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MARINE GEOLOGY

Contourites in the Seas of Russia

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Abstract—Contourite drift studies in six seas of Russia have been compiled and analyzed for the first time. The considered sedimentary bodies vary in size, age, and structure, are located at different depths, occur in various environments, and are attributed to several classification types. Our study combines these contourite drifts in two groups. The first includes shallow-water drifts on the shelves of Kara, Pechora, and Baltic seas; the second consists of deep-water drifts on the slopes and in the basins of the Sea of Japan, Sea of Okhotsk, and Caspian Sea. The relationship between the studied sedimentary bodies and bottom currents is considered.

Keywords: seas of Russia, environments, contourite drifts, structure features, bottom currents

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INTRODUCTION

Contourites are sediments formed or significantly reworked as a result of bottom current activity [37, 48], which can be considered any stable currents near the seafloor [43]. At the bottom, bottom currents form accumulative sedimentary bodies: contourite drifts, which sometimes stand out in the bottom relief, have a characteristic structure of the sedimentary cover, and are found in various settings, varying significantly in size and thickness [29, 43, 44, 46]. Currently, the database includes 380 contourite drifts [30] and indicates a global distribution of these formations in the World Ocean on passive continental margins and in closed and semiclosed marine basins. This database is continually being expanded as contourites are found everywhere, including the Arctic Ocean, where a small field of contourite sedimentary waves has been described on the Chukchi Rise [34].

Contourites has been actively studied abroad since the end of the 1960s [43]. The results of these studies provided the basis for identifying a new type of sediment, contourites, which form accumulative sedimentary bodies, contourite drifts. For contourite drifts, characteristic features of their morphological, lithological and seismic appearance were determined, shallow-water drifts (depth less than 300 m) were identified, and types were determined that differ in their structure and structural position, which together formed the basis of the contourite paradigm. Under this paradigm, active work is being carried out on both the classification of drifts and the classification of erosional contourite forms [33, 43] and studies are being conducted to identify the relationship between contourite deposits, the evolution of sedimentary basins and oceanographic processes [44, 49].

In Russia, these accumulative sedimentary formations were hardly studied at all at the end of the 20th—beginning of the 21st centuries, except for isolated works in the straits between the Kuril Islands [15], in the lower part of the Kuril—Kamchatka Trench, in the pelagic region of the Pacific and Indian oceans and on the Kyushu—Palau Ridge (Philippine Sea) [16]. Today, this situation is being corrected owing to research into contourite systems by specialists from the Shirshov Institute of Oceanology, Russian Academy of Sciences (IO RAS) in the Central and South Atlantic. These studies are important not so much for the discovery of new systems, but for the scale of the work. They cover contourite systems formed by deep and bottom waters from Antarctica, along nearly their entire distribution path in the Atlantic: from systems on the continental slope near Argentine Patagonia [35] and Florianopolis Fracture Zone [39] to the Discovery Passage [32].

Work devoted to studying contourite drifts has also carried out in the seas of Russia (Fig. 1); their results are presented below. They are based on the analysis of bathymetric and seismoacoustic data, and a number of diagnostic criteria were used to identify contourite drifts [28, 40]. These include the presence of: (1) mounds in the bottom relief and associated contourite moats, which are accumulative and erosional landforms, respectively; (2) unconformities between contourite and precontourite deposits, which marks the time of occurrence of the bottom current; (3) len-

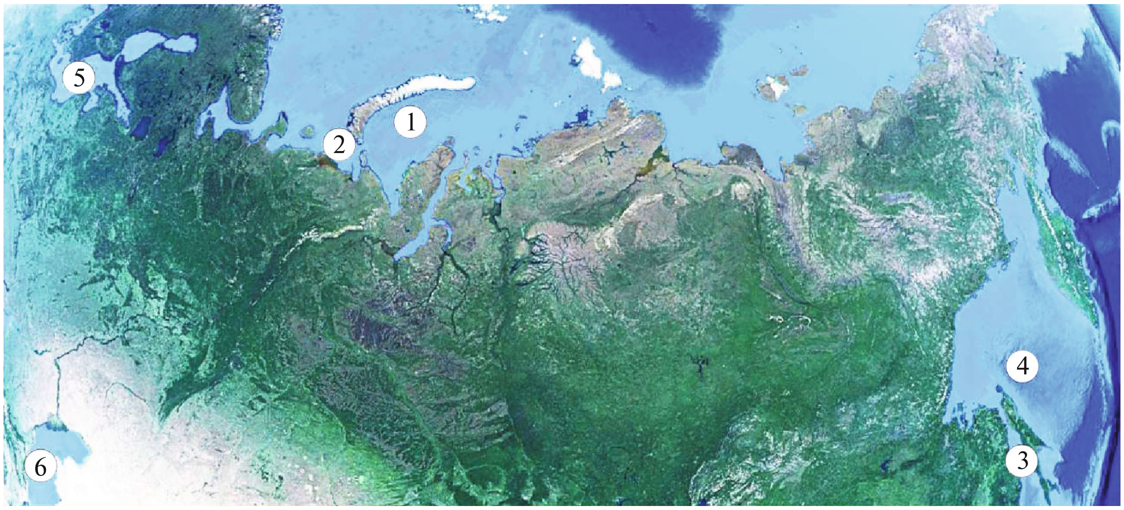

Fig. 1. Seas of Russia where contourites were discovered: (1) Kara ([3] and this study); (2) Pechora ([14] and this study); (3) Japan [3]; (4) Okhotsk [53]; (5) Baltic [45]; (6) Caspian [11]. Google Earth Pro map was used as basis.

ticular reflectors in the section and migration of the contourite moat upslope; (4) changes in the geometry and amplitude of reflecting boundaries in the contourite drift body, associated with the velocity of the bottom current and fluctuations in the size of the transported material, respectively. The data obtained from sampling contourite drifts with gravity corers in the Kara and Pechora seas [7, 8] are currently being analyzed, and the results will be the subject of subsequent publications.

The article focuses on seismoacoustic studies of contourite drifts in the Kara [3], Pechora [14], Japan [1], and Okhotsk [53] seas, carried out with the participation of the authors; work of recent years is considered in more detail and with the use of unpublished data. The results of work by other researchers in the Baltic [45] and Caspian [11] seas are analyzed in the discussion.

In this article, for the first time, a both published and our own original data on contourite drifts of the seas of Russia are generalized and analyzed. The article presents the aggregate results obtained in studying contourite drifts in the seas of Russia, identifies types of drifts differing in characteristic features, and determines the relationship of these features with depth, age of the basin and features of its morphology, and bottom currents. This work is intended to draw the attention of Russian researchers to the contourite paradigm in order to take into account the possible presence of contourite drifts in the sedimentary section when interpreting seismic data.

CONTOURITE DRIFT ON THE KARA SEA SHELF

The Kara Sea is located on a passive continental margin, and its southwestern part consists of three morphostructural elements, including the Novaya Zemlya Trough, the West Kara Step, and the Yamal–Gydan Shoal [12]. The Western Kara Step hosts widespread depressions (Fig. 2, inset), which are considered modern subsidence grabens formed as a result of tectonic creep of the crust during its bilateral stretching [4].

Contourite drifts were discovered in the Kara Sea when analyzing bathymetric and seismoacoustic data [3] obtained during cruises of the R/V *Akademik Nikolay Strakhov* in 2019–2021 under the program "Geological, Geophysical, Geomorphological, and Hydrophysical Studies in the Barents and Kara Seas" [17, 18]. During these cruises, surveys in study areas were carried out with a Reason SeaBat 8111 shallow-water echo sounder with an operating frequency of 100 kHz. The equipment also included an EdgeTech 3300 high-frequency profiler (USA) with a frequency of 2–12 kHz [17].

