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DISTRIBUTION OF SUBSEA PERMAFROST (FROZEN GROUND) IN THE LAPTEV SEA BASED ON SEISMIC REFRACTION DATA

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For the first time, for an area of 454 thousand km^2 of the Laptev Sea, processing and comprehensive analysis of a large volume of records of the first arrivals of refracted waves of common shot gathers was carried out along 113 CDP seismic lines of JSC MAGE with a total length of about 20.7 thousand km. Fundamentally new information was obtained on the state of the subsea cryolithozone, and the boundary between the predominant distribution of frozen (Southern zone) and thawed (Northern zone) ground was identified. It was substantiated that a number of identified through taliks in the Southern zone have an endogenous genesis and are associated with large disjunctive displacements. High seismic activity in the central part of the Laptev Sea improves faults permeability, which contributes to the activation of subvertical migration of deep fluid flows and enhances the role of the endogenous factor in the degradation of permafrost (frozen ground) and gas hydrates. A large thawed zone was discovered in the North Western area of JSC MAGE activities, approaching close to the coast of Taimyr. A comparison of the results obtained with the data of the stratigraphic well DL-1, drilled in 2022 by FSBI VSEGEI and JSC Rosgeologia (RosGeo) near the eastern border of the Laptev Sea, showed their complete correspondence, clearly indicating completed degradation of subsea permafrost in a significant part of the seas of Eastern Siberia.

Keywords: *the Laptev Sea, seismic survey, refraction waves, upper part of the section, permafrost (frozen ground), taliks, gas seeps, gas hydrates.*

1. Introduction

In the last decade, the problem of global climate change on the Earth has been one of the most important and widely discussed in the global scientific community [1–6]. Numerous publications provide justification for climate warming with increasing concentrations of greenhouse gases, among which carbon dioxide and methane play the key roles [1]. The combustion of huge volumes of hydrocarbon fuel in various forms and forest fires are complemented by the emission of methane of natural and man-made origins.

One of the most discussed regions with an ambiguous forecast for the volume of methane emissions in the global distribution of its sources is the Arctic, especially the shallow areas of the Arctic Ocean. Forecasts about moderate [1; 4] and extremely high [5; 6] volumes of methane emissions are given. Based on the latter, it is possible to propose relationship between the degradation of subsea permafrost (frozen ground) with the dissociation of gas hydrates (GHs) on the shelf of the Eastern Arctic seas, predominantly consisting of methane hydrates [5–7], and a possible "methane catastrophe" [5]. The special significance of the GH topic is also confirmed by the great interest in GHs as a possible highly promising source of energy resources of the future, as well as a possible threat during the development of conventional hydrocarbon deposits. Among the seas of the Arctic Ocean, much attention is attracted to the Laptev Sea, where a large zone of seeps was discovered in the central part of the bottom [5; 6; 8].

According to generally accepted ideas, the main regions of the possible existence of frozen ground and associated zones of stability of GHs in the Arctic Ocean are the giant Russian shallow areas (up to 100-120 m) of the seas of Eastern Siberia and Chukotka – the Laptev, East Siberian and Chukchi seas [5–16]. During the last ice age, these areas were lowlands that were subject to harsh subaerial conditions.

In well studied regions, frozen ground distribution maps are based on drilling and geophysical data, while in poorly studied regions they are mainly based on the results of numerical modeling, in which limited actual information about the thermal conductivity of sedimentary deposits and the heat flow of the Earth and/or their predicted values play an important role [7; 9–15].

In numerical modeling [7; 10-13] the presence of frozen ground on the shelf of the Laptev Sea is predicted in some places up to isobaths of about 100–120 m, and in certain areas (especially in the central part of the sea) to isobaths of 60–70 m. On the official website of the International Permafrost Association (IPA) [9] a map is shown on which permafrost exists on most of the shallow shelf of these waters. In some places, the northern boundary of the permafrost is located near and/or relatively close to the isobaths of 100–120 m [9], but in some places (particularly, in the central part of the Laptev Sea) it reaches the isobaths of 40–50 m. A similar situation with the boundary of permafrost is observed in a map based on new numerical modeling [14; 15].

The limited amount of data on the state of permafrost in the eastern seas of Russia makes highly significant any new information based on drilling data or geophysical methods, treated as reliable for determining the presence or absence of frozen ground and, possibly, GHs. On the Arctic shelf of the Beaufort Sea (Canada and Alaska, USA), among seismic exploration methods, the refracted wave method has been known as remarkably effective. [17; 18].

In 2018, we made a forecast of the potential GH distribution in the areas of the Circum-Arctic region with the main focus on the Arctic Ocean, on the shallow (up to 120 m) shelf of which, in zones of existence of subsea permafrost, thermobaric conditions exist for occurrence of GHs, often called as cryogenic GHs [19; 20]. In subsequent years, the causes of active gas emission in the Laptev Sea were analyzed [21] and dangerous gas-saturated objects in the East Siberian Sea were studied [22]. At the same time, the first stage of research was conducted aimed at analysis of approximate position of the boundary of subsea frozen ground distribution in the seas of Eastern Siberia based on analysis of seismic data from JSC Marine Arctic Geological Expedition (JSC MAGE) [23–27].

The main objective of this work is expanding the areas of research of distribution of frozen ground and associated GHs in the Laptev Sea in combination with data previously obtained by the authors [23–25] and other available materials from open sources, including well drilling results.

2. Brief information on the study area

The geological structure and oil and gas potential of the Laptev Sea are not sufficiently studied by seismic exploration (the density of the seismic line grid is about 0.14 km/km^2), which is additionally aggravated by the lack of deep wells drilled in open offshore area [28, p. 39]. In 2017, from the shore of the Khara–Tumus Peninsula, PJSC Rosneft drilled the Tsentralno–Olginskaya–1 well (73.725° N, 109.61° E; bottom depth 5523 m), with which an oil field was discovered in the near-shore part of the Khatanga Bay in Permian clastic sediments with recoverable reserves of 81 million tons (categories C_2+C_1 in Russian classification of reserves) [28; 29].

Most researchers believe that the sedimentary cover of the Laptev Sea is Cretaceous-Cenozoic in age [28; 30; 31]. In the Cretaceous - Paleocene, the Laptev Sea rift system was formed; in the Miocene - Pliocene, an additional phase of activation of the faults of the rift system occurred. The rocks of the upper part of the section (usually, depths up to 500-900 m) and especially near-bottom sediments (depths up to several tens of meters, usually characterized by weak consolidation), are predominantly composed of silty-clayey and sandy Pliocene-Quaternary deposits with a thickness of up to 0.8–1.2 km [28, p. 61], the occurrence of which is close to horizontally layered, which is clearly visible in the CDP seismic data of the JSC MAGE.

