Paleotectonic Conditions Responsible for the Formation of Sedimentary Basins in the East Siberian and Chukchi Seas

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Abstract

We have studied sedimentary basins in the Eastern Arctic Seas using a specialized step-by-step technique of paleotectonic and geodynamic analyses. The initial steps of the workflow involve analyzing present-day structural geometries of the main unconformities to define key tectonic stages in the evolution of the sedimentary cover. Specific aspects of vertical movement during each stage are also examined. This is followed by the analysis of thickness maps of sedimentary strata between the main unconformities, and the determination of basin boundaries and areas of persistent downwarping. Next, we calculate and analyze sedimentation rates at each key stage of evolution. Final steps involve examining paleogeographic environments, identifying structural-formational complexes, and performing geodynamic zonation of the study area. Paleotectonic and geodynamic studies conducted as part of basin analysis have enabled us to detect depocenters at each structural level, trace their migration amid the territory's geodynamic evolution, and estimate the rates at which sedimentary material has accumulated. The identified sedimentary basins have undergone their own evolution against the background of major tectonic events that have taken place in the region. Specific aspects of this evolution are expectedly observed in the internal structure of the basins.

Key words

East Siberian Sea, Chukchi Sea, paleotectonic analysis, sedimentary basin, geodynamic studies, basement, depocenters.

Introduction

The basins of the East Siberian Sea and Chukchi Sea cannot be regarded as analogues, as they differ in a number of factors, e.g. tectonic regime, age, thickness of sedimentary complexes, the degree of their exposure to heat, and so on. There is still debate among geoscientists about fundamental problems such as the formation of hydrocarbon pools and zones of fractured uncompacted rocks in the crystalline basement, the formation of reservoirs and seals, certain aspects concerning the formation of granite massifs and how they are emplaced into upperlying horizons, and so on. This lack of consensus makes it impossible to create a comprehensive geologic basis for the prospecting and exploration for hydrocarbon accumulations in the basement. Moreover, there is no consensus on the age of deposits that make up the sedimentary cover of the basins as well as the conditions under which it has formed, which prevents us from adequately assessing their resource potential [1-7].

Technique of Paleotectonic Analysis

Paleotectonic analysis is a component of basin analysis and aims to reconstruct a region's tectonic evolution. A model of tectonic evolution provides necessary constraints for understanding the evolution of a sedimentary basin and allows us to divide it into stages (tectonic-stratigraphic phases) that correspond to important structural rearrangements caused by major tectonic events.

A tectonic-stratigraphic phase is a period in the evolution of a sedimentary basin, during which a certain combination of sedimentary and deformational processes that play a key role in the evolution of a sedimentary basin produces a paragenesis of tectonic and stratigraphic elements.

We have studied hydrocarbon systems of sedimentary basins in the Eastern Arctic Seas using a specialized step-by-step technique of paleotectonic and geodynamic analyses (Figure 1).

The initial steps of the workflow involve analyzing present-day structural geometries of the main unconformities to define key tectonic stages in the evolution of the sedimentary cover. Specific aspects of vertical movement during each stage are also examined [8].