Additional information on the presence of these sedimentary bodies on the Kara Sea shelf was collected during the cruise of the R/V *Akademik Mstislav Keldysh*, conducted within the framework of two expedition programs of the IO RAS: "Ecosystems of the Siberian Arctic Seas" and "The European Arctic: Geological Record of Environmental and Climate Change" in 2020–2023 [7, 8, 23]. This vessel used a Kongsberg EA600 ship mounted echo sounder, which operates at a constant frequency of 12 kHz and provides the ability to receive digital and analog recordings in xyz and bmp formats, respectively. On analogue records, the structure of the sedimentary cover can be discerned to a depth of 20–30 m [2].

Research carried out during the cruise of the R/V *Akademik Nikolay Strakhov* and *Akademik Mstislav Keldysh* give grounds to conclude that the contourite drifts discovered to date in the southwestern Kara Sea are confined to depressions within the West Kara Step and are located in canyons on the western slope of the Yamal–Gydan Shoal. The relief and structure of the

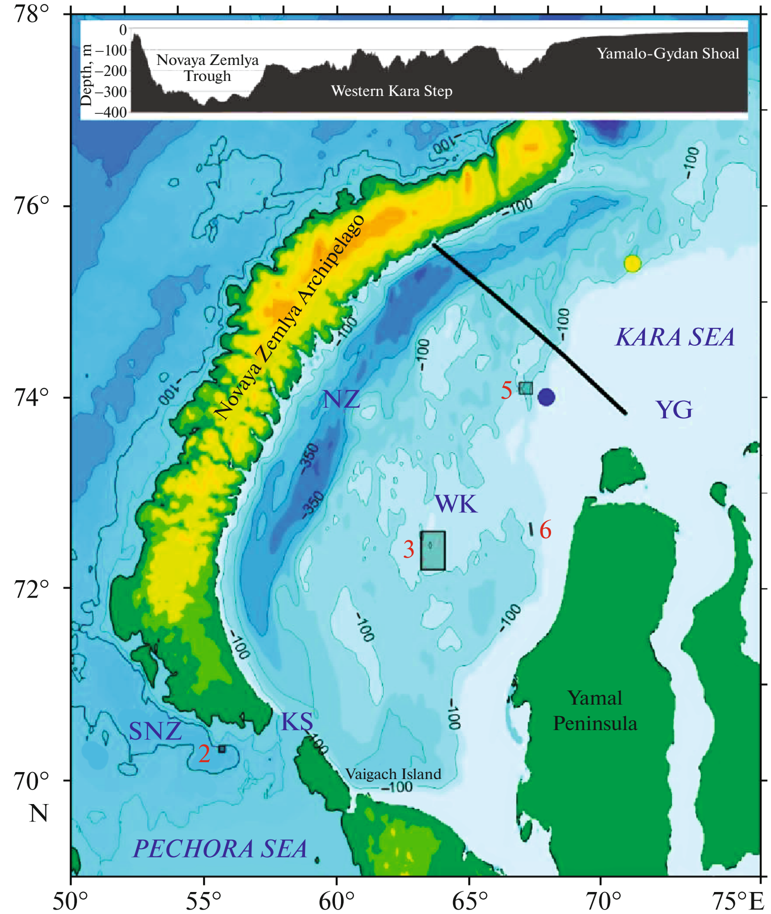

Fig. 2. Bathymetric map of southwestern Kara Sea [12], on which filled rectangles with numbers show study areas of cruise 52 of R/V *Akademik Nikolay Strakhov*. Thick line shows, bathymetric profile obtained during cruise 69 of R/V *Akademik Mstislav Keldysh* (inset); yellow and blue circles mark, positions of fragments of seismic profiles shown in Figs. 4c and d, respectively. Abbreviations: *NZ*, Novaya Zemlya Trough; *WK*, West Kara Step; *YAS*, Yamal–Gydan Shoal; SNZ, Southern Novaya Zemlya Trough; *KS*, Kara Gates Strait.

sedimentary cover of two depressions (study areas 3 and 5) and a canyon (study areas 6) were studied during a cruise of the R/V *Akademik Nikolay Strakhov*; the remaining data presented in the article were obtained during intersections of depressions (Fig. 2).

The relief of study areas 3 and 5 has common morphological features, where the most striking feature is linear depressions with submeridional extension. At study area 3, the depression was mapped throughout its entire length and its morphology is discussed here as an example (Fig. 3a). The length of this structure is 18 km, the depth is up to 240 m, and the width varies from 1.5 to 3 km. The transverse profile of the depression is U-shaped, and the slope angles are on average 15°–20°, reaching 27°–30° in the steepest slopes [21].

The transverse profile of the depression bottom is asymmetrical with respect to its axis or has a convex shape due to a gentle mound (Figs. 3b, 3c). According to seismoacoustic data, the depression is filled with sediments, which, based on the geometry and amplitude characteristics of the reflectors, are subdivided by unconformity into two seismic units. The lower seismic unit consists of horizontally layered reflections; in the upper unit, the reflectors are inclined or have a lenticular shape, overlapping the lower unit with a downlap (Figs. 3b, 3c).

Three sediment columns up to 7 m long were collected with large diameter gravity core in the northern, central and southern parts of this sedimentary body. Preliminary studies of the columns showed that the type of deposits consists of muddy contourites [20].

A similar depression with a depth of up to 296 m and a maximum width of up to 3.9 km was mapped to the northeast of study area 3 at study area 5 (Fig. 2) [6]. The average steepness of the depression slopes is 7°–9°; in some areas the steepness increases to 20°. The bottom of the depression at this area, as at study area 3, has an asymmetrical or slightly convex shape. On seismoacoustic sections, two seismic units separated by a unconformity are also distinguished here (Fig. 4a).