Judging by the rock outcrops on the Taimyr Peninsula in the Byrranga Mountains, the acoustic basement is composed of the Paleozoic highly metamorphosed complex overlying the crystalline basement of the Archaean-Proterozoic age [28; 31]. In the central part of the Laptev Sea, the depth of the acoustic basement reaches 11–14 km [28; 31].

The Laptev Sea region with the adjacent land is the most seismically active zone in the Russian Arctic [32; 33]. This is due to geodynamic processes at the junction of the Eurasian and North American tectonic plates. Here, at latitude from 69.7° to 79.4° in 1927-2019, 28 earthquakes with a magnitude above 5.0 were registered, with the magnitude of four of them being in the range of 6.0–6.7 [27; 33]. High seismicity makes systems of faults and subvertical fractures highly permeable to vertical gas migration.

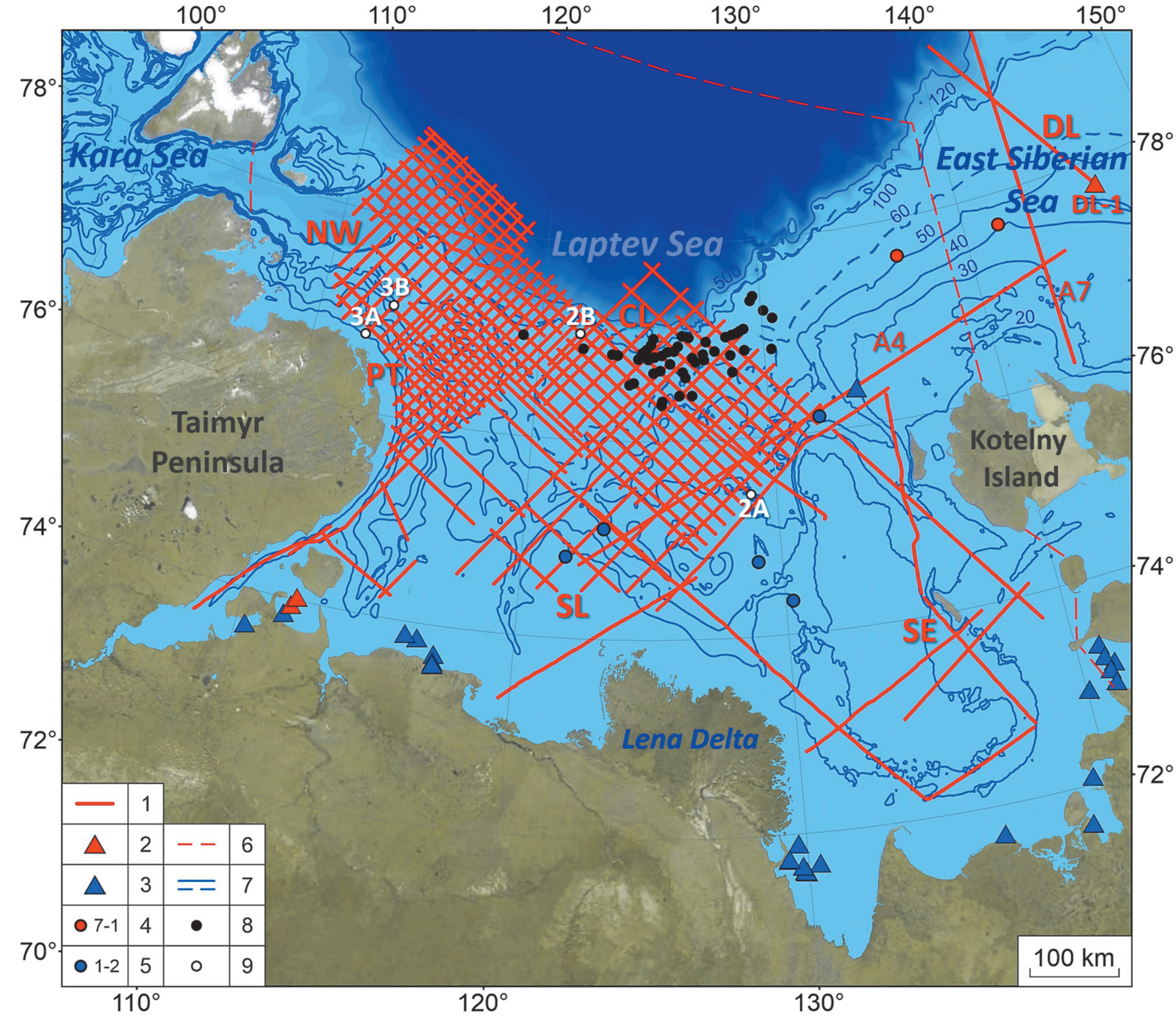

Fig. 1. Scheme of the location of the studied seismic lines by JSC MAGE in the Laptev Sea.
Legend: 1 — CDP seismic lines, including Central Laptev (CL), South Laptev (SL), South-Eastern (SE), Near-Taimyr (PT), North-Western (NW) and De Long (DL) areas; 2 and 3 — absence (2) and presence (3) of frozen ground based on drilling data; 4 and 5 — absence (4) and presence (5) of frozen ground based on ocean bottom hydrophone systems [39, 40]; 6 — boundaries of the Laptev Sea; 7 — isobaths in m (created by the authors based on GEBCO data); 8 — gas seeps; 9 — common shot gathers (CSGs), presented in figs. 2 (2A and 2B) and 3 (3A and 3B). Basis of the figure — GEBCO bathymetry and ESRI satellite image

The bottom of the shallow shelf is a plain gently dipping to the north, on which five paleo valleys of the channels of the Khatanga, Anabar, Olenyok, Lena and Yana rivers are distinguished (in order from west to east) [34].

The processes of frozen ground formation and degradation depend on a number of factors, including thermal conductivity of sediments, the Earth heat flow and the temperature of the near-bottom water layer. Subsea frozen ground exists in a large volume of the upper part of sedimentary cover; by analogy with land, its thickness in some areas can reach and even exceed 600–700 m [7; 13; 16]. The Lena and Yana rivers have a great influence on the state of subsea permafrost on the shelf of the Laptev Sea, providing a significant input of heat with fresh water, affecting the salinity of the sea, as well as the processes of thermohaline circulation and ice formation [35].

