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MAIN STRUCTURE FORMATION UNITS IN SEDIMENTARY BASINS OF RUSSIA'S EASTERN ARCTIC SEAS: STAGES AND CONDITIONS OF FORMATION

In order to reach this paper's objectives aimed at studying hydrocarbon systems in the sedimentary basins within the East Arctic Seas, we have applied a specialized step-by-step technique of paleotectonic and geodynamic analyses. The initial steps of this procedure involve analyzing the present-day structural geometries of the main unconformities with a view to determining key tectonic stages in the evolution of the sedimentary succession. Specific aspects of vertical movement at each stage are also examined. This is followed by analyzing thickness maps of sedimentary formations between the main unconformities, identifying basin boundaries and areas of persistent downwarping. Next, depositional rates for each key stage of evolution are calculated and analyzed. Based on the studies of geodynamic conditions, we have conducted geodynamic zonation, and identified and described six structure formation units within the examined Eastern Arctic offshore areas: a unit of intermontane and foredeep depressions, an intracontinental unit, units resulting from shear and extension near plate boundaries, compression near plate boundaries, rift-driven extension, and a unit of overlying passive margins. A total of four structural levels have been identified in the Laptev Sea area (Cretaceous, Paleocene–Eocene, Oligocene and Miocene–Quaternary) and three structural levels in the East Siberian and Chukchi Seas (Cretaceous, Paleocene–Eocene and Oligocene–Quaternary).

Keywords: *The East Siberian Sea, the Chukchi Sea, the Arctic, structure formation units, depocenter, downwarping area*
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Introduction

The present geodynamic analysis used the rotational evolution model of the Eastern Arctic supported by many researchers [1–3]. This model is in good agreement with the completed structural imaging as well as with the integrated interpretation of the collected geological/geophysical and geochemical information about the Eastern Arctic offshore areas and adjacent landmass, including the up-to-date data over the period of 2019–2022 (seismic studies, radiometric and geochemical studies of rock samples from outcrops in the Verkhoyansk–Chukotka fold belt and the New Siberian Islands).

The model assumed that the initial opening of the Canada Basin in the period of 125–80 Mya years was coupled with the counterclockwise rotation of the Alaska–Chukotka microcontinent from the Canadian Arctic margin towards the Siberian Platform, similar to the rotation of a windscreen wiper.

This hypothesis is consistent with the present-day triangle-shaped geometry of the Canada Basin, the presence of a relict spreading axis detected in the gravity field and by two accompanying magnetic anomalies, as has been noted earlier. The apex of rotation lies in the Mackenzie River Delta, while the estimated angle of rotation relative to the pole is about 66 degrees. The absence of a series of magnetic anomalies (typical of spreading) along the axis of the opening suggests extension during the Cretaceous "quiescent zone" (118–84 Mya), slow spreading rates and spreading attenuation about 80 Mya. The rotational opening of the Canada Basin was accompanied by the formation of a right-lateral shear transform zone during the Early Cretaceous. The location of this zone is a debatable question, given the current lack of reliable geologic data [4]. For example, Grantz et al. (1979) [3] infer that the location of this shear zone matches the Lomonosov Ridge with the continuation toward the Siberian Platform. According to another view [5], the shear zone lies within the Alpha-Mendeleev Ridge.

The results of the plate tectonic reconstructions show that the opening of the Canada Basin caused the Alaska–Chukotka microcontinent to attach to the Siberian Platform from the west (relative to the north paleopole) [6]. The Kolyma–Omoloy terrane attached to the Siberian Platform from the north, forming the Verkhoyansk–Chukotka fold belt, as confirmed by the recent studies of tectonic events. This happened at the end of the Jurassic (slightly earlier than the active phase of extension in the Canada Basin), which matched the early stage of the South Anyui Ocean closure [7].

By way of example, according to E. A. Pavlovskaya and co-authors, deformations affected the frontal part of the Verkhoyanie in two separate stages, i.e. in the Early and Late Cretaceous, interrupted by an erosional hiatus (130–60 Mya). The completion of the main folding stage (90–85 Mya) was determined using U–Pb dates from dikes cutting across folds in the eastern part of the Kharaulakh segment.

