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Geological History Of East Siberian Sea Shelf

Aleksandr F. Safronov[a]

[a]Institute of Oil and Gas Problems of the Siberian Branch of the RAS, Yakutsk, RUSSIA

ABSTRACT
In our study we discuss the traditional and novel concepts of East Siberian Shelf origin with regards to the structure and composition of the Paleozoic and early Mesozoic sediments, coming to the surface on the Siberian Islands archipelago. The core idea is to summarize the existing concepts of East Siberaisn Shelf formation and to draw up the strong theory of its origin. We suggest that before the Middle Paleozoic, the Siberian Islands archipelago (Novosibirsk unit) was part of the Siberian craton. The formation of the South Anyui small oceanic basin became one of the key events in the geologic history of this territory. Formation of South Anyui small oceanic basin is associated with the Late Devonian-Early Carboniferous rift genesis. During the Late Paleozoic, the passive continental margin was formed on the southern slope of the Novosibirsk unit. After the closure of the South Anyui Ocean under the influence of Late Cretaceous stretching processes the rift system of the northwestern strike was formed, over which the East Siberian basin was later formed.

KEYWORDS
Middle Paleozoic, Siberian Sea Shelf, geological history, oceanic basin, continental margin

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Introduction

The future of Russian fuel and energy complex is connected with the development of oil and gas resources of the Arctic shelf. Therefore, regional geocryology is on the verge of becoming a new scientific field, associated with the study of submarine SMP, requires the study of the history of the development of the natural environment and its role in the formation of the modern state of the permafrost zone. The latter refers to data on its material composition; vertical structure; distribution and power; depth and power tier permafrost, their temperature at the present stage of development of SMP (Gusev et al., 2012).

The larger part of the East Siberian Sea shelf belongs to the western part of the Novosibirsk-North Chukchi basin. Different researchers consider this water area in different configurations and under different names. The "Yakut" part of

CORRESPONDENCE Aleksandr F. Safronov a.f.safronov@mail.ru

these waters is bounded from the west by the Kotelnichesk-Svyatonossky swell, which, according to the author's opinion, presents the deep erosional incision of the pre-upper Paleozoic base of the northern continuation of the West Verkhoyansk folded belt. To the east, the "Yakut" part is limited by the Vilkitskiy deflection (Andreassen et al., 2013; Cronin et al., 2012).

Submarine permafrost (SMP) on the shelf of the northern hemisphere covers an area of about 5 million km2. In its structure stand tiers cooled below 0 °C, and permafrost. Permafrost (MMP) are overwhelmingly relic (Alekseev Arkhangelov & Ivanova, 1992). The latter, in contrast to the thick subaerial MMP, characterized in its development a pronounced cyclical. At the stage of drying the shelf they are formed on the stage of flooding and degraded. Their present distribution, the depth and the power is more important than MMP subaerial settings depend on the history of the development of the natural environment (Andreassen et al., 2013).

To a certain extent, the nature of the East Siberian Sea shelf structure can be regarded by the cut fragments of the sedimentary cover, which becomes evident on the Novosibirsk archipelago islands and the adjacent structures of the Eastern Yakutia. There are several viewpoints and all of them to various extent recognize the existence of a major depression between the Verkhoyansk-Chukchi folded area and the DeLong median mass (many researchers link the tectonic position of this depression with the Hyperborean platform) (Andreassen et al., 2013; Fritz et al., 2012). There are different views regarding the stratigraphic range of the sedimentary cover of the East Siberian Sea shelf – from the total Phanerozoic stratigraphic range up to considering the Riphean-Silurian sediments as elements of the Caledonian bed (Fritz et al., 2012; Kirchner et al., 2013).

According to the views expressed in the works of M.N. Alekseev, A.A. Arkhangelov & N.M. Ivanova, 1992; D. Dove, L. Polyak & B. Coakley, 2014; Minakov et al., 2012, the Siberian Islands archipelago is a fragment of the ancient Arctic continent (Arctida).

The Paleozoic-Valangin cut of Kotelnyi Island opened by current erosion is deformed into folds of the north-west strike combined with the southwestern and northeastern vergence (Drachev & Saunders, 2006). The displacement age (late Mesozoic) is determined by the structural discordance on the Stolbovoy island dated late Early Cretaceous (Drachev, 2002). The western section structure of the Novosibirsk segment of the previously mentioned frontal zone is quite significant. Taking into account ruptures in the northwest strike, the Paleozoic-Early Mesozoic deposits of the far northwestern part of the Siberian Islands archipelago are in tectonic contact with Upper Cretaceous-Cenozoic sediments.Formation of the South Anyui small oceanic basin is one of the key events in the geologic history of the studied territory (Alexanderson et al., 2014).

Formation of the South Anyui small ocean basin is apparently related to the late Devonian-early carboniferous rift genesis. This rifting, as noted by N.L. Dobretsov (2005), S. Drachev & S. Saunders (2006) led to the formation of the Alazeya-South-Anyui Ocean (Pacific Bay) on the studied territory, which separated from the Novosibirsk unit from the Kolyma-Omolon unit. Apparently, the Oimyakon Ocean was simultaneously formed, which divided the Kolyma-Omolon unit from the Siberian continent (as it was previously mentioned, the author believes that the Kolyma-Omolonsky unit during the late Precambrian - early Paleozoic was a part of the Siberian continent).