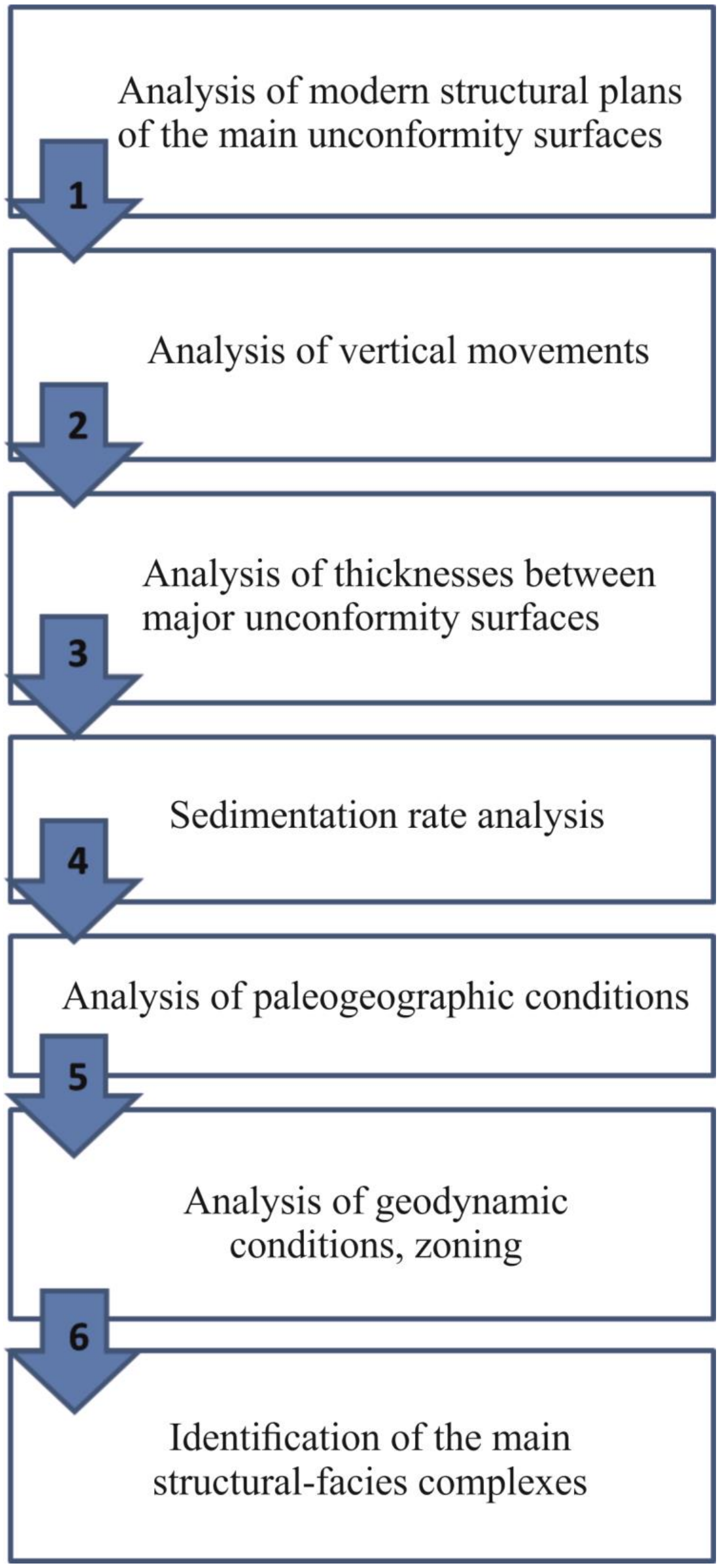

Figure 1 - Flowchart for paleotectonic and geodynamic analysis aimed at identifying structural-formational complexes and structural levels.

This is followed by the analysis of thickness maps of sedimentary strata between the main unconformities, and the determination of basin boundaries and areas of persistent downwarping. Next, we calculate and analyze sedimentation rates at each key stage of evolution. Final steps involve examining paleogeographic environments, identifying structural-formational complexes and performing geodynamic zonation of the study area.

Results of Paleotectonic and Geodynamic analyses.

Analyzing Present-day Structural Geometries of the Main Unconformities

Three main unconformities are recognized in the East Siberian and Chukchi Seas: the pre-Aptian unconformity at the base of the sedimentary cover (horizon A), the Top Cretaceous unconformity (horizon mBU), and the Top Eocene unconformity (horizon UB). These are regional unconformities for the Eastern Arctic, as they are attributed to tectonic stages in the evolution of the Arctic Ocean and adjoining continental margins that affected the entire territory (see Table 1).

It should be noted, however, that the effect exerted by these tectonic events varied, sometimes dramatically, across certain areas of the region. For example, rifting in the Eurasian basin did not have a major impact on the formation of the sedimentary cover in the East Siberian and Chukchi Seas and did not produce the respective unconformity [9]. Given these considerations, we built depth structure maps for these offshore areas using surfaces at the base of the sedimentary cover, the top of the Cretaceous and the top of the Eocene (Figures 2a, 2b, 2c).

The base of the sedimentary section lies at markedly different depths in the East Siberian and Chukchi Seas. In the northern part of the shelf there is a sizable depression in which the base of the sedimentary cover reaches a depth of 15-20 km (Figure 2a), while in the rest of the study area the pre-Aptian surface does not occur deeper than 9 km and has an average depth of 3-6 km.

The northern depressional area is heterogeneous in nature and comprises a series of roughly N-S trending basins, the largest being the Dremkhed and North Chukchi troughs. We believe that their origination was driven by the formation and subsequent development of a system of strike-slips conjugated with the rift zone of the Makarov-Podvodnikov basin.

The southwestern part of the East Siberian Sea area hosts several minor depressions where the base of the sedimentary cover is buried at a depth of 6 km. They are controlled by a system of NW-SE trending faults and appear to be associated with the attachment of the Alaska-Chukotka microcontinent (ACMC) to the Siberian platform [10].

The isolated roughly E-W trending South Chukchi trough is recognizable in the southern Chukchi Sea and is separated from the North Chukchi trough by the uplifted Wrangel-Chukotka folded area.

Compared to the pre-Aptian unconformity, the top of the Cretaceous is marked by an abrupt change in structural geometry (Figure 2b). The depth of the Cretaceous surface does not occur deeper than 6 km. The northern depressional area degenerates and changes its orientation from roughly N-S to EW. The geometry of depressions in the southwestern part of the East Siberian Sea area is substantially altered [11].

