogoyavlensky et al., 2021a; Bogoyavlensky et al., 2023; Sergienko et al., 2012; Matveeva et al., 2017], gas emissions into the water column (gas flares) and gas accumulations are described. The identification of hazardous geological objects is mainly carried out using acoustic and seismoacoustic equipment. Based on the research results, maps of hazardous phenomena on an irregular grid of routes from observations in the Barents Sea have been published [Sokolov et al., 2023]. Further systematic study of the upper part of the geological environment of shelf waters, especially in areas of transport and logistics routes, will lead to an increase in the completeness of information for safe navigation.

The influence of the fluid dynamic factor in the Arctic shelf waters is considered using examples of areas with high levels of gas saturation in bottom sediments in the Barents, East Siberian, Chukchi, and Laptev Seas (Fig. 1).

In the eastern part of the Arctic Ocean, there are at least two areas with major upward gas flows to the seabed. One extends for 630 km along the shelf and slope west of Spitsbergen [Serov et al., 2023]; the second occurs on the Laptev Sea shelf [Baranov et al., 2020; Shakhova et al., 2015]. Large-scale mapping of the region showed that widespread leakage (possibly a thousand gas bubble release sites) is mainly associated with a deep fault zone. At present, the idea has been proposed that faults represent migration pathways for gas from deep reservoirs.

2.1. Barents Sea

Gas hydrates were not the main source of methane in the oceans, but rather acted as a dynamic seal regulating the release of methane from deep geological reservoirs. The authors [Wallmann et al., 2018] suggest fluid migration through structural channels created by faults.

In the northern part of the Barents Sea, acoustic research data revealed a series of root sound-scattering objects with widths near the bottom of up to 250 m (mega-flares) and the presence of fluid migration channels moving upward through the section, which may be associated with a deep fault system [Sokolov et al., 2023]. This makes it likely that upward-migrating fluids discharge along inclined and permeable layers. The Upper and Middle Triassic marine shale layers may inhibit fluid migration.

The composition of hydrocarbon gas in the sediments reveals a proportion of C_2-C_5 hydrocarbon gas (ethane, propane, etc.), indicating the thermogenic origin of the gas. Datasets from across the central Barents Sea show more than seven thousand hydrocarbon gas seeps containing thermogenic hydrocarbon sources [Serov et al., 2023].

2.2. Laptev Sea

Several studies [Baranov et al., 2020; Shakhova et al., 2015; Shakhova et al., 2019; Bogoyavlensky and Bogoyavlensky, 2021; Bogoyavlensky et al., 2022; Sergienko et al., 2012; Lobkovsky et al., 2015] have investigated the causes of active methane emissions and dangerous gas-saturated objects in the waters of the Laptev Sea and the East Siberian Sea.

The works [Shakhova et al., 2019; Sergienko et al., 2012] reflect observations during which powerful numerous methane seeps were recorded in the depth range of 60-110 m. It was previously assumed that the most significant degradation of subsea permafrost occurs in this depth interval, facilitating the appearance of through pathways for methane release. On some oceanographic transects, flares with diameters exceeding 100 m were discovered, which merged into a single multi-root giant flare with a diameter of more than 1000 m.

In the work [Baranov et al., 2020], an idea was proposed about methane emissions in the system of fault - gas reservoir - talik zones associated with recent fault zones. The authors suggest that methane migrates upward along faults to the seafloor and then is released into the ocean. The thickness of sediments on the Laptev Sea shelf reaches 12 km, which can potentially lead to the formation of hydrocarbons. Deep faults serve as channels for gas migration from the lower layers of sediments to the upper ones, where a gas reservoir can form under the gas hydrate stability zone and the permafrost horizon [Shakhova et al., 2015; Shakhova et al., 2019; Sergienko et al., 2012].

The presence of gas reservoirs/gas pockets is confirmed by the analysis of seismic data obtained on the Laptev Sea shelf [Bogoyavlensky et al., 2018].

In the central part of the Laptev Sea, a zone of powerful methane emission was identified [Shakhova et al., 2010; Bogoyavlensky et al., 2021a], where according to research data, the acoustic basement lies at a depth of 11-14 km [Bogoyavlensky et al., 2023]. As a result of a comprehensive analysis, the confinement of gas seeps in this area to deep faults was shown for the first time, and the seeps cause direct gas migration from great depths.

The work [Bogoyavlensky et al., 2021a] confirms the well-known fact of possible gas migration upward through systems of active faults. The studies demonstrate the confinement of seeps to deep gas migration channels and prove that numerous tectonic disturbances and significant volumes of thermogenic hydrocarbons are the main cause of gas release at the edge of the Laptev Sea shelf.

The results of studies on the carbon isotopic composition of methane $\delta^{13}C$ (CH_4) from gas seeps in the Eastern Arctic waters almost universally confirmed its deep origin [Baranov et al., 2020; Bogoyavlensky et al., 2021a]. In the vast majority of Laptev Sea studies, thermogenic methane with $\delta^{13}C$ (CH_4), as well as heavier molecular compounds (ethane, propane, etc.), were found in bottom sediments and seeps. This indicates long-term migration of deep gas through systems of active faults and subvertical fractures into the atmosphere.

Studies of gas seeps, carbon composition of methane, together with seismic survey data and bottom water temperature measurements, substantiated the consistency of gas seep locations in the central part of the Laptev Sea and deep faults [Bogoyavlensky et al., 2021a].

The work [Bogoyavlensky et al., 2023] proved that through taliks identified in the permafrost zone on the Laptev Sea shelf have an endogenous origin and are associated with major rock discontinuities. The seismicity of the central part of the Laptev Sea is the most intense; it leads to increased permeability of taliks, activating vertical movement of fluid flows and causing permafrost destruction and gas hydrate decomposition [Bogoyavlensky et al., 2018].

The high activity of degassing processes is confirmed by numerous gas shows associated with terraced subhorizontal surfaces fractured by modern tectonic disturbances. Based on the results of geophysical work by JSC "Marine Arctic Geological Expedition" using the common depth point method (CDP), multiple gas saturation foci in sedimentary rocks in the upper part of the section (UPS) at depths of more than 50-60 m were also often confined to tectonic faults [Bogoyavlensky et al., 2023].

In the eastern part of the Laptev Sea, a system of riftogenic grabens passes in a wide strip, which significantly exceeds the width of the rift zone of the Gakkel Ridge. The work [Lobkovsky et al., 2015] suggests that methane migration in the sedimentary rock mass and its subsequent release may be associated with recent faults that originate from older disjunctive structures with deep roots.

2.3. East Siberian Sea

The East Siberian Sea is a shelf sea of the Arctic Ocean located off the shores of Eastern Siberia.

The work [Bogoyavlensky et al., 2022] investigated hazardous gas-saturated objects in the East Siberian Sea, where, unlike the Laptev Sea, there is no active seismicity, and the number of active faults is significantly lower. Thus, gas seeps were discovered in the central part of the East Siberian Sea.

Anomalous objects in bottom sediments, which are presumably associated with gas deposits and channels of its subvertical migration, were identified during the interpretation of high-frequency CDP seismic data in the northwestern part of the East Siberian Sea. Tectonically screened gas deposits at depths of 300-800 m from the bottom are confined to faults extending from the acoustic basement [Bogoyavlensky et al., 2022].

2.4. Chukchi Sea

Unlike other shelf seas of Northern Eurasia, the western and eastern boundaries of the Chukchi Sea are conventional and run along the meridians of Wrangel Island (180°) and 155-156° west longitude in the area of Cape Barrow in Alaska [Bogoyavlensky and Kishankov, 2020].