Some authors (Dobretsov, 2005; Kirchner et al., 2013) believe that these two oceans were connected (presumably, in the north-west – with regard to the present coordinates).

The main geological stages of the East Siberian Sea shelf can be studied with regard to the structure and composition of the Paleozoic and early Mesozoic sediments, coming to the surface on the Siberian Islands archipelago (Kos'ko & Trufanov, 2002).

Conditionality of the current state SMP is mainly factors which had developed in the past, determines the need for a retrospective (geohistorical) approach to research (Dobretsov, 2005). It is carried out with the use of mathematical modeling of the evolution of the temperature field of rocks, carried out on the basis of the script development environment and the geological and tectonic model of the region. Linking modeling and field data makes it possible to use according to the IMF by natural factors, obtained by simulation, for distribution of drilling, geothermal and geophysical materials for the research area (Kleshchev, Shein, 2008). Modern computer software allows you to solve the heat equation for any boundary conditions in not only one dimension, but also two-dimensional versions. The main problems impeding the preparation of representative model data, due to the difficulty of drawing up a realistic scenario of the dynamics of the environment due to its insufficient study of the Arctic (Lakeman & England, 2012).

One of the least understood is the shelf of Eastern Siberia (the Laptev Sea and the western part of the East-Siberian). The first estimates of distribution and power of MMP-tier shelf, made in 60-80 years of the twentieth century, based on studies in the coastal part of the sea, and mathematical modeling. The results - until the opposite - failure were due at the reference data, the differences in the perception of climate variability and sea level rise, the poor development of computer technology (Dove, Polyak & Coakley, 2014).

Aim of the Study

Aim of the Study to summarize the existing concepts of East Siberaisn Shelf formation and to draw up the strong theory of its origin.

Research questions

1. Modify the Method of paleogeographic scenario to study the evolution and current state of SMP and create a script on the middle Pleistocene - Holocene shelf for Eastern Siberia, adapted for mathematical modeling and taking into account the cyclical nature of the global climate, sea level and specificity of the natural conditions of the region.

2. Determine the role of the geological structure, climate and global fluctuations in sea level in the permafrost development offshore Eastern Siberia in the Middle Pleistocene-Holocene. Create reconstruction of Late-Holocene sea transgression, taking into account the shelf topography changes.

3. Justify the idea of the development of local, mostly passive glaciation in the East Siberian Arctic.

Methods

The ice-grounding events are possibly related to floating ice masses from the Chukchi Borderland (Drachev & Saunders, 2006; Gusev, 2012) or from the East Siberian Shelf (Astakhov, 2013 & Bjarnadóttir et al., 2013). In seismic profiles across the shelf edge of the East Siberian and Chukchi seas, the top of Neogene sedimentary sequences is truncated. This truncation, accompanied by correlative sedimentary wedges on the upper slope, has tentatively been attributed to ice erosion (Alexanderson et al., 2014). In several locations along the East Siberian continental margin, this erosion is associated with MSGL mapped by swath bathymetry or wedges of debris-flow deposits visible in high resolution sub-bottom profiles (Hegewald & Jokat, 2013). Debris-flow deposits adjacent to eroded areas on the slope are interpreted as being formed by gravitational redeposition of eroded sediments near former ice-grounding lines.

In all locations the MSGL and glaciogenic wedges are covered by hemipelagic sediments, which drape several generations of grounding events. The thickness of well-stratified sediments overlying proglacial and subglacial diamicton ranges from 3 m on top of the Arlis Plateau to 20 m on the East Siberian continental slope. Older glacial streamlined lineations are found in deeper water where they survived subsequent grounding events in shallower water, for example, at about 900 m below present sea level on the Arlis Plateau (Fig. 1). In summary, the mapped landforms on the Arlis Plateau and along the East Siberian Sea margin may stem from thick coherent ice shelves or local ice sheets covering the Chukchi and East Siberian shelves during several glacial cycles in the past.

Iceberg plough marks from the final glacial event are mapped at present water depths between 350 m and 100 m in the entire area between the Chukchi Borderland and the East Siberian slope to 170E (Fig. 1). The pattern is irregular with crosscutting plough marks. These glaciogenic features are similar to the iceberg scouring described from the Chukchi Sea margin and overlain by deglaciale Holocene marine deposits (Kirchner et al., 2013; Lakeman & England, 2012). More mapping in this part of the Arctic Ocean is required in order to unravel the glacial history of the outer East Siberian Sea margin and adjacent bathymetric highs.

The main provisions of the retrospective approach to the study of permafrost shelf. The Low Permafrost study of the shelf of Eastern Siberia, despite the considerable amount of marine data and previously obtained in the coastal zone, determines the need for a retrospective approach to research. The retrospective approach is to study the modern state based on SMP recovery and tracing the history of the natural environment and the development of the permafrost zone from the beginning of the study period to the present.

This approach includes:

- preparation of the script of the dynamics of the environment;
- compilation of geological and tectonic model of the region;
- mathematical modeling of the evolution of the temperature field of rocks;
- linking of model and field data and making models of modern state SMP.

Geological-tectonic model of the shelf is intended to summarize and schematize in accordance with its geological and tectonic structure of the variability in the context of the area and the composition, moisture, thermal characteristics of the rocks and set the value of geothermal flow.