The structural geometry of the Top Eocene surface becomes considerably more simplified (Figure 2c). The unconformity is not deeper than 5 km in a single isolated depressional zone in the northern part of the shelf, while in the rest of the study area the boundary separating Eocene deposits from the upperlying ones occurs at a depth of 1-2 km.

Thus, there (the latest Early Cretaceous - Late Cretaceous, Paleocene - Eocene, and Oligocene - Quaternary) have been recognized in the evolution undergone by the continental margin of the East Siberian and Chukchi Seas. They result from the irregular manifestation of regional tectonic events.

Each stage corresponds to a structural level bounded by unconformities [12].

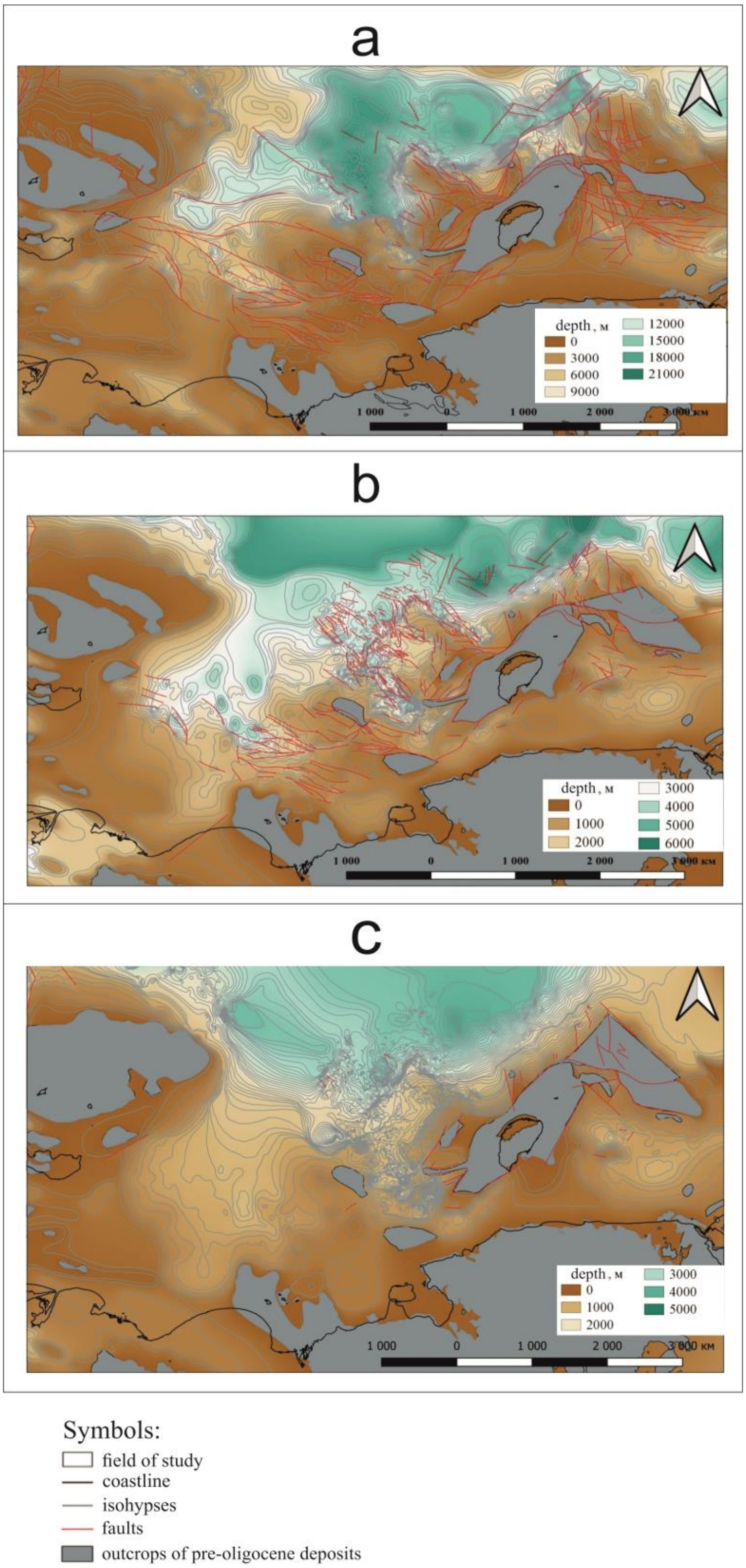

Figure 2 - Depth structure maps of: a) the pre-Aptian unconformity at the base of the sedimentary cover; b) the Top Cretaceous surface; c) the Top Eocene surface, within the East Siberian and Chukchi Seas

Analysis of Vertical Movement

The northern part of the study area underwent minor subsidence in the Eocene and Oligocene. The base of the sedimentary cover had progressively subsided to a depth of 1-2 km by the latest Eocene and to 2-3 km by the earliest Miocene. Descendent movements in the northern part of the study area began in the Eocene and have continued to the present day [13, 14].