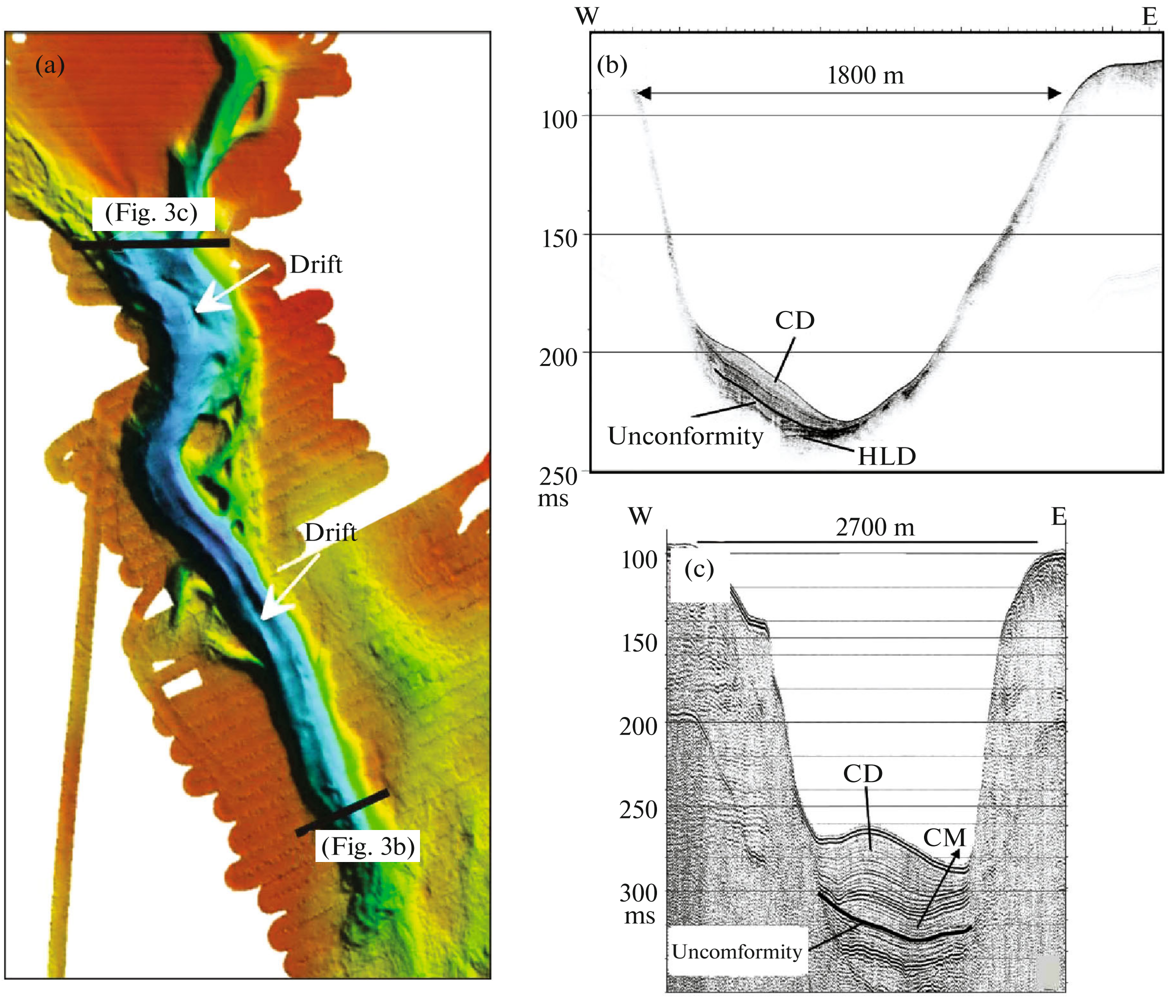

Fig. 3. Digital elevation model of study area 3 (a) and fragments of seismoacoustic sections (b, c) ([3, 21], modified]. Position of sections is shown in Fig. 3a. Abbreviations: CD, contourite drift; HLD, horizontally layered deposits; CM, contourite moat migration. For location of test site, see Fig. 2.

The lower unit of visible thickness up to 40 m is represented by a layered sedimentary strata with parallel reflectors slightly inclined in the easterly direction. The reflectors of the upper seismic unit pinch out at the base of the depression wall, demonstrating an increase in thickness with distance from its slope and the accompanying upward bending of individual reflectors, which leads to the formation of a gentle mound at the bottom of this depression. The presence of a gas chimney beneath the contourite drift masks the seismic record below the high-amplitude horizon corresponding to the gas chimney roof; the visible thickness of the contourite deposits is about 40 m.

A similar structure of the sedimentary cover was obtained in the canyons on the western slope of the Yamal–Gydan Shoal (Fig. 4b). Here, study area 6 was investigated and bathymetric and seismoacoustic surveys were conducted there. As a result, the canyon was mapped, which consists of two segments oriented in the submeridional and northeastern directions and joining almost at a right angle (Fig. 4b, inset). In both segments of the canyon, the seismoacoustic section consists of two units separated by an unconformity. The upper unit, based on the characteristic pattern of reflectors, can be interpreted as a contourite drift.

The depressions with submeridional direction established on the West Kara Step, which were already discussed above, were repeatedly crossed during the cruise of the R/V *Akademik Mstislav Keldysh*. Special studies of the sedimentary cover within these structures have not yet been carried out. Nevertheless, on the bathymetric profiles at the bottom of the depressions, gentle mounds up to 25–30 m high are distinguished. The configuration of the reflectors in the section has a lenticular, upwardly curved shape (Fig. 4c), which gives grounds to assume a contourite origin of these mounds.

The formation of contourite drifts, discussed above, continues at present. A buried contourite drift was identified on the shelf east of study area 5 at depths of approximately 50 m (Figs. 2, 4d). On the seismoacoustic profile obtained in this area, a sedimentary body

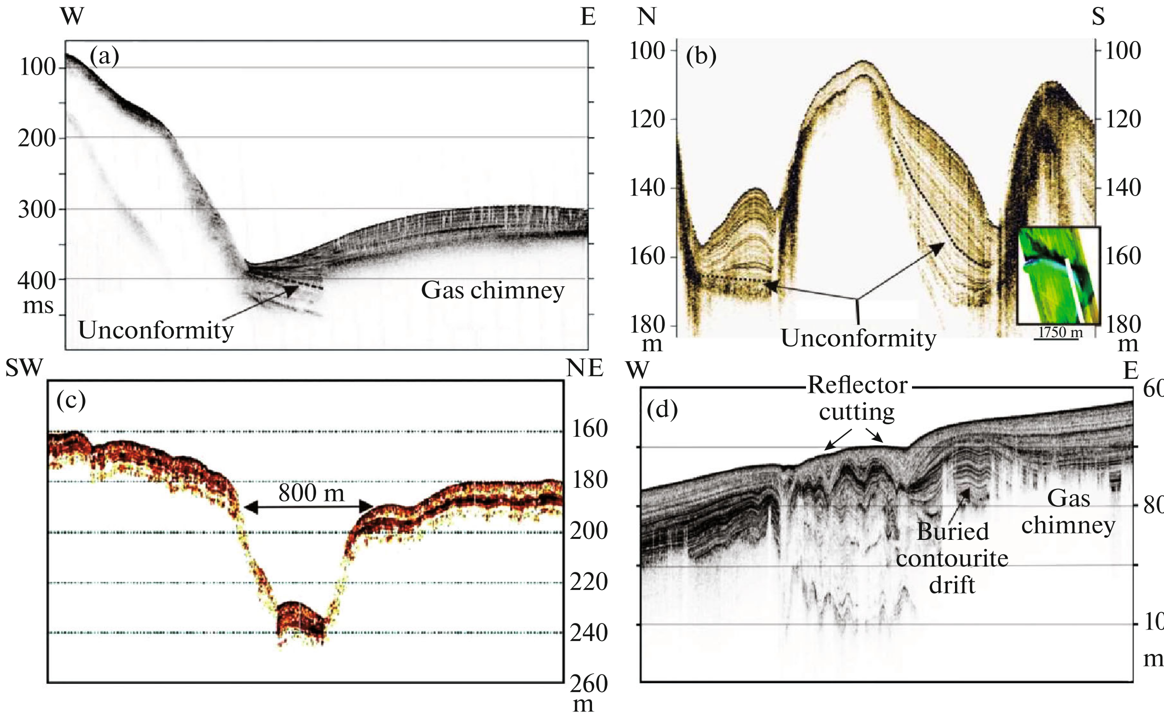

Fig. 4. Fragments of seismoacoustic sections showing structure of sedimentary cover: (a) in depression at study area 5; (b) in canyon at study area 6, with inset showing digital relief of study area and white line indicating position of profile, (c) fragment of analog echo sounder record along profile intersecting one of depressions (cruise 81 of R/V *Akademik Mstislav Keldysh*), (d) buried contourite drift on shelf (cruise 52 of R/V *Akademik Nikolay Strakhov*). Vertical scale in Figs. 4a, 4d is two-wave travel time in milliseconds. Location study area 5, 6 and sections can be seen in Fig. 2.

with upwardly convex horizons, which lie unconformably on a high-amplitude reflector, is distinctly visible in the sedimentary cover section (Fig. 4g). The body's thickness is 10 m, and it is covered by a sedimentary horizon with single, low-amplitude reflecting boundaries. There are no signs of contourite sedimentation in this sedimentary horizon. Moreover, in its section, located above the deformed horizons, in the sedimentary horizon, according to the nature of the seismic record on the seabed surface, a modern erosional cut and formation of negative forms are observed. This indicates that erosion, rather than sedimentation is currently occurring here.

Thus, as a result of the analysis within the Western Kara Step, areas of the bottom with the presence of contourite drifts were identified based on the morphology of the relief and the structure of the sedimentary cover. Drifts are located at the bottom of depressions and in canyons at depths of less than 300 m, have a characteristic relief, and a distinctive structure of the sedimentary cover on seismoacoustic sections and, in accordance with the generally accepted classification [43, 46], are shallow-water confined contourite drifts.