In the Chukchi Sea, seismicity is recorded in the area of the Bering Strait and opposite the coast of Alaska with earthquake focal depths ranging from 0 to 40 km.

Most of the Chukchi Sea area (70% of the area) is characterized by sediment thickness of more than 2 km: the South Chukchi Basin has a sedimentary thickness of 2-4 km, while in the North Chukchi Basin the maximum thickness of the sedimentary cover reaches 22 km. Thus, the thickness of the sedimentary cover is sufficient to provide favorable conditions for gas formation and, consequently, for the formation of gas hydrates. Bottom sedimentary rocks formed in the Chukchi Sea are enriched with organic matter, which is a consequence of special geodynamic conditions: sufficiently long stretching of the earth's crust with the formation of a system of troughs and modern fluid activity.

The significant thickness of the sedimentary cover and the high hydrocarbon potential of the Chukchi Sea make it possible to predict the formation of thermogenic gases (including methane homologues) and their subsequent migration to the seabed through weakened zones and faults. The content of methane homologues in the Chukchi Sea sediments varies widely [Matveeva et al., 2017].

The potential amount of gas stored under the Chukchi Sea in the form of hydrates is estimated based on mapping their stability zone [Matveeva et al., 2017].

The paper [Bogoyavlensky and Kishankov, 2020] presents the results of studying the potential gas content of the Chukchi Sea based on seismic data. The study identified groups of potential gas deposits distributed vertically, as well as faults through which migration occurs from deep horizons. In most cases, the deep origin of methane in bottom sediments is confirmed by the presence of its homologues.

The presence of structural channels for fluid inflow to the surface in the form of faults contributes to the jet effect of degassing. Source rocks with reservoir properties and subsequent manifestation of degassing are assumed.

3. RESEARCH METHODS AND MATERIALS.

In order to study the specifics of the deep structure of regions with increased properties, an analysis of the magnetic and density properties of the lithosphere in the Arctic seas was carried out. The initial data used were magnetic anomalies of the geomagnetic field module [Kopytenko and Petrova, 2016; Kopytenko and Petrova, 2020] and gravity anomalies [Bonvalot et al., 2012]. Based on magnetic anomalies and gravity anomalies, deep magnetic and density sections were calculated along profiles crossing areas of methane seeps and gas flares (Fig. 1). The overview figure (Fig. 1) shows the locations of profiles for which petrophysical sections were calculated through confirmed areas of gas-saturated objects, methane seeps, and gas hydrates [Shakhova et al., 2010; Shakhova et al., 2015; Shakhova et al., 2019; Bogoyavlensky and Bogoyavlensky, 2021; Wallmann et al., 2018; Andreassen et al., 2020; Serov et al., 2023; Sokolov et al., 2023; Bogoyavlensky et al., 2022; Bondur and Kuznetsova, 2015; Bogoyavlensky et al., 2021a; Bogoyavlensky et al., 2023].

The methodology for constructing deep crustal sections is based on the spectral-spatial representation of anomalous geophysical fields, which are converted into magnetic and density sections through sequential linear filtering of the original field spectrum, followed by inverse transformation of the resulting set of spectra in the range of anomaly periods of interest. Petrophysical sections are calculated from magnetic anomalies and gravity field anomalies using the method of spectral-spatial analysis (SPAN). The methodology for applying SPAN to form magnetic and density models of deep sections has been presented by the authors in a series of articles [Petrova and Kopytenko, 2019].

The results of SPAN, obtained from high-precision magnetic survey data, were used to solve oil and gas exploration problems in Russia and in the waters of the North, Barents, Bering, and Mediterranean seas. When constructing petrophysical sections using the SPAN method, the experimental-theoretical dependence of the spectral structure parameters of the magnetic field on the depth of magnetic-active bodies was taken into account. This approach allows estimating the thickness and depth of complexes that differ in physical properties, and determining the depths of objects with an error of 5-10%.

Comparison of density sections calculated by the SPAN method with seismic sections made it possible to identify marker horizons of media with different velocity characteristics, correlate them with the location of lithological-stratigraphic complexes in the geological section, and identify the detected surfaces. Weakened layers with reduced magnetic and density properties in the sections correspond to zones of seismic velocity inversions. The depth calculations performed using SPAN sections have been repeatedly confirmed by drilling in oil and gas-bearing areas (more than 100 wells) [Petrova and Kopytenko, 2019].

The spectral-spatial representation of high-precision magnetometric measurements allows to present vertical objects of weakly magnetic differences, traceable from a depth of several kilometers to the surface in the complexes of the sedimentary cover and basement. On density and magnetic sections, fluid system lenses, zones of crustal schistosity, lateral and vertical faults, which are migration pathways for thermofluid flows, are reflected as zones of reduced density and magnetization.

Deep sections clearly represent the location of fluid systems in the Earth's crust and mantle. From magnetic sections, one can obtain an estimate of rock magnetization, and from density sections – an estimate of the density of rocks in the Earth's crust and mantle. Petrophysical sections determine the location of fluid system lenses and channels of thermofluid processing. Traces of mineralized fluid flow migration appear on the sections as weakly magnetic supply channels of reduced density. In the lower crust and mantle, where rocks are in a demagnetized state due to high temperatures (over 560°C), the location of fluid systems is determined by density sections [Petrova et al., 2019]. Joint analysis of satellite monitoring of ice cover with deep sections crossing large areas of meltwater and through taliks showed that one of the main endogenous factors of melting is fluid flow rising through subvertical channels and receiving recharge from deep-focus lenses of fluid systems at different depth levels of the Earth's crust.

Specific features of the Earth's crust in areas with increased gas saturation of bottom sediments are presented on deep petrophysical sections constructed through methane release fields in the Barents Sea, Laptev Sea, East Siberian and Chukchi Seas (Fig. 2-5).

To study the deep structure of the Earth's crust in areas of methane release, the following tasks were addressed:

– analysis of the location of methane emission zones in the Arctic seas was conducted [Shakhova et al., 2010; Shakhova et al., 2015; Bogoyavlensky et al., 2018; Shakhova et al., 2019; Bogoyavlensky and Bogoyavlensky, 2021; Wallmann et al., 2018; Andreassen et al., 2020; Serov et al., 2023; Sokolov et al., 2023; Bogoyavlensky et al., 2022; Bondur and Kuznetsova, 2015; Bogoyavlensky et al., 2021a; Bogoyavlensky et al., 2023];

– density and magnetic profiles of the Earth's crust were constructed for confirmed areas in methane release fields;

– deep-seated fault zones and the location of fluid-saturated layer lenses in the Earth's crust and mantle were identified using petromagnetic profiles;

– trajectories, depth, and outlets of fluid flows through thermoactive channels to areas of methane seeps and gas flares were determined;

– based on satellite measurements of the main magnetic field and areal calculations of weakened zones in the Earth's crust at depths of about 20 km, the most probable areas of possible influence of the endogenous fluid dynamic factor were identified in the considered water areas.

Fluid-conducting channels represent weakened zones with low magnetization, reduced density properties, and may have elevated heat flow values. Lenses of fluid systems are characterized by inversion of seismic velocities and reduced electrical resistance [Shipilov, 2016]. On the profiles, channels of thermofluid processing and lenses of fluid layers are visualized as zones of reduced density and magnetization in the lower Earth's crust and mantle.

Identifying the location of thermofluid channel outlets to the seabed surface makes it possible to predetermine the most likely distribution of stable areas of thawed waters arising under the influence of the fluid dynamic factor of the Earth's crust and mantle.