In order to study vertical movement in the East Siberian and Chukchi Seas, we built paleotectonic maps showing the surface at the base of the sedimentary cover by the latest Cretaceous and the latest Eocene (Figure 3a and 3b).

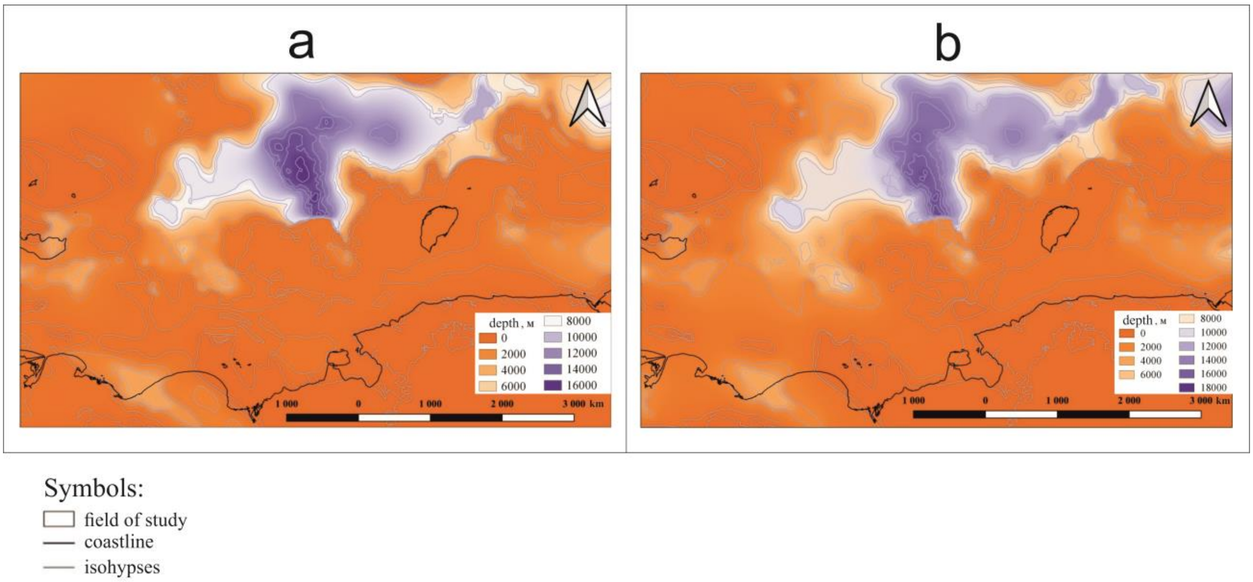

Figure 3 - Paleotectonic maps of the East Siberian and Chukchi Seas illustrating structures at the surface of the sedimentary cover: a) by the latest Cretaceous; b) by the latest Eocene.

As shown in Figure 3a, the depressional area in the northern part of the East Siberian Sea shelf had formed by the end of the Cretaceous. The base of the sedimentary section had time to subside to a depth of 16 km in the Dremkhed trough and to 14 km in the North Chukchi trough. The downwarping in this area also continued during the next stages in the formation of the sedimentary cover, albeit subsidence intensity decreased successively.

Our paleotectonic reconstructions indicate that the North Chukchi trough subsided at a slower rate (compared to the Dremkhed trough), when the depressional zone was in the early stages of its formation.

In the rest of the East Siberian and Chukchi Sea shelves, the main features of the modern-day structural geometry of the pre-Aptian unconformity originated in the second half of the

Cretaceous. The study area has experienced a quiescent tectonic regime throughout the Cenozoic and has undergone gentle successive subsidence at minor rates (Figure 3a and 3b).

Analysis of Thickness Between the Main Unconformities

The thickness of the main structural-formational complexes bounded by regional unconformities is analyzed with a view to detecting depocenters (sedimentary basins), tracing their migration amid the region's tectonic evolution and determining areas of persistent downwarping within the study area [15]. The dominant element in the pattern of distribution of Upper Cretaceous rocks across the East Siberian and Chukchi Seas is a vast depocenter located in the northern part of the modern shelf of these offshore areas. The depocenter has an exceptional thickness of 16,000 m in the central part (Figure 4a).

The western part of the offshore area hosts several small isolated depressions. The thickness of the deposits is 2,500-3,500 m, reaching 4,000 m in some depocenters. In the southern Chukchi Sea there is an area where Upper Cretaceous sedimentary strata are relatively thick, varying from 1,500 to 3,500 m in thickness. In the rest of the offshore area, Upper Cretaceous rocks are about 500 m thick.

