UDC 552.5:551.24

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PALEOTECTONIC CONDITIONS RESPONSIBLE FOR THE FORMATION OF THE LAPTEV SEA SEDIMENTARY BASIN

A review of both historical and recent geologicalф and geophysical data has provided a comprehensive examination of the sedimentary cover architecture in the Laptev Sea, as well as the tectonic conditions for its evolution. The well-established hypothesis regarding the rift-driven origin of sedimentary basins in the Laptev shelf has been challenged based on extensive geophysical data obtained in recent years and the results of fission track and radiometric dating of rock samples from the surrounding onshore area. Structural mapping of the entire Laptev shelf has allowed for the delineation of the main sequences, revealing the development of sedimentary basins, including shifts in depocenters and temporal changes in sedimentation rates. The current understanding of Arctic Ocean tectonic development, which is grounded in plate tectonic theory, has facilitated geodynamic restoration in the study area. This endeavour has yielded a consistent background model suitable for subsequent basin analysis, geological risk assessment and estimation of hydrocarbon potential.

Keywords: *Arctic Ocean, geodynamic evolution, geologic structure, Laptev Sea, geophysical data, sedimentary basins*
DOI: *10.17580/em.2025.01.01*

Introduction

The absence of wells on the Laptev shelf hampers the development of a reliable geological model and subsequent estimation of hydrocarbon potential, which is still considered significant. Most current tectonic models of the Laptev Sea are based on and illustrated by several 2D seismic sections. However, sedimentary basins are complex 3D structures that can be misrepresented by 2D sections, leading to unreliable geological models. The existing patchwork of seismic datasets from various surveys with their own stratigraphic models exacerbates this issue. Therefore, creating a unified 3D structural model that incorporates all available data across the entire area is crucial.

The shelfal and deep-water regions of the Arctic Ocean have been influenced by a series of tectonic events that have shaped their origin and development. However, experts hold differing views on this development. The prevailing hypothesis suggests that the East Arctic offshore contains significant Cretaceous and Cenozoic continental rift systems underlying deformed Palaeozoic formations [1–14]. However, Doré et al. [15] presented geological evidence contradicting the rift origin hypothesis of the Laptev Sea basin. Based on their examination of outcrops on the New Siberian Islands, Kosko et al. [16] proposed that the sedimentary basins of the Laptev and East Siberian Seas formed in a transtentional setting.

To date, approximately 113 000 line km of 2D seismic data have been collected in the Laptev Sea. By 2022, the density of seismic lines had reached 0.11 line km/sq. km. Most seismic studies have been conducted in the past decade. In addition to seismic research, numerous investigations in recent years have focused on analyzing the rock composition in adjacent onshore areas such as Taimyr, Verkhoyansk Folded System, and the New Siberian Islands among others, as well as reconstructing tectonic events in the region [16–20]. The new data challenge established concepts of the geodynamic evolution of the Laptev Sea shelf.

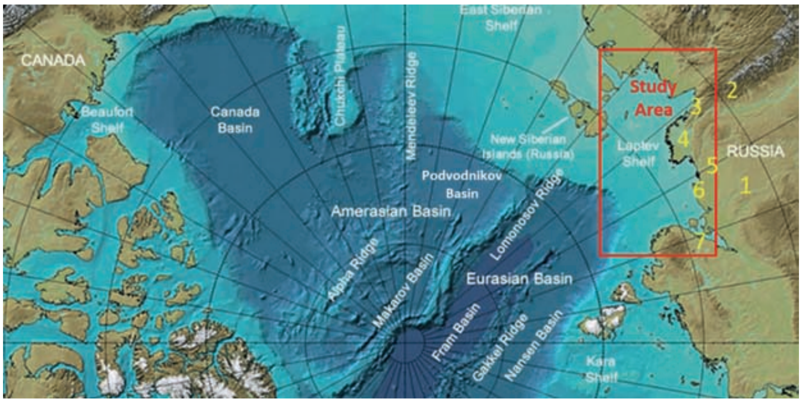

Fig. 1. Location map of the study area indicating the sites of the low-temperature thermochronology investigations discussed in the paper:
1 – Siberian Plate; *2* – Verkhoyansk orogenic fold belt; *3* – Kharaulakh anticlinorium; *4* – Ust-Lena metamorphic complex; *5* – Priverkhoyansk foredeep; *6* – Olenek fold zone; *7* – South Taimyr

Therefore, the main objectives of this study were to comprehensively review historical and recent geological and geophysical data to reassess and update the geological model of the Laptev Sea in order to facilitate a thorough assessment of its hydrocarbon potential. The resulting model, covering the entire Laptev shelf, has been integrated with the regional plate tectonic model of the Eastern Arctic developed by Doré et al [15].

Regional setting

The Laptev Sea, along with the East Siberian and Chukchi Seas, geographically belongs to the East Arctic. The adjacent deepwater oceanic zone is composed of the Eurasian Basin and the Amerasian Basin. The Eurasian Basin is divided into the Nansen and Amundsen subbasins by the rift zone of the Nansen–Gakkel Ridge. The Amerasian Basin can be further divided into the Makarov–Podvodnikov and Canada Basins, separated by the Alpha–Mendeleev Ridges (**Fig. 1**).

The submarine Lomonosov Ridge separates the Eurasian and Amerasian Basins. It is an elongated block of continental crust that stretches for 1.800 km between the Canadian Arctic Islands and the New Siberian Islands. This microcontinent is highly segmented and is believed to be composed of Cenozoic sedimentary rocks resting upon the Mesozoic basement [21–23]. The ACEX well drilled in 2004 penetrated 420 m of Cenozoic deposits that are unconformable to underlying Mesozoic sandstones [24].

The Eurasian Basin is a depression with oceanic crust that was a continuation of the Atlantic Rift System and split apart during the Mesozoic–Cenozoic. The boundary between the oceanic and continental crust in the Barents–Kara continental margin and the Lomonosov Ridge can be distinctly recognized in potential fields and bathymetry. In the Laptev Sea, this boundary runs along the Khatanga Shear Zone.

The Laptev Sea is located at the junction between the Eurasian and North American lithospheric plates. The plate boundary extends along the axial zone of the Nansen–Gakkel rift system, crosses the Laptev Sea, and extends farther south within the Verkhoyansk–Chukotka fold belt. Due to the anticlockwise motion of the North American Plate and the clockwise motion of the Eurasian Plate, shear and compressional deformations occur along the plate boundary [25].