Inclinometer measurements of bottom currents at study area 3 [3] made it possible to record tidal bottom currents, the average speeds of which over 4 days were about 3 cm/s, with maximum values reaching 10 cm/s. The total water transfer with respect to one of the sensors was 17821 m, and the geographic, 10229 m in the NE or NNE direction; for the second sensor, these values were 15398 m and 8992 m, respectively.

CONTOURITE DRIFTS IN THE PECHORA SEA

The Pechora Sea occupies the southeastern periphery of the Barents Sea and differs significantly from the latter in terms of relief morphology [19]. The most notable landform in this area is a large negative morphostructure with depths of up to 250 m (Fig. 2). The morphostructure extends along the southwestern coast of the Novaya Zemlya archipelago and is called the Southern Novaya Zemlya Trench on the Russian maps and in publications (e.g., [13]), but we believe that this term is not correct for this structure and use the term trough.

Study area located in the Southern Novaya Zemlya Trough, was studied during cruise 52 of the R/V *Akademik Nikolay Strakhov* using a multibeam echo sounder and a complex of seismoacoustic methods [14, 17]. As a result, it was established that the maximum thickness of the sedimentary cover down to the Mesozoic basement exceeds 100 m in this area. A seismostratigraphic complex was identified in the section, forming an accumulative body, which is interpreted as a shallow-water contourite drift formed by the activity of bottom currents at the deglaciation stage at the end

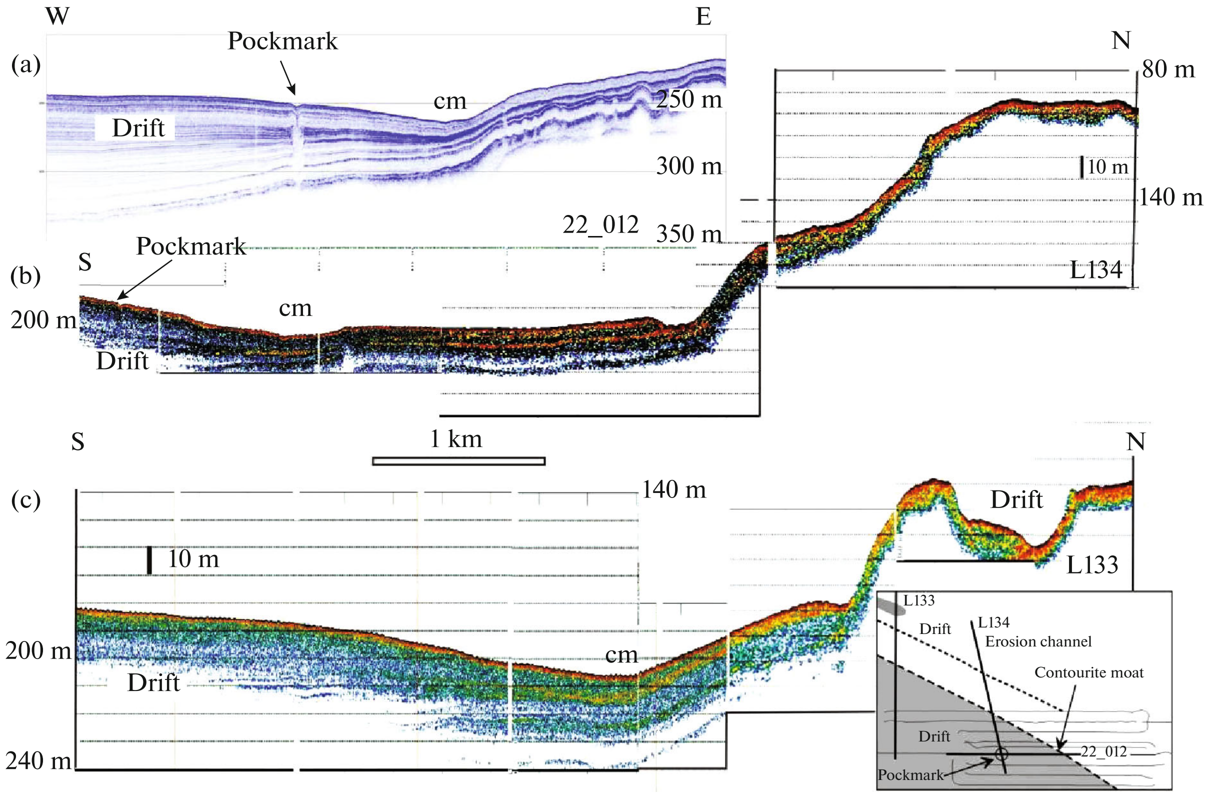

Fig. 5. Seismoacoustic section along profile 22_012, obtained by profiler during cruise 52 of R/V *Akademik Nikolay Strakhov* (2021) (a) and fragments of analog echo sounder recording along profiles L134 (b) and L133, (c) cruise 93 of R/V *Akademik Mstislav Keldysh* (2023) in Pechora Sea at study area 2. Contourite moat is marked by cm. Position of profiles is shown in inset by bold lines; thin lines are survey profiles during cruise 52 of R/V *Akademik Nikolay Strakhov*; position of study area 2 is shown in Fig. 2.

of the Late Pleistocene [14]. The thickness of the drift reaches 60–65 m and decreases as it approaches the moat located on the axis of the depression (Fig. 5a).

During cruise 93 of the R/V *Akademik Mstislav Keldysh* (2023), three bathymetric profiles with an analog record were obtained at this site, while profile L132 was identical in its position and structure of the sedimentary cover to profile 22_012 of cruise 52 of the R/V *Akademik Nikolay Strakhov*. The location of the profiles of cruise 52nd in the southern part of the study area and their northern continuation extension prevented obtaining an idea of the structure of the northern part of the study area (Fig. 5a, inset).

On two profiles of cruise 93 of the R/V *Akademik Mstislav Keldysh*, oriented in the N–S direction, the contourite drift is distinguished quite confidently even on the analog echo sounder recordings. The drift is located south of the contourite moat, confined to the axis of the depression (Figs. 5b, 5c, inset). The second moat appears at the foot of the northeast slope of the depression, limiting from the north a sedimentary body with a visible thickness of up to 20 m and transverse dimensions of about 1 km. The seismoacoustic appearance of the body is represented by parallel, horizontal, or slightly inclined reflectors, which gives no grounds for considering it a contourite drift (Figs. 5b, 5c). The moat on the axis of the depression is a contourite moat and stands out throughout the entire study area. The moat at the foot of the slope is an erosion channel and can be traced only to the northernmost of the seismoacoustic profiles (Fig. 5, inset).

The presence of a contourite moat and an erosion channel may indicate a jetlike nature of the bottom current, the speed of which increases near the base of the slope with bedrock outcrops, leading to erosion and removal of sedimentary material to a distal distance. The jet nature of the bottom current is also confirmed by the presence of a sedimentary body with a thickness of 15 m on the northeast slope of the depression, confined to a small depression with a trough-shaped profile. The depression is oriented parallel to the strike of the main depression and is clearly visible on the bathymetric map of study area 2 above the 140 m isobath (see Fig. 2 in [14]). The sedimentary body in the depression has characteristic lenticular bends of its surface and reflectors, is bounded to the north by a contourite moat, and is a small contourite drift (Fig. 5c).