4. RESEARCH RESULTS

Based on the interpretation of Earth's magnetic field anomalies and gravity anomalies, the structure of the lithosphere of the Arctic seas in areas of increased gas saturation of bottom sediments was studied . The paper investigates the specific structure of the lithosphere in areas of potential and recorded methane emission fields in the Barents, Kara, Laptev, and East Siberian Seas (Fig. 1) [Shakhova et al., 2010; Shakhova et al., 2015; Bogoyavlensky et al., 2018; Shakhova et al., 2019; Bogoyavlensky and Bogoyavlensky, 2021; Wallmann et al., 2018; Andreassen et al., 2020; Serov et al., 2023; Sokolov et al., 2023; Bogoyavlensky et al., 2022; Bondur and Kuznetsova, 2015; Bogoyavlensky et al., 2021a; Bogoyavlensky et al., 2023; Sergienko et al., 2012; Matveeva et al., 2017; Lobkovsky et al., 2015]. Analysis of petrophysical sections showed that subvertical thermofluid channels of deep-seated faults can serve as pathways for the supply of endogenous fluids to areas of increased gas saturation. Petrophysical sections have been constructed for the Barents, East Siberian, Chukchi Seas and the Laptev Sea (Fig. 2-5), which reflect the most probable depths and pathways of gas fluid migration in case of activation of fluid-saturated lenses, for example, under the influence of seismic events.

Studies of the Russian Arctic shelf show that the risks of emergencies may be associated with a high level of gas saturation in bottom sediments containing gas in both hydrate and free states [Bogoyavlensky and Bogoyavlensky, 2021].

4.1. Barents Sea

According to geophysical and geochemical studies in the Barents Sea, zones of gas hydrate development have been confirmed [Andreassen et al., 2020], as well as the emergence of gas flares, including mega-flares, and deep genesis methane [Sokolov et al., 2023]. Petrophysical sections along profiles 1-1' and 2-2' (Fig. 1-2) crossed gas hydrate horizons and areas of gas flare manifestations.

On the basis of the density section of profile 1–1' (Fig.2a), magnetic field anomalies obtained from CHAMP satellite measurements for an altitude of 100 km are presented [Thebault et al., 2016]. The magnetic field minimum in the gas hydrate zone corresponds to the presence in this area of the Barents Sea of weakened layers with reduced magnetization and density, manifesting at a depth of about 20 km in the Earth's crust and at a depth of more than 45 km in the mantle (Fig.2 *a – b*). A significant vertical zone of thermofluid processing under the gas hydrate zone on profile 1-1' can be traced on the density section and even more vividly on the magnetic section from a depth of 25–30 km (Fig. 2 *a – b*). The ascending vertical migration of fluids through the thermofluid channel from a depth of more than 20 km provides the possibility for sudden thermal flow release to the surface in the area of solid gas hydrates. This can create conditions for the emergence of an explosive natural phenomenon of deep origin in the gas hydrate area.

The mega-flare zone on profile 1–1' is located in the Barents Sea magmatic province [Shipilov, 2016]. The density and magnetic sections show a possible trajectory of subvertical feeding of mega-flares from a depth of more than 15 km (Fig. 2 *a – b*).

The mega-flare zone on profile 2−2' may be fed from a depth of 10–15 km (Fig. 2 *g*). A powerful influx of thermogenic gas flows through faults and systems of subvertical fractures. The extensive field of methane emission recorded in the flare zone [Bogoyavlensky et al., 2022] on profile 2–2' is located above a large complex zone of disturbances, where methane can enter the rocks of the upper part of the Earth's crust from depths of 10–15 km. On profile 1–1' in the mega-flare section, migration of deep genesis methane from deep geological reservoirs along a subvertical trajectory from a depth of about 30 km is possible. Fault zones under mega-flares form areas of concentrated discharge, through which powerful emissions of gas can occur.

4.2. Laptev Sea

According to geophysical and geochemical studies in the Laptev Sea, powerful methane emission fields have been detected in the form of plumes with gas flash widths up to 100-150 m, and merged fountains in a multi-rooted giant plume with a diameter of more than 1000 m [Shakhova et al., 2019]. Petrophysical sections along profiles 3-3' and 4-4' (Fig. 1, 3) crossed methane emission fields in the form of gas seeps recorded near the CMTC.

The density sections 3-3' and 4-4' (Fig. 3 *a* - *c*) demonstrate a fault zone along which the trajectory of subvertical fluid migration passes, which makes it possible to bring the thermal flow to the surface from a depth of 20-30 km to the area of methane emission fields in the form of gas seeps near the CMTC.

On the magnetic section 3-3' (Fig. 3 *b*), an ascending subvertical trajectory of possible fluid migration along the thermal fault to the gas seep zone from a depth of about 30 km is well expressed, which may be the cause of active gas emission in this area and cause intense bubble methane release. On the magnetic section 4-4' (Fig. 3 *d*), fluid migration is possible from a depth of 10-12 km.

On the background of magnetic sections 3-3' and 4-4' (Fig. 3 *b-d*), zones of potential gas hydrate development near the NSR waters [Shakhova et al., 2019] are shown. Thermal flow from the earth's crust can enter the gas hydrate zones along inclined faults from a depth of about 10-15 km.

Thermal flows of deep fluid contribute to accelerating the melting of the ice cover. In the work [Bogoyavlensky et al., 2023], it is noted that one of the major disruptive disturbances of the bottom rocks north of Begichev Island (Fig. 4 *b*), "exactly coincides with the thawed zone identified during the analysis of refracted waves along seismic profile PT1101". Petrophysical sections 3-3' and 4-4' (Fig. 3), as well as 6-6' (Fig. 4 *b*) cross the Great Siberian Polynya in the area from Bolshoy Begichev Island in the Laptev Sea to the Medvezhyi Islands in the East Siberian Sea [Atlas..., 2019]. On the magnetic sections 3-3' and 4-4' (Fig. 3), it can be seen that the polynya is located above a zone of subvertical thermoactive faults reaching a depth of 15 km with the possibility of additional flow when seismic activity increases from a depth of more than 20 km.

The results of the Arctic shelf of Russia studies obtained in this work have, for the first time, made it possible to assess the specifics of the lithosphere in areas with high gas saturation manifested as gas flares, mega-flares, gas hydrate horizons, and to forecast the emergence of risks for navigation in the Barents Sea, Laptev Sea, East Siberian and Chukchi Seas.

4.3. East Siberian Sea

According to seismic data, a relatively uniform distribution of potential gas-saturated objects has been identified in the East Siberian Sea [Bogoyavlensky et al., 2022]. In the northwestern part of the East Siberian Sea, anomalous objects have been detected in near-bottom sediments, presumably associated with free gas deposits and channels of its sub-vertical migration. Seismic data recorded potential gas migration channels approaching close to the seabed. The work [Bogoyavlensky et al., 2022] shows that tectonically screened gas deposits are confined to rupture disturbances that extend from the acoustic basement. A seismic reflecting horizon presumably identified with the presence of gas hydrates has been revealed.

The authors of this work have constructed two petrophysical sections through the identified zones of potential gas-saturated objects in the East Siberian Sea [Bogoyavlensky et al., 2022]: along profiles 5 and 6 (Fig. 1, Fig. 4 *a* – *b*).

The magnetic section along profile 5-5' crosses the strike of the linear zone of predicted gas deposits and passes through the horizon identified with the presence of gas hydrates (Fig. 4 *a*). A shallow fault from a depth of about 4 km extends to the gas hydrate horizon.