The U–Pb calcite ages (76–60 Mya) from the central part of the Kharaulakh segment are consistent with the fission track ages but are younger than the dikes cutting across the folded structure. In the authors' opinion, this fact permits interpreting the tectonic event at 76–60 Mya as the reactivation of thrusts in the setting of the east-west compression, without a substantial influence on the structure of the segment. This event is also identified in the south of Taimyr and in the Olenek fold zone [8].

A. V. Prokopiev and co-authors established the successive order of formation of tectonic structures in the northern flank of the Verkhoyansk fold-and-thrust belt front using structural observations and low-temperature thermochronology data (apatite fission track dating — AFT, U–Th–He zircon dating — ZHe).

Paleotectonic analysis technique

As defined in [5], a sedimentary basin is an area of persistent downwarping of the Earth's crust, where sediments are either accumulating or accumulated in the geologic past. The existence and development of a sedimentary basin therefore requires accommodation space that can be filled with a sedimentary material. A basin cannot exist if accommodation space is absent.

With regard to the specific aspects of accommodation space generation, we can distinguish the following three main groups of basins: basins associated with lithospheric extension and subsequent cooling (different types of rifts), basins resulting from flexure-shaped bending of continental and oceanic lithosphere, and basins associated with shear deformations.

Thus, the essence of a geodynamic analysis lies in defining geodynamic settings that control specific aspects of the evolution undergone by sedimentary basins within the context of plate tectonics. This results in a geodynamic map showing these settings.

In order to reach this paper's objectives aimed at studying hydrocarbon systems in the sedimentary basins within the East Arctic Seas, we have applied a specialized step-by-step technique of paleotectonic and geodynamic analyses.

The initial steps of this procedure involve analyzing the present-day structural geometries of the main unconformities with a view to determining key tectonic stages in the evolution of the sedimentary succession. Specific aspects of vertical movement at each stage are also examined.

This is followed by analyzing thickness maps of sedimentary formations between the main unconformities, and by identifying basin boundaries and areas of persistent downwarping.

Next, depositional rates for each key stage of evolution are calculated and analyzed.

Results

The results of the studies suggest that the end of the Late Jurassic was a time when the Verkhoyansk orogeny showed itself for the first time and the northern branch of the Priverkhoyansk foredeep began taking shape. This is confirmed by a thermal event (~156 Mya) identified in the Ust'-Lena metamorphic complex [9].

The first stage of thrust-related deformations was accompanied by a tectonic uplift and a thermal event in the Early Cretaceous (~140 Mya, ZHe). The second stage of compressional deformations took pace 93–132 Mya (ZHe).

Short-lived extension at the beginning of the Late Cretaceous was accompanied by the emplacement of 86–89 Mya dolerite dikes [10].

Another deformational event took place about 60–75 Mya. The authors attribute it to the final stages of the closure of the South Anyui oceanic basin with formation of the Novosibirsk–Chukotka orogenic belt.

The results of thermochronology studies conducted at the front of the northern part of the Verkhoyansk fold-and-thrust belt and the Priverkhoyansk foredeep show that a tectonic event that took place 77–57 Mya (Campanian–Paleocene) was accompanied by high denudation rates. The eroded thickness increases from west to east and is estimated at about 2.0 to 3.4 km of rocks, respectively. In the northern part of the Priverkhoyansk foredeep, the denuded thickness ranges from 2.0 to 3.3 km, reaching 3.0 to 3.4 km in the Kharaulakh anticlinorium. Such pronounced erosion indicates denudation probably related to vigorous tectonic uplift [11].

Therefore, the Laptev Sea margin started taking shape at the end of the Jurassic with a tectonic event associated with the attachment of the Kolyma–Omoloy continent. This brought about the formation of the northern branch of the Verkhoyansk fold-and-thrust belt close to the northern boundary (relative to the position of the present-day North Pole) of the Siberian Platform.