During seismoacoustic studies at study area 2, clouds of increased turbidity with an enhanced type of reflection were discovered in the water column, which

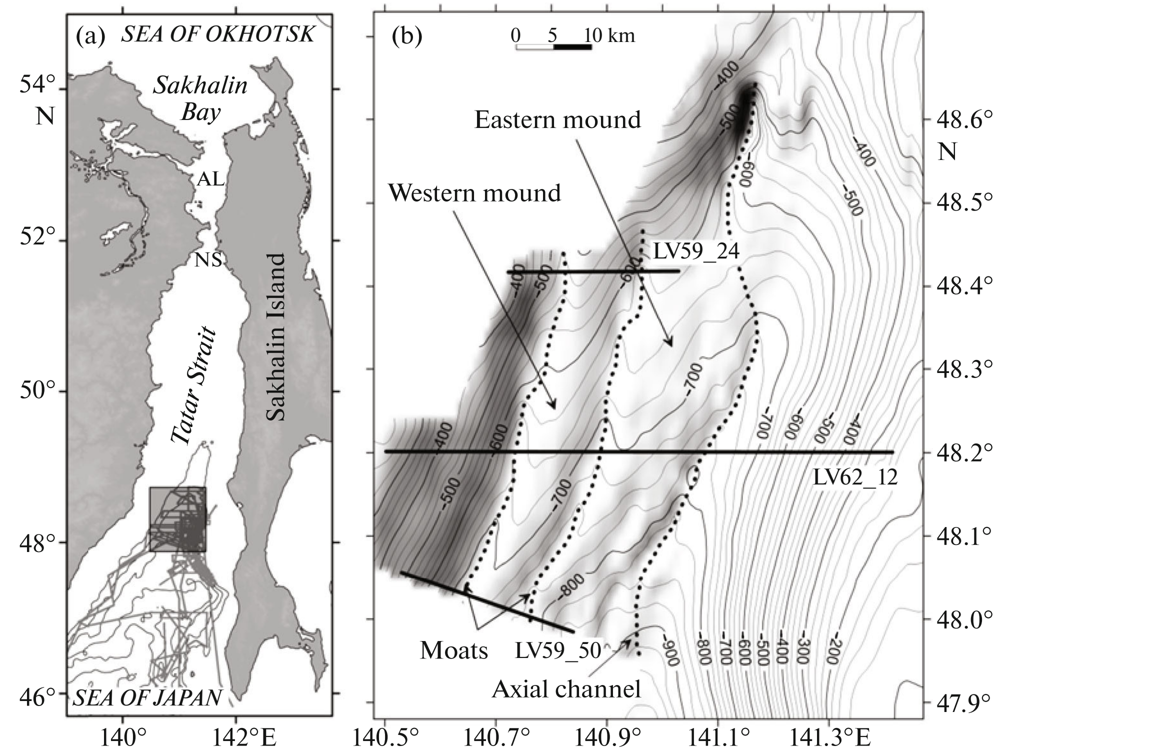

Fig. 6. Position of study area (filled rectangle) and geophysical survey profiles (gray lines) (a); shadow bathymetric map of study area (b), compiled fromn results of bathymetric survey during cruises of R/V *Akademik M.A. Lavrentyev*, illumination from southeast. Contour interval is 25 m. Bold lines indicate position of numbered profiles of seismoacoustic sections presented in Figs. 7a–7c. Abbreviations: *AE,* Amur estuary; NS, Nevelskoy Strait ([1], modified).

is associated with an increase in the suspension content in the bottom layer of water, which the authors of [14] associate with the release of sedimentary material during sediment degassing. The stirring up of the upper sediment layer and formation of a nepheloid layer can also occur under the influence of quasi-stationary bottom currents. The presence of such currents is confirmed by the transfer of suspension in the studied area in the WNW direction [14].

CONTOURITE DRIFTS IN THE TATAR STRAIT, SEA OF JAPAN

The Tatar Strait is located at the northern end of the Sea of Japan and separates the mainland from Sakhalin Island; it also conntects with the Sea of Okhotsk through the narrow and shallow Nevelskoy Strait (Fig. 6a). In the bottom relief, the Tatar Strait corresponds to the trough of the same name, which extends in a NS direction. The depth of the trough at 46° N is 1800 m and decreases to 250 m north of 49° N. The Tatar Trough was formed as a result of the stretching of the crust in the Middle–Late Oligocene–Late Miocene and is filled with Cenozoic sediments up to 8–10 km thick, in the formation of which Paleoamur deposits played a significant role [24].

Contourite drifts were discovered in the central part of the Tatar Strait [1]. This area was studied during four cruises of the R/V *Akademik M.A. Lavrentyev*, conducted under the international project "Sakhakin Slope Gas Hydrates" (SSGH) from 2012 to 2015. The cruises involved complex studies, including bathymetric survey with a single-beam echo sounder with a frequency of 12 kHz and seismic survey by continuous seismic profiling (CSP). During the seismic survey, a Sonic 4M sparker was used as the source; recording was done with a single-channel seismic streamer in the frequency range 210–1500 Hz; a Geo Pulse Subbottom Profiler system with a frequency of 3.5 kHz was also used [42].

As a result of the bathymetric survey, two extended mounds were identified at the bottom of the trench in the depth range 500–800 m (Fig. 6b). The mounds adjoin the western slope of the trough in the north, and to the south they are separated from slope and from each other by moats extending for a distance of more than 80 km. A channel runs along the axis of the trough, which can be traced throughout the entire study area.

The time section of the CSP along profile LV62_12 clearly shows that the mounds are contourite drifts (Fig. 7a). An angular unconformity is distinctly visible at the contact of the western contourite drift with the slope deposits. On the seismic section, the drift consists of parallel high-amplitude reflectors that divide the section into separate horizons with a thickness of

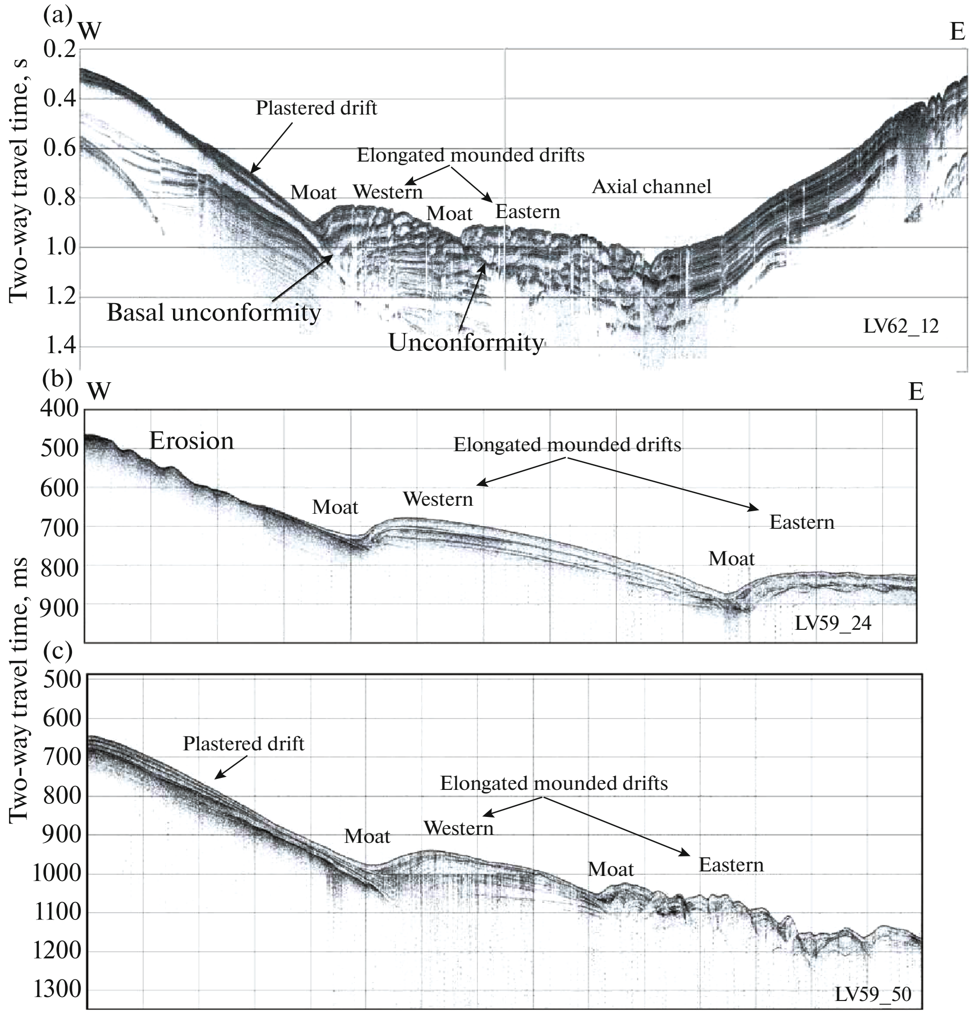

Fig. 7. Time seismic section of CSP along profile LV62_12 (a); fragments of seismoacoustic sections of profiler along profiles LV59_24 (b) and LV59_50 (c). For position of profiles, see Fig. 6b.