Material and methods

This paper relies on a comprehensive set of seismic data acquired between 2000 and 2021. The dataset includes interpretation results from approximately 30 seismic surveys covering the study area obtained with permission from the Russian State Geological Depository (**Fig. 2**). Seismic stratigraphy varies markedly between datasets from different surveys. The total number of interpreted seismic reflectors (unconformities), which have different names, positions on the seismic time section and geologic ages, ranges from three to nine (**Fig. 3**). This variation is due to the complex development of the sedimentary cover under a combination of local and regional tectonic activity. However, four unconformities, including the base of the sedimentary cover, are persistent and recognizable among most datasets (**Fig. 4**). Due to the lack of deep wells on the Laptev shelf, we dated the unconformities considering the regional tectonic events suggested by Doré et al. [15] (**Table**).

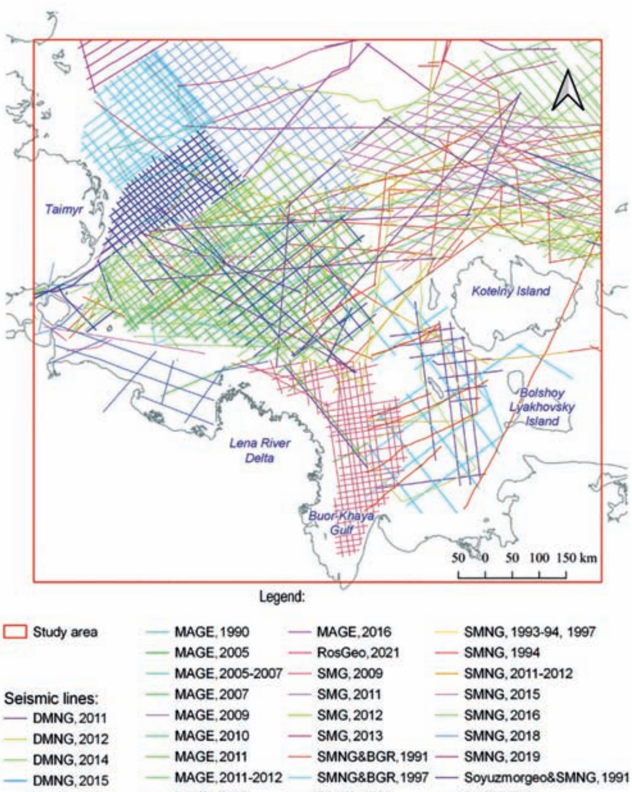

Fig. 2. The location of the seismic lines from the various surveys involved in the study

Table. Correlation between the main unconformities in the sedimentary cover of the Laptev Sea and regional tectonic events in the Eastern Arctic

Unconformity (horizon)	Tectonic event
Pre-Aptian (A)—base of sedimentary cover	Collision between the Siberian platform and the Alaska–Chukotka microcontinent (ACMC)
At the Upper Cretaceous–Paleogene boundary (mBU)	Rifting in the Makarov–Podvodnikov Basin
At the Eocene–Oligocene boundary (UB)	Rifting in the Eurasian Basin (the Nansen–Gakkel Rift Zone)
At the Oligocene–Miocene boundary (RU)	The onset of postrift subsidence in the southern part of the Nansen–Gakkel Rift Zone

Depth structure maps from various surveys were combined to create unified surfaces of the four main unconformities across the Laptev Sea. Analyzing the initial stacked seismic data helped improve the quality of the final maps.

From a geodynamic perspective, the method and velocity of relative plate movement influence critical aspects related to the formation and evolution of sedimentary basins, such as the creation of accommodation space. By assuming that similar geological processes are likely to occur in comparable geodynamic settings, one can tentatively assess the potential for petroleum system development in a sedimentary basin. This approach is particularly valuable and sometimes the only method for exploring and evaluating frontier areas like the Laptev shelf. Therefore, to achieve the goals of this project, we implemented a systematic technique of tectonic and geodynamic analyses. This method involves examining current depth structure maps, sedimentary unit thicknesses between the main unconformities, and sedimentation rates, and conducting back-stripping analysis to identify depocentres and areas of consistent subsidence. The resulting geodynamics map of the study area highlights key tectonic features within specific geodynamic settings. The geodynamic zonation of the study area, developed with consideration of the contemporary understanding of the Arctic Ocean and adjacent continent's key elements and structure, is based on the geological and geophysical data reviewed in this project, as well as structural mapping.

Results

The present-day structure of the pre-Aptian unconformity at the base of the Laptev Sea sedimentary cover (**Fig. 5*a***) is notably faulted. NW–SE-oriented strike-slip motions prevail over most of the study area. Few elongated depressions delineate the Khatanga transform, which extends SW–NE. Normal faults are mostly situated outside the Laptev Sea shelf in the Eurasian Basin.

The authors suggest the first two faulting systems formed when the Arctic Alaska–Chukotka microcontinent collided with the Siberian Platform, while moving rotationally (counterclockwise). The third system of faults originates at the time of expansion of the Eurasian oceanic basin. A curvilinear subsided zone distinctly distributed in the central part of the Laptev shelf. Two systems of faults and the stiff continental blocks control the shape of this zone, namely, the Taimyr Folded Area in the west and a part of the Verkhoyansk orogenic fold belt outcropped in the Lena River Delta. This subsided zone is intensely faulted and consists of multiple small depressions of various depths (8–15 km), shapes and orientations. A folded trough where the base of the sedimentary cover occurs at a depth of 5–7 km encompasses the southwestern part of the Laptev Sea. It conjugates with the Verkhoyansk orogenic fold belt. The eastern part of the offshore area in the vicinity of the New Siberian Islands and Lyakhovsky Islands hosts an uplifted zone with minor narrow depressions driven by a system of strike-slip motions. The base of the sedimentary cover here is not deeper than 3–4 km. Narrow depressions in the north at depths of 5–8 km are related to a system of normal faults.

The structure of the top Cretaceous unconformity (mBu) is generally inherited from the underlying horizon (A), but its topography is gentler (**Fig. 5*b***). The depth of mBU does not exceed 10 km. Most of the subsided zone occurs in the central part of the Laptev shelf.