In the Laptev Sea, the main volume of water (annually about 500–542 km^3, or 71–77%) is supplied by the Lena River, which is the longest (about 4400 km) and largest river in Eastern Siberia [36; 37]. According to remote sensing data, its width near the delta reaches 2.5–3 km (in some places even about 7 km), the dimensions of the delta are 140×260 km, and its area is about 29.6 thousand km^2 [36]. During the last ice age (17–15 thousand years ago), the sea level was significantly (about 120 m) lower than today, and the Lena delta “was located hundreds of kilometers north from its present-day alluvial fan” [36]. On the continental land, the Lena is completely located in the zone of frozen ground existence, however, in a number of parts of the river, there are through taliks under the

Table 1. Geophysical equipment used in CDP seismic survey by JSC MAGE in 1985—2014

Area	Vessel	Shot point interval, m	Number of channels	Channel length, m	Offset of the first channel from the shot point, m
Central Laptev – CL	GDN and PK	37.5	648	12.5	120–130
South Laptev – SL	PK	25	324	12.5	167.25
Near-Taimyr – PT	GDN	37.5	648	12.5	130
North-Western – NW	GDN and NT	37.5	648	12.5	130
South-Eastern – SE	NT	37.5	648	12.5	130
Regional line A4	GDN	37.5	648	12.5	130
Archive lines 1986	GDN	50	12	100	425
Archive lines 1985 and 1987	G	50–100	24	50	225–300

Notes. GDN - "Geolog Dmitry Nalivkin", PK – "Professor Kurentsov", NT – "Nikolai Trubyatchinsky", G – "Geofizik".

channel [38], which is important for understanding the possible subsea setting in the Laptev Sea.

3. Methods and materials of the research

When studying the distribution of relic and degraded (thawed) frozen ground in the Laptev Sea, we used records of the first arrivals of refracted waves registered on seismograms of common shot gathers (CSGs) during standard CDP seismic survey by JSC MAGE in 1985-2014 with research vessels "Professor Kurentsov", "Geolog Dmitry Nalivkin", "Nikolai Trubyatchinsky" and "Geofizik". The main characteristics of the surveys are given in Table. 1. More detail information is given in [21-23].

In areas of distribution of weakly consolidated rocks of the upper part of sedimentary cover, the registration of high-velocity refracted waves indicates the presence of frozen ground and/or GHs, having similar physical characteristics [13; 14]. A similar analysis was carried out previously for the Canadian and American sectors of the Beaufort Sea [17; 18], as well as by the authors in previous studies of the Laptev and East Siberian seas [21–27].

For unification of the results, according to studies of the Alaska shelf [18], the minimum velocity value indicating the presence of ice–saturated sediments was considered 2.3 km/s (based on well logging data), and the second boundary value of 2.8 km/s was used for separating the frozen rocks according to the level of ice saturation (cementation) into less and more ice-saturated [18], which depends on the level of negative temperatures. The reliability of the results of studies of the subsea frozen ground distribution based on records of refracted waves is confirmed by data from studies of a number of deep wells, including those on the Alaska shelf in the Beaufort Sea [18]. An analysis of the velocities of recorded refracted waves in the zone of transition from frozen to thawed ground in the Laptev Sea shows that they can also exist in the range of about 2.0–2.3 km/s, which apparently corresponds to deposits with significantly degraded frozen ground.

Calculation of the velocities of refracted waves in CSGs was conducted using RadExPro software (Deco–Geophysical, Russia). Maps illustrating the distribution of values of refracted wave velocities in the study area were created in ArcGIS software (ESRI, USA). Calculations of the areas of the predicted distribution of thawed and frozen ground in the areas of the Arctic seas were done in ArcGIS software based on the General Bathymetric Map of the Oceans (GEBCO, https://www.gebco.net/).

In addition, analytical studies of a large amount of available information, including seismic and drilling data, were conducted. In particular, the seismic data acquired in 1997 by BGR together with SMNG (Sevmorneftegeofizika) using seven ocean bottom hydrophone systems (OBH) was analyzed [39; 40]. The results of drilling more than 30 engineering-geological wells in the Laptev Sea were collected, analyzed and uploaded into the geographic information system, most of which revealed frozen ground [28; 34; 36; 41; 42 and others]. In particular, according to the profile of the Mamontov Klyk wells, frozen ground was discovered at distances of up to 11 km from the shore [36]. We also used data from the stratigraphic well DL–1, drilled in 2022 at a seafloor depth of 47.5 m by VSEGEI and JSC Rosgeologia with the support from PJSC NK Rosneft near the eastern border of the Laptev Sea and which showed the absence of frozen ground (see section 5) [43].

4. Results of the research

As a result of the research for the Laptev Sea, we conducted the analysis of field CDP seismic data in a total volume of 20.71 thousand km acquired by JSC MAGE in several areas, as well as along separate regional seismic lines, including:

- Central Laptev area – CL (2009, 28 lines, 5930 km);
- South Laptev area – SL (2005, 9 lines, 1370 km);
- Near-Taimyr area – PT (2011–2012, 38 lines, 5450 km);
- North-Western area – NW (2012–2014, 27 lines, 4480 km);
- South-Eastern area – SE (2014, 2 lines, 530 km);
- Archive lines in the South Laptev area (1985–1987, 8 lines, 2290 km);
- Regional line – A4 (2007, 660 km).

Thus, in addition to the processing of 28 seismic lines of the Central Laptev area (CL) and the line A4, carried out in 2021-2022 [21–25], in this research, 14.12 thousand km of 84 new seismic lines in the Laptev Sea were processed. Besides, for understanding the regional setting in the north-eastern part of the Laptev Sea, two seismic lines from the adjacent area of the De Long High in the north-western part of the East Siberian Sea were included in the research [26; 27]. Their high significance for this study is due to the drilling of the DL–1 well in 2022, located in the southern part of the DL1101 seismic line of JSC MAGE [43]. As a result, the total number of the processed and analyzed seismic lines was 113.

At the first stage of the research, the pattern of the wave fields of CDP seismic sections and field CSGs was analyzed. According to the results of the analysis, the reflecting and refracting seismic horizons in the upper part of the sedimentary cover on the shallow shelf (from the shore to the isobaths of 120-150 m) have a predominantly flat structure, occasionally slightly dipping to the north, close to horizontally layered. In the CSGs, everywhere in the near parts of the registration, direct waves are clearly visible, propagating in the water column at a speed of about 1.43 km/s (travel-time curve – green dotted line), with reflected and refracted waves from a number of horizons of the sedimentary cover (Fig. 2).