The current understanding of how continental lithosphere behaves in tectonic compression settings implies that the building of an orogen is accompanied by the formation of troughs (flexural basins) on its either side. They exhibit negative Bouguer gravity anomalies suggesting that a mass deficit exists at depths [4]. Such troughs also include the Priverkhoyansk foredeep located within the Siberian Platform on the southern side of the Verkhoyansk orogen. Therefore, there is a flexural trough on the opposite side (in the Laptev Sea area) that matches the Priverkhoyansk foredeep and is composed of the Late Paleozoic, Triassic and Jurassic folded and predominantly marine deposits laid down earlier in the setting of the Siberian continental margin. This trough makes up the southern segment of the Laptev Sea margin.

As noted above, the first half of the Cretaceous saw the America–Chukotka microcontinent attach itself to the Siberian Platform, completing the Laptev Sea margin from the north, against the background of the continued closure of the South Anyui Ocean and rifting in the Canada Basin.

By the mid-Cretaceous, the closure of the South Anyui Ocean had come to an end, with the Alaska–Chukotka microcontinent forming the northern continental margin of the Siberian Platform. The southern boundary (the junction zone) between the microcontinent and the platform runs along the line of the South Anyui suture, while the East Laptev zone of compression forms the western boundary.

In this model, the New Siberian Islands are the part of the Alaska–Chukotka microcontinent and do not belong to the Verkhoyansk folded system extending into the Laptev Sea area, as believed by some researchers, including N. L. Vernikovsky and co-authors [12] and M. K. Kosko [10]. In their view, the tectonic basement in the area of the islands represents a fold-and-thrust structure in the outer zone of the Late Cimmerides of the Verkhoyansk–Chukotka fold belt.

The first scenario is supported by the Paleozoic zircon data for the Triassic and Jurassic deposits on the New Siberian Islands, Franz Josef Land, the Sverdrup Basin and the Lisburne Ridge that indicate their common source (**Fig. 1**). These areas are inferred to be located within the single intracontinental paleo-Barents basin. During the Triassic, its dominant source areas were Taimyr and the Polar Urals.

Moreover, according to Prokopiev, the Early Triassic mafic magmatism (235–245 Mya) on the Belkovsky Island supports connection between the formation of these dikes and the extensional processes at the rear of a magmatic arc. The latter could exist in the Early Mesozoic before the attachment of the Kotelny terrane to the Siberian craton [13].

It is generally agreed that the Lyakhovsky Islands belong to the South Anyui Late Cimmerian collisional suture [2, 6]. According to Kosko [10], the southeastern part of the Bolshoy Lyakhovsky Island represents its western link.

The second stage of the Amerasian Basin development was dominated by the opening and spreading in the Makarov–Podvodnikov Basin in the Late Cretaceous (80–60 Mya) against the background of the ongoing counterclockwise rotation of the entire Amerasian Basin (being a part of the North American lithospheric plate). The apex of rotation lies in the area of Greenland, while the axis of spreading is directed perpendicular to the axis of the Canada Basin opening. The model of the Makarov–Podvodnikov Basin formation from the results of the plate tectonic reconstructions [2] defines: 1) the presence of a shear zone along the shelf of the East Siberian Sea; 2) precursors of the spreading zone in the Makarov–Podvodnikov Basin (extensional zones) within the continental margin of the East Siberian Sea. Their opening came to an end after the formation of the transform zone.

The reviewed seismic data capture the geology in this part of the shelf as well as specific aspects of potential fields, and demonstrate a sharp boundary in the contact zone between the continental and oceanic crust. This contradicts gradual transition at the continent–ocean boundary (typical of the passive margin settings) [14, 15] and supports the existence of a transform zone.

Several small grabens (rifts), e.g. the Pegtymel graben, that experienced partial inversion [16] are mapped in the inner shelf of the East Siberian Sea. The results from our reconstruction of structural deformations along a seismic line indicated that the lower interval in the sedimentary succession of the Pegtymel graben formed in extensional settings that were later replaced by shear and compression, leading to inversion. The time interval for this period of extension is constrained by the time during which the boundary at

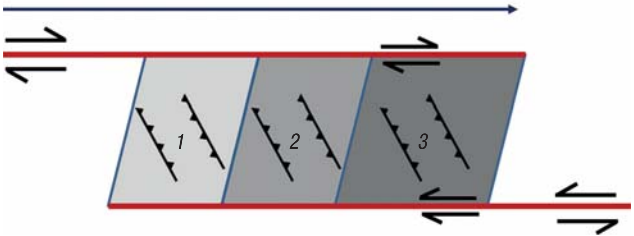

Fig. 1. Schematic map of formation of the Upper Cretaceous pull-apart basins in the East Siberian Sea

the base of the upper clinoform complex formed and can apparently be assigned to the Eocene. This does not contradict the proposed model for the contact between the rifted Makarov–Podvodnikov Basin and the adjoining area of the East Siberian Sea shelf along the shear zone.