Mathematical modeling, produced in accordance with the scenario of the dynamics of the environment and the geological and tectonic model of the region, aims to reconstruct the evolution of the permafrost zone and its current state. It is performed under different conditions (composition and properties of rocks, sea depth, the geothermal flow, latitude, and so on.) Modeling allows to find out the regularities of formation of power-tier MMP and SMP in general, changing them in the waters of the area.

Results

Here we summarized the present status of the East Siberian Arctic Shelf Ice Sheet (ESASIS).

Glacial lineations found on the flank and top of the Arlis Plateau, located on the southern Mendeleev Ridge, are interpreted as MSGL and/or iceberg plough marks, which have NNEeSSW and NWeSE directions, respectively (fig.1).

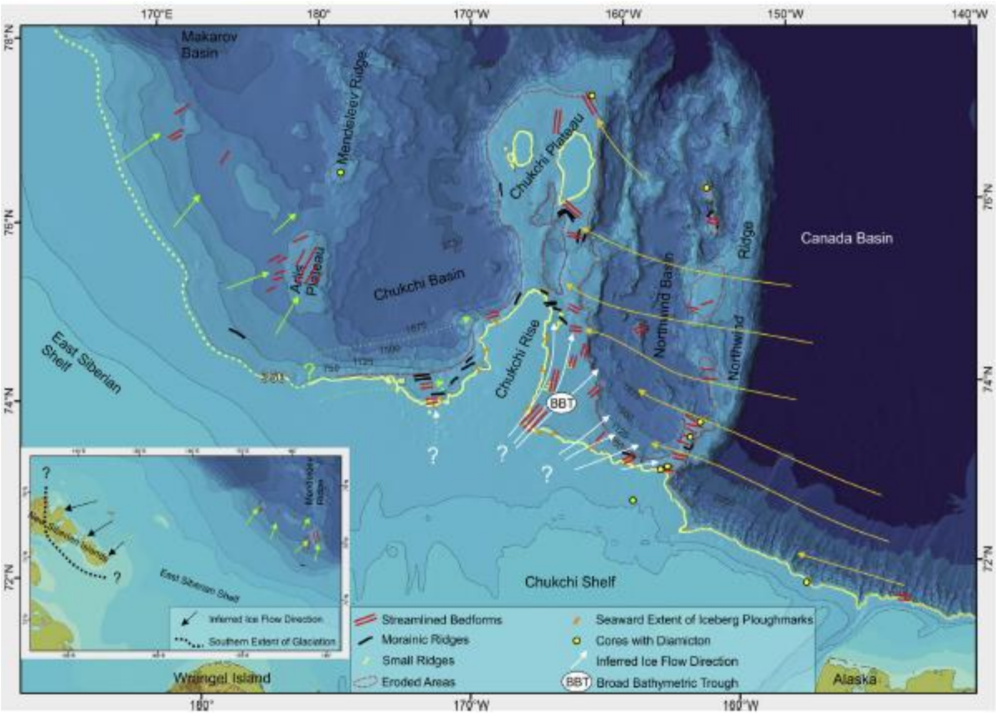

Figure 1. Distribution of observed glaciogenic features in the Chukchi and East Siberian seas (Dove, Polyak & Coakley, 2014; Niessen et al., 2013). Inset shows south-western limit of glaciation mapped on the New Siberian islands. Yellow line is the 350 m isobath which correlates well with observed seaward limits (orange) of iceberg-scoured seabed. Colour-coded arrows show inferred ice flows of different provenance. Dotted arrows are most hypothetical. Cores shown recovered glacial and iceberg-turbated diamictons on the borderland and shelf, respectivel.

Contrary to the Western Arctic with its extensive record of glacial geology, the ESASIS hypothesis was not based on geological evidence except for some interpretations of surface topography. It was theoretically postulated for East Siberia, and its most enthusiastic supporters never conducted field studies in the area except only during brief excursions. They consider that the main bulk of previous Quaternary work in Arctic East Siberia is inadequate, as it does not confirm to the theory.

Permafrost of the Arctic shelf unit and features SMP shelf of Eastern Siberia. The geographical position of the shelves is a major factor in determining patterns of formation and the current state of the shelf SMP. It reflects both the distribution of land and sea in the Arctic, which has developed as a result of its geological development and the dynamics of heat and moisture, to follow fluctuations in climate and sea level in the Pleistocene - Holocene.

According to the geographical location of the shelves marked sectors: Atlantic region (Barents Sea shelf), West Siberian (Kara shelf), Eastern Siberia (Sea shelf of the Laptev and East Siberian) Pritihookeansky (Chukchi shelf) and North American (Sea shelf Beaufort). Modern sectorial differences of submarine permafrost zone due mainly Sartan - Holocene history of changes of heat and moisture exchange shelf with the North Atlantic, the Pacific Ocean and the continents.

We came to conclusion that about a defining role compensation glacioisostatic movements in the formation of submarine SMP Beaufort Sea. Glacioisostatic movement bed Laurentian glacier led to the formation in his framing glacioisostatic uplifts during the existence of the glacier, is replaced by subsidence - during and after thawing. Fragment zone compensatory movement is the Beaufort Sea shelf. So it happened in the draining effect of raising, to compensate for a dive under the weight of the bed to grow Laurentian ice and flooding - due to the lowering of the lifting transformation. glacier degradation time (6 t.l.n.) corresponds to the shelf time of flooding, the assessment of which (5-2 t.l.n.) We state on the basis of time-dependent temperature field of frozen submarine rocks.