The thickness of Paleocene-Eocene strata does not exceed 1,000 m over a large territory of the East Siberian and Chukchi Sea shelves. No rocks of this age are present in the sedimentary succession (Figure 4b). The central part of the East Siberian Sea shelf hosts a sizable area where Paleocene-Eocene strata vary in thickness from 1,000 to 3,000 m. Another three isolated depocenters are found along the northern boundary of the study area. Of these, two depocenters in the Chukchi Sea have the greatest thickness.

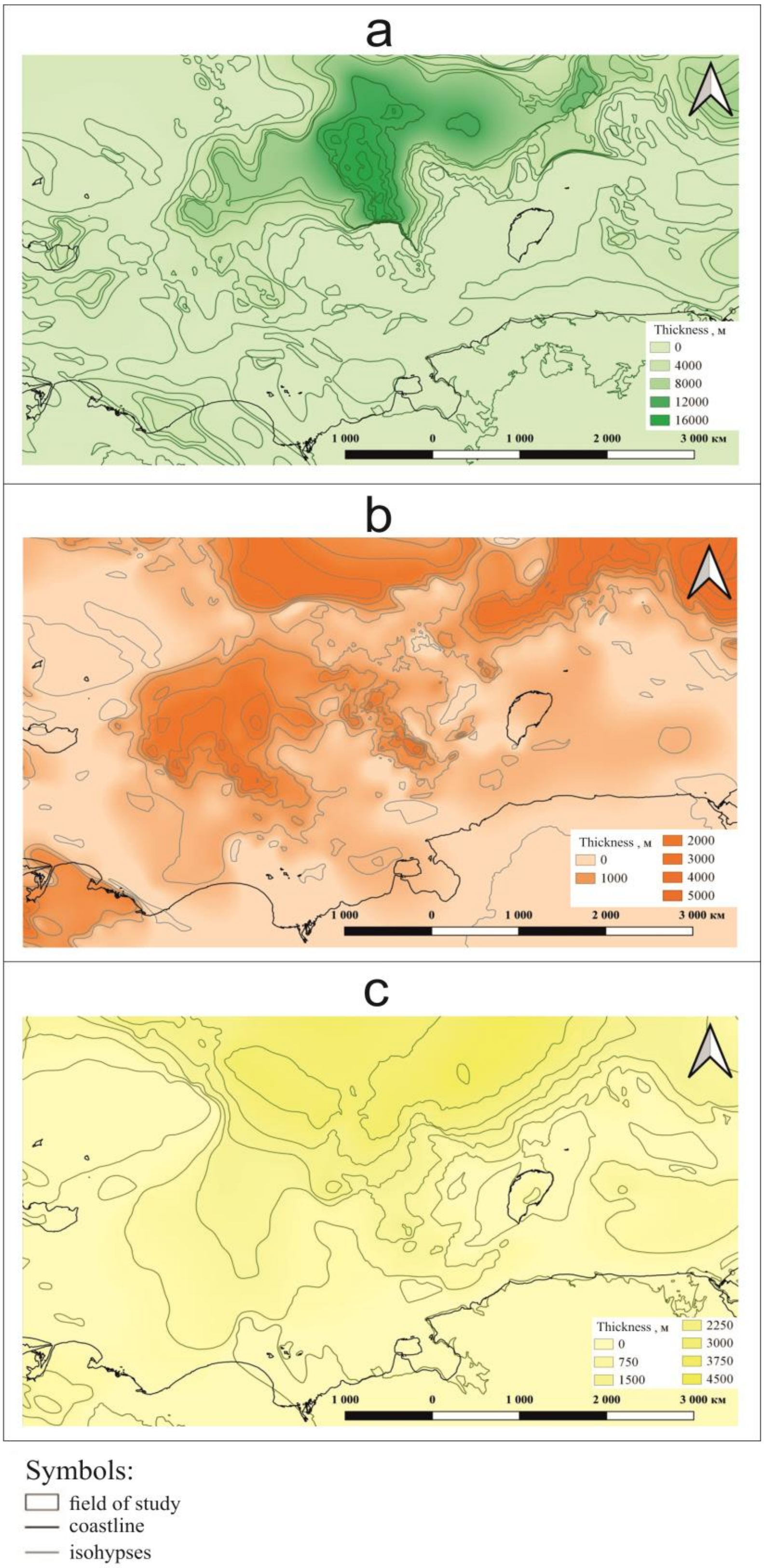

Figure 4 - Thickness distribution of: a) Upper Cretaceous deposits; b) Paleocene-Eocene deposits; c) Oligocene-Quaternary deposits, in the East Siberian and Chukchi Seas.

The thickness of Oligocene-Quaternary sediments is distributed in a fairly regular manner and varies from zero to 1,000-1,500 m (Figure 4c).