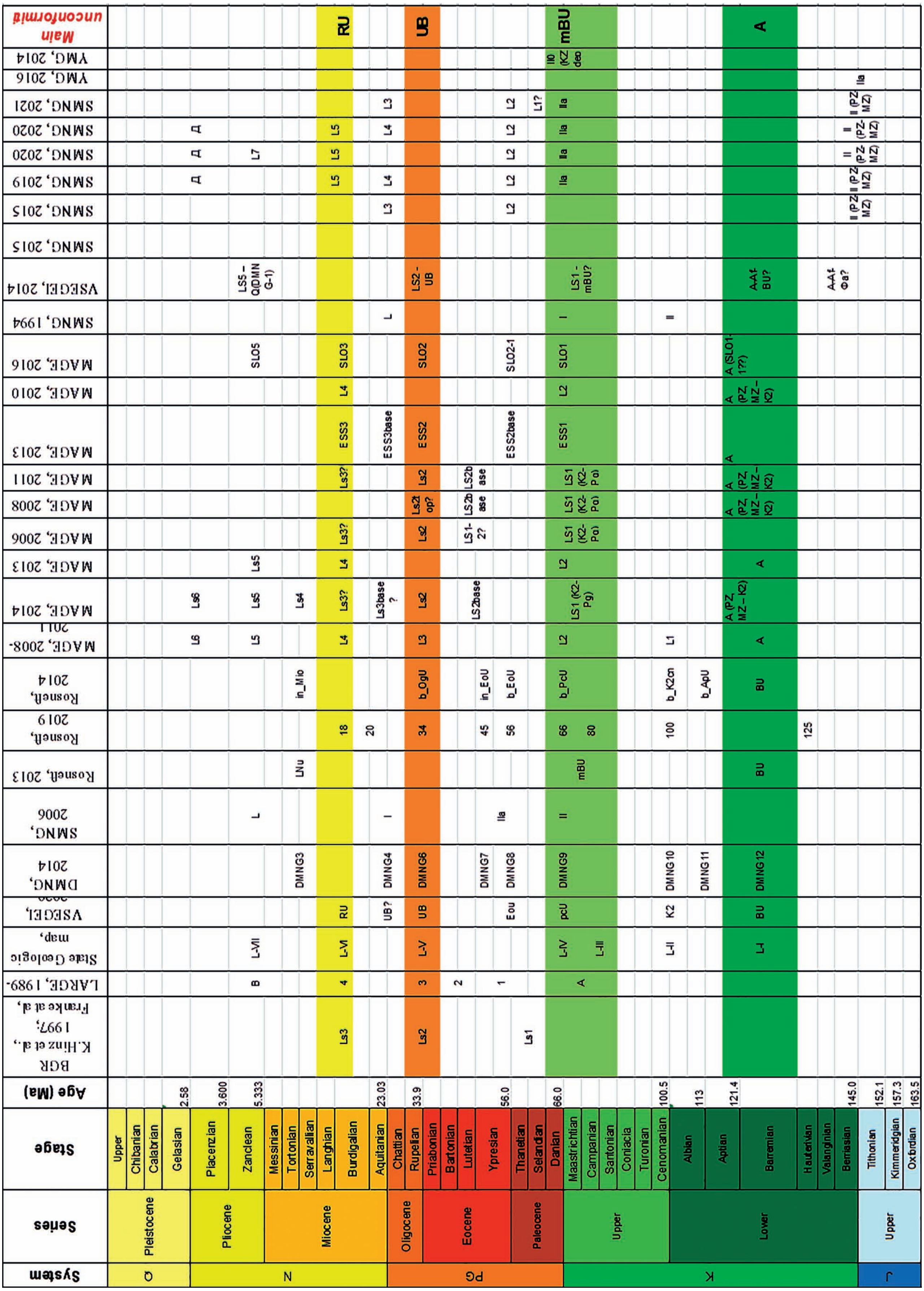

Fig. 3. Available seismic stratigraphy of the Laptev shelf showing significant variations between interpreted datasets from different surveys

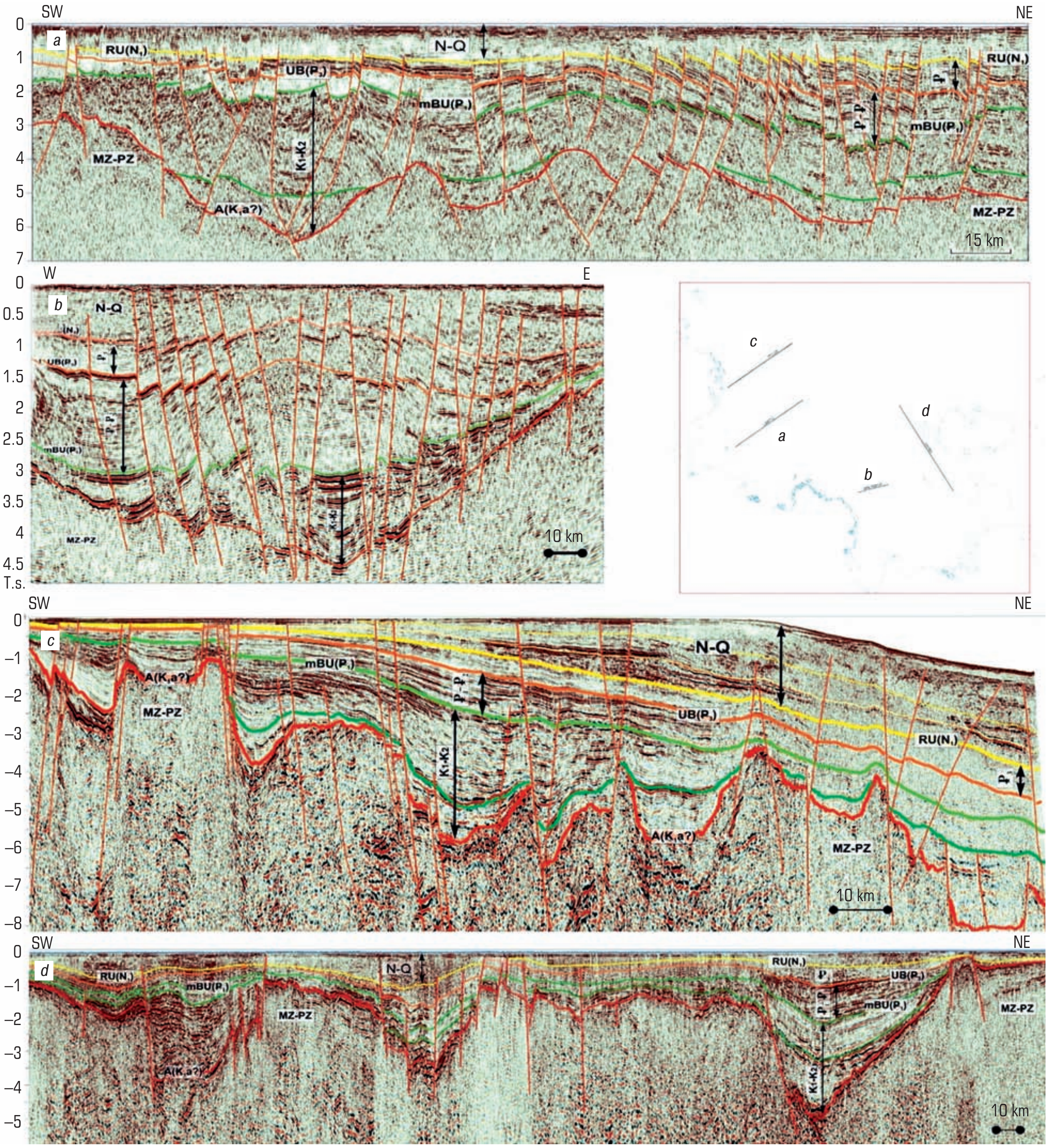

Fig. 4. Examples of different time sections are as follows:

a – along the line L200712; *b* – along the line OML192D10, which illustrate the complex shear nature of the Central Laptev (these sections were revised after the MAGE 2007 technical report and again after the RosGeo 2021 technical report); *c* – along the line PT1129, showcasing the extensional tectonics of the Pritaimyr area (it was revised after the MAGE 2013 technical report); *d* – along the line LH1401, providing insights into the geology of the Eastern Laptev and revealing mostly lower thicknesses of sedimentary cover with a few small grabens (this section was revised after the MAGE 2014 technical report

