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STRATIGRAPHY

Stratigraphic Drilling in the Northeastern Part of Laptev Sea: First Results

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Abstract—The Stratigraphic Drilling Project of the Russian Arctic Shelf, conducted by the Rosneft Oil Company, focuses their attention on the stratigraphic age and composition of rock complexes of the sedimentary basins. In 2021, six shallow boreholes for the first time were drilled with core sampling in the eastern part of the Laptev Sea. Drilling recovered sedimentary rocks of the folded basement that have been dated to the Late Barremian–Early Aptian. The synrift complex lying with angular unconformity has been dated to the Paleocene. The section of the overlying Eocene–Pleistocene sediments contains significant hiatuses. The data obtained by drilling together with the results of seismic interpretation allowed us to clarify the regional geological model and to date the stages of its tectonic evolution.

Keywords: Arctic Shelf, biostratigraphy, tectonics, Laptev Sea Basin

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INTRODUCTION

The age and composition of the sedimentary cover is crucial for solving both the fundamental scientific issues about the geological structure and evolution of the Arctic region and for a well-grounded prediction of the oil and gas prospectivity. The concepts about the age and composition of rocks of the sedimentary basins of the Eastern Arctic and the northern part of the Kara Sea have remained controversial and uncertain because of the absence of direct drilling data.

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Rosneft Stratigraphic Drilling in the Arctic (RoSDAr) has been carried out since 2020. The drilling is intent on determining the age and composition of the structural and rock complexes of poorly studied sedimentary basins (SBs) and elements of their oil and gas systems [1]. In the 2020 season, pilot works were carried out within the northern part of the water area of the Kara Sea (in the North Kara SB). In 2021 the works were continued in the Laptev Sea, in 2022 in the Chukchi Sea, in 2023 in the East Siberian and Chukchi seas. In 2022, Rosnedra initiated the drilling of the first borehole on the Arctic continental shelf in the northwestern part of the East Siberian Sea in the area of the De Long Rise together and with the assistance of Rosneft Stratigraphic Drilling Program in the Chukchi Sea. It was part of the program to substantiate the outer border of the continental shelf (OBCSh) of the Russian Federation [2].

As a result of this work, six boreholes, uncovering a section from 100 to 199.5 m (Fig. 2), were drilled within the Anisinsko-Novosibirskii license area of Rosneft, located to the north of the New Siberian Islands (Fig. 1). The boreholes were arranged in such a way as to characterize the entire section of the sedimentary cover of the study area from the top of the