The main depocenter, where the deposits attain a thickness of 2,000-4,000 m, lies in the northern portion of the East Siberian and Chukchi Sea shelves. Our analysis indicates that the East Siberian and Chukchi Sea areas exhibit substantial lateral and time variations in the pattern of distribution of the main sedimentary complexes. This can apparently be explained by an abrupt change in tectonic regime [16].

An integrated schematic map (Figure 5) shows the location of depocenters within the studied Eastern Arctic offshore areas.

The largest depocenters are attributed to the Late Cretaceous stage in the formation of the sedimentary cover. Our thickness analysis shows that the section is dominated by Upper Cretaceous deposits.

The Paleocene-Eocene interval has the least thickness among the key recognized sedimentary complexes and contains a number of isolated depocenters.

We assume that the identified Upper Cretaceous depocenters are associated with the major sea? basins. Within the East Siberian and Chukchi Seas, the basin probably developed on a continental margin.

This period saw very intense accommodation space generation. Thick masses of sediment accumulated, as there was no lack of sediment supply.

In the latest Cretaceous - earliest Paleogene, the rate of accommodation generation slowed down abruptly and Paleocene-Eocene sediments filled depressions that persisted from the previous stage.

From the Oligocene onward, depocenters in the East Siberian and Chukchi Sea areas migrated in the northern direction. Deposits formed in a setting of epicontinental basins [17].

Our studies have resulted in identifying areas of persistent downwarping (sedimentary basins) within the study area (Figure 5).

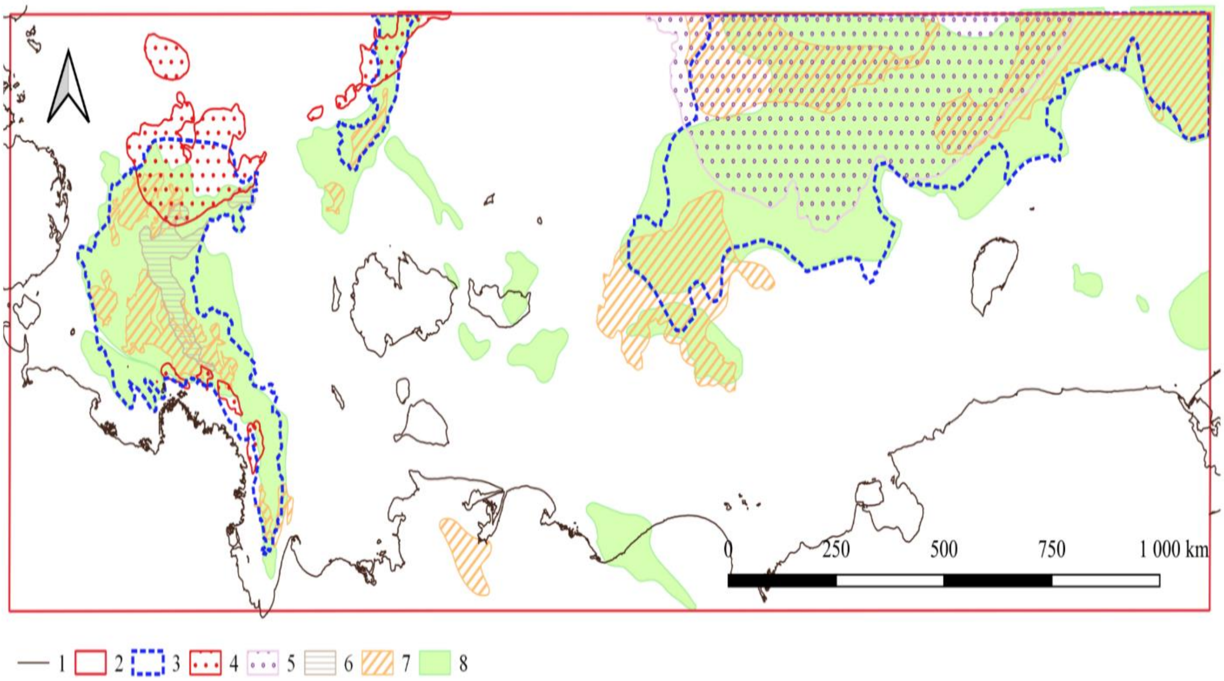

Figure 5 - Schematic map showing the location of heterochronous depocenters and areas of persistent downwarping in the Eastern Arctic offshore areas.

Legend: 1 – shoreline, 2 – areas of persistent downwarping. Key depocenters: 4 – in the Miocene - Quaternary, 5 – Oligocene - Quaternary, 6 - Oligocene, 7 – Paleocene - Eocene, 8 – Late Cretaceous

One of them is the major Dremkhed - North Chukchi sedimentary basin that lies in the northern part of the East Siberian and Chukchi Sea shelves and predominantly comprises Upper Cretaceous and Oligocene - Quaternary strata. Pre-Upper Cretaceous and Paleocene-Eocene deposits are subordinate in amount throughout the succession [18].