Compared with the underlying horizons, perceptible changes occur in the structure of the top Eocene unconformity (UB) (**Fig. 5*c***). That is, the northern depressions join together, whereas the curvilinear depression in the central part of the Laptev Sea, which is clearly recognizable at deeper levels, becomes narrow and fragmented. The depth of this unconformity flattens from the center northward. A series of small sags surround the Lena River Delta.

The depth of the RU unconformity does not exceed 5 km (**Fig. 5*d***). Its structure is fundamentally different from the deeper ones. The only sizable subsided zone occurs in the northern part of the study area. A system of shallow depressions rims the Lena River Delta.

A back-stripping analysis revealed that by the end of the Cretaceous, the base of the sedimentary cover (A) had subsided to depths between 4 and 6 km in the central part of the Laptev shelf and in the area north of the New Siberian Islands. Successive downward movements persisted until the beginning of the Miocene, when (A) had subsided to 6–10 km. The northern and eastern parts of the study area, including the islands, occupied an uplifted position at the end of the Cretaceous. This is consistent with the established

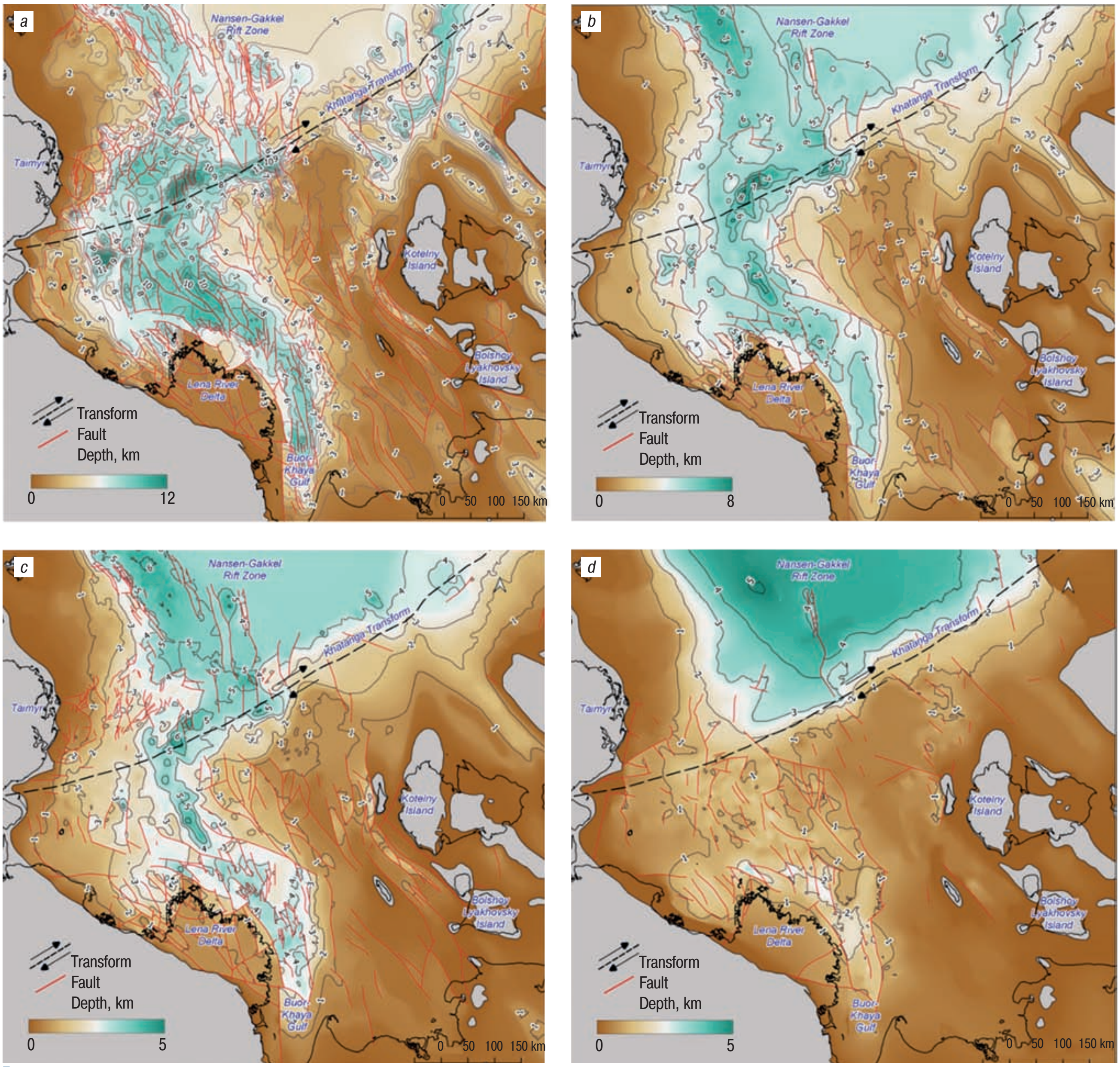

Fig. 5. Depth structure maps of the main unconformities in the sedimentary cover of the Laptev Sea:
a – Pre-Aptian unconformity at the base of the Laptev Sea sedimentary cover shows a major curvilinear subsided zone in the central part. The zone is intensely faulted and consists of multiple small depressions of varied shape and orientation. The area near the New Siberian Islands and Lyakhovsky Islands hosts an uplifted zone with minor narrow depressions controlled by a system of strike-slips. A system of normal faults controls subsided zones in the northern part of the territory; *b* – The top Cretaceous unconformity (mBu) in the Laptev Sea shows an inherited structural pattern of the *underlying* pre-Aptian unconformity with gentler topography; *c* – Top Eocene unconformity (UB) in the Laptev Sea illustrates changes in structural geometry compared to the underlying surface. These changes led to the fragmentation of the central curvilinear depression and the development of an extensive depression in the north; *d* – Base Miocene unconformity (RU) in the Laptev Sea shows the only sizable depression in the north of the study area and a system of shallow depressions rimming the Lena River Delta

continental origin of Upper Cretaceous rocks from the New Siberian Islands (**Fig. 6**). Strong downward movements of the basement in the northern part of the territory started only in the Miocene.