The independence of the power of MMP from the depths of the sea due to the fact that the draining-flooding (and, accordingly, aggradation - degradation of MMP) were caused by a sequence involving one or another offshore sites in glacioisostatic lifting at the beginning of the Ice Age and glacioisostatic lowering - at its end. The confinement of the shelf of the Beaufort Sea to raise the compensation is confirmed by the depth of its freezing. It is much larger than the surrounding land, are covered by a glacier (300-100 m).

Link the two-layer structure of the submarine permafrost from thawing under the dammed reservoirs in the drying stage of the shelf. We shares the view by (Dobretsov, 2005; Drachev & Saunders, 2006) of the thawing Late MMP top shelf at the stage of drying. However, thawing could occur in subaerial conditions. According to the author, it was carried out under the dammed ponds deglaciation. Compensatory lifting, blocking the advancement of the glacier to the north, in the era of deglaciation served as an obstacle to the flow of the rivers into the sea. With the raising of the transformation in the lowering of the Holocene is associated descent dammed reservoirs and change of freezing thawing. Thawed layer prior to the flooding of the sea was frozen only in part, led to a two-layer structure of submarine permafrost. The upper layer is the Holocene, the bottom - Late.

Thus, the main features of the Beaufort Sea SMP, SMP distinguish it from the shelf of Eastern Siberia (especially powerful tier of the IMF, and its two-layer structure; transient mode permafrost and lack of communication of its power from the depths of the sea), due glacioisostatic movements.

Thus, the permafrost conditions of the East-Siberian sector are the most severe in the Eurasian shelf, which stands in connection with the arrangement of the sector in the area of influence of the Asian anticyclone in cryochrons and in thermochrons.

From the interpretation of seismic data we conclude that the described rift basins of the Laptev Shelf were primarily formed in interaction with the opening of the Eurasia Basin. This view is only partly shared by S.S. Drachev (2002), who relates the opening of the New Siberian Basin to the opening of the Makarov Basin, a sub-basin of the Amerasia Basin, in Late Cretaceous (80–53 MA).

The fact that the north-northwest to south-southeast trending rifted basins of the Laptev Shelf coincide with the general trend of the South Anyui suture suggest that these basins formed along a zone of weakness that presumably was created in association with the subduction of the proto-Anyui Ocean.

Due to the distinct difference concerning size and architecture between the Anisin, Neben, and New Siberian Basins, which are best described as half-grabens, and the Ust'Lena Rift, we propose an additional major tectonic boundary close to the location of the MV Lazarev Fault. If the South Anyui suture extends to the Laptev Sea this tectonic boundary might have been formed by the further extent of that suture onto the Laptev Shelf and/or a major global-scale transform. The latter is proposed within the popular hypothesis of a counter-clockwise rotational opening of the Amerasia Basin (Drachev & Saunders, 2006) to trend along the eastern base of the Lomonosov Ridge and to meet the South Anyui suture somewhere around the New Siberian Islands.

Adding the width of all the major rift basins of the Laptev Shelf in east-west direction we get a value of about 580 km extension since the Paleocene. This value is close to a model of (Bjarnadóttir et al., 2013), who studied the deformation along the Laptev Sea's plate boundary on the basis of magnetic and gravity data. In the Laptev Sea, at 72◦ N and 122◦ E, their model predicts extension and transtension in the range of 452 km±20 km from 68.7 Ma to the Middle Eocene, and extension in the range of 186 km±28 km until the present. An episode of transpression from the Oligocene to the Middle Miocene as suggested by S.S. Drachev (2002) is predicted by (Bjarnadóttir et al., 2013) model only for the southern part of the Laptev Shelf with 9 km±3 km at 69◦ N and 130◦ E for the Early to Middle Miocene.

We found only negligible evidence for compression in these data. The seismic data from the East Siberia Shelf (Andreassen et al., 2013; Batchelor et al., 2012; Dove, Polyak & Coakley, 2014) allow the statement that large late Lower Cretaceous–Tertiary rift basins of the tectonic style of both the Ust' Lena Rift and the Anisin, Neben and New Siberian Basins, do not exist on the surveyed part of the East Siberia Shelf. The East Siberia Shelf can be considered as a relative stable epicontinental platform, composed of a complex suite of Paleozoic and Mesozoic rocks that subsided and sediments were deposited gradually since Late Cretaceous with stronger subsidence toward the north.