The magnetic section along profile 6-6' (Fig. 4 *b*) crosses the same gas hydrate horizon at a different angle. With this cross-section, it is visible that a fault zone traceable to a depth of 4 km extends to the gas hydrate horizon. The thermal flow from a depth of 15-18 km is possible only along an inclined fault zone in the form of an indirect lateral inflow.

Under the area of predicted gas deposits, a channel of vertical fluid migration along the fault zone extending to a depth of 8 km is manifested (Fig. 4 *a*).

However, below on the cross-section, a vertical zone of fluid migration is clearly expressed from the lenses of the fluid system at depths of 10-15 km and 20 km (Fig. 4 *a*). Such a vertical channel creates conditions for the sudden release of a powerful thermal flow to the bottom surface from a depth of more than 20 km and from the mantle from a depth of more than 40 km in the waters of Bennett Island (Fig. 4 *a*). Apparently, the plume phenomenon discovered here in the form of a gigantic methane plume hundreds of kilometers long and 10-25 km wide was created by this thermally active deep-seated fault as a result of methane release from deep geological reservoirs

[Bogoyavlensky et al., 2022]. This creates conditions for the melting of the ice cover, emission of thermogenic methane, and the occurrence of explosive natural phenomena of endogenous origin.

The southern part of the cross-section along profile 6-6' extends into the Laptev Sea, where it crosses the Great Siberian Polynya regularly forming beyond the outer edge of the fast ice [Atlas..., 2019] at a section near 115° E. The magnetic cross-section along profile 6-6' indicates that a powerful wide zone of geothermal fluid flow from a depth of 10-13 km reaches the large polynya. This creates conditions for the melting of the ice cover and the formation of a stable strip of open water.

4.4. Chukchi Sea

Based on the results of studying the potential gas content of the Upper Part of the Cross-Section (UPCS) of the Chukchi Sea using seismic data, three petrophysical cross-sections were constructed through identified anomalous potentially gas-saturated objects along profiles 7-7', 8-8', and 9-9' (Fig. 1, Fig. 5 *a* - *c*), crossing zones of predicted gas deposits [Bogoyavlensky et al., 2018; Bogoyavlensky and Kishankov, 2020].

On all cross-sections in the areas of predicted gas deposits, migration channels from deep horizons of the Earth's crust are identified. The deep genesis of the gas is confirmed by the presence of methane homologues [Bogoyavlensky et al., 2018].

On profile 7-7' (Fig. 1, Fig. 5 *a*), a fault zone from a depth of more than 20 km and a vertical channel from 10 km reach the predicted areas. The complex pattern of interlayering of rocks with different magnetic properties with depth – weakly magnetic lenses with overlying layers such as fluid seals – inside the fault zone may indicate that the bedrock of the identified areas potentially possesses reservoir properties.

On profile 8-8' (Fig. 1, Fig. 5 *b*) in the northern part of the seismic survey area, a sub-vertical channel from a depth of about 10 km reaches the predicted gas deposit sites. In the southern part of the work, a powerful fault zone is identified, traceable from the mantle, passing through the entire earth's crust with an outlet into the near-surface rocks. Fluid-saturated layers appear in the earth's crust at depths of about 5 km and 15 km.

On profile 9-9' (Fig. 1, Fig. 5 *c*) in the northern part of the seismic survey area, a sub-vertical geothermal channel from a depth of about 10-15 km extends to the predicted gas deposit sites.

On the cross-sections 8-8' and 9-9' a large thickness of the sedimentary cover of the Chukchi Sea was revealed, presumably with good reservoir properties .

Analysis of petrophysical sections allows predicting the manifestation and migration of thermogenic gases in the Chukchi Sea into near-surface rocks through fault zones. The presence of structural channels in the form of faults may contribute to the flow of fluids to the surface with a possible contribution of the jet effect of degassing [Matveeva et al., 2017].

The results of studies conducted by the authors for the Barents, Kara, Laptev, and East Siberian Seas showed that in some sections of the Northern Sea Transport Corridor, navigational safety problems may arise. Near-surface complexes of gas hydrates, fields of methane seeps create factors of increased risk, complicating navigation, operation of offshore oil and gas fields, and transportation of hydrocarbon raw materials in areas where fluid flows emerge from the lower earth's crust and upper mantle along vertical thermoactive faults.

5. DISCUSSION OF RESULTS

The significant acceleration in the reduction of Arctic ice area is associated with global climate warming. But the ice cover is destroyed not only due to external causes, but also under the influence of a deep fluid-dynamic factor. Analysis of satellite observations of changes in ice thickness and visualization of fluid flow trajectories along thermoactive faults on magnetic and density sections allows predicting and identifying areas of large thawed areas, including in the waters of the NSR. As a result of studying the structure of the lithosphere in the cryolithozone of the Arctic shelf using magnetic field anomalies and gravity anomalies, an assumption was made about the influence of fluid flow from deep-seated faults on the formation of ice cover by reducing ice thickness due to the formation of lead zones and through taliks.

The increase in temperature and power of the fluid flow affects the process of ice degradation. The possibility of forming zones of large thawed areas and polynyas occurs when the fluid flow power increases to 100 mW/m. Analysis of petrophysical sections 3-3' and 4-4' (Fig. 3) and 6-6' (Fig. 4 *b*), crossing the Great Siberian Polynya [Atlas..., 2019] in the Laptev Sea, showed that the polynya is located above subvertical thermoactive fault zones reaching a depth of 15 km with the possibility of additional flow during increased seismic activity from a depth of more than 20 km.

The locations of fluid lenses in the Earth's crust and fluid systems in the mantle influence the spatial distribution of stable ice melting areas. The location of fluid-saturated layers in the Earth's crust and mantle is clearly represented on magnetic anomaly maps obtained for altitudes of 100 and 400 km based on CHAMP satellite data [Thebault et al., 2016]. Crustal lenses appear as zones of negative anomalies of the geomagnetic field module at an altitude of 100 km (Fig. 1 *b*), while mantle fluid systems appear at an altitude of 400 km (Fig. 1 *a*) [Thebault et al., 2016]. On magnetic and density cross-sections, fluid layers of the Earth's crust in the form of lenses with reduced magnetization and density most frequently appear in the depth range of 20-30 km. Component measurements from the CHAMP satellite at an altitude of 400 km in negative anomalies of the module and vertical component of the geomagnetic field clearly display the position of large mantle fluid systems in the Laptev Sea, East Siberian Sea, and Chukchi Sea [Petrova and Latysheva, 2023].

Areas where subvertical thermoactive channels emerge are confined to minimums of lithospheric magnetic anomalies created by fluid lenses in the lower crust and upper mantle. Magnetic measurements from satellites at a flight altitude of 400 km in the form of minimums of lithospheric anomalies (Fig. 2 *b*) reflect the position of mantle fluid systems identified in the Arctic shelf at depths greater than 30 km. Analysis of satellite measurements of ice thickness showed that the most probable zones of accelerated ice degradation under the influence of the fluid dynamic factor are confined to minimums of magnetization in the lower crust and mantle rocks [14-15]. The outlets of SMTC channels to the seabed enable the prediction of localization of zones of sustainable ice melting under the directed influence of the deep fluid dynamic factor. Fluid layers represent weakened lateral zones of reduced seismic velocities and density, weak magnetization, and increased electrical conductivity.

Tectonic waves that arise in the lithosphere as a result of strong seismic events can cause pulsations of fluid layer lenses and be one of the causes of activation of fluid dynamic processes in fault zones of the Earth's crust.