The main difference between most of the studied CSGs in the Laptev Sea is the presence or absence of high-velocity (from 2.3 to 4.0 km/s) refracted waves from horizons in the upper part of the sedimentary cover (mainly from the horizon near the seafloor) (Fig. 2A and 2B) [26; 27]. In particular, in the south-eastern part of line LS0907 (Fig. 2A), refracted waves from an acoustically rigid horizon (travel-time curve – red dotted line) are observed, associated with the top of frozen ground at a depth of about 20 m from the seabed. These refracted waves can be traced only at small distances from the shot point (mainly up to 1.5–2.0 km) and in the example of Fig. 2A have a velocity of 3.3 km/s. The mentioned features of refracted waves in the Laptev Sea are in a good agreement with data for the Beaufort [18] and East Siberian [26; 27] seas and can be explained by more intensive attenuation of seismic waves propagating in frozen ground compared to the geological horizons of shallow poorly consolidated deposits in usual unfrozen state. Refracted waves from near-bottom frozen ground differ significantly from refracted waves from deeper unfrozen strata in the upper part of sedimentary cover, which for the CL region have boundary velocities of about 2.1 and 2.4 km/s and can be traced to large distances from the shot point on almost the entire CSG (see Fig. 2B). Thus, in the southern part of the LS0907 line, high-velocity refracted waves from the frozen ground top are observed, while in its northern part they are not observed, which means the absence of frozen ground.

CSGs in the western part of the Laptev Sea in the North-Western (NW) and Near-Taimyr (PT) regions differ significantly from those mentioned above (CL area) by the presence of refracted waves from heterogeneous acoustic basement of varying age [28] with very high propagation velocities, mainly from 4.5 to 5.5 km/s, which, gradually attenuating, can be traced to distances of 8.1 km (Fig. 3). These waves are detected both near the Pronchischev Coast in the upper part of the sedimentary cover at shallow depths from the seafloor (Fig. 3A, velocity 5.3 km/s), and deeper at large distances to the north from this coast (Fig. 3B, velocity 4.5 km/s). In Fig. 3B, in the interval of 450-2400 m from the shot point, in the first arrivals, refracted waves from the geological horizon at a depth of about 300 m are clearly visible, presumably of the Pliocene age with a boundary velocity of about 2.2 km/s. It is worth noting that in the CSG of Fig. 3A they are also distinguished, but in the first arrivals they are visible only at distances of approximately 400–750 m from the shot point. In Fig. 3B, refracted waves from the acoustic basement, located at a depth of about 900 m, have a velocity of about 4.5 km/s. Refracted waves from horizons that we associate with frozen ground and/or GHs were observed mainly in the south-eastern part of the PT area near the Pronchischev Coast not far from the Khatanga Bay.

When analyzing the wave fields and calculating the velocities of refracted waves, the results were divided into three parts according to the description given in Section 3. Shallow deposits, for which the velocities of refracted waves appeared to be 2.3–4.0 km /s, were considered cemented with ice at various degrees [18]. Values of refracted wave velocities depend on the level of negative temperatures. It should be noted that for the most part (about 73%), the estimated velocity values were in the range of 2.8-4.0 km/s, and refracted waves with velocities of 2.3–2.8 km/s were

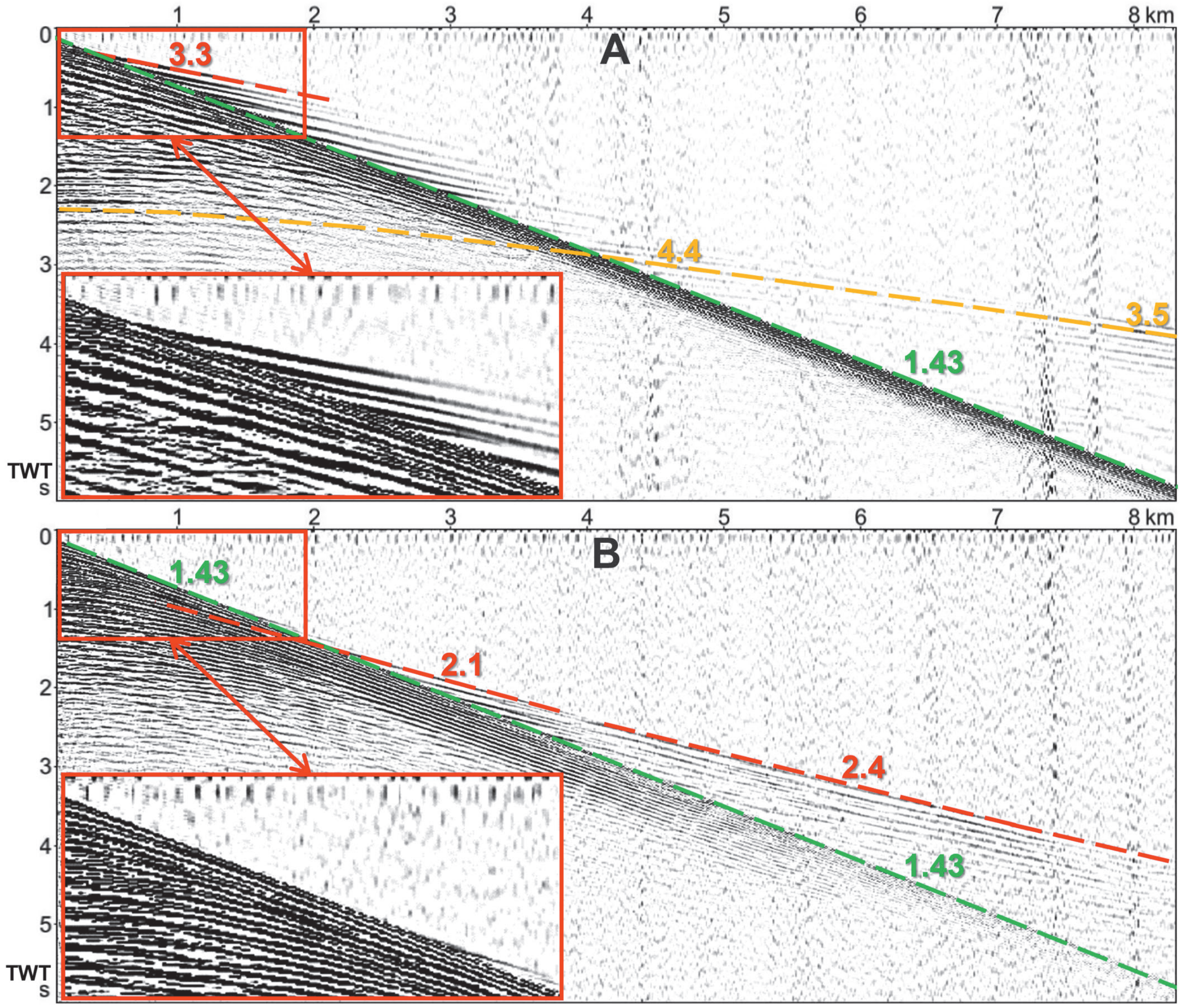

Fig. 2. CSGs in the south-eastern (A) and north-western (B) parts of the LS0907 line in the Central Laptev area of the Laptev Sea (CL) with enlarged fragments. Comments: length of the streamer — 8.1 km; offset from the shot point — 130 m; shot points of the CSGs are shown in fig. 1 (2A, 2B)