Therefore, the boundary between the oceanic crust underlying the Makarov–Podvodnikov Basin and the Alaska–Chukotka microcontinent (being the part of the Siberian continental margin) runs along a major shear zone, i.e. a transform fault frequently referred to as the Khatanga–Bering transform in the published literature [1, 2].

This is a very important conclusion that fundamentally changes the current understanding of how the major sedimentary basins of the East Siberian and Chukchi Sea shelves originated, i.e. the Dremkhed Basin and the North Chukchi Basin. Until now, they were regarded as rifted depressions [7, 17, 18].

According to our interpretation, the Dremkhed Basin is a pull-apart basin formed in the zone of extension of the right-lateral shear zone during the second half of the Cretaceous due to the opening of the Makarov–Podvodnikov Basin.

This is evidenced by:

The presence of a system of orthorhombic faults according to seismic data (**Fig. 2**).

The diamond-shaped basin (**Fig. 3**).

The character of basin filling with sedimentary material, high rates of deposition (**Fig. 4**).

This scenario dictates the time range of the sedimentary fill, which is dominated by the Upper Cretaceous sediments, as well as a quiescent (platform) thermal regime.

As the Makarov–Podvodnikov Basin opened, the shear zone gradually moved eastward, causing the depocenters to shift successively. Figure 1 shows a simplified diagram illustrating formation of a series of pull-apart basins, with their depocenters denoted by numbers. In turn, the latter appear in a local extensional zone bounded by normal faults (or normal faults with a strike-slip component) that form at an angle to the main shear zone. As the shear zone moves farther and a new depocenter forms, the extension and the accommodation space generation in the depocenters from previous stages of the shear zone gradually fade away.

A series of such depocenters comes into clear focus on the thickness map between the pre-Aptian unconformity (BU) and the surface near the top of Cretaceous deposits (mBU) (see Fig. 2). The Dremkhed graben is the largest one in this series.