Thus, the depression zones of the second half of the Cretaceous period in the center and northeast of the Laptev Sea gradually subsided during the whole Cenozoic era. The downward motions in the north continue from the Eocene until now.

Thickness analyses of the main depositional units bounded by regional unconformities enabled the identification of depocenters and their shifting caused by the succession of tectonic events. A vast area of thickened Upper Cretaceous rocks delineated by the 2.000 km closing contour (**Fig. 7*a***) occupies the entire central part of the Laptev Sea, follows the Lena River Delta and spans the central part of the Buor-Khaya Gulf. This area comprises several multioriented depocenters, with sediment thicknesses varying from 3.500 to 5.500 km. Another area, in which the sediment thickness reaches 5.500 km, lies in the northeastern part of the offshore area. In the rest of the Laptev Sea, the average thickness of Upper Cretaceous sedimentary rocks ranges from 500 m to 1.500 km.

The maximum thickness of the Palaeocene–Eocene sediments does not exceed 2.500 km in the Laptev Sea (**Fig. 7*b***). These deposits are absent throughout much of the study area. Although the position of the depocenters was inherited from the Late Cretaceous, this sedimentary unit is much thinner (approximately 1.000 km), increasing to 2.000–2.500 km locally.

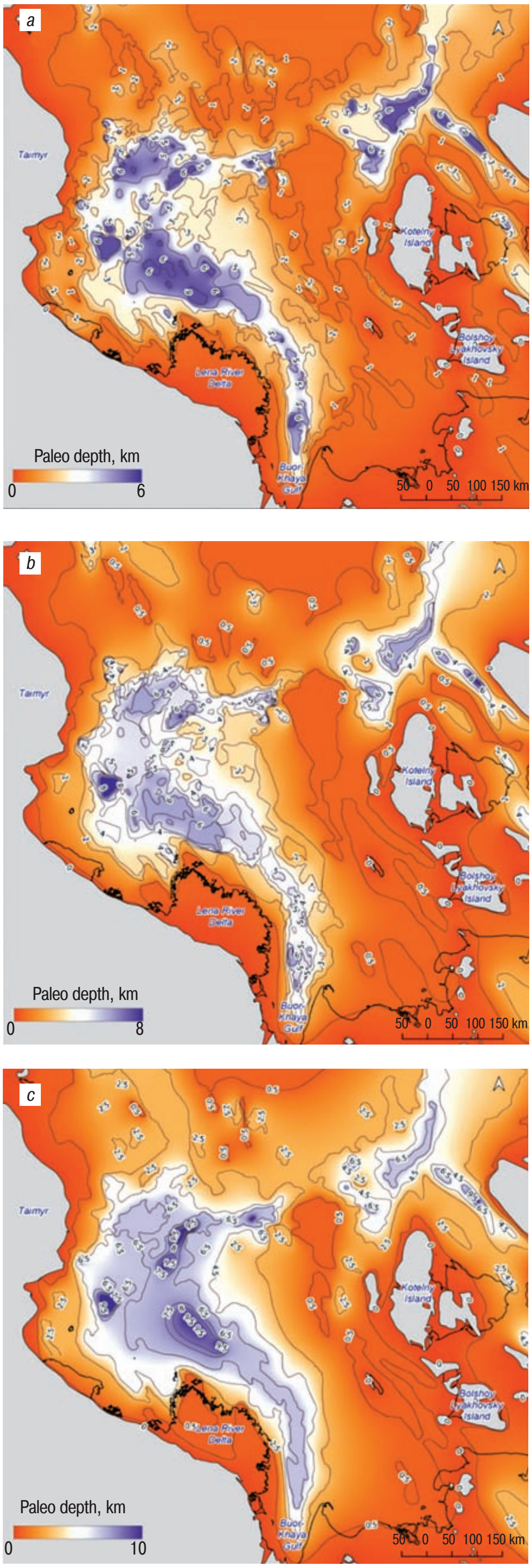

Fig. 6. Results of back-stripping analysis illustrate the base of the sedimentary cover structure at three different periods:
a – at the end of the Cretaceous; *b* – at the end of the Eocene; *c* – at the beginning of the Miocene

There are significant changes in thickness distribution patterns in the Oligocene depositional unit (**Fig. 7*c***). On average, the thickness of the Oligocene sediments varies from 1.500 to 2.000 km, increasing to 4.000 km in the area of the central depocenter. The depression itself becomes narrower, with its axis shifting eastward. The northeastern depocenter is severely reduced. Additionally, new depressions with sediment thicknesses of approximately 2.000 km emerged alongside the present-day shelf break.

The thickness distributions of the Miocene–Quaternary sediments notably differ from those of the underlying complexes (**Fig. 7*d***). The central depocenter degrades completely. The area of intense deposition shifted to the northern part of the study area. Its internal structure hosts several depocenters with relatively thickened deposits. A group of minor depressions with thickened (up to 2.000 km) Miocene–Quaternary sediments rim the Lena River Delta.

The thickness analysis reveals certain patterns in formation of the main sedimentary cover due to stage-wise tectonic evolution of the Laptev Sea area. These patterns relate with both lateral differentiation of thicknesses and their absolute values.

The analysis of sedimentation rates revealed considerable temporal and spatial variations. The northern and eastern parts of the study area experienced slow deposition (less than 50 m per million years) during the Late Cretaceous. The highest values (100–200 m per million years) are observed in the central Laptev Sea. Small areas with sedimentation rates of up to 200 m per million years are also observed to the north of the New Siberian Islands.

During the Palaeocene–Eocene, depositional processes slowed substantially (several folds), although the lateral differentiation of deposition rates was inherited from the previous stage of evolution.

When high rates of sedimentation resumed in the Oligocene, the area with high rates (more than 100 m per million years) expanded considerably, covering a large part of the Laptev shelf. Depositional rates reached 500 m per million years in the central Laptev Sea. The depositional process slowed again during the Miocene–Quaternary. The area with higher-than-usual values (100–130 m per million years) shifted to the northern part of the Laptev Sea margin.

These investigations enabled the delineation of two areas of consistent subsidence (region-scale depressions) (**Fig. 8**). One of these areas is the Central Laptev Depression, which covers a large area in the middle of the Laptev shelf. It contains sedimentary complexes from the Upper Cretaceous, Palaeocene–Eocene, Oligocene, and Miocene–Quaternary periods of various thicknesses due to the migration of depocenters during its development. The second area is the Novosibirsk Depression, located north of the New Siberian Islands. Its sedimentary cover is primarily composed of Upper Cretaceous deposits, with additional Palaeocene–Eocene and Miocene–Quaternary deposits.