Earlier published geological maps and structural interpretations (Andreassen et al., 2013; Dobretsov, 2005; Ingólfsson & Landvik, 2013; Landvik et al., 2013) assume a continuation of the rift-related New Siberian Basin from north of the Cotel'nyi-Faddeya Islands onto the shelf of the East Siberian Sea. However, our suggestions provide no support for this widely accepted assumption. Instead, the data unequivocally show that the NW trending New Siberian Basin disappears as a distinct rift basin when approaching the New Siberian Islands (Faddeya Island and Novaya Sibir' Island). The surveyed part of the East Siberian Sea definitely does not show large Upper Cretaceous-Tertiary rift basins with the tectonic style of the Ust' Lena Rift and the Anisin Basin on the adjacent Laptev Sea shelf. Moreover, no indication for the Blagoveshchensk Basin, in its postulated form to stretch several hundred kilometers from south of the New Siberian Islands onto the East Siberian Shelf, could be found nor any indication for the so-called Anzhu Ridge postulated to form its northern boundary (Fig. 2). In contrast to the Laptev Shelf the entire region of the East Siberian Shelf is tectonically rather quiet; no large earthquakes (magnitude > 4.5) occurred in the past 30 years in that region (Alekseev Arkhangelov & Ivanova, 1992; Astakhov, 2013; Cronin et al., 2012).

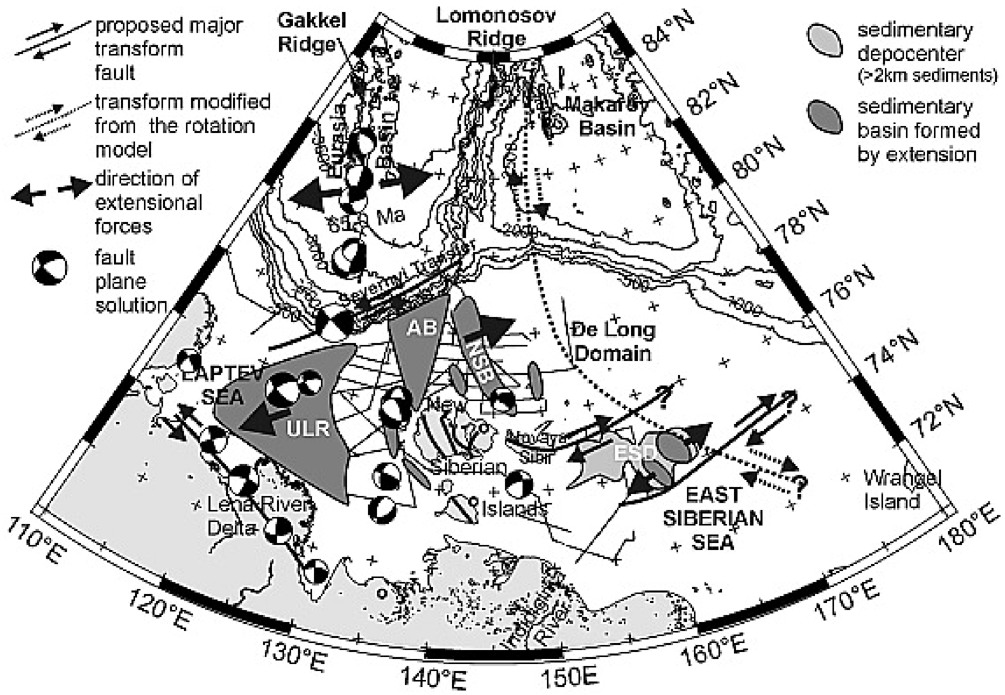

Figure 2. Basins and depocenters on the Laptev and East Siberian Shelf. The capital letters denote URL, Ust' Lena Rift; AB, Anisin Basin; NSB, New Siberian Basin; and ESD, East Siberian Depocenter.

We considered that starting from the Late Paleozoic the passive continental margin was formed on the southern slope of the Novosibirsk unit (Fig. 3).