found in transition zones between strongly cemented and thawed deposits, possibly, including areas of the existence of non-through taliks. Through taliks are characterized by the absence of high-velocity refracted waves.

Fig. 4 shows the resulting cartographic scheme, which, using color coding, demonstrates the results of the analysis of physical state of the shallow deposits in the areas studied with CDP seismic survey by JSC MAGE in the Laptev Sea and in the north-western part of the East Siberian Sea.

As a result of the analysis of the wave fields of the CSGs in the studied areas of the Laptev Sea, extensive areas of the presence and absence of high-velocity (2.3–4.0 km/s) refracted waves from the boundaries in the upper part of sedimentary cover were revealed and mapped with a significant level of detail, indicating, respectively, the existence or absence of changes in their physical properties due to the cementing effect of frozen ground and, possibly, GHs.

5. Discussion of the results

The results of studies of the regional level in the shallow (up to 120 m) part of the Laptev Sea (see Fig. 4) covered an area of 454 thousand km^2 (see Fig. 1 and 4), which is by 36.7% more than that in our previous works in 2021–2022 (332.2 thousand km^2) [26; 27]. Based on new research (see Fig. 4), a cartographic scheme of the distribution of frozen and thawed ground within the shelf of the Laptev Sea and the western part of the East Siberian Sea has been compiled, shown in Fig. 5.

According to the cartographic scheme of Fig. 5, it was determined that frozen ground and/or GHs exist in an area of approximately 324.7 thousand km^2, and in an area of about 89.2 thousand km^2 they have degraded. Certain areas in the coastal parts, in which there is no seismic data and/or ambiguous results of the data analysis, were identified by us as a “grey zone” that requires additional study. In particular, these areas included the large Khatanga Bay and small narrow

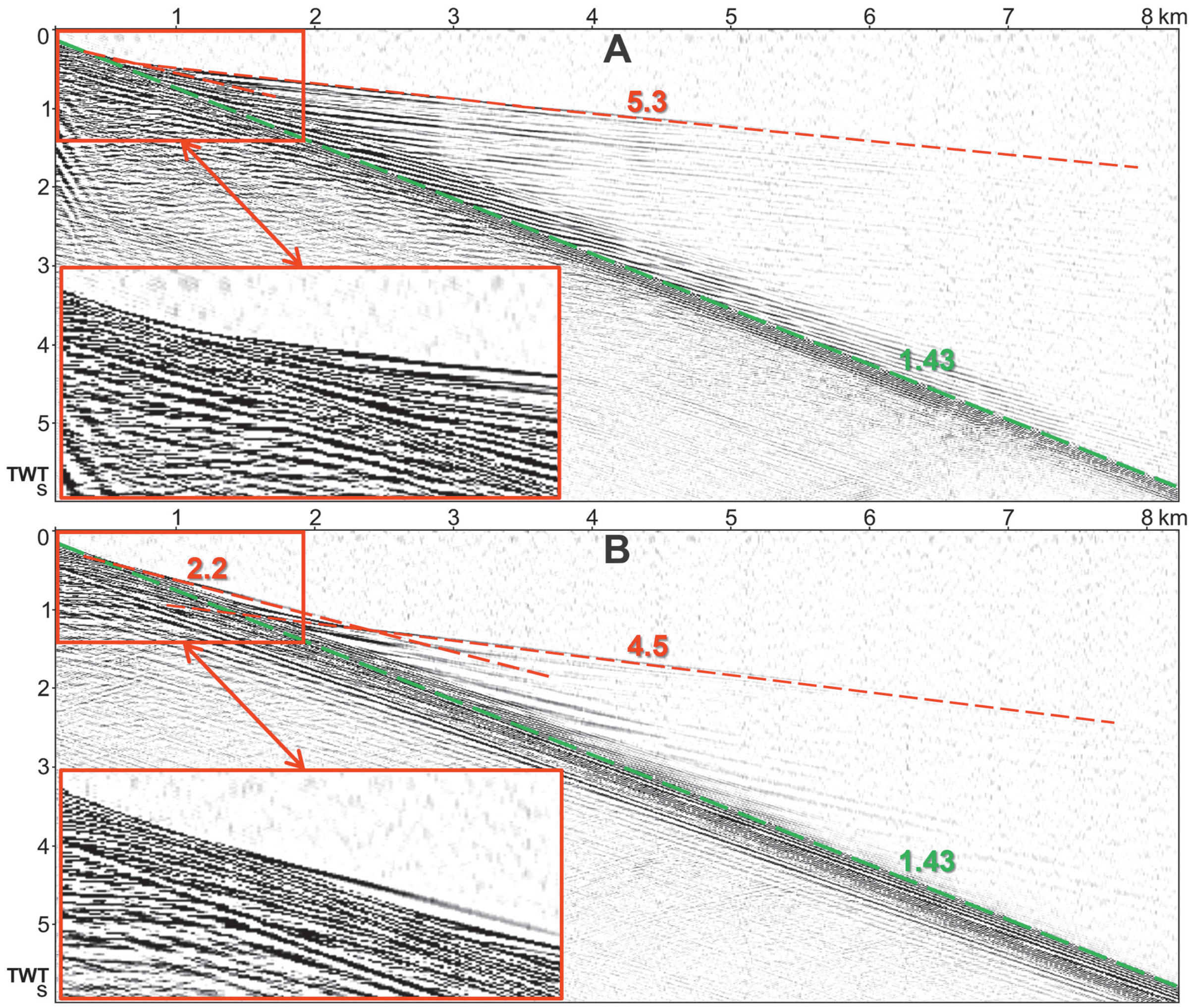

Fig. 3. CSGs in the south-western part of the NW1304 line in the North Western area of the Laptev Sea (NW) (A and B) with enlarged fragments. Comments: length of the streamer — 8.1 km, offset from the shot point — 130 m; shot points of the CSGs are shown in fig. 1 (3A, 3B)

bays with a total area of about 40.1 thousand km^2. Taking this into account, at the current stage of study, it is substantiated that frozen ground has degraded mainly in the northern part of the Laptev Sea, approximately in 21.6% of the substantially well studied area. It is worth noting that at the previous stage this value was 18.8% [26; 27]. At the same time, small areas were identified in the thawed zone, which we identified as remnants of frozen ground ("patchy frozen ground") and/or GHs. Judging by preliminary data, the share of degraded frozen ground and dissociated GHs in the Laptev Sea is significantly lower than in the western part of the East Siberian Sea, where it is about 62.2% [26; 27].