Discussion

Our study reveals that the sedimentary cover of the Laptev shelf generally comprises Upper Cretaceous, Palaeocene–Eocene, Oligocene and Miocene–Quaternary units. The Ust-Lena Pro-Foreland covering the southern part of the shelf is the only exception, as the lower section of its sedimentary cover possibly includes deformed Upper Palaeozoic, Triassic and Jurassic rocks. Upper Cretaceous deposits prevail, among others.

The investigation allowed for the identification of four prominent stages of sedimentary cover development. The sedimentary units associated with each stage exhibit distinct spatial patterns in terms of thickness and sedimentation rates, primarily influenced by accommodation, which is in turn related to regional tectonic events. Deformations occurred at the transitions between the Early and Late Cretaceous, Late Cretaceous and Palaeocene, Eocene and Oligocene, and Oligocene and Miocene periods. This conclusion is supported by low-temperature thermochronology data obtained by Prokopiev et al. [26]. Based on structural observations and low-temperature thermochronology (apatite fission-track dating or AFT and U-Th-He zircon

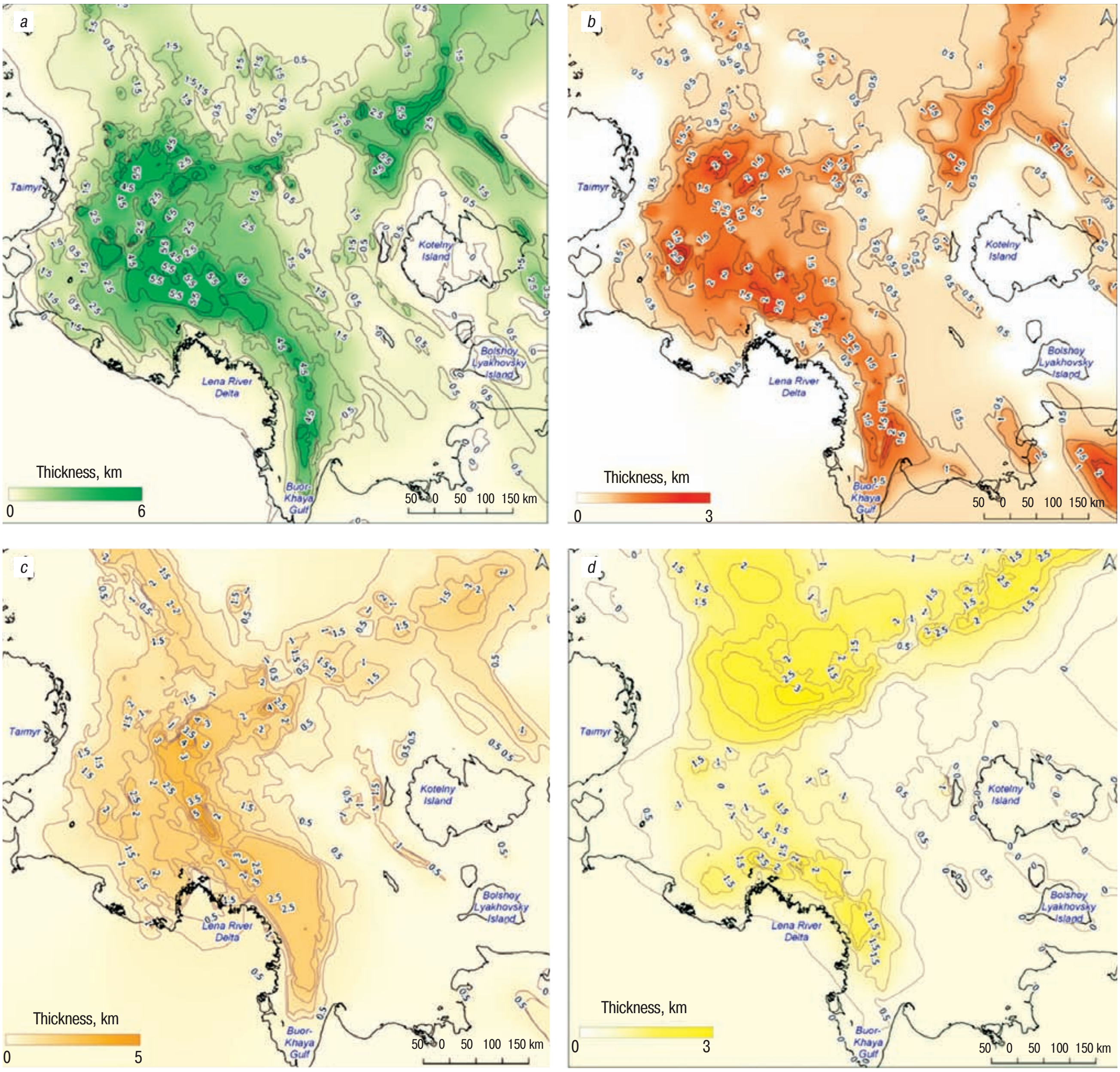

Fig. 7. Isopach maps represent the thickness of the main sedimentary units.

a – The Upper Cretaceous strata show a vast thickened area covering the entire central part of the Laptev Sea shelf and comprising several multioriented depocenters. Another zone where this unit is considerably thick lies in the NE part of the offshore area; *b* – The Palaeocene–Eocene unit shows a minor thickness of deposits. The location of the depocenters is inherited from the Late Cretaceous; *c* – The Oligocene unit shows a change in thickness distribution, such as a newly formed elongated depression in the northern part of the study area that follows the present-day shelf break; *d* – The Miocene–Quaternary isopach map shows a general change in thickness distribution. The central depocenter deteriorated, and the area of severe deposition shifted northward

dating or ZHe). Prokopiev et al. [26] established the successive order of tectonic events shaping the northern flank of the Verkhoyansk orogenic fold belt. According to the authors, the Verkhoyansk orogeny manifested itself for the first time at the end of the Jurassic, with a tectonic event associated with the attachment of the Kolyma–Omoloy continent to the Siberian platform. This assertion is supported by a thermal event (~156 mya) documented in the Ust'-Lena metamorphic complex [26]. The next thermal event was caused by thrust-related deformation accompanied by tectonic uplift in the Early Cretaceous (~140 mya, ZHe). The subsequent phases of compressional deformation (93–132 Ma and 60–75 Ma) interrupted by brief extension at the beginning of the Late Cretaceous were accompanied by the emplacement of dolerite dikes aged 86–89 Ma. The authors attributed this to the final stages of the closure of the South Anyui Ocean and the formation of the Novosibirsk–Chukotka fold belt [18].