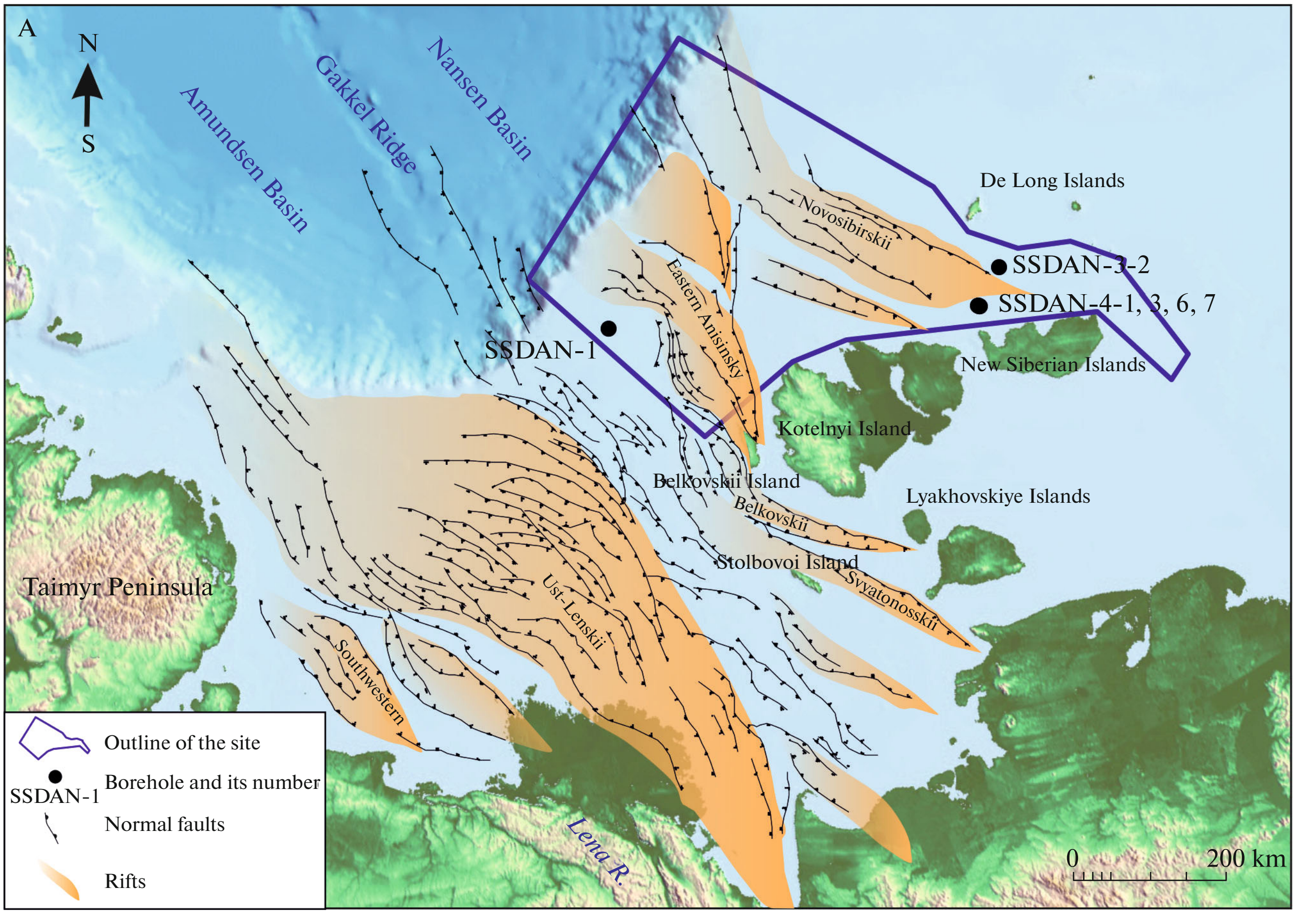

Fig. 1. Scheme of the main structural elements of the Laptev Sea region, compiled using data of [17] and [11] and materials of the Arctic Research Center of Rosneft.

folded basement with its penetration. A total of 415 m of core was obtained (Figs. 2, 3).

During the expeditionary works, an engineering shallow ultra-high resolution seismic survey (UHRS) was also carried out along profiles passing through drilling points in order to obtain a detailed seismic image of the upper part of the section and to refer seismic horizons to the data of boreholes. The vessels *Captain Voronin* and *Kern* were engaged to perform engineering and geophysical works.

PRELIMINARY RESULTS OF DRILLING

According to the seismic stratigraphic data, two structural levels are distinguished within the Anisinsko-Novosibirskii area—the folded basement and the unconformably overlying cover. They separated by the surface with distinct angular unconformity (reflecting horizon (RH) Fa), below which a seismic pattern typical for the areas of folded thrust tectonics is observed. The overlying cover complex has essentially different features of the seismic stratigraphy and tectonics (rift-related structure).

To determine the age of rocks from the cores of all boreholes, a palynological analysis was performed; the foraminifer fauna was studied in borehole SSDAN-1 (Fig. 2). We analyzed 150 core samples from five boreholes SSDAN-1, SSDAN-4_1, SSDAN-4_3, SSDAN-4_6, and SSDAN-4_7. The analysis of the palynomorph complexes allowed us to establish several associations, one of which characterizes the Lower Cretaceous, the rest are from the Paleogene and Neogene.