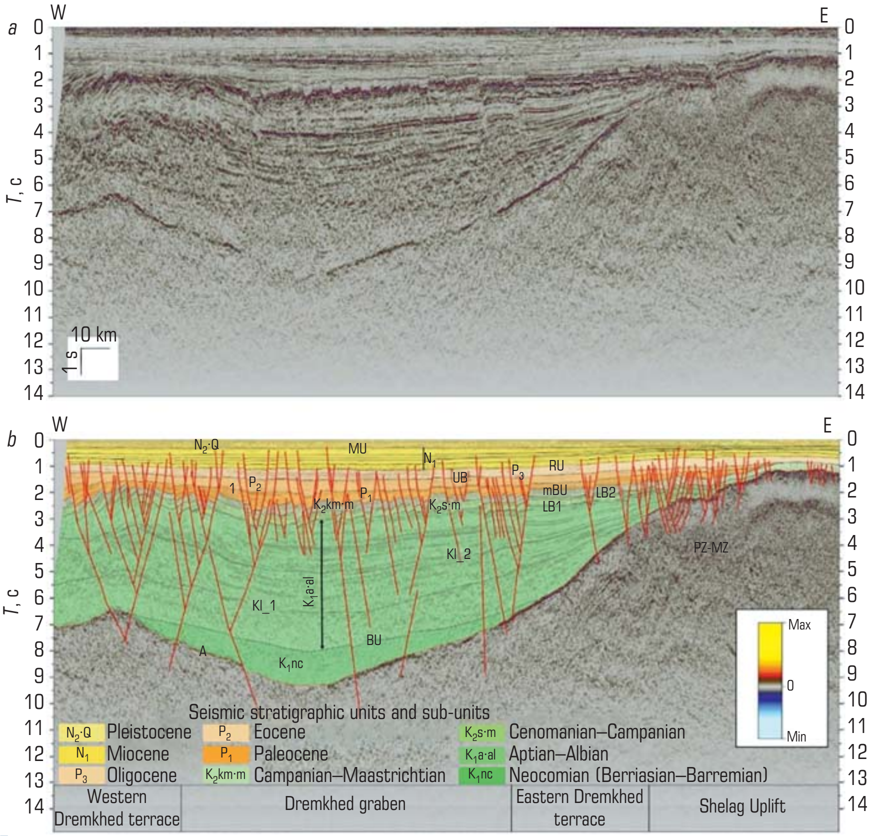

Fig. 2. Example of development of orthorhombic faults across the southern part of the Dremkhed graben: *a* – seismic section along the line; *b* – interpreted seismic [19]

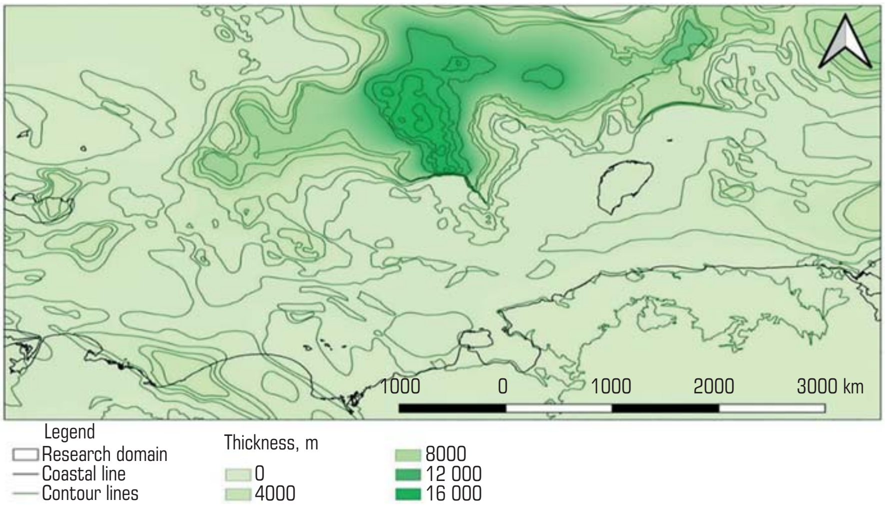

Fig. 3. Thickness distribution in Upper Cretaceous deposits in the East Siberian and Chukchi Seas

According to plate tectonic reconstructions [1, 2], the North Chukchi Basin differs from the Dremkhed Basin in that it began taking shape in the Early Cretaceous on the continental margin of the Canadian rift, and, thus, the Lower Cretaceous deposits play an important role in the lower interval of the sedimentary succession in the basin. When the Makarov–Podvodnikov Basin was opening, the North Chukchi Basin became drawn into the shear stress zone of the Khatanga–Bering transform at the final stage of the basin opening. As a result, the combined subsidence/deposition rates during this period were considerably lower than those in the Dremkhed graben. Extension came to an end in the Makarov–Podvodnikov Basin during the Paleocene. The Dremkhed and North Chukchi Basins were rapidly filled with sedimentary material and ceased existing within their previous boundaries without the key factor in accommodation space generation (**Fig. 5**).

From the Oligocene onward, the sedimentary succession of the East Siberian Sea shelfal area formed in a passive continental margin setting, with thick clinoform deposits accumulating in its outer zone and prograding toward the ocean.

It is noteworthy that the plate tectonic model used as a basis for our tectonic analysis gives a good explanation of the present-day tectonic position of the Wrangel Island and Brooks Range orogen. In this model, after the completion of the Canada Basin opening, they are the part of the North American Cordillera. A possible common origin of these two structures was