Analysis of deep petrophysical cross-sections of the Earth's crust and mantle allows identifying the location of fluid-saturated lenses, as well as trajectories and outcrops of thermoactive faults. By a combination of features, fluid layers are identified as rheologically weakened layers. According to seismic deep studies, weakened zones of the Earth's crust are fractured fluid-saturated environments that play an important role in the process of fluid transport to the surface [Pavlenkova, 2018].

Determining the locations of thermofluid channel outlets to the seabed makes it possible to better predict the position of the most probable areas of meltwater and thin ice that occur under the influence of the fluid dynamic factor of the Earth's crust and mantle.

The spatial arrangement scheme of fluid-saturated lenses in the Earth's crust of the Arctic shelf at a depth of about 20 km (Fig. 1 *in*) demonstrates zones of the most probable manifestations of the fluid dynamic factor influence, and, as a consequence, the possible appearance of fields with increased methane concentrations in the Arctic seas.

Deep-focus fluid systems of the mantle are identified on density cross-sections at depths of ~40-50 km and ~70-90 km. In the presence of a significant seismic event, these fluid systems can act as a trigger mechanism affecting fluid flows ascending through thermoactive channels, with the occurrence of explosive phenomena in gas-saturated areas.

Studies of the Russian Arctic shelf show that risks of emergencies in the NSR water area may be associated with high levels of gas saturation in bottom sediments. Analysis of petrophysical cross-sections of areas with increased gas saturation revealed the depths of fluid flows moving along faults into the area of gas hydrate development, gas flares and mega-flares manifestations. This makes it possible to predict the location of dangerous areas in the NSR water area. Such information will allow choosing the safest navigation routes.

Currently, the East Siberian Arctic shelf is at the center of active research due to the detection of increased methane concentrations in the atmosphere and hydrosphere, recorded during numerous expeditions on the shelves of the Arctic seas [Baranov et al, 2020; Shakhova et al., 2010; Shakhova et al., 2015; Bogoyavlensky et al., 2018].

The paper investigates the specific features of the lithosphere structure in areas of recorded and potential fields of forecasted gas deposits and methane emissions in the Barents, Laptev, East Siberian, and Chukchi Seas.

The magnetic sections of the Barents Sea clearly reflect the pathways of ascending vertical fluid movement in areas of "flare-type" gas manifestations, which indicates the possibility of sudden thermal flow release to the surface in the area of methane emission fields. The extensive methane emission field in the flare zone is fed from a depth of 10-15 km.

In the area of mega-flares, migration of deep-genesis methane from deeper geological reservoirs along a subvertical trajectory from a depth of about 30 km is possible. Fault zones under mega-flares form areas of focused discharge through which large-scale methane emissions are possible. A powerful thermal flow from the mantle may emerge from a depth of more than 40 km to the giant methane plume in the coastal waters of Bennett Island [Sokolov et al., 2023] (Fig. 4 *a*). This contributes to the release of thermogenic methane and the occurrence of explosive natural phenomena of endogenous origin.

In the gas hydrate development zone in the Barents Sea, a vertical zone of thermofluid processing has been identified under the gas hydrate zone, which is clearly traced on the density section and even more prominently on the magnetic section from a depth of 25-30 km. This creates conditions for the destruction of gas hydrates, methane release, and the occurrence of explosive situations.

Analysis of petrophysical sections along profiles 3-3' and 4-4' in the Laptev Sea made it possible to investigate the cause of activation of powerful methane emission fields in the form of gas seeps near the CMTB boundary (Fig. 3). The fault zone is well-expressed on density and magnetic sections, along which the ascending trajectory of subvertical fluid migration passes, enabling the release of thermal flow to the surface from a depth of 20-30 km to the area of methane emission fields. In this area, fluid migration along the thermal fault from a depth of 30 km may be the cause of active gas emission and contribute to intensive bubble release of methane.

In the East Siberian Sea, two petrophysical cross-sections were constructed: along profiles 5 and 6 through zones of potential gas-saturated objects (Fig. 4) [Sokolov et al., 2023]. Under the zone of predicted gas deposits, a vertical fluid migration zone is manifested along a fault zone reaching a depth of 8 km. A shallow fault from a depth of about 4 km extends to the gas hydrate horizon.

In the Chukchi Sea, three petrophysical cross-sections were constructed along profiles 7–7', 8–8', and 9–9' through potentially gas-saturated objects [Bogoyavlensky et al., 2018; Bogoyavlensky and Kishankov, 2020]. In all areas of predicted gas deposits, migration channels from deep horizons of the Earth's crust are identified. The deep genesis of gas is confirmed by the presence of methane homologues [Bogoyavlensky and Kishankov, 2020].

On profile 7–7' (Fig. 1, Fig. 5 *a*), a fault zone from a depth of more than 20 km and a vertical channel from 10 km extend to the predicted areas. Here, interlayering of rocks with different magnetic properties with depth is observed – alternation of weakly magnetic lenses with layers like fluid barriers – inside the fault zone, which may be a sign of good reservoir properties in the bedrock.

In the northern part of the seismic survey area on profile 8–8' (Fig. 1, Fig. 5 *b*), a subvertical channel from a depth of about 10 km extends to potential areas of gas deposits, and in the southern part, a powerful fault zone is identified, rising from the mantle through the entire Earth's crust with an outlet in the NSR rocks. Fluid-saturated layers are identified in the Earth's crust at depths of about 5 km and 15 km.

In the northern part of the seismic survey area on profile 9–9' (Fig. 1, Fig. 5 *c*), a subvertical geothermal channel from a depth of about 10–15 km extends to the predicted areas of gas deposits.

On cross-sections 8–8' and 9–9' in the Chukchi Sea, a large thickness of the sedimentary cover is revealed, possibly with good reservoir properties.

In the Chukchi Sea, analysis of petrophysical cross-sections allows predicting the manifestation and migration of thermogenic gases into NSR rocks through fault zones from depths of 10–20 km.

Based on magnetic anomalies and gravity field anomalies, studies of the conditions of influence of the deep fluid dynamic factor in gas-saturated areas and zones of gas hydrate accumulations in the Barents, Kara, East Siberian, Chukchi seas and the Laptev Sea have been conducted. This provided an understanding of the deep structure model of the Earth's crust in areas with high gas saturation levels.

6. CONCLUSION

Comparison of satellite monitoring data on ice thickness in the Arctic Ocean shelf seas with petrophysical sections of the Earth's crust showed that the lithosphere in zones of accelerated ice melting has a specific structure that allows migration of deep fluids to the seafloor surface.

A study of the Arctic shelf lithosphere structure was conducted based on petrophysical sections constructed from anomalies of the Earth's magnetic field and gravity anomalies. Analysis of remote sensing data on ice conditions and visualization of fluid flow trajectories and thermoactive faults on magnetic and density sections makes it possible to identify and predict areas of large thawed areas and polynyas. The study of endogenous fluid dynamic influence on the ice regime of the Northern Sea Transport Corridor will optimize the selection of the safest transport and logistics routes for uninterrupted year-round navigation.

As a result of complex interpretation of the Earth's magnetic field anomalies and gravity anomalies, the specific structure of the lithosphere of the Arctic seas with proven active gas emission and in areas with increased gas saturation was investigated for the first time. The specifics of the lithosphere structure in areas of recorded and potential gas deposits and methane emissions in the Barents, Laptev, East Siberian, and Chukchi seas were visualized. The pathways of gas fluid inflow were identified and the depths of thermogenic gas migration into the upper part of the geological section through fault zones were estimated.

Analysis of petrophysical sections of areas with increased gas saturation allowed estimating the depths of fluid flows emerging along faults in areas of gas flare and mega-flare manifestations. Studies in offshore areas where methane emissions have been confirmed by geochemical research have shown that the most significant role is played by subvertical thermofluid flows in zones of deep-seated disturbances.