The proposed sequence of tectonic events is consistent with the results obtained by Pavlovskaya et al. [17] on the basis of U–Pb dating from dikes. The authors conclude that the frontal part of the Verkhoyansk orogenic fold belt experienced two separate phases of deformation, one during the Early Cretaceous and the other during the Late Cretaceous. They interpreted the tectonic event at 76–60 Ma (Campanian–Palaeocene) as the reactivation of thrusts under compressional conditions in the east-west direction. This event, also recognized in southern Taimyr and in the Olenek fold zone, was

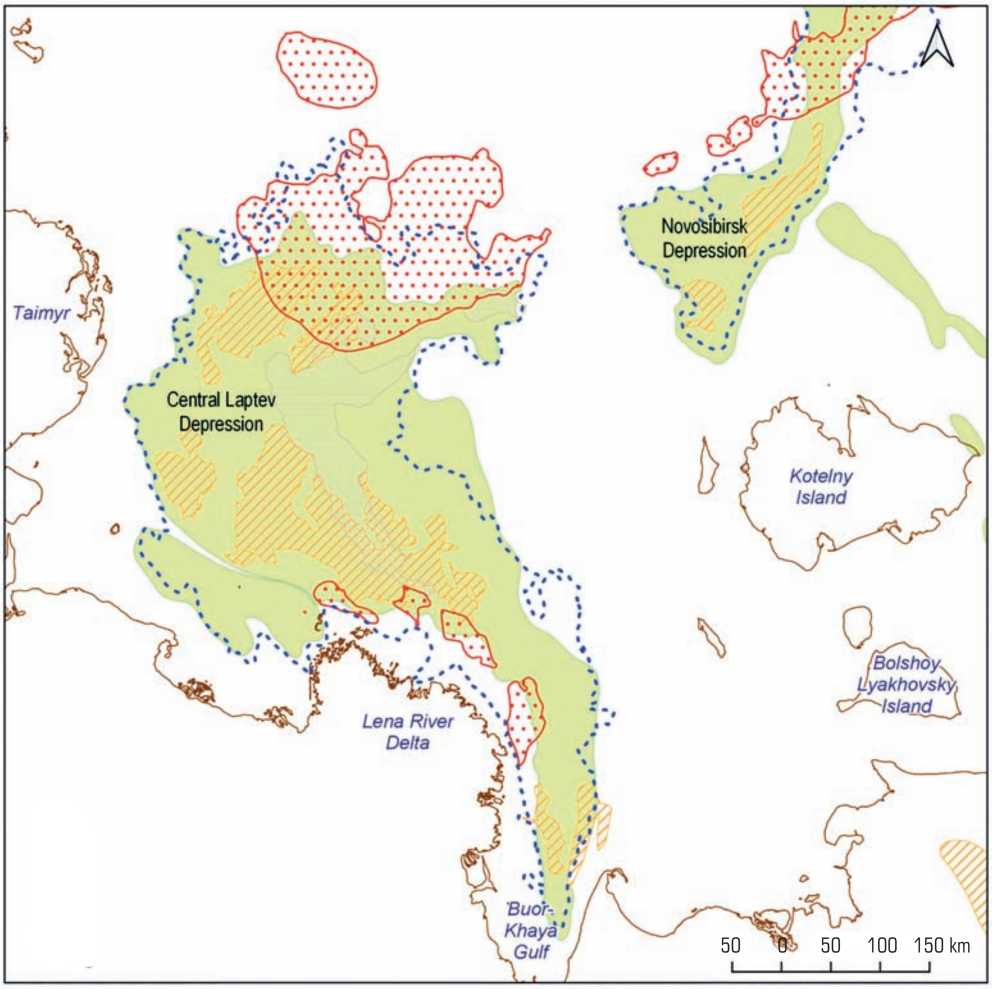

Fig. 8. Locations of the main depocenters and domains of consistent subsidence include the Central Laptev and Novosibirsk Depressions

Furthermore, the Lyakhovsky Islands are associated with the South Anyui Late Cimmerian collision suture [15, 16, 33, 34]. According to Kosko et al. [16], the southeastern part of Bolshoy Lyakhovsky Island represents its western segment.

During this period, a series of multioriented depressions with high subsidence rates formed under a transtensional shear setting in the central part of the shelf when the Alaska–Chukotka microcontinent attached to the Siberian Platform. Strike-slip faults in the northwest to southeast directions identified on the mBU depth structure map are believed to have developed during this time. Additionally, it appears that the southwest segment of the Khatanga transform fault occurred as an oblique fault within the curvilinear principal displacement zone.

During the Late Cretaceous period (80–60 mya), the opening and spreading in the Makarov-Podvodnikov Basin occurred as part of the North American lithospheric plate's counterclockwise rotation in the Amerasian Basin. The apex of this rotation was located in Greenland, while the spreading axis was perpendicular to the Canada Basin opening [15]. In the study area, compressional settings in the east-west direction with relatively low subsidence rates prevailed. The Verkhoyansk orogenic fold belt underwent tectonic uplift and erosion during this time.

accompanied by high denudation rates with increasing eroded rock thickness from west to east [17]. In the northern part of the Priverkhoyansk foredeep, the eroded thickness ranges from 2.0–3.3 km, reaching 3.0–3.4 km in the Kharaulakh anticlinorium. Such pronounced erosion suggests that denudation was probably related to vigorous tectonic uplift [19].

Thus, the Laptev shelf began to form in the Late Jurassic period. This happened around the same time as the early stages of the closure of the South Anyui Ocean and slightly preceding the active extension phase in the Canada Basin. Some researchers, including those referenced in studies [15, 27–30], support the rotational model of East Arctic development. According to this model, the initial opening of the Canada Basin (125–80 mya) coincided with a counterclockwise rotation of the Alaska–Chukotka microcontinent, moving it away from the Canadian Arctic margin towards the Siberian platform. This rotation occurred simultaneously with the ongoing closure of the South Anyui Ocean and the rifting in the Canada Basin.

By the mid-Cretaceous, the closure of the South Anyui Ocean had been completed, and the Alaska–Chukotka microcontinent had formed as the northern continental margin of the Siberian platform. The southern boundary between the microcontinent and the platform follows the South Anyui suture [31, 32], while the Western Laptev Shear Zone marks the western boundary. In this model, the New Siberian Islands are considered part of the Alaska–Chukotka microcontinent and not part of the Verkhoyansk Folded System, as proposed by Vernikovsky et al. [33, 34]. They argue that the Late Cimmerian fold-and-thrust basement of the islands is the outer zone of the Verkhoyansk–Chukotka fold belt that extends into the Laptev Sea [33–34].