The rocks of the folded basement (pre-rift complex) were recovered in borehole SSDAN-4_1 at a depth of 49.13 m and in borehole SSDAN-4_3 at a depth of 123.85 m. They are represented by steeply dipping fractured silty mudstones weathered near the top. Their age is the Early Cretaceous, Late Barremian—Early Aptian (the oldest of those recovered). This sequence is overlapped with angular unconformity by Lower Paleocene light gray clayey sands.

The Early Cretaceous palynological association was established in the lower part of the section of borehole SSDAN-4_3 and in most of the section of borehole SSDAN-4_1. The complex is characterized by

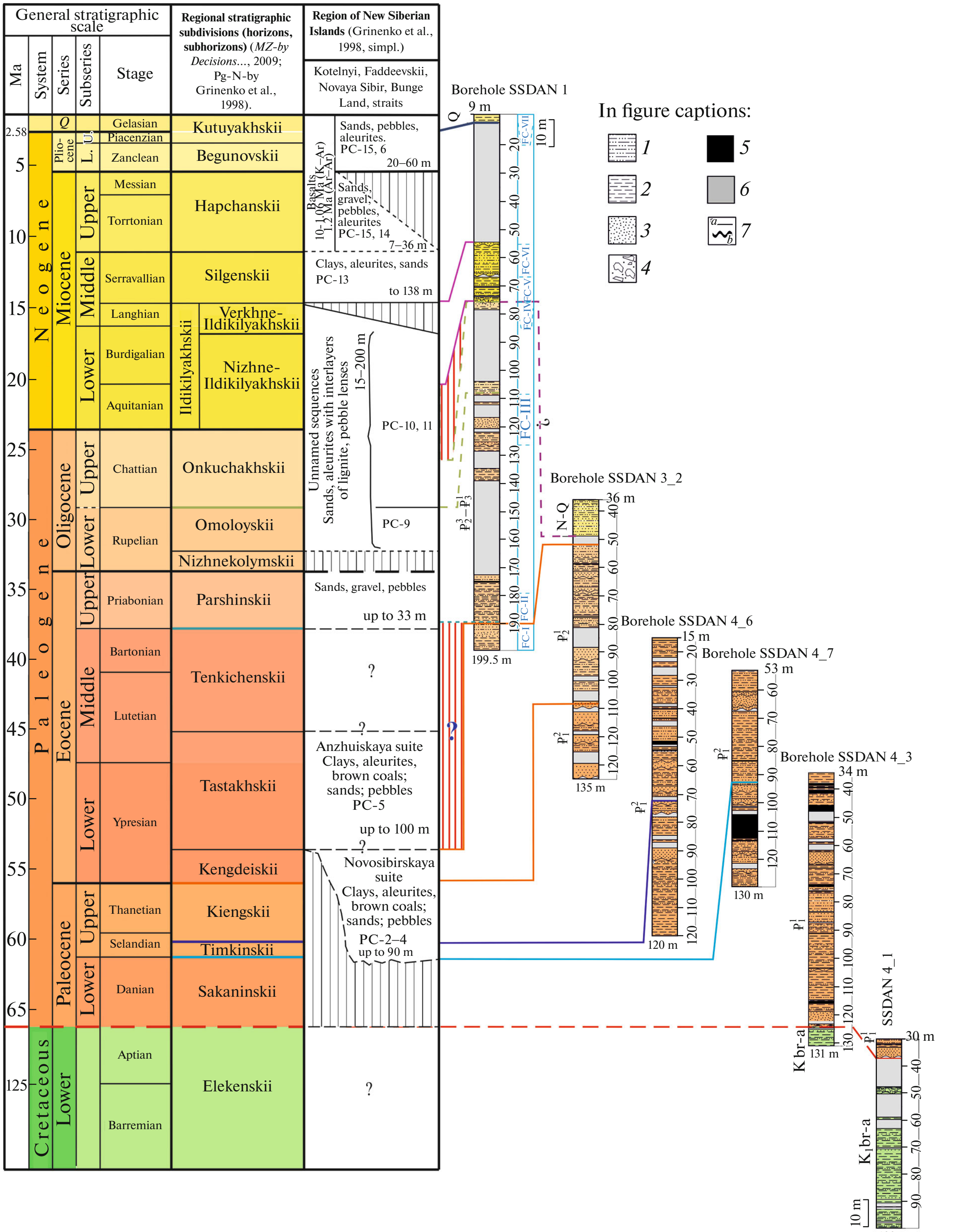

Fig. 2. Scheme of correlation of the sections of shallow stratigraphic boreholes. (*1*) Aleurites, siltstones; (*2*) clays, mudstones; (*3*) sands, sandstones; (*4*) breccias; (*5*) coals; (*6*) intervals of the section without coring; (*7*) boundaries: *a*, flat; *b*, wavy. The level