The configuration of the boundary between frozen and thawed ground has a complex curving character; it is located in a wide range of seafloor depths, mainly from 40 to 60 m (see Fig. 5 – 1). This is apparently explained by the nature of the seafloor topography (depths) and local features of the Earth heat flow, which was considered in detail in our previous works [26; 27].

Apparently, near the basement highs in the North-Western (NW) and partly in the Near-Taimyr (PT) regions in the Laptev Sea, as well as south from the De Long High (DL) in the East Siberian Sea, thawed zones are distributed relatively close to the shore (see Fig. 4 and 5). The exact boundary of thawed and frozen ground has not been determined here due to location of seismic lines mainly at sea depths of more than 20-30 m. It is very likely that in these areas, the frozen ground has degraded to isobaths of about 20 m, as in the Beaufort Sea on the Alaska shelf [18], or even less. In this regard, near the coast of Taimyr, relatively narrow coastal strips (mainly 5–15 km wide) up to 20 m isobaths, not covered by seismic survey by JSC MAGE, are speculatively shown as a "grey zone". It is possible that in these areas the frozen ground zone will exist up to 4 km from the coast, as was shown by drilling from fast ice and electrical prospecting in 2017 in

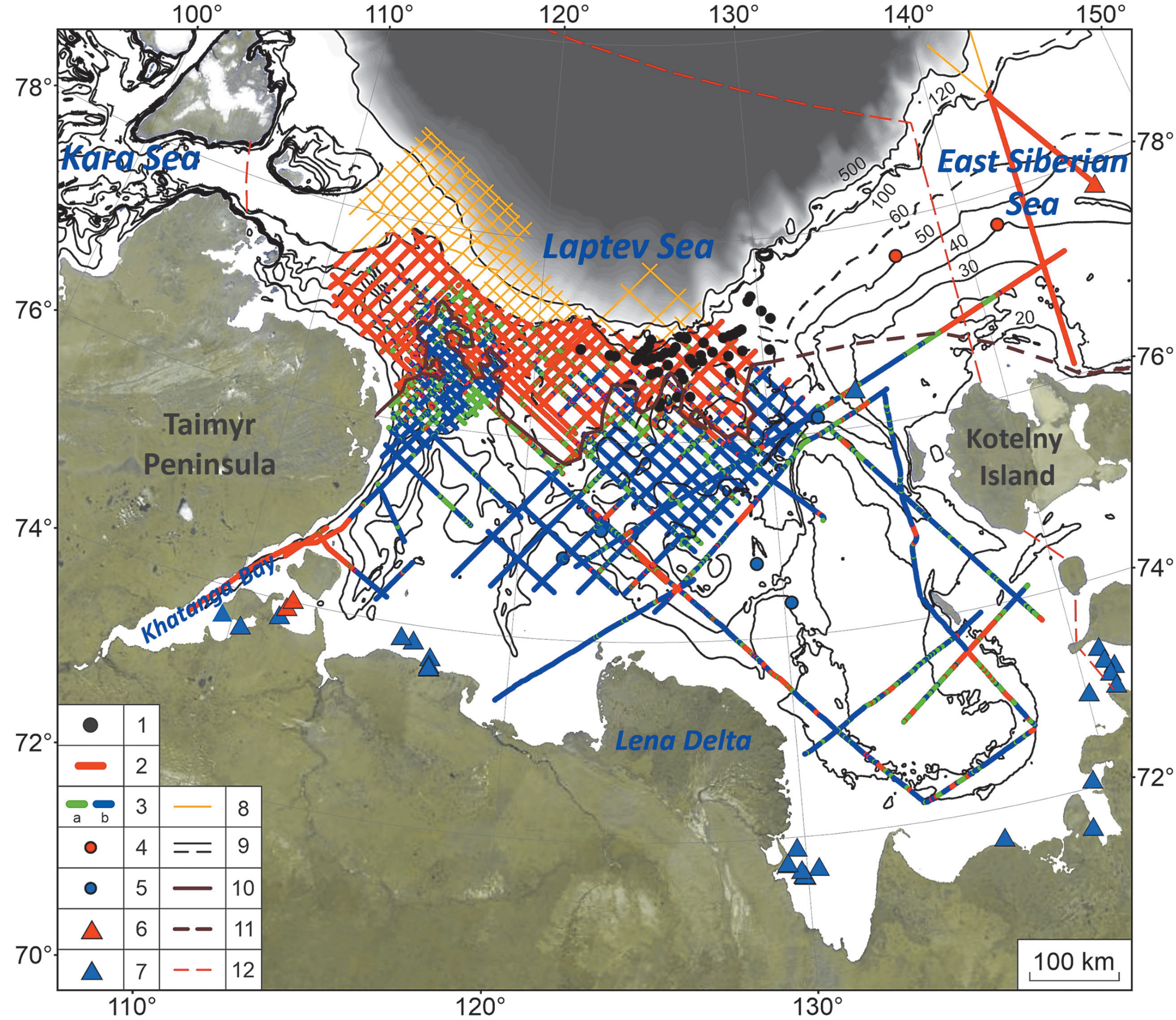

Fig. 4. Results of an analysis of near-bottom deposits state in the areas studied with CDP seismic by JSC MAGE in the Laptev Sea and the north-western part of the East Siberian Sea. Legend: 1 — gas seeps [5, 6, 8], 2 — absence of refracted waves in near-bottom deposits (or their velocities are lower than 2.3 km/s), 3 — refracted waves with apparent velocities of 2.3—2.8 km/s (a) and 2.8—4.0 km/s (b), 4 and 5 — absence (4) and presence (5) of frozen ground based on ocean bottom hydrophone (OBH) systems [39, 40], 6 and 7 — absence (6) and presence (7) of frozen ground based on drilling data, 8 — parts of seismic lines at seafloor depths greater than 120 m, 9 — isobaths in m (created by the authors based on GEBCO data), 10 and 11 — forecasted boundaries of frozen ground distribution: accurately defined (10) and requiring additional study (11), 12 — boundaries of the Laptev Sea. Basis of the figure — GEBCO bathymetry and ESRI satellite image

Nordvik Bay (it is important to note that due to limited penetrating depths, the wells may have not reached the frozen ground) [16; 42]. Such a strong degradation of subsea frozen ground near the Taimyr Peninsula can be explained by an increased heat flow due to the proximity of the basement rocks to the seafloor surface. An additional factor may be the proximity of the continental slope to Taimyr, which is closely approached by relatively warm water brought into the Arctic Ocean by the North Atlantic Current, as shown in our publication [20, Fig. 4].