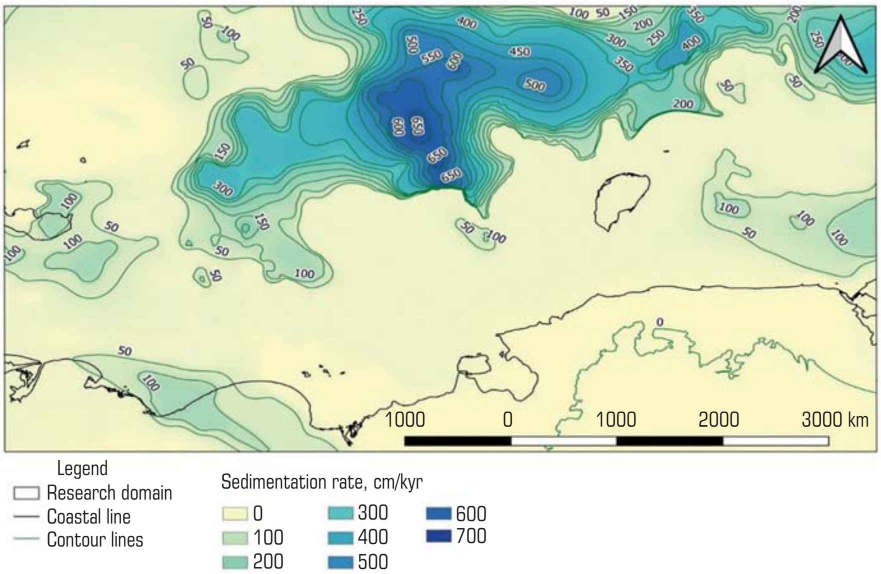

Fig. 4. Sedimentation rates in the East Siberian and Chukchi Seas (Late Cretaceous)

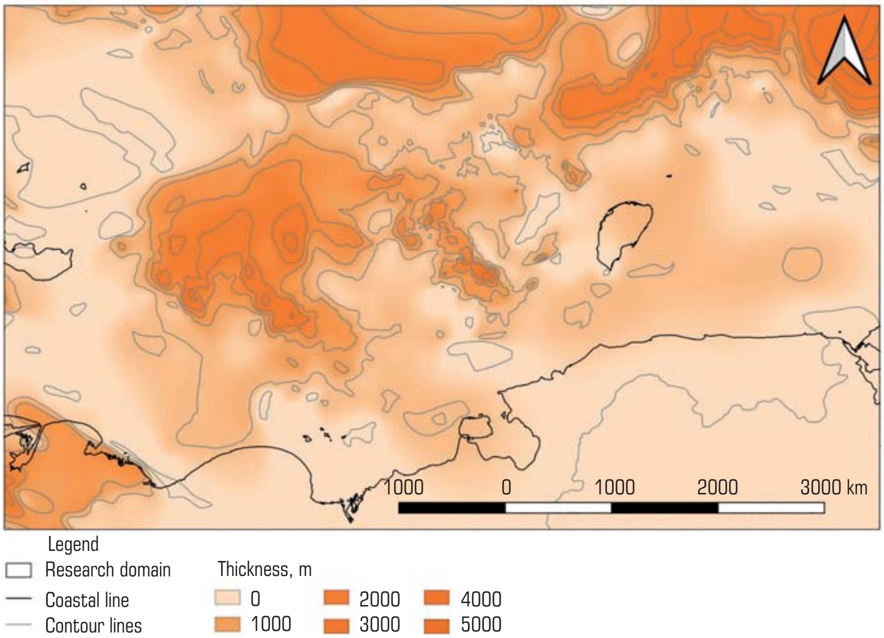

Fig. 5. Thickness distribution in the Paleocene–Eocene deposits in the East Siberian and Chukchi Seas

mentioned by some researchers [16, 20, 21]. This seems doubtful, as they are now 600 km apart. The proposed shear-related plate tectonic model eliminates these contradictions.

The third stage of the Arctic Ocean evolution involved the formation of the Eurasian Basin driven by spreading in the Nansen–Gakkel rift zone (55–33 Mya). This geologic event is reliably recognizable from magnetic surveying data, integrated interpretations of seismic and drilling results, etc. [2, 22, 23].

The spreading caused the Lomonosov Ridge microcontinent to break off from the Barents–Kara Sea margin. The boundary between the Eurasian Basin and the Laptev Sea continental margin (formed through the attachment of the Alaska–Chukotka microcontinent to the Siberian Platform in the Early Cretaceous) runs along the shear zone [24, 25].