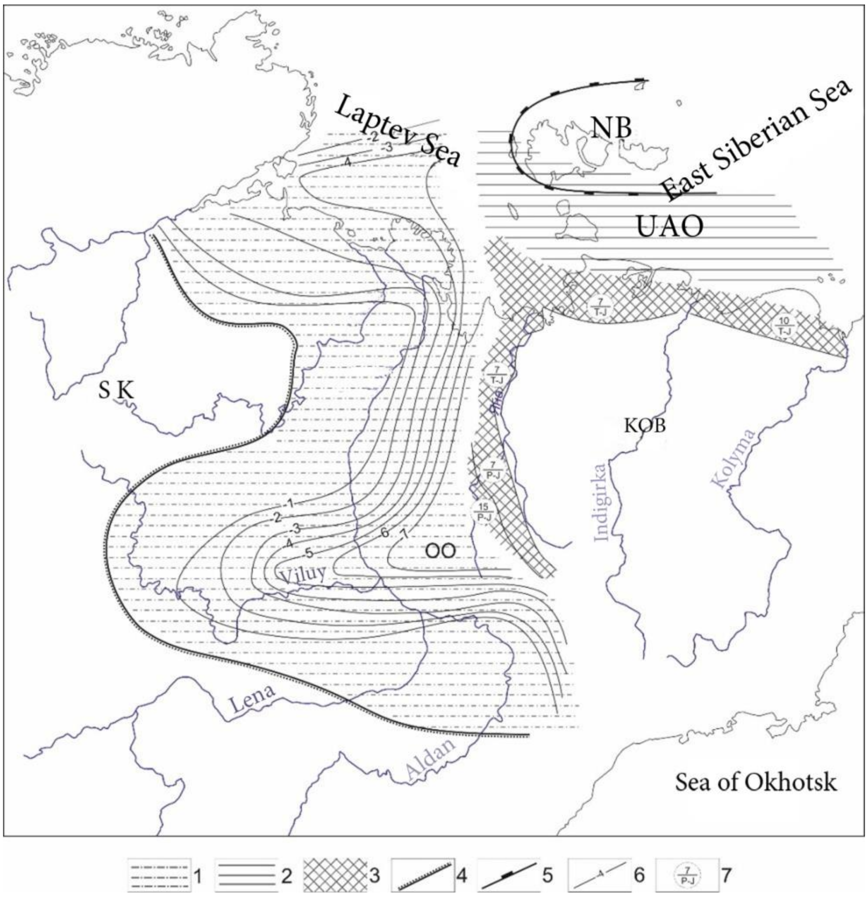

Figure 3. Geodynamics of the East Siberian continent and the northeastern sector of the Russian Arctic during the Upper Jurassic period. Legend: 1 – Late Paleozoic - Lower Mesozoic passive continental margin of the Siberian craton; 2 – Late Paleozoic passive continental margin of the Novosibirsk unit ; 3 – active continental margins of the Kolyma-Omolon unit; 4- inner boundary of PZ3 -MZ1 deposits on the Siberian craton ; 5 – Novosibirsk unit boundary; 6 – tessellationA lines of PZ3 –MZ1 thickness (km); 7 – thickness (denominator) and the age of sediments (numerator) of the active continental sediment complexes Continental units: СК=SC – Siberian continent , НБ=NU – Novosibirsk unit; КОБ=KOU- Kolyma-Omolon unit. Oceanic basins (bays): OO – Oymyakon ocean; ЮАО= SAO – South Anyui Ocean.

The existence of transform faults with the same general east strike as the Severnyi Transfer is proposed. The onshore extension of a major fault located on Novaya Sibir' Island and the faults located on the New Siberian Islands were adapted from M. Kos'ko and G. Trufanov (2002). Apart from the event south of Novaya Sibir' Island (Avetisov, 1993) the focal mechanisms are from (Niessen et al., 2013). At the intersection of the supposed east trending transform faults with the fault proposed by the rotation model the sag-shaped basins within East Siberian Depocenter may have formed. See text for a more detailed discussion.

We assumed to be composed of a complex suite of mainly Paleozoic and Mesozoic rocks that gradually subsided since Upper Cretaceous time with increasing rates toward the northeast but was also affected by some form of extensional/transtensional stresses that created the relatively small ESE–WNW striking sag basins. The discovered sag basins are thought to result from a deep-seated process in the kind of "flexural cantilever model" (Noormets at al., 2012) or of "depth depending stretching" (Ingólfsson & Landvik, 2013; Lakeman & England 2012); that is, upper crustal extension is significantly smaller than whole crust and/or whole lithospheric extension, affecting the pre-Cenozoic crust of the East Siberian Sea shelf during the Neogene.

With this scenario we would expect that the axes of the pull-apart basins, which developed along a northwest-southeast striking transform fault, have the same orientation as the transform fault. However, the axes of the discovered sag basins show an east-southeast to west-northwest strike orientation.

Therefore our favored interpretation is that the formation of the relatively small sag basins within the East Siberian Depocenter is closely linked with the opening of the Eurasia Basin instead of with the opening of the Makarov Basin.

We propose that the spreading process in the Eurasia Basin created extensional forces on the East Siberian Shelf resulting in east-west trending strike-slip or transform faults and thus the formation of pull-apart basins on the shelf of the East Siberian Sea. These assumptions are capable of explaining the basins geometry, but it is not clear why the extensional forces were transferred from the Laptev Sea to the east onto the East Siberian Shelf. A possible explanation is that the area of the basins of the East Siberian Shelf is located on an older zone of weakening that was reactivated by far-field stresses that also formed the rift basins in the Laptev Sea and resulted in seafloor spreading in the Eurasian Basin.

Discussion

The hypothesis of vast Arctic ice sheets was proposed in the 1960s when evidence for a grounded marine ice sheet was discovered in the northwestern Barents Sea (Drachev, 2002). Later it developed into the theory of a marine Eurasian ice sheet. Initially, the latter appeared as a complex of two ice domes grounded on the Barents-Kara continental shelf (Bjarnadóttir et al., 2013; Fritz et al., 2012). As more data were gathered, the limits of the reconstructed ice sheet were extended eastward to encompass the East Siberian shelf (Alexanderson et al., 2014), and even further east- and southeastward to cover the Chukchi, Beaufort and Bering Seas (Avetisov, 1993; Dove, Polyak & Coakley, 2014). A 1980 version of this theory was adopted by Denton and Hughes (Dobretsov, 2005) and CLIMAP Project Members (1981), and it gained support from certain glaciological M.G. Grosswald modeling (Jakobsson et al., 2012; Lakeman & England, 2013).

That version was repeatedly used by paleoclimatologists as data on boundary conditions for climate sensitivity experiments. Since the early 1980s, a comprehensive program of geological studies has been undertaken by Norwegian scientists in the western Barents Sea (Dove, Polyak & Coakley, 2014).

In the process, the glacialistic concept defended here was confirmed and substantiated by a wealth of new evidence of marine and terrestrial geology (Avetisov, 1993; Bjarnadóttir et al., 2013; Fritz et al., 2012). These results turned the Arctic ice sheet hypothesis into a piece of common wisdom as far as the western Barents Sea was concerned. However, in Russia, it has not been acknowledged and accepted by the prevailing number of specialists (Andreassen et al., 2013; Avetisov, 1993).