In the zone of predominant frozen ground distribution, a number of taliks of different genesis are distinguished. We especially note the long (more than 60 km) talik, clearly confined to the Lena paleochannel. There is no doubt that taliks (through and/or non-through) also exist in Khatanga Bay. The results of electrical prospecting [44] led to the conclusion that in the bay around the Khara-Tumus Peninsula and to the south-west, there is frozen ground, but its top in the central part of the bay is at a depth of up to 240 m from the seafloor, and "in the north-eastern part of the Khatanga Bay frozen ground is completely absent… frozen ground is also absent in the central part of the Nordvik Bay". It is worth noting, that one of the large faults north of the Be-

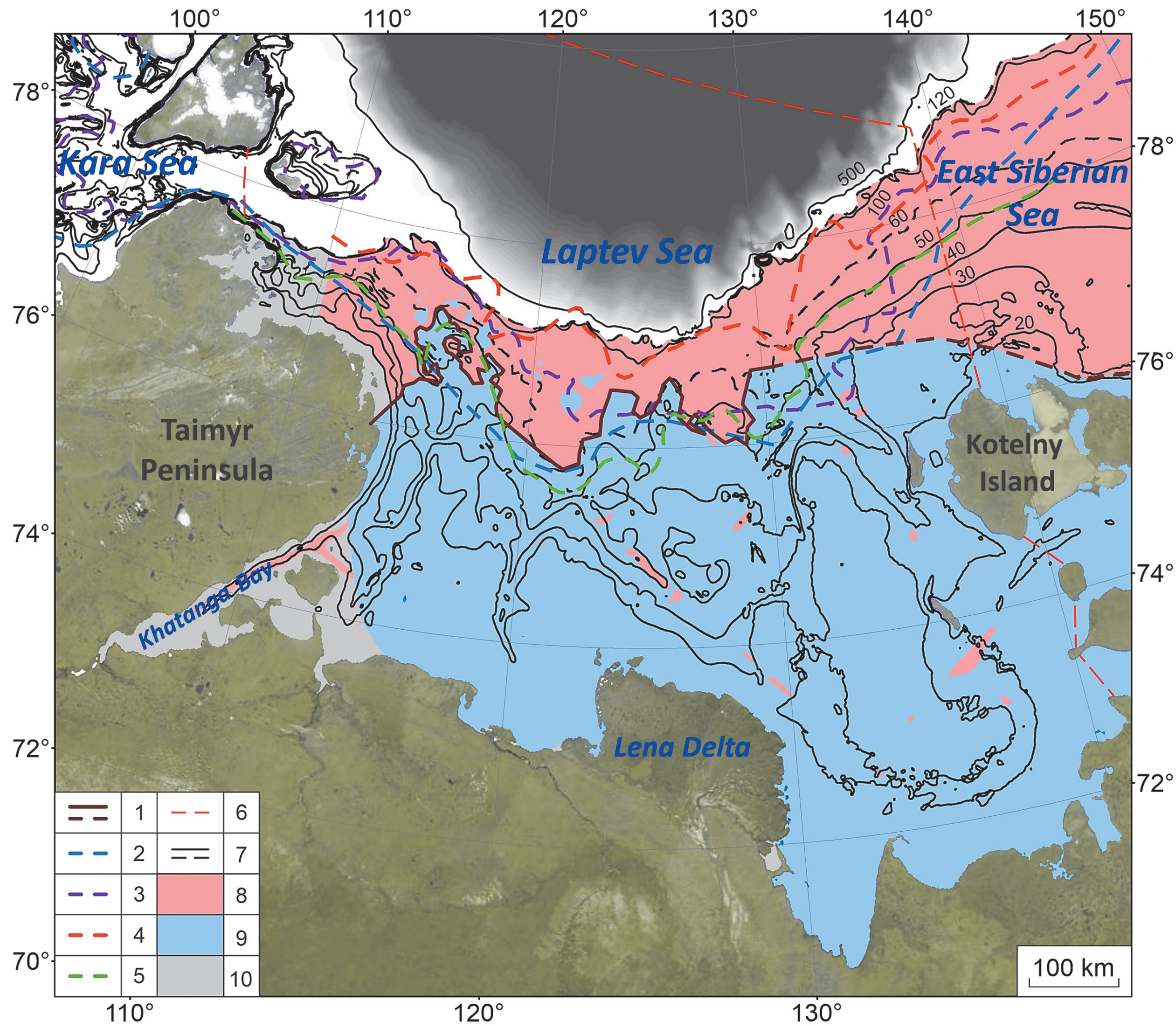

Fig. 5. Zones of frozen and thawed ground distribution on the shelf of the Laptev Sea and the western part of the East Siberian Sea. Legend: boundaries of predominantly frozen and thawed ground, distinguished by: 1 — authors of this paper, 2 — J. Brown with coauthors [9], 3 — P. Overduin and M. Angelopoulos with coauthors [14; 15], 4 — N. N. Romanovskii and V. E. Tumskoi [13], 5 — T. V. Matveeva with coauthors [7]; 6 — boundary of the Laptev Sea; 7 — isobaths (m); 8 — zone of forecasted prevailing absence of frozen ground, 9 — zone of forecasted prevailing presence of frozen ground, 10 — "grey zone" (lack of information)

gichev Island, shown on the cartographic scheme [31, fig. 6], exactly coincides with the thawed zone identified in the analysis of refracted waves along the PT1101 seismic line. Our data in the northern part of the bay near the Begichev Island (see Fig. 4) are in good agreement with electrical prospecting data [44], but to the south-west they contradict. It is possible that this is due to the proximity of consolidated rocks to the seafloor, from which high-velocity refracted waves mask the effect of frozen ground. In this regard, at the current stage of the research, the Khatanga Bay as a whole is shown in Fig. 5 as a "grey zone", but the thawed zone to the west and north of the Begichev Island is marked as reliably identified.