In this respect, the commonly accepted rifted structure of the Laptev Sea continental margin appears doubtful considering our integrated analysis.

Given the current ratio between the width of the Laptev Sea rift system and the degree to which the Eurasian Basin has opened, the extension of the rift system must have reached about 600 km, in line with plate tectonic reconstructions [2, 26, 27]. However, such a large amount of extension implies a considerably thinned continental crust, which contradicts the results of gravity studies (gravity inversion) that estimate crustal thickness in the Laptev Sea area at 20 km [28, 29]. Similar estimates were obtained from refraction data [30]. The extension of more than 500 km must inevitably lead to the complete destruction of continental crust. Dor´e and co-authors believe that this is inconsistent with the present-day shallow depths of the Laptev Sea shelfal zone [2].

The arguments outlined above and the established regional tectonic events (the Verkhoyansk orogeny, the collision between the Alaska–Chukotka microcontinent and the Siberian Platform) suggest that since the end of the Jurassic, the Laptev Sea margin evolves in the setting of predominant general compression rather than extension.

The results of our structural–tectonic and paleotectonic analyses, as well as the thickness analysis of the deposits that make up the main structural levels, do not support the hypothesis about the rift-driven origin of the Laptev Sea margin and indicate its shear-induced (transpressional) character [31].

This is consistent with the specific aspects of the tectonic framework of the Mesozoic–Cenozoic deposits within the New Siberian Islands. In particular, M.S. Kosko and co-authors [4] differentiate two generations of faults while describing the folding on Kotelny and Belkovsky Islands, i.e. the Cretaceous NW-trending thrusts and normal faults with a shear component, as well as the Cenozoic north-south trending faults with shear, extensional and transpressional components. A Late Cimmerian structure formed in the setting of NE trending compression and its shear component manifested itself in an echelon mutual arrangement of second-order folds and their oblique orientation to the general strike of the structure [32].

The shear-induced character of the tectonic framework of the Laptev Sea margin results from the counterclockwise rotation of the Alaska–Chukotka microcontinent in the process of its collision with the Siberian Platform during the Cretaceous. The collisional character of the junction between the Siberian Platform and the Laptev Sea margin is confirmed by the studies by E.A. Pavlovskaya and co-authors [24, 33, 34]. They distinguish the 76–60 Mya tectonic event that took place in the Priverkhoyansk foredeep, Olenek fold zone and in southern Taimyr in the setting of east-west compression by studying stress fields and determining U–Pb calcite ages from slipping planes [35].

The spreading of the Eurasian Basin (55–53 Mya) caused the Laptev Sea margin to experience a left-lateral movement along the Khatanga transform fault. Local extensional settings originated against the background of predominant shear and compression, forming small multi-oriented depressions (both parallel to the axis of the main curvilinear shear and along the cutting tangential faults). For instance, such depressions (grabens) are studied within the Kharaulakh segment of the Verkhoyansk fold zone. Slipping planes characterizing the Paleocene–Eocene stage of deformations demonstrate an extensional stress field associated with normal fault movement [19, 36–38].

The high present-day seismicity at the junction between the Siberian Platform and the Laptev Sea margin (especially vigorously in the East Laptev compressional zone) is indicative of high stress still persisting in the subsurface and driven by the mutual transpressional movement of the Eurasian and North American Plates, confirming the shear-related character of the tectonic regime on the Laptev Sea shelf.

Our paleotectonic analysis shows that the northern areas of the Laptev Sea shelf were drawn into post-rift subsidence from the Miocene onward and make up the Laptev Sea segment in the passive continental margin of the Siberian Platform.

Conclusions

We have established a relationship between the seismically detected unconformities and the tectonic events associated with the three stages of evolution undergone by the Arctic Ocean.

Unconformities at the base of the sedimentary cover (pre-Aptian), at the top of the Cretaceous deposits and at the top of the Eocene have been detected throughout the succession in not only the Chukchi and East Siberian Seas but also the Laptev Sea. They are attributed to the following two stages in the evolution of the Arctic Ocean: opening of the Canada Basin (125–80 Mya) and rifting in the Makarov–Podvodnikov Basin (80–60 Mya).