up to 0.1 s. Upsection, the reflectors gradually acquire lenticular outlines, leading to migration of the contourite moat upslope. Sedimentary waves are present in the upper part of the section. The apparent thickness of the drift section is 0.5 s.

The eastern drift contacts the western via an unconformity, where the western drift reflectors pinch out or are cut off. In contrast to the latter, the eastern drift is characterized by a less ordered internal (lenticular) structure, which is associated with many sedimentary waves, the number and degree of their expression in the relief and section increases from north to south (Figs. 7b, 7c).

In fragments of seismoacoustic sections of the profiler, crossing various parts of the drifts, it is clear that in the north, a thin layer of sediments fills only the contourite moat (Fig. 7b), while in the southern profile, the sediments are not only in the moat, but also cover the western slope (Fig. 7c). Here they form a sedimentary body, which on the seismic section along profile LV62_12 has a lenticular outline. Of the three adjacent accumulative bodies located along the western slope of the Tatar Trough, two are confined to the floor of the trench. Based on their structure and position [43], they should be classified as elongated mounded drifts and the subtype of "isolated drifts." The third accumulative body, located on the slope, is a plastered drift (Fig. 7).

The presence of two contourite moats running along the slope and separating the western and eastern drifts suggests that bottom currents are involved in the formation of these sedimentary bodies. The boundary of the bottom currents is the axial channel, to the east of which the side of the trough is composed of a sedimentary layer with parallel reflectors with a total thickness of up to 250–300 ms or approximately 200–240 m (Fig. 7a). This type of reflection is typical for layered strata formed in environments of accumulation of pelagic and/or hemipelagic sediments in a low-energy environment on continental slopes and slopes of submarine rises [27].

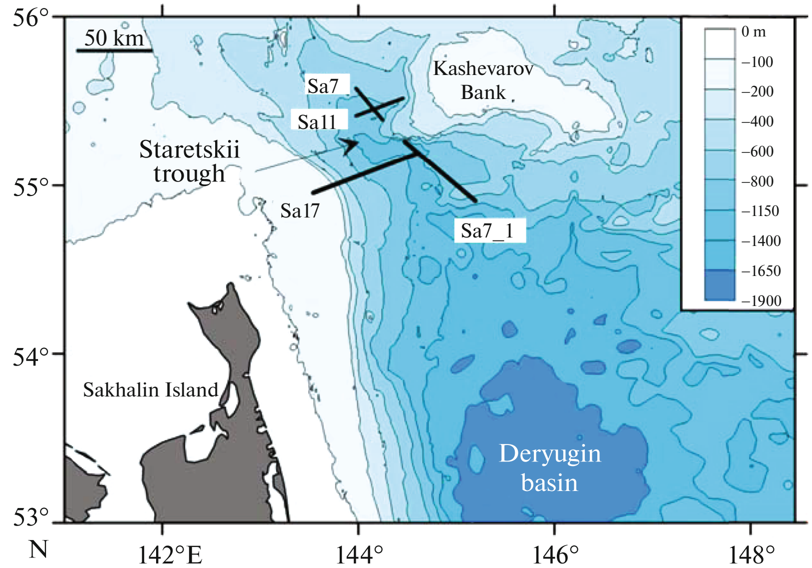

Fig. 8. Bathymetric map of northwestern Sea of Okhotsk indicating main relief forms, GEBCO grid [31] and position of numbered fragments of seismic profiles shown in Fig. 9.

Unlike the eastern mound of the Tatar Trench, its western mound is subject to erosion, which is evident from the gradual thinning and cutting of reflectors downslope on the CSP section (Fig. 7a) and from the wavy bottom with the absence of subbottom reflections on the profiler section in the northern part of the studied area (Fig. 7b). To the south, erosion gives way to sedimentation with the formation of a plastered drift on the western slope of the trench (Figs. 7a, 7c), which may indicate a slowdown in the velocity of the bottom current.

CONTOURITE DRIFTS IN THE SEA OF OKHOTSK

The northwestern Sea of Okhotsk includes the northern shelf and slope of Sakhalin Island, the slope of the western North Okhotsk Rise with the Staretsky Trough, the Kashevarov Bank, and the Deryugin Basin (Fig. 8). The Sakhalin shelf is 60–90 km wide, expanding to 140 km at its northern end. The depth of the Staretsky Trough is 500–100 m; it extends from northwest to southeast, separating the slope of Sakhalin Island from the Kashevarov Bank. The top of the Kashevarov Bank is leveled and located at depths less than 200 m. The southwestern slope of the bank is steep, and large inclined basement blocks stand out in its relief. The Deryugin Basin is bounded by the 1500 m contour line; the floor of the basin is flat with individual low heights.

Quaternary sedimentation in the northwestern Sea of Okhotsk was studied using materials from 8443 km of high-resolution seismic sections on four expeditions under the Russian–German project KOMEX (Kuril–Okhotsk Marine Experiment) [53]. The survey used a seismic system consisting of air guns with a volume of 1.44 or 3.36 L and a Geco-Prakla Mini Streamer with a total active part length of 100 m.

Within the studied area, several types of contourite drifts were identified on seismic sections: plastered, mounded, and confined (Fig. 9). The distribution areas of these accumulative sedimentary bodies in the northwestern Sea of Okhotsk are bounded by the Staretsky Trough, the southwestern slope of the Kashevarov Bank, and the northern part of the eastern slope of Sakhalin Island. South of these areas, contourite sedimentation is not dominant, probably due to a decrease in flow velocity, giving way to gravitational transport of sedimentary material and hemipelagic sedimentation [53].

Plastered drifts were discovered on the slope of Sakhalin Island and in the Staretsky Trough (Figs. 8, 9a, 9b). According to sampling data [26], they are represented by finely stratified, predominantly aleuritic silts. The drifts have a consistent thickness, and their internal reflectors are characterized by a moderate amplitude. Several internal unconformities were identified in the plastered drift in the Staretsky Trough. As it approaches the wall of the trough, the plastered drift turns into a mounded drift, accompanied by a contourite moat (Fig. 9b). A typical mounded drift, divided by unconformities into three seismic units, is distinguished on seismic section Sa7 at the base of the slope of the Kashevarov Bank (Fig. 9c). The drift extends parallel to the slope, separated from it by a contourite moat.