Another one is the Novosibirsk sedimentary basin that lies north of the New Siberian Islands and covers a minor area. Its sedimentary fill is largely composed of Upper Cretaceous rocks as well as Paleocene - Eocene and Miocene - Quaternary strata.

The identified sedimentary basins have undergone their own evolution against the background of major tectonic events that have taken place in the region.

Analysis of Sedimentation Rates

Our basin analysis involved calculating rates of deposition in the key sedimentary complexes.

There is no clear relationship between the value of a sedimentation rate and hydrocarbon potential of a sedimentary basin due to the fact that, on the one hand, the sedimentation rate is not the only factor and it affects hydrocarbon potential as part of the cumulative impact of other factors. On the other hand, its impact is evident at different levels, which is well exemplified by source rock properties.

The initial hydrocarbon-generating potential of oil and gas source rocks is defined not by the amount of organic carbon deposited in a basin, but by its portion that has transformed into kerogen during diagenesis. In this case, high sedimentation rates are a positive factor, as they contribute to the rapid removal of TOC from the surficial layer of sediments, where its content is reduced through oxidation and consumption by living organisms.

Regional-scale studies deal with averaged characteristics of sedimentation rates, which are calculated as a ratio between the thickness of a layer and the time period during which this layer was formed. Regional stratigraphic units vary in thickness from few kilometers to several dozen kilometers, while sedimentation rates define periods lasting for several dozen million years.

For the purpose of basin analysis, average sedimentation rates are interpreted from the perspective of trend identification. With this approach, high sedimentation rates are seen as a positive factor needed for a sedimentary basin to form and potential oil and gas source rocks to mature in the sedimentary cover [19].

Late Cretaceous sedimentation rates are distributed in an extremely irregular manner across the East Siberian and Chukchi Sea areas (Figure 6a).

Modest values (of less than 50 m per million years) are contrasted with several areas in the western and southern portions of the shelf, where sedimentation rates rise to 200 m per million years.

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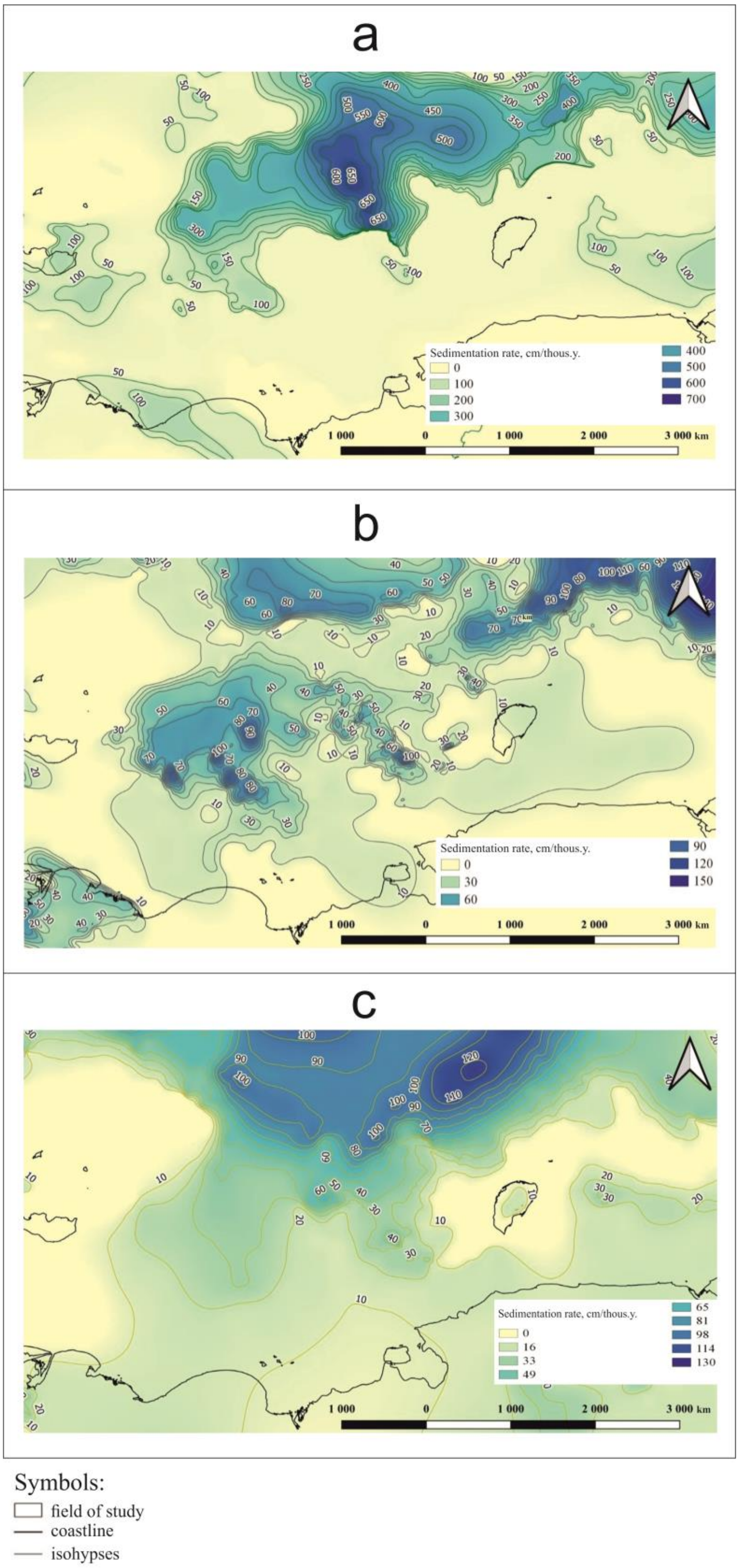