of the beginning of coring from the bottom surface is indicated in meters. PC is the palynological complex and its number in the regional stratigraphic scheme [10]. Colors on the columns show the correlation of intervals of the borehole section with the regional stratigraphic subdivisions. The foraminifer complexes (FC-I–FC-VII) described in the text are marked in blue color to the right of the SSDAN 1 borehole section.

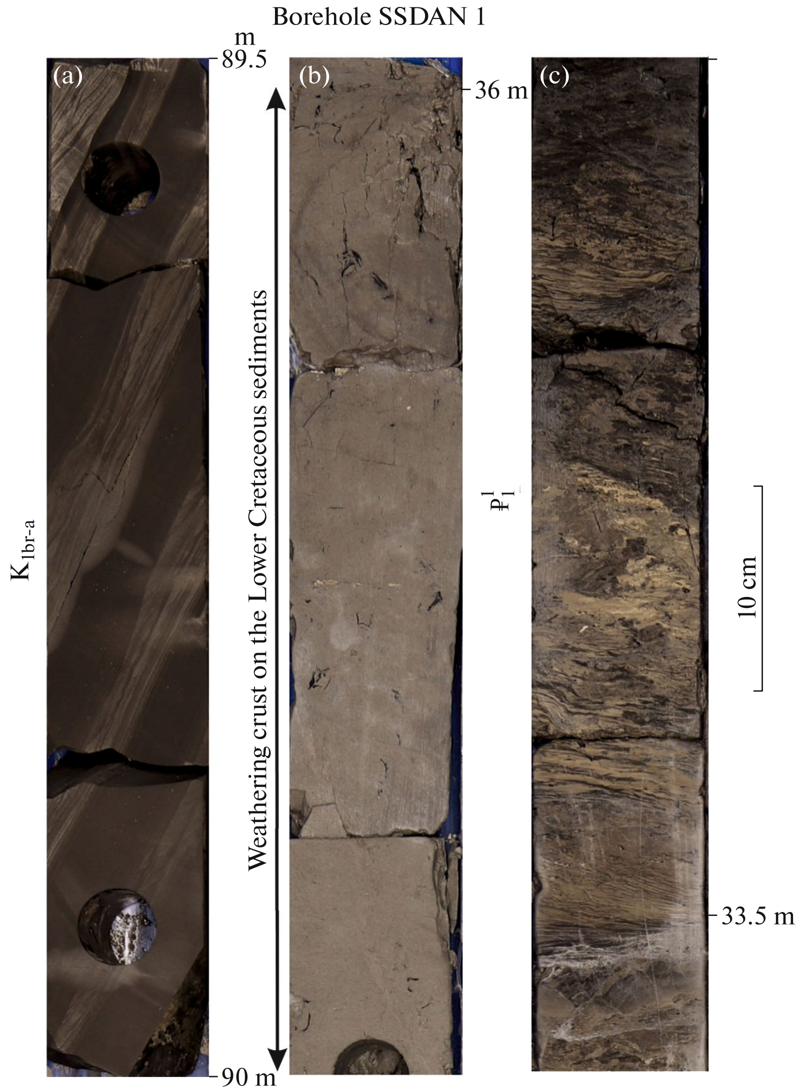

Fig. 3. Photos of core from borehole SSDAN-4_1: (a) deformed Upper Barremian–Lower Aptian sediments represented by interlayering of siltstones and mudstones (interval 89.5–90 m); (b) weathering crust on the Lower Cretaceous sediments composed of massive brown clays with fragments of plant root systems (in the interval 35.9–36.4 m); (c) the Paleocene sediments represented by a member of sand and siltstone interbedding with the interlayers enriched with coal detritus (in the interval of 33.1–33.55 m).