On the southwestern slope of the Kashevarov Bank, between two inclined basement blocks at a depth of about 1100 m, there is a confined drift (Figs. 8, 9d). This section is a classic example of this type of drift,

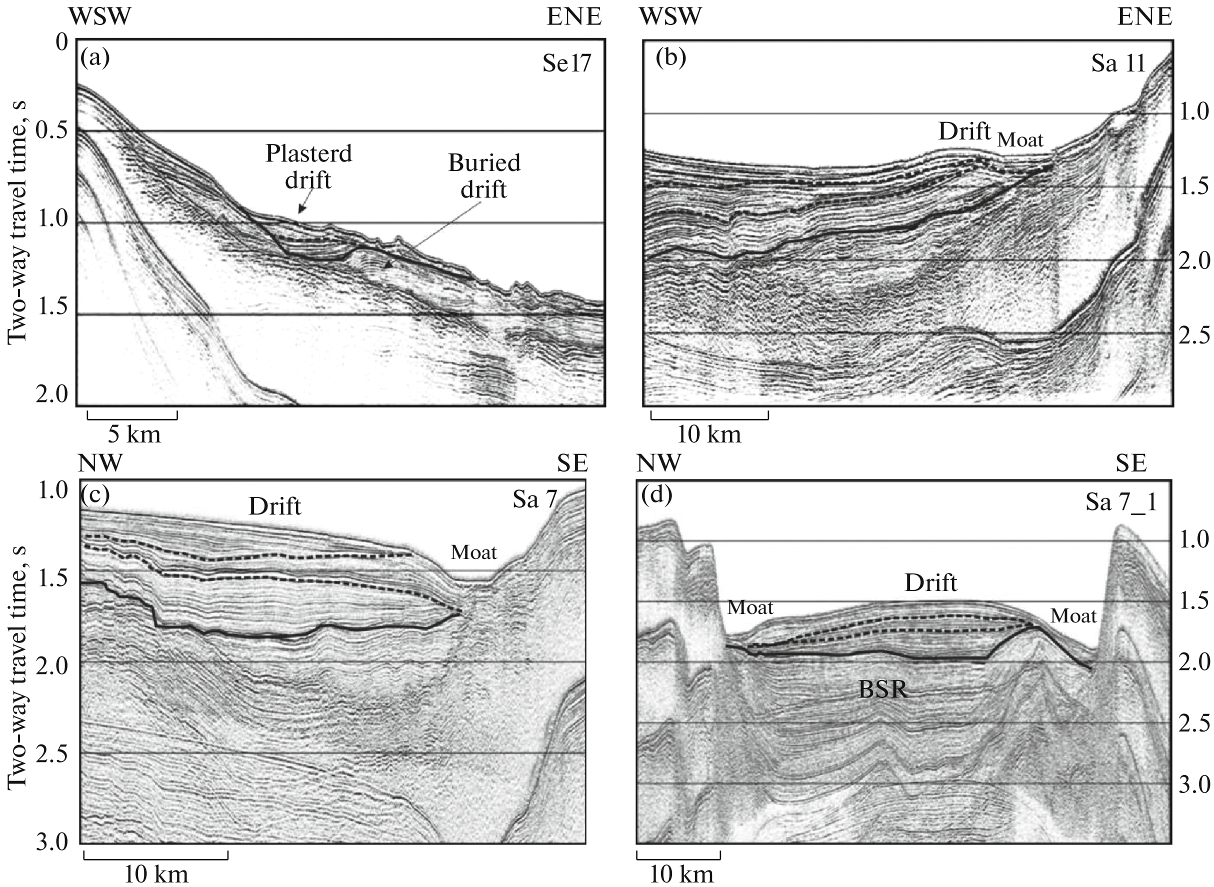

Fig. 9. Fragments of time seismic sections with different types of contourite drifts: plastered drifts on slope of Sakhalin Island (a) and on northeast slope of Staretsky Trough (b); elongated, mounded at foot of Kashevarov Bank (c); confined on southwest slope of Kashevarov Bank (d). Solid line shows unconformity between contourite and precontourite deposits; dotted line shows unconformity in drift body ([53], modified). Position of sections is shown in Fig. 8. See text for further explanation.

where the flow velocity increases between basement blocks, leading to the formation of contourite moats at the foot of the blocks and large mounded drifts between the blocks. The buildup of drift units upward or along the periphery gives grounds to assume a change in the regime of bottom currents at different intervals of geological time.

The obtained seismic data show that sedimentation along the slope was controlled by strong bottom currents that prevailed in the northwestern Sea of Okhotsk. The bottom currents have a thermohaline nature, but could also be tidal, especially on the shelves and Kashevarov Bank. Currently, contourite deposits are formed in the depth range 350–1000 m, and their age is assumed to be Quaternary [53]. Buried Early Pliocene–Pleistocene contourite deposits in the Sea of Okhotsk have been detected in seismic sections down to modern depths of 3000 m [36].

DISCUSSION

Contourite drifts have been discovered and, to varying degrees of detail, studied in six seas of the Russian Federation. These accumulative sedimentary bodies can be divided into two groups according to their formation environments. The first group includes shallow-water contourite drifts at depths less than 300 m; the second group includes drifts formed on continental slopes or the floor of basins below the 300 m contour line and which are classified as deep-water drifts [43].

Shallow-water contourite drifts. Shallow-water contourites were previously known in the Mediterranean Sea, on the shelves of Antarctica, South America, Europe, and Africa [37, 45]. Data on the presence of drifts in the Baltic Sea at depths less than 100 m near the island of Bornholm east of the Danish Straits (Fig. 1) were obtained relatively long ago [45]. At present, contourite drifts have been discovered in the Kara and Pechora seas of the western Arctic sector of Eurasia [3, 14] and data on their position and structure are systematized for the first time in this article.

Shallow-water drifts are formed in two sedimentation environments: the outer shelf, including the upper part of the slope, and sills/passages between separated basins through which hydrological exchange occurs between sea basins with different salinities [52].

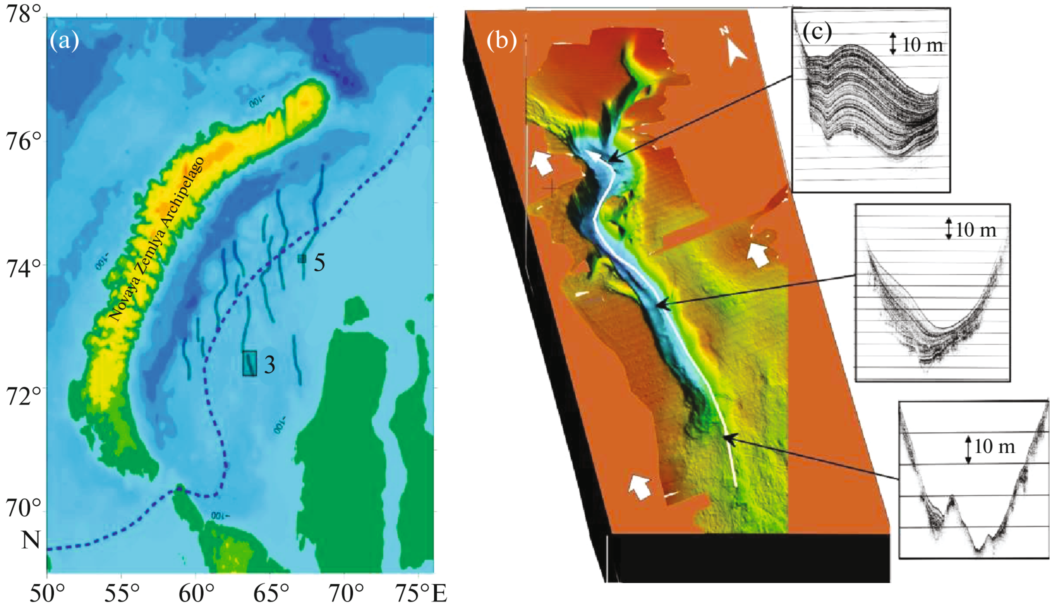

Fig. 10. Location of depressions (thick lines) in Kara Sea (a), compiled from map [12] with 20 m contour line. Dotted line, eastern boundary of Barents–Kara ice sheet at time of last glacial maximum (LGM) [18, 41, 51]. Rectangles show study area. Three-dimensional image of one of depressions (study area 3) (b), thin line with an arrow indicates focused water flow in depression, thick arrows indicate direction of bottom currents on shelf. Seismoacoustic profiles showing an increase in thickness of contourite drift from south to north (c).