The results of studies conducted for the Barents, Kara, Laptev, and East Siberian Seas showed that navigational safety problems may arise in some sections of the SMTK. Gas hydrate horizons, fields of methane seeps and fountains create high-risk factors that complicate navigation, operation of offshore oil and gas fields, and transportation of hydrocarbon resources.

The petrophysical sections of the Chukchi Sea revealed a large thickness of the sedimentary cover, presumably with good reservoir properties. A fault zone from a depth of more than 20 km and a vertical channel from 10 km extend to the predicted areas of gas-saturated objects [Bogoyavlensky et al., 2018; Bogoyavlensky and Kishankov, 2020]. The revealed pattern of interlayering with depth of rocks with different magnetic properties – weakly magnetic lenses with overlying layers of fluid seal type – inside the fault zone may indicate that the bedrock of the selected areas potentially has reservoir properties.

The obtained research results of the Russian Arctic shelf for the first time made it possible to assess the specifics of the lithosphere in areas with high levels of gas saturation in the form of gas seeps, fountains, plumes, and mega-plumes, and to make a forecast of the emergence of risks for navigation in the Barents Sea, Laptev Sea, East Siberian and Chukchi Seas.

Based on a two-dimensional areal analysis of the magnetic properties of rocks at a depth of about 20 km, an assessment of the distribution of possible areas of natural phenomena of endogenous nature is provided. As a result of the study, the most probable zones of dangerous natural phenomena in the waters of the NSR were identified.

The study of the localization of zones of endogenous influence of the fluid-dynamic factor in areas with high levels of gas saturation in the Arctic shelf waters has scientific, practical, and applied significance for clarifying long-term ice forecasts and reducing navigational risks of an endogenous nature. Studying the specific structure of the Earth's crust of the Arctic shelf allows predicting areas of the most likely occurrence of explosive zones and is important for choosing navigation trajectories along the SMTK transport and logistics system.

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FIGURE CAPTIONS

Fig. 1. Geophysical characteristics of the Arctic shelf cryolithosphere: anomalies of the EMF module (CHAMP satellite) [Thebault et al., 2016]: (*a*) - h = 400 km; (*b*) - h = 100 km; (*c*) - magnetization of the Earth's crust rocks (depth ~20 km); (*d*) - gas hydrate zones. *1* - NMTC; *2* - NSR routes; *3* - position of petrophysical cross-sections; *4* - gas hydrates [Shakhova et al., 2019]; *5* - Arctic seas: 1 - Barents Sea, 2 - Laptev Sea, 3 - East Siberian Sea, 4 - Chukchi Sea.

Fig. 2. Cross-sections of the Barents Sea lithosphere in the zones of gas hydrates and gas flares development: (*a*) - density cross-section (profile 1-1'), base - magnetic anomalies of the EMF module (h = 100 km) [Thebault et al., 2016]; (*b*) - magnetic cross-section (profile 1-1'), base - Barents Sea magmatic province [Shipilov, 2016]; (*c*) - density cross-section (profile 2-2'), (*d*) - magnetic cross-section (profile 2-2'). *1* - Area of solid hydrates [Andreassen et al., 2020; Serov et al., 2023]; *2* - mega-flares; *3* - Barents Sea magmatic province; *4* - gas flares [Sokolov et al., 2023]; *5* - Barents Sea.

Fig. 3. Cross-sections of the Laptev Sea lithosphere in the zones of gas hydrates and gas flares development: (*a*) - density cross-section (profile 3-3'), (*b*) - magnetic cross-section (profile 3-3'); (*c*) - density cross-section (profile 4-4'), (*d*) - magnetic cross-section (profile 4-4'). *1* – SMTK; 2 – SMP; *3* – methane seeps [Baranov et al, 2020; Shakhova et al., 2015; Bogoyavlensky and Bogoyavlensky, 2021; Sergienko et al., 2012]; *4* – gas hydrates [Shakhova et al., 2019]

Fig. 4. Cross-sections of the lithosphere of the East Siberian Sea and the Laptev Sea in zones of predicted gas-saturated objects, gas hydrates, and methane seeps: (*a*) – magnetic cross-section (pr. 5-5'), (*b*) – magnetic cross-section (pr. 6-6'). *1* – SMTK; *2* – SMP; *3* – predicted gas deposits; *4* – seismic profiles; *5* – predicted gas hydrate deposits [Bogoyavlensky et al., 2022]; *6* – methane seeps [Bogoyavlensky and Bogoyavlensky, 2021]; *7* – seas: 2 – Laptev Sea, 3 – East Siberian Sea; *8* – islands: 1 – Bolshoy Begichev Island, 2 – Bennett Island.

Fig. 5. Cross-sections of the lithosphere of the Chukchi Sea in zones of predicted gas deposits. *1* – predicted gas deposits [Bogoyavlensky and Bogoyavlensky, 2021], *2* – CDP seismic profiles; *3* – Chukchi Uplift.