Spreading in the Nansen–Gakkel Rift Zone (55–33 mya) initiated the development of the Eurasian Basin. This geologic event is reliably recognized based on magnetic data, as well as the integrated interpretation of seismic and well data [15, 29]. Spreading caused the Lomonosov Ridge microcontinent to break off from the Barents–Kara Sea margin, while the Laptev Sea margin experienced left-lateral movement along the Khatanga transform fault, separating it from the Eurasian Basin [15]. North of the Khatanga transform, a system of normal faults formed as the Eurasian oceanic basin opened. On the Laptev shelf, local extensional settings occurred against the background of predominant shear and compression, leading to subsidence adjacent to the main shear and along the oblique faults. Depressions with high subsidence rates in the Oligocene have been identified in the central Laptev shelf. This conclusion is consistent with data published by Pavlovskaya et al. [17], who studied small grabens containing Palaeogene sedimentary rocks in the Kharaulakh segment of the Verkhoyansk fold belt. The mirror-like slip surfaces indicate an extensional stress field associated with normal fault movement.

Since the Miocene, as back-stripping analysis revealed, the northern areas of the Laptev shelf have been involved in postrift subsidence, forming the Laptev segment of the East Arctic passive continental margin.

The geodynamic evolution described above affects the specific conditions of sedimentary cover development, which in turn control the size, facies, and thermal regime of sedimentary basins. In cases where deep wells are absent, such as in the Laptev Sea, assigning a basin to a certain geodynamic setting allows for predicting its geological structure and composition. The sedimentary basins identified on the Laptev shelf vary in terms of their formation mechanics and are linked to flexure, shear deformation, and lithospheric stretching.

The Ust-Lena Flexural Pro-Foreland is connected to the Verkhoyansk orogenic fold belt. The tectonic evolution of the study area reveals Late Palaeozoic to Jurassic folded rocks, primarily of marine origin, which formed along the Siberian continental margin. Additionally, Cretaceous and Cenozoic sedimentary rocks are present. Lower Cretaceous synorogenic deposits, consisting of coarse clastic material (molasse), were deposited in marine to marginal marine environments. Upper Cretaceous to Cenozoic clastic rocks were deposited in shallow marine to continental environments. Due to the thickened lithosphere in plate collision zones, heat flows in the basin are expected to be close to or lower than average values.

Basins related to shear deformation are found in the western and central Laptev Sea, where divergent (transtentional) shears are well represented. These basins are more tectonically complex than other types and form as a result of localized extension along a system of strike-slips. The composition of deposits in shear-induced basins reflects their complex history, with highly asymmetric lateral and vertical facies distributions, as well as widespread hiatuses and unconformities. It is believed that the delineated Late Cretaceous depressions contained extensive, relatively deepwater intracontinental basins. During the Palaeocene–Eocene period, accommodation slowed, and sediments filled the depressions persisting from the previous stage. This explains why the Palaeocene–Eocene interval has the least thickness of deposits among the main sedimentary complexes and hosts small, isolated depressions. Continental depositional environments apparently dominated the study area during this period. At the end of the Palaeogene, the basins experienced short-lived deepening, and since the Miocene, depocenters migrated northward, where sediments were deposited under epicontinental marine conditions. Heat flows in these areas are expected to be low.

The northern Laptev Sea hosts basins that belong to the passive margin associated with lithospheric stretching caused by extension in the Nansen–Gakkel Rift Zone. The sedimentary cover of these basins comprises a prograding wedge of sediments, predominantly formed in marine and shallow marine settings. Passive margins typically exhibit normal heat flows.

Therefore, considering the results of the integrated analysis, the commonly accepted theory regarding the rift origin of the Laptev shelf is doubtful. This theory was also challenged by Dor et al. [15]. According to plate tectonic reconstructions, the extension of the rift system must have reached approximately 600 km, based on the current ratio between the width of the Laptev Sea Rift System and the degree of Eurasian Basin opening [15, 35, 36]. However, this significant extension implies a substantial thinning of the continental crust, contradicting the results of gravity inversions estimating crustal thickness in the Laptev Sea area at 20 km [37]. Similar estimates were obtained from refraction data [12]. Moreover, an extension exceeding 500 km would have inevitably resulted in the complete destruction of the continental crust. Doré et al. [15] believe this finding is inconsistent with the present-day shallow depths of the Laptev Sea.

These arguments, along with the results of our investigations and established regional tectonic events such as the Verkhoyansk orogeny and the collision between the Alaska–Chukotka microcontinent and the Siberian platform, suggest that since the Late Jurassic, the Laptev shelf has been primarily affected by a compressional setting rather than an extensional setting, implying its shear-induced nature.

The analytical results obtained by the authors on the structural tectonics, paleotectonics and thickness of the main sedimentation levels point on the origination of the Laptev Sea margin through shearing (transpression) rather than through rifting.

Conclusions

The investigations we conducted have led to a significant reconsideration of the conventional geodynamic model of the Laptev continental margin. The new model of tectonic evolution suggests that the sedimentary cover on most of the Laptev shelf since the late Mesozoic developed under compressional and strike-slip deformation, disproving its rifting origin. This major conclusion is crucial for understanding the thermal evolution of basins for petroleum system modelling purposes.

Given that the Laptev shelf is considered promising for hydrocarbon exploration, the key outcomes of these studies are essential for further basin analysis, geologic risk assessments, and subsequent estimations of hydrocarbon potential in the area. The reconstruction of the geodynamic conditions behind the development of sedimentary basins allows for the prediction of their geologic framework, composition of deposits, and thermal regime, despite the lack of drilling data from offshore areas.

These studies have provided new insights into the internal structure of the main sedimentary complexes, including delineating depocenters, restoring their shifting throughout basin evolution, and estimating sedimentation rates.

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UDC 550.379

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INTEGRATED GEOLOGICAL INTERPRETATION OF GEOPHYSICAL DATA BASED ON 2.5D VOLUMETRIC MODELING

The relevance of the research is based on the need to enhance the efficiency of geophysical work in the search for zones of sulfide mineralization in the Northwestern Balkhash region, Kazakhstan. The aim of the study is to analyze, summarize and interpret geological and geophysical materials in order to identify promising areas. A comprehensive set of geological and geophysical methods has been applied, including high-precision gravity and magnetic surveys as well as electrical exploration. As a result of 2.5D volume modeling, taking into account various prerequisites and signs of mineralization, we have identified geological and geophysical criteria for detecting gold mineralization. It has been found that ore mineralization is associated with two types of deposits: terrigenous deposits of carbonates and terrigenous rock masses of the Famennian stage of the Upper Devonian. Geophysical criteria for distinguishing ore zones have been defined for these areas. It is found that non-ore areas show a widespread increase in all parameters of geophysical fields. The conducted research allows forecasting supplementary gold mineralization zones, facilitating future geological exploration for gold and associated metals.

Keywords: *Northwestern Balkhash region, gold, ore mineralization, 2.5D modeling, geophysical studies*
DOI: *10.17580/em.2025.01.02*