Figure 6 - Sedimentation rates in the East Siberian and Chukchi Seas: a) Late Cretaceous; b) Paleocene - Eocene; c) Oligocene - Quaternary.

In the northern part of the shelf, sedimentation rates exceed 300 m per million years, becoming abnormally high (600 m per million years and more) in some areas.

The pattern of sedimentation rate distribution changed profoundly in the Paleocene - Eocene (Figure 6b), when sedimentation processes slowed down considerably, as evidenced by lower sedimentation rates.

In the northern part of the shelf, the area of intense sedimentation becomes fragmented and degenerates into several narrow zones with rates of 100 m per million years. At the same time, a vast area with higher than average sedimentation rates (of up to 100 m per million years) is identifiable in the central East Siberian Sea. This area exhibits significant lateral differentiation [20].

From the Oligocene onward (Figure 6c), the area of maximum sedimentation rates (of up to 100 m per million years) shifted to the northern part of the shelf. In the rest of the territory, the rate of accumulation of deposits decreased abruptly to 50 m per million years. Our analysis of sedimentation rates in the Eastern Arctic offshore areas has revealed their variations in time and space controlled by the region's tectonic regime. Sedimentation rates rose in the second half of the Cretaceous and slowed during the Paleocene - Eocene [21].

Conclusions

The geoinformation base prepared by the authors comprises seismic, drilling and geochemical databases, collected factual evidence in these fields, and the results of its review and interpretation. These results include structural imaging of the main unconformities within the Eastern Arctic offshore areas, geodynamic and paleotectonic reconstructions, tectonic zonation, analysis of hydrocarbon indications, and identification of potential oil and gas source rocks throughout the succession.

We have established a relationship between seismically derived unconformities and tectonic events associated with the three-stage evolution of the Arctic Ocean.

The unconformities at the base of the sedimentary cover (pre-Aptian), at the top of the Cretaceous and at the top of the Eocene are traceable throughout the succession in the Chukchi and East Siberian Seas and are attributed to two stages in the Arctic Ocean evolution, i.e. the opening of the Canada basin (125-80 Ma) and rifting in the Makarov-Podvodnikov basin (80-60 Ma).

The unconformities split the sedimentary section into structural levels. Thus, we have recognized (Cretaceous, Paleocene - Eocene, and Oligocene - Quaternary) within the East Siberian and Chukchi Sea areas.

Paleotectonic and geodynamic studies conducted as part of basin analysis have enabled us to detect depocenters at each structural level, trace their migration amid the territory's geodynamic evolution, and estimate the rates at which sedimentary material has accumulated. As a result, we have identified two areas of persistent downwarping: the Novosibirsk and Dremkhed - North Chukchi sedimentary basins. These sedimentary basins have undergone their own evolution against the background of major tectonic events that have occurred in the region. Specific aspects of this evolution are expectedly observed in the internal structure of the basins.

The Dremkhed - North Chukchi sedimentary basin located in the northern part of the East Siberian and Chukchi Sea shelves is dominated by Upper Cretaceous and Oligocene - Quaternary strata. Pre-Upper Cretaceous and Paleocene-Eocene deposits are subordinate in amount throughout the succession. The Novosibirsk sedimentary basin lying north of the New Siberian Islands is largely composed of Cretaceous rocks and subordinate Paleocene-Eocene and Miocene-Quaternary strata.

In general, the study area is predominantly cut by the NW system of normal faults. This oldest system apparently dates back to the Early Cretaceous and is related to strike-slip faults with a normal fault component that rejuvenated during the Late Cretaceous-Cenozoic. NE-trending faults within the study area generally represent shear zones and the N-W trending of the main structures changes along these zones to roughly N-S and NE.

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