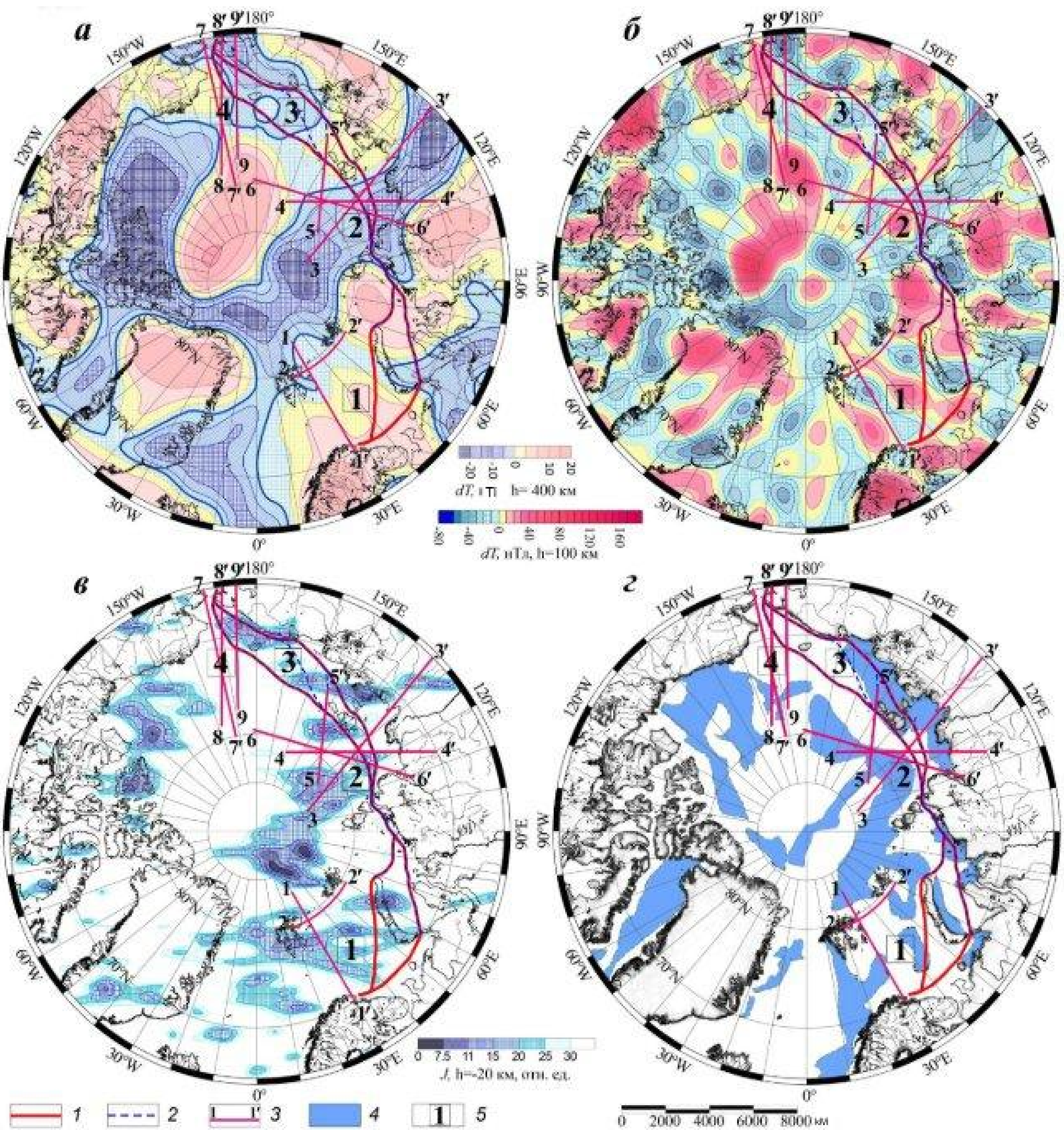
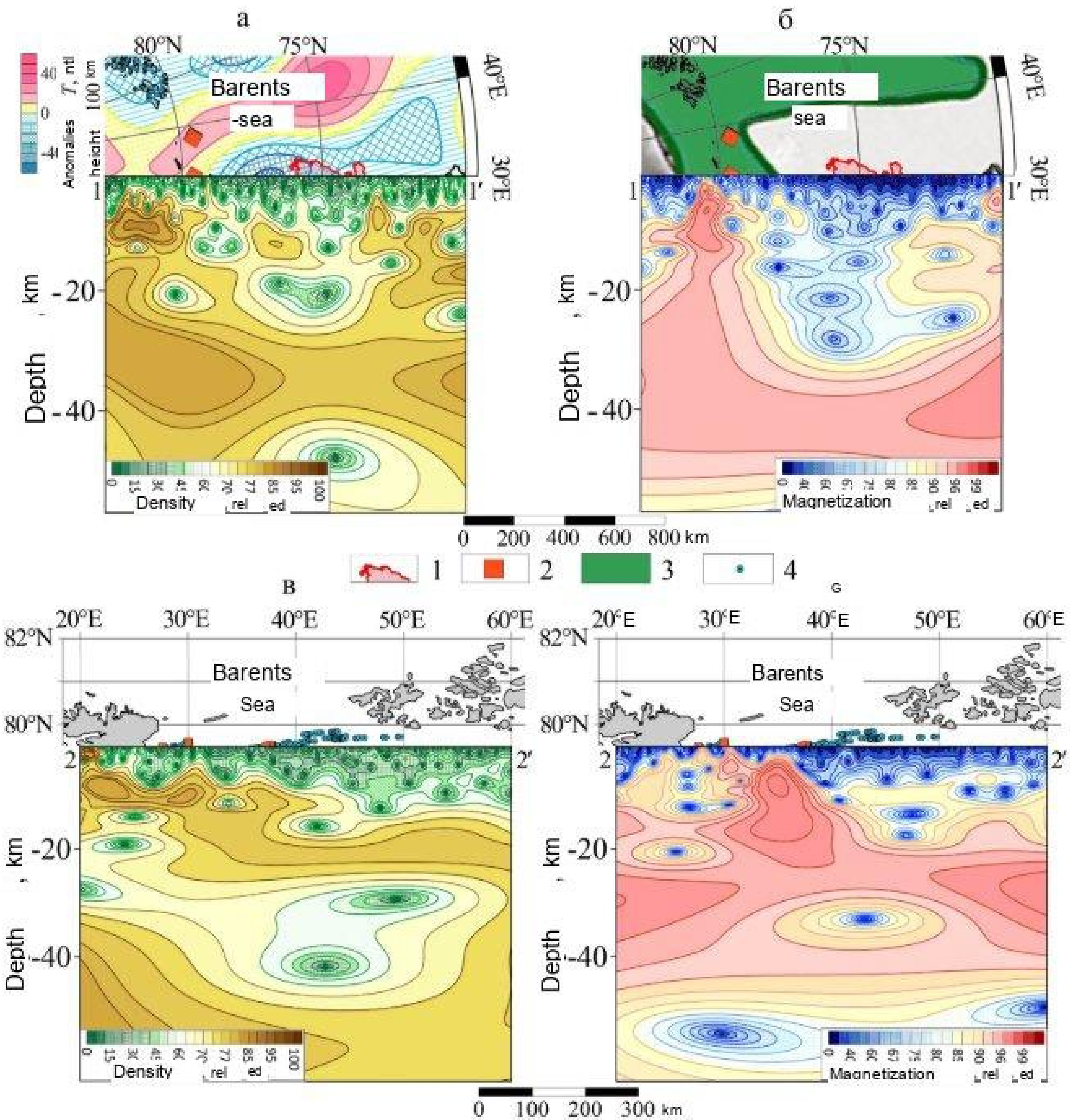

а
б
в
г
180°
150°W
150°E
120°W
120°E
90°W
90°E
60°W
60°E
30°W
30°E
0°
dT, нТл, h=400 км
dT, нТл, h=100 км
J, h=-20 км, отн. ед.
1
2
3
4
5
0 2000 4000 6000 8000 км

Fig. 1.

Fig. 2.



a
б
80°N
75°N
40°E
30°E
Barents
-sea
sea
Depth, km
-20
-40
Density
Magnetization
0 200 400 600 800 km
1
2
3
4
B
G
20°E
30°E
40°E
50°E
60°E
82°N
80°N
Sea
0 100 200 300 km