the joint occurrence of dinocysts *Palaeoperidinium cretaceum, Odontochitina nuda, Chlamydophorella trabeculosa, Oligosphaeridium complex,* and *Odontochitina operculata* known since the Barremian, and in high-latitude sections of Greenland and Spitsbergen limited to the Upper Barremian–Lower Aptian [3, 4]. Together with the absence of pollen of angiosperms, these findings limit the age of the lower part of the section of borehole SSDAN-4_3 and most of the section of SSDAN-4_1 to the Upper Barremian–Lower Aptian.

On the UHRS sections, within the complex of the folded basement, we revealed the interval of the section building up the pre-Cenozoic sediments at a distance from the drilling points (Fig. 6) in the northwesterly direction. This fact allows us to assume the younger in relation to dated rocks in its composition. Their thickness is at least 250 ms (more than 400 m). In this part of the stratified sequence, no angular unconformities that could be compared with the unconformities at the base of the Upper Aptian–Albian of Kotelnyi Island (Balykhtakh Formation) were observed. Thus, we conditionally accept the Early Aptian age of the entire above-mentioned interval.

Therefore, the extension of the Late Mesozoic folded basement to the north of the New Siberian archipelago has been confirmed for the first time. It is shown that its formation took place not earlier than the Early Aptian (Fig. 4). This conclusion, together with the age of post-folding granitoids, the oldest of which are dated as the beginning [5] and middle [6] of the Aptian age, allows us to narrow the interval of the final phase of collision of the New Siberian–Chukotka orogen to the first half of the Aptian. Earlier, the youngest sediments involved in collisional compressional deformations were dated as Hauterivian within the South Anyui suture [7]. The post-folding sediments of Kotelnyi Island began to accumulate at the end of the Aptian and are predominantly of the Albian [8]. This result compares well with the time of the Anjou Islands uplift according to the low-temperature thermochronology at ~120–90 Ma, that is, in the Aptian–Turonian [9].

In the section of the cover, there are two structural levels separated by boundary I. The reflecting horizons IV, III, and II are traced within the lower level (Fig. 4). Most of the observed normal faults with a visible amplitude of displacement are not traced above horizon I.

The complex at the base of the cover, between RH Fa and IV is characterized by the wide development of fault dislocations of normal-fault kinematics and by syntectonic filling of the associated grabens and half-grabens (Figs. 5, 6). The amplitude of dislocations on individual faults exceeds hundreds of meters to a few kilometers.

In the sections of boreholes SSDAN-4_3 and SSDAN-4_1 immediately above the RH Fa, there are spore–pollen complexes of the Sakaninskii horizon of the Lower Paleocene and Timkinskii horizon of the lower part of the Upper Paleocene [10].

The spore–pollen complex (SPC) of the Kiengskii horizon of Northeastern Russia, dated to the upper part of the Upper Paleocene [10], is established upward through the section of boreholes SSDAN_4-7 and SSDAN-4_6, as well as in the lower part of the section of boreholes SSDAN-3_2, below RH IV. Dinocysts *Apectodinium parvum, A. homomorphum,* and *A.*cf. *hyperacanthum* of the Late Thanetian Apectodinium hyperacanthum zone are present at this level.

The seismic complex between RH Fa and IV has all signs of a synrift origin, and the horizon IV, bordering it at the top, can be referred to the "rift–postrift" type unconformity and is associated with a regional event—the beginning of spreading in the Eurasian Basin close to the Paleocene–Eocene boundary, about 56 Ma ago (Fig. 4) [11].