Up to now, it is generally believed that the available evidence for and against the ice-sheet glaciations in the rest of Arctic Eurasia is scant and incomplete, thus permitting a range of alternative reconstructions. This is no longer true.

Today we are in a position to make a sensible selection from the existing alternatives, based on the facts of glacial geomorphology and geology. There are sufficient data to permit a single reconstruction. Moreover, the hypotheses which purport to pose as 'alternative concepts' do not stand even the elementary test: they fail to conform with the evidence provided by geological surveys and space image interpretations. Until recently, all evidence for ice-sheet glaciation of the East Siberian shelves and coastal lowlands was sparse, indirect, and equivocal. The glaciation itself was considered highly problematic - especially since the ice-age climates of that part of Siberia were, and still are, broadly believed to have been too dry to enable initiation and growth of large ice sheets. Conversely and quite paradoxically, recent computer simulations based on advanced climate models suggest the opposite. Specifically, they yield vast ice-sheet glaciation of the Siberian North East, which appears more extensive than the Scandinavian ice sheet (Lakeman & England, 2012; Landvik et al., 2013).

Judging from current publications (Fritz et al., 2012; Löwemark et al., 2012; Pieńkowski et al., 2013), only cirque and valley glaciers occurred in the north of East Siberia during the Quaternary. Even Hopkins (Petrovskaya, Trishkina & Savishkina, 2008), who envisaged larger glaciers there, related them to the penultimate, not to the last glaciation. What is more important, he maintained that they were basically terrestrial features, restricted to highlands, and not marine ice sheets transgressing from continental shelves.

The fundamental study (Leonov et al., 2007) considered that according to the well-known rotary hypothesis (Drachev & Saunders, 2006) the Siberian Islands archipelago is a terrain, which until the end of the Early Carboniferous period was part of the North Asian (Siberian) Craton; then, during the late Triassic period, it moved to the North American continental slope, and during the Jurassic period returned to the North Asian craton again. The main argument presented by the study – is the presence of North Alaskan faunal associations in their deep-sea Triassic sediments. The author of this study believes there is no need for such intricate paleo geographic constructions.

Almost the same viewpoint was expressed by M.G. Leonov et al. (2007) stating that "during the early Mesozoic, before the American oceanic basin appeared, the Siberian Islands unit was a single terrain with the East Siberian shelf massif..." and that "the East Siberian Arctic Shelf unit is not an exotic terrain displaced during the Mesozoic period from the Arctic Canada, but is a continuation of the Siberian structures".

However, they also write that these two elements formed one single unit together with the Siberian platform at the beginning of the Mesozoic period. However, this is hardly logical, as the same authors argue (Cronin et al., 2012; Fritz et al., 2012) that "paleo Arctic (Anyui) ocean basin existed at least since the late Paleozoic and till the first half of the Late Jurassic" (Dobretsov, 2005; Larour et al., 2012; Noormets, Hogan & Austin, 2012).

The arguments presented by (Dove, Polyak & Coakley, 2014), which are critical to this conclusion and note the wide geographical distribution of the Late Permian Triassic traps, not specific only for the Siberian craton, in the author's opinion, does not deny it. In this regard, N.L. Dobretsov (2005) believes that although the traps are widespread, there is a difference in the magmatic series sequence - South China, for example, shows their reverse sequence as compared with the sequence of the Siberian platform - from tholeiitic to alkaline.

We believed that further immersion initiated the formation of the East Siberian over-rift basin, which at the basis was formed by a rift. Silt and clay-silt sediments accumulated in this basin. The age of these deposits is Aptian-Cenozoic. Throughout the formation of the East Siberian deflection, its structure was presented by a system of cavities separated by the substantially raised saddles.

The sediment thickness reached 9-10 km within the depressions, and within saddles - less than 5 km (Kos'ko & Trufanov, 2002; Kuzmichev & Pease, 2007). According to seismic surveys (Petrovskaya, Trishkina & Savishkina, 2008) a large number of rifts is observed within the East Siberian deflection. These rifts control the distribution of the sedimentary cover layer - horst uplifts and saddles separate depressions with a maximum thickness of the section. The Pliocene-Pleistocene cover sediments negate the previous structural plan.

Summing up the main ideas, we state that they are well linked with the conclusions made by (Laverov et al., 2012), who defines three main stages of the Mesozoic-Cenozoic evolution of the Arctic region. The very first stage, which lasted from the late Jurassic to Aptian age and which led to the formation of the Canada Basin, is the reason of collision between the Novosibirsk unit, the East Siberian Shelf massif (Dobretsov, 2005) and the active continental margin of the Kolyma-Omolon unit resulting in the closure of the South Anyui oceanic basin.

Considering the marginal basin formation because of isostatic immersion caused by the belt layers, it can be assumed that the moved structures of Anyui Chukchi belt blocked the margin depression that may have existed in the Upper Jurassic - Lower Cretaceous on the southern slope of the Novosibirsk unit. In other words, within the Novosibirsk consolidated unit under the influence (as it was previously noted) of the subsequent stretching process in the Arctic basin, the rift system was formed in the transformed continental margin streak body, over which the East Siberian basin was later formed.