Fig. 3

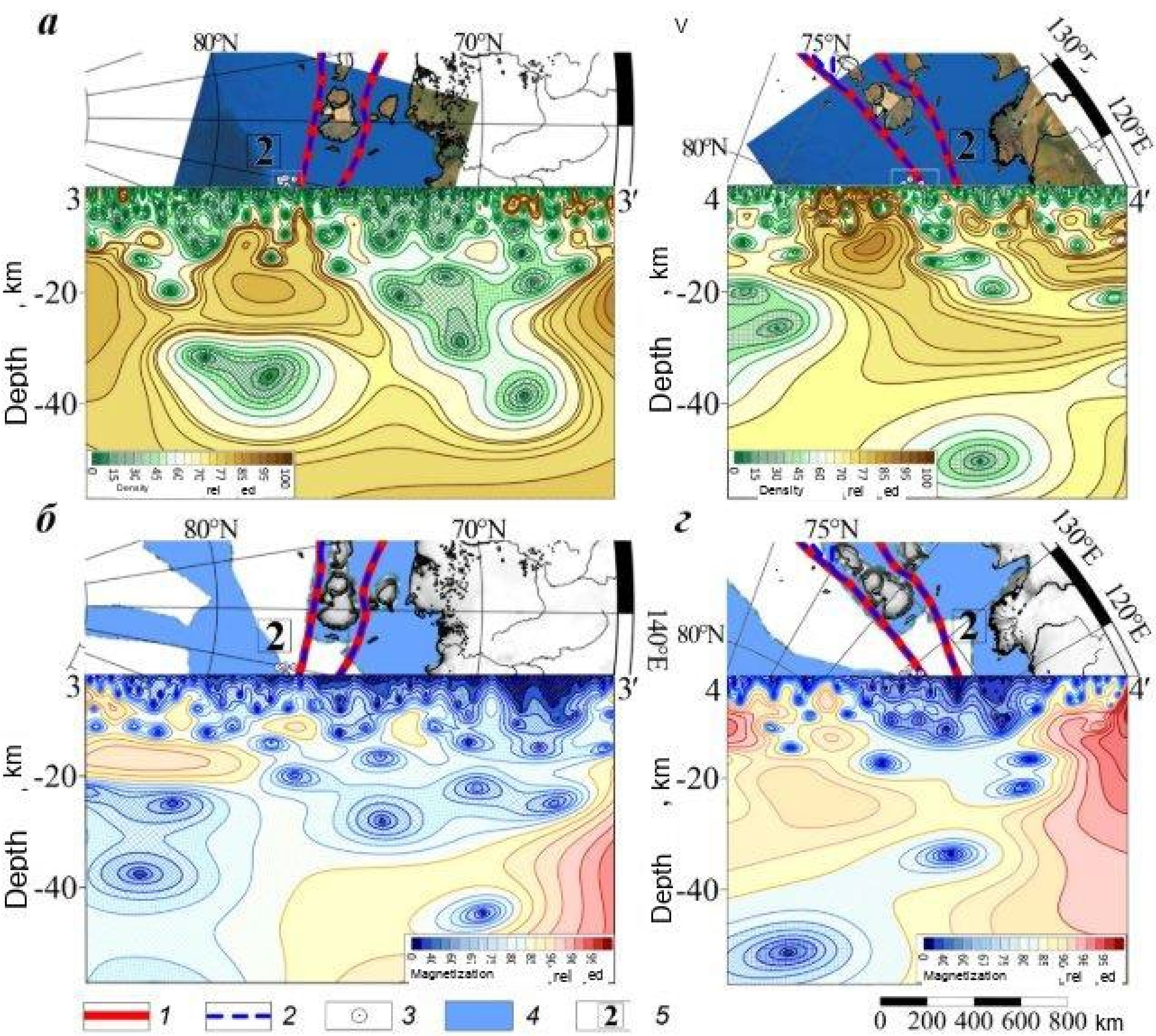

a
80°N
70°N
75°N
130°E
120°E
80°N
2
3
3′
4
4′
Depth, km
-20
-40
0 15 30 45 60 70 77 85 95 100
Density
б
80°N
70°N
140°E
г
75°N
130°E
120°E
80°N
Magnetization
1
2
3
4
5
0 200 400 600 800 km

Fig. 4

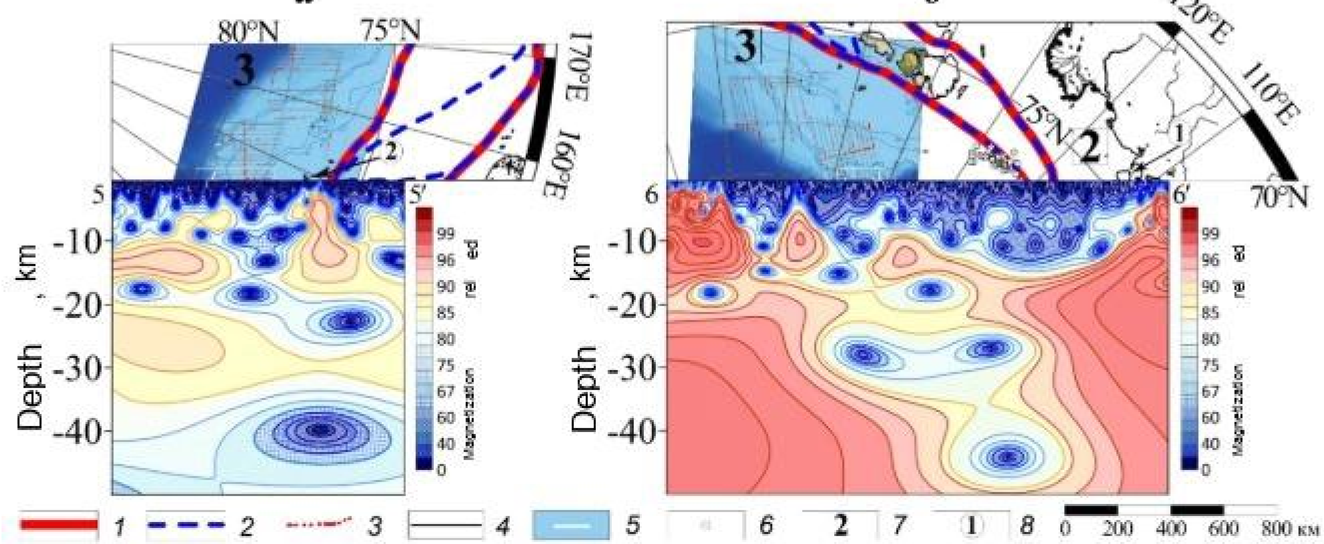
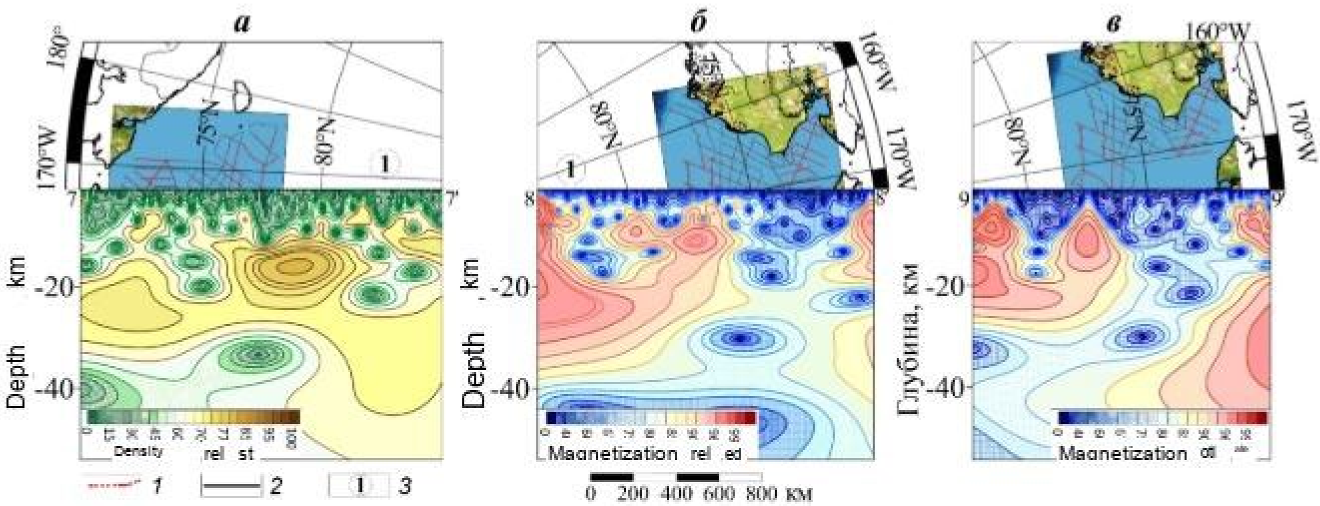

a
б
80°N
75°N
170°E
160°E
120°E
110°E
70°N
Depth, km
-10
-20
-30
-40
Magnetization
1
2
3
4
5
6
7
8
0 200 400 600 800 км

Fig. 5


a
б
в
180°
170°W
75°N
80°N
160°W
Depth, km
Глубина, км
-20
-40
Density
Magnetization
1
2
3
0 200 400 600 800 км