The unconformity detected at the base of the Miocene in the Laptev Sea is related to the opening of the Eurasian Basin (55–53 Mya).

These unconformities divide the sedimentary succession into structural levels. Thus, a total of four structural levels have been identified in the Laptev Sea area (Cretaceous, Paleocene–Eocene, Oligocene and Miocene–Quaternary) and three structural levels in the East Siberian and Chukchi Seas (Cretaceous, Paleocene–Eocene and Oligocene–Quaternary).

Based on the studies into geodynamic conditions, we have conducted geodynamic zonation, identified and described six structure formation units within the examined Eastern Arctic offshore areas: a unit of intermontane and foredeep depressions, an intracontinental unit, units resulting from shear and extension near plate boundaries, compression near plate boundaries, rift-driven extension, and a unit of overlying passive margins.

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GEOLOGY AND METALLOGENY OF THE MOBILE MAGONDI BELT IN THE WEST OF THE REPUBLIC OF ZIMBABWE

Western Zimbabwe is the Paleoproterozoic Magondi Mobile Belt activated in the Neoproterozoic and Mesozoic. The Paleoproterozoic volcanogenic–sedimentary deposits contain copper and ores deposits attributed respectively to stratiform formations of cuprous sandstone and polymetallic formations in carbonate rocks. As a result of the analysis of geological structure of the deposits, an assumption is made that they belong to the pyritic copper and polymetallic pyrite formations and are related to volcanism. A large number of deposits and ore occurrences of tin, beryllium, tantalum and lithium in granite pegmatites and tungsten in quartz veins are associated with the Neoproterozoic era. Kimberlite pipes are found in the Mesozoic sediments of the cover. Most of the deposits are mined out but the prospects for discovering new objects are far from being exhausted. Despite many years of geological study of the area under discussion, many questions of the genesis of mineralization, its age and connection with geological formations remain insufficiently studied, and no metallogenic studies have been carried out.

New ideas about the origin of the Belt and on the connection of copper and polymetallic mineralization with volcanism are substantiated. Metallogenic zoning of this part of Zimbabwe is carried out on a scale of 1:2500000 with the delineation of metallogenic zones.

The occurrence patterns of the deposits and the metallogenic zoning of the western part of Zimbabwe can allow determining ore contents in the delineated metallogenic zones and estimating the metallogenic potential.

Keywords: *Magondi Belt, Dete-Kamativi Inlier, granite–gneiss, granite, metallogenic zone, pegmatite, copper, lead, zinc, tin, beryllium, lithium, kimberlite*
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Introduction

To the west of the Zimbabwe Craton, the area is characterized by widely occurring strata of the Mesozoic–Cenozoic sedimentary cover. Proterozoic metamorphic rocks that crop out in its fensters belong to heterochronous mobile belts. The craton is bordered in the west by the Paleoproterozoic Magondi Belt. Lying north and southwest of the latter are fensters with strata that respectively belong to the Neoproterozoic Zambezi Mobile Belt and the southern branch of the Neoproterozoic Damara Mobile Belt. In Botswana, deposits of cupriferous sandstones with high silver grades are commonly found in the Ghanzi–Chobe series of the Damara Belt. Confined to the knot of junction between these belts in Zambia is the Choma–Kalomo Block of metamorphic rocks (1.37–1.18 Ga) representing a remnant of the Mesoproterozoic Irumide Mobile Belt. It does not seem possible to clarify the geometry of the belts and their boundaries.

During the Middle and Late Proterozoic, the Magondi Belt underwent metamorphism and magmatism associated with the orogeny of neighboring belts.

In recent years, geologists have begun to view the Magondi Belt as part of the Paleoproterozoic Magondi–Okwa–Kheis mobile belt [1, 2]. This belt presumably stretches north to south from the Zimbabwe Craton through the territory of Botswana up to the western edge of the Kaapvaal Craton (**Fig. 1**) [3]. The belt extends for over 1.5 thousand km and is 250 km across at its widest point.

In Botswana, the outcrops of Paleoproterozoic metamorphic rocks are known in several small inliers (Okwa, Gweta, etc.), whereas in South Africa they occur along the western contact with the Kaapvaal Craton (the Kheis Belt) [1, 3, 4].