The palynocomplex of the Kengdeiskii horizon of the lower part of the Lower Eocene was determined at the base of the overlying seismic complex (SC) between RH IV and RH III in the sections of boreholes SSDAN-3_2 and SSDAN-1 [10]. Here, *Saeptodinium* sp. predominates among dinocysts, accompanied by both taxa encountered below and new taxa — *Dracodinium* cf. *astra*, *Wetzeliella* aff. *articulata*-group, *Wetzeliella* sp., *Stenodinium meckelfeldensis*, and others. In borehole SSDAN-1, *Phelodinium* sp. *A* and *Senegalinium* cf. *obscurum* predominate among dinocysts at the level of the Early Eocene foraminifera complex (FC) FC-I with *Hemisphaerammina apta*; *Spiniferites* spp. and *Impagidinium* sp. are often encountered. These dinocyst associations are close to those established in the Early–Middle Eocene part of the section of borehole M0004A on Lomonosov Ridge [12].

Palynological data indicate the absence of deposits of the Tastakhskii and Tenkichenskii horizons in the section of borehole SSDAN-1 at the level of RH III, which suggests the hiatus in sedimentation involving part of the Early Eocene and the lower part of the Middle Eocene. Apparently, this boundary is close to the ~45-Ma boundary in the scheme [11].

SCs IV-III and III-II form a post-rift sequence separated by the distinct surface of RH III, confined to the top of the package of the coherent high-amplitude reflections of the upper part of SC IV-III.

The SC between RH III and RH II in the section of borehole SSDAN-1 is represented by silty-clayey shallow-marine sediments. Here, the FC-II of the Middle?–Upper Eocene and the palynocomplex of the Parshinskii horizon of the second half of the Middle Eocene and the first half of the Upper Eocene was identified [10]. Upward through the section, FC-III with *Elphidiella brunnescens* and the palynocomplex of the Omoloiskii horizon of the Lower Oligocene of the northeastern part were determined, compared with the Atlymskii and Novomikhailovskii horizons of Western Siberia [10, 13].

In the upper part of the SC section in borehole SSDAN-1, the Late Oligocene FC-IV with *Turillina alsatica* and the palynocomplex of the Zhuravskii horizon of Western Siberia and its analogs in northeastern Russia in the first half of the Late Oligocene was established [13]. Dinocysts are presented by *Pthnanoperidinium* sp. 1, *Operculodinium centrocarpum*, *Lejeunecysta* sp.

The SC between RH II and RH I was recovered by borehole SSDAN-1. It is represented by extended high-amplitude reflections and has a small thickness (up to 200 m).

The complex is dated in borehole SSDAN-1 by foraminifera complexes FC-V with *Asterigerina guerichii* and FC-VI with *Elphidiella groenlandica* of the Lower–Middle Miocene and corresponds to the range of co-occurrence of dinocysts *Hystrichosphaeropsis complanata–Hystrichosphaeropsis obscura* group, *Labyrinthodinium truncatum, Palaeocystodimium golzowense, P.* cf. *miocaenicum* of the second half of the Early Miocene and the beginning of the Late Miocene (Burdigalian and the middle part of the Tortonian). These data, as well as the presence of conglomerate breccias and phosphorites in the section, indicate the hiatus in the SC base including the upper