It is important to note that in September 2022, the reliability of our forecast based on refracted wave records was confirmed by drilling the DL-1 stratigraphic well on the De Long High in the north-western part of the East Siberian Sea near the border with the Laptev Sea (77.75336° N, 146.63212° E) [43]. Well DL–1 was drilled at a sea depth of 47.5 m, it has a bottom at a depth of 472 m from the seafloor in the Jurassic-Cretaceous deposits and it is located directly in the southern part of the CDP seismic line DL1101 of JSC MAGE. Before drilling the well on the line DL1101, due to the absence of high–velocity refracted waves from near-bottom deposits, the authors justified the absence of frozen ground and GHs [26; 27], later confirmed by the well DL–1 [43].

Also, the reliability of the results of studies of subsea frozen ground distribution based on records of refracted waves is confirmed by data from a study of a number of deep wells in the Beaufort Sea on the shelf of Canada [17] and Alaska [18].

In Fig. 5, in addition to the boundary between frozen and thawed ground (1) that we revealed, four analogous boundaries are demonstrated for comparison, they were predicted based on numerical modeling in the works of colleagues: J. Brown and co-authors – 2 [9], P. Overduin and M. Angelopoulos and co-authors – 3 [14; 15], N.N. Romanovskii and V.E. Tumskoy – 4 [13], T.V. Matveeva and co-authors – 5 [7]. As a general pattern, the approximate coincidence (at a qualitative level) of the position of the three boundaries in the central part of the Laptev Sea [7; 9; 14; 15] can be noted, reflecting significant degradation of frozen ground. This is apparently due to the fact that the authors of these models set approximately the same high values of heat flow in this area. This is justified by actual data and a common understanding of the area deep structure, including significant destruction of the sedimentary cover by faults of the Laptev Sea graben-rift zone, as well as the proximity of the southern junction of the Gakkel Ridge. Here the calculated boundaries are relatively close to the boundary that we revealed as a result of processing and analysis of the CSGs (see Fig. 5). High seismic activity in this area improves the permeability of faults, which contributes to the activation of subvertical migration of deep fluid flows and enhances the role of an endogenous factor in the degradation of frozen ground and/or GHs. This is confirmed by the results of geochemical studies, which showed the predominance of methane of deep origin in certain locations of the area [40; 45]. The high level of gas saturation of near-bottom sediments is confirmed by the fact that long-lasting (up to half an hour) gas releases were recorded for many shallow wells drilled in the shallow areas of the Laptev Sea shelf [46].

In the western and eastern parts of the Laptev Sea, there is mutual disagreement between the model boundaries [7, 9, 13–15], their position significantly and in some places radically differs from our border. According to our data, north from the Kotelny and New Siberia islands, frozen ground has degraded up to isobaths of about 20 m (see Figs. 4 and 5). A significant part of near-bottom water temperature measurements showed positive values [21, Fig. 8], and on the De Long High and to the north from the Kotelny Island, heat flow measurements showed increased values, in some places reaching 100–110 mW/m^2 [27, Fig. 1]. Actually, for the East Siberian Sea our preliminary conclusions showed even greater regional differences from all model results [7, 9, 13–15]. Besides, the results we obtained from studies of frozen ground distribution on the shallow shelf of the seas of Eastern Siberia are fundamentally different from calculations based on an analysis of the distribution of near-bottom temperatures, in which "ice-bearing permafrost in the Siberian Arctic shelf extends from the shoreline till sea depths of 80-100 m" and "permafrost remnants may exist locally at sea depths within 120 m" [47]. However, discussion of the reasons for such differences is not a goal of this work.

6. Conclusion

At the current stage of studying the distribution of frozen and thawed ground in the Laptev Sea [23–25], for the first time in a large volume (about 20.7 thousand km), processing and comprehensive analysis of records of the first arrivals of refracted waves in CSGs was carried out for 113 CDP seismic lines of JSC MAGE. The studies covered an area of 454 thousand km^2 from the coast to the 120 m isobath. The obtained results were supplemented by data from other studies, including drilling shallow wells.

Comparison of the obtained results with the data of the stratigraphic well DL-1, drilled in 2022 by VSEGEI and JSC Rosgeologia with the support of PJSC NK Rosneft near the eastern border of the Laptev Sea at a sea depth of 47.5 m [43], showed their complete correspondence, which clearly indicates the completed degradation of subsea frozen ground in a significant part of the seas of Eastern Siberia.

As a result of comprehensive studies on the shallow shelf of the Laptev Sea, fundamentally new information was obtained on the state of the subsea permafrost. Particularly, two large zones were identified – Southern and Northern.

In the Southern zone, shallow deposits are predominantly in a frozen state. Within this zone, there are areas without frozen ground (taliks) of different sizes and configurations. In the central and western parts of the shallow shelf, two relatively large elongated areas of thawed rocks were mapped, most likely associated with the paleochannels of the Lena and Khatanga rivers and, possibly, with deep faults with anomalous heat flows to which these paleochannels were confined. It is highly likely that a number of other identified through taliks also have an endogenous genesis and are associated with major faults. High seismic activity in the central part of the Laptev Sea improves the permeability of faults, which contributes to the activation of subvertical migration of deep fluid flows and enhances the role of the endogenous factor in degradation of frozen ground and/or GHs.

In the Northern zone, shallow deposits are predominantly in a thawed state, but there are isolated frozen ground remnants here. Of particular interest is the large thawed zone in the North-Western area of the research, which is close to the coast of Taimyr. The estimated share of thawed ground area appeared to be about 21.6%. The share of thawed ground area in the Laptev Sea is significantly less than that in the western part of the East Siberian Sea, in which, according to preliminary data, it is about 62.2% [26, 27].

Comparison of the obtained results with modeling data [7, 9, 13-15] showed the presence of significant differences, especially strong in the western and eastern parts of the Laptev Sea. Taking into account the high reliability of prediction of physical state of shallow deposits, proven by drilling, based on seismic records of refracted waves, in future modeling of the state of subsea permafrost and calculations of the volumes of possible methane emission into the atmosphere (for example, [48]), it is recommended to take into account our definition of zones of frozen and thawed ground existence in the Laptev Sea, as well as previously obtained results for the western part of the East Siberian Sea [26, 27].

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