The accretion of several terranes to the paleo-Siberian continental margins in the Late Paleozoic and Mesozoic resulted in the formation of several large fold belts: the New Siberian fold belt, which includes the New Siberian Islands and surrounding Laptev Sea–East Siberian Sea continental shelves, the Taimyr, Verkhoyansk and Cherskii fold belts.

The Chukchi fold belt, which includes the mainland, Wrangel Island, and associated Chukchi Sea shelf lies east of the study area. The fold belts underwent intensive pervasive deformation and were intruded by granitic plutons during Middle Jurassic to Lower Cretaceous time. Following this regional deformation the formation of large extensional basins has been postulated, which are named Blagoveshenk, New Siberian, North Chukchi/Vil'kitskii, and which are believed to be filled primarily with Paleozoic to Mesozoic – and possible some Cenozoic – sediments.

Conclusions

As a result of the research created new ideas about the current state of the permafrost zone of Eastern Siberia shelf. This regional study is also the paleogeographic and paleogeocryological, because the model of the modern state SMP obtained as a result of the evolution of the environment to date. The methodology of such studies has been almost no developed. This work was a comprehensive search character. Its main findings are as follows.

Concerning the evolution of the wide East Siberian Depocenter, the major transform fault as predicted by the rotation model offers a scenario with a slightly adjusted location of the fault to the east. With this configuration it is possible to explain the general dip of the relatively stable platform of the East Siberian Shelf toward the north that may be caused by dip-slip movements along this fault. The fault correlates with a gravity anomaly in the De Long Domain (152°E, 77.5°N to 157°E, 76°N) and contacts the location of the small basins within the East Siberian Depocenter.

A continuous Eurasian ice sheet impounded northward-flowing rivers, causing the formation of large proglacial lakes and their integration into transcontinental meltwater drainage system. The lakes experienced drastic changes in their extent, outlines, and levels, resulting from retreat and re-advances of the ice sheet, from consequent isostatic rebound, and from erosional deepening or sediment infilling of spillways and overflow channels.

So far, the drainage systems are not properly studied; however, the very fact of their existence, documented by a number of spillways, paleolake terraces and other features, constitutes a strong and independent argument confirming a continuous ice sheet in the Arctic.

It might be speculated that the major transform fault as predicted by the rotation model led to the weakening of the crust at the location of the small sag basins that were finally formed in the Tertiary, i.e., between early Oligocene and late upper Miocene according to our seismic-stratigraphic concept by E–W extension in connection with the opening of the Eurasia Basin.

In conclusion, it should be noted that before the Middle Paleozoic, the Siberian Islands archipelago (Novosibirsk unit) was part of the Siberian craton. The formation of the South Anyui small oceanic basin became one of the key events in the geologic history of this territory. Formation of South Anyui small oceanic basin is associated with the Late Devonian-Early Carboniferous rift genesis.

During the Late Paleozoic, the passive continental margin was formed on the southern slope of the Novosibirsk unit. After the closure of the South Anyui Ocean under the influence of Late Cretaceous stretching processes the rift system of the northwestern strike was formed, over which the East Siberian basin was later formed.

The tasks of further research. Our study is the first learning experience SMP on new information and methodological level. Due to the extremely weak study of the shelf of Eastern Siberia (geological, paleogeographic, geocryological) and the conditionality of the current state of the shelf SMP history of development priorities are twofold:

- Obtaining support material on the geological structure, the structure of power and SMP tier MMP; check nominated performances;

- Detailing ideas about the dynamics of the environment, especially in the last climatic cycle and glacioeustatic (sea-level dynamics, sedimentation, landscapes, cryospheric processes, temperature and species). Of primary importance, in connection with the involvement of the Barents Sea and the Kara Sea shelf to economic use, acquires a development technique issues permafrost research and mapping of the shelf SMP, including - a retrospective approach to research.

Implications and Recommendations

For the first time developed ideas about geocryological cycling on the shelf of Eastern Siberia, which inherits the cyclical fluctuations of global climate and sea level, and is manifested in the cyclic changes of direction in the development of the permafrost zone and cryogenic morpholithogenesis. The concept of cyclical cryogenic morpholithogenesis and differences in its expression in the positive and negative neotectonic structure will first reconstruct the Late Pleistocene-Holocene sea transgression, adjusting the shelf relief.

On the basis of complex traits put forward ideas about the existence of local, mostly passive glaciers in the East Siberian Arctic cooling in the Middle Pleistocene - Holocene. As used geothermal features, permafrost, geodynamic, geomorphic, geological and hydro-geochemical phenomena geographically connected to the area set by the glaciations.

Essentially new ideas about the current state of the relic SMP East Siberian Shelf. It is - with continuous permafrost MMP tier distributed in the range of modern sea depths from 0 to 50-60 m in the depth interval from 50-60 to 80-100 m (shelf edge) tier of the IMF and has intermittent island spread.

Produced division of the Arctic shelf by geographical location, which enabled them to separate from each other in terms of the formation of the permafrost zone and its current state. It was established that peculiarities of SMP in East Siberian shelf are determined by cryogenic processes, caused by the influence of the Asian continent.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

Aleksandr F. Safronov is Professor, Director of Institute of Oil and Gas Problems of the Siberian Branch of the RAS, Yakutsk, Russia.

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