In the Pechora Sea, the Kara Gates Strait plays the role of such a passage, through which saltier and denser Barents Sea water flows through the Pechora Sea into the Kara. In the northern part of the strait is a countercurrent, the Litke Current, which is directed from the Kara Sea to the Barents, and its measured speed reaches 30 cm/s [25]. The Southern Novaya Zemlya elongated depression is located along this strait (see Fig. 2), and the formation of a contourite drift here is apparently associated with the Litke Current. This is confirmed by the transport of suspension in the WNW direction at study area 2 [14].

The shallow-water contourite drifts on the Kara Sea shelf form in narrow linear depressions of N–S extension (Fig. 10a). Data on the presence of contourite drifts in such a sedimentary environment have been absent until now. These depressions (study areas 3 and 5) against leveled shelf relief are traps for sedimentary material and sedimentation depocenters. The drift thickness at the northern closure of the depression of study area 3 is increased compared to its southern end, which indicates transport of sedimentary material in the northern directions (Figs. 10b, 10c).

The formation of shallow-water contourites was significantly influenced by changes in sea level that occurred during the Quaternary [52]. This is particularly noticeable in the Arctic seas of the western sector of Eurasia, where during the maximum stage of development of the Barents–Kara ice sheet (MIS 2), the sea level was 130 m lower than its current position [38]. The edge of the ice sheet was at a depth of about 100 m (Fig. 10a) and periglacial conditions existed on the Kara Sea shelf. The flooding of the shelves of these seas during the postglacial transgression occurred in the period from 18 to ka, i.e., at the end of the Pleistocene–beginning of the Holocene [47]. The establishment of marine sedimentation conditions led to the emergence of bottom currents and formation of contourite drifts. A similar change in the environment associated with climate change is clearly evident in seismoacoustic sections in the unconformity that separates two seismic units: the lower, formed by precontourite deposits, and the upper, consisting of contourites.

Currents and their variations, especially in the bottom layer of the Kara Sea, have been poorly studied; recently, significant progress has been achieved with drifting autonomous buoy stations. With the help of these stations in measurements of the direction of currents were carried out in the southwestern waters of the Kara Sea up to a depth of 70 m at sea depths of up to 245 m during the year [5]. As a result, it was established that at all studied horizons, the current was directed N–NNE–NE. These data agree with our short-term measurements obtained with inclinometers in one of the depressions at a depth of 123 m (study area 3) [3], where water transfer occurred in the NE–NNE direction over a distance of up to 10 km. Instrumental observations of the direction of bottom currents correspond to an increase in the thickness of the contourite drift in the northern direction (Fig. 10c).

A typical example of a shallow sill environment are also the channels of the Danish Straits, through which salt waters penetrate into the Baltic Sea from the North Sea, resulting in the formation of contourite drifts to the northeast of the Bornholm Island. The first penetration of salt water through the Danish Straits occurred during the Littorina Sea stage 7.6–4.5 ka. This penetration of salt water and formation of contourite bodies with short-term hiatuses began at the Baltic Sea stage (4300 years ago) and has continued to the present [45].

Thus, shallow-water contourite drifts located in young marine basins have small sediment thicknesses and distribution areas. Thus, the thickness of the most studied drift in the Kara Sea does not exceed 50 m, and its area is about 10 km^2. Contourite drifts in each sea we studied are represented by one type: confined drifts in the Kara Sea, a mounded drift in the Pechora Sea, and patch drifts in the Baltic Sea. The age of shallow-water contourite drifts is determined by the age of the basin: for the Kara and Pechora seas, this is the Late Pleistocene–Holocene, and for the Baltic Sea, the Holocene.

Deep-sea contourite drifts. Contourite drifts, which are combined into the second group, were discovered in the Japan and Okhotsk marginal seas and in the inner Caspian Sea (Fig. 1). The drifts of the Okhotsk and Caspian seas are in similar sedimentation environments, located on the slopes of Sakhalin Island and the North Okhotsk Rise in the Sea of Okhotsk [53] and on the slope of the Derbent Basin of the Caspian Sea [11]. The formation of contourite drifts in these seas occurs in settings close to the setting of formation of contourite drifts on passive continental margins.

In a continental margin environment, large contourite drifts form with a contourite deposit thickness of up to 4.5 km and an area from 10^2 to 10^6 km^2 [29, 48–50]. Here, erosion–accumulative systems form, including several related contourite drifts and sedimentary wave fields. A similar type of erosion–accumulative system was identified in waters of the Middle Caspian, and its formation is well linked with the circum-Caspian contour current in the closed Derbent basin [10]. According to seismostratigraphic interpretation, the formation of the contourite complex in the Middle Caspian corresponds to the Khvalynsk transgression [11], which, according to luminescence dating, began 27 ka [9].

In the northwestern Sea of Okhotsk, a system of contourite drifts and sedimentary wave fields has been discovered, which is controlled by the hydrological regime of this basin and was formed in the Quaternary. Within the studied area, as shown in Fig. 12 from [53], it is governed by thermohaline bottom currents directed from north to south along the eastern slope of Sakhalin Island and in the southeast direction along the slope of the Kashevarov Bank. On the Kashevarov Bank, an additional contribution comes from tidal currents directed down its southwestern slope.

In the Tatar Strait, the erosion–accumulative system includes drifts of the floor of the Tatar Trough and its western slope, which are under the influence of the Schrenk Current, which formed approximately from the Early–Middle Pleistocene [1]. This current is a flow of desalinated cold water that runs from north to south along the western (coastal) coast of the Tatar Strait [22].

The thickness of deep-water contourite drifts of the Okhotsk, Japanese, and Caspian seas, compared to shallow-water drifts of the Kara, Pechora, and Baltic seas, reaches 500–600 m; drifts occupy areas of a few thousand square kilometers and are represented as different types. Drift systems form erosion–accumulative contourite systems that form in more ancient basins with a more constant flow structure.

CONCLUSIONS

To date, contourite drifts have been discovered in six Russian seas and studied in varying degrees of detail. Based on their position on the seafloor, these accumulative sedimentary bodies can be divided into shallow- and deep-water contourite drifts. The first are located on the shelves of the Kara, Pechora, and Baltic seas, while the second are confined to the slopes and bottoms of the basins of the Okhotsk, Japan, and Caspian seas. Shallow- and deep-water drifts differ in the thickness and area of deposits, age, structure, and their subtypes, which are governed by the environment of sedimentation. The main factors in sedimentation conditions are the parameters of the sea basin, such as its depth and age, which determine the presence of bottom currents and the formation of various types of contourite drifts.

Shallow-water contourite drifts are typical of the shelves of Arctic seas, the basins of which were formed in the late Pliocene–Holocene period. In these basins, the system of bottom currents adapted to the rise in sea level during the melting of the Barents-Kara ice sheet in the period 18–9 ka and to the volumes and distribution patterns of large-scale river runoff.

Deep-sea contourite drifts are characteristic of more ancient basins with a well-established quasi-stationary system of bottom currents, less susceptible to the influence of sea level fluctuations. From this viewpoint, the considered Far Eastern and inland seas are close to ocean basins, where constant contour currents act along their continental margins, forming systems of contourite deposits.

The location on the bottom and the structural features of accumulative sedimentary structures are used to reconstruct bottom currents [54]. In this regard, a comprehensive study of contourite drifts allows us to obtain the necessary information about the history of hydrodynamic and sedimentary processes that form systems of bottom currents in young shallow Arctic basins. These studies are extremely important for paleoclimatic reconstructions and ensuring the safe operation of oil and gas production facilities on the shelves of the Russian seas.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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