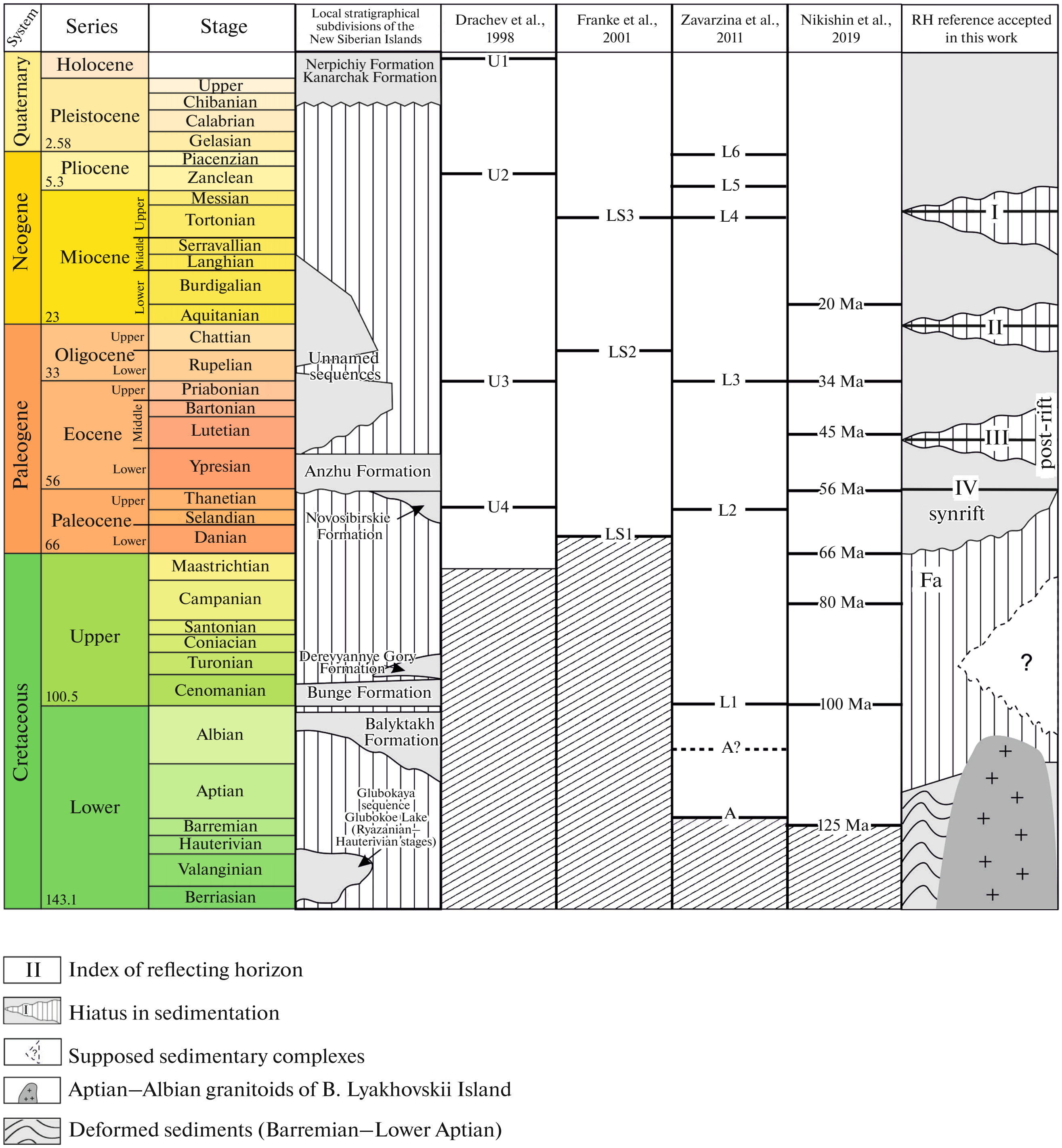

Fig. 4. Comparison of the seismic stratigraphic schemes of the sedimentary cover of the Laptev Sea region according to [18–20, 11] with the one adopted in this work for the northeastern part of the Laptev Sea based on the results of shallow drilling.

part of the Late Oligocene and the lower part of the Early Miocene.

All the above-mentioned SCs are cut by normal faults (Figs. 5, 6), which indicates the manifestation of a stage of relatively young extension that preceded the formation of the RH I erosion surface.

The youngest SC, distinguished between RH I and the seafloor, was uncovered by all boreholes. However, the core was taken only in the upper part of the SSDAN-1 section, where the Pleistocene palynocomplex, with reconstructed tundra landscapes with predomination of grass pollen, and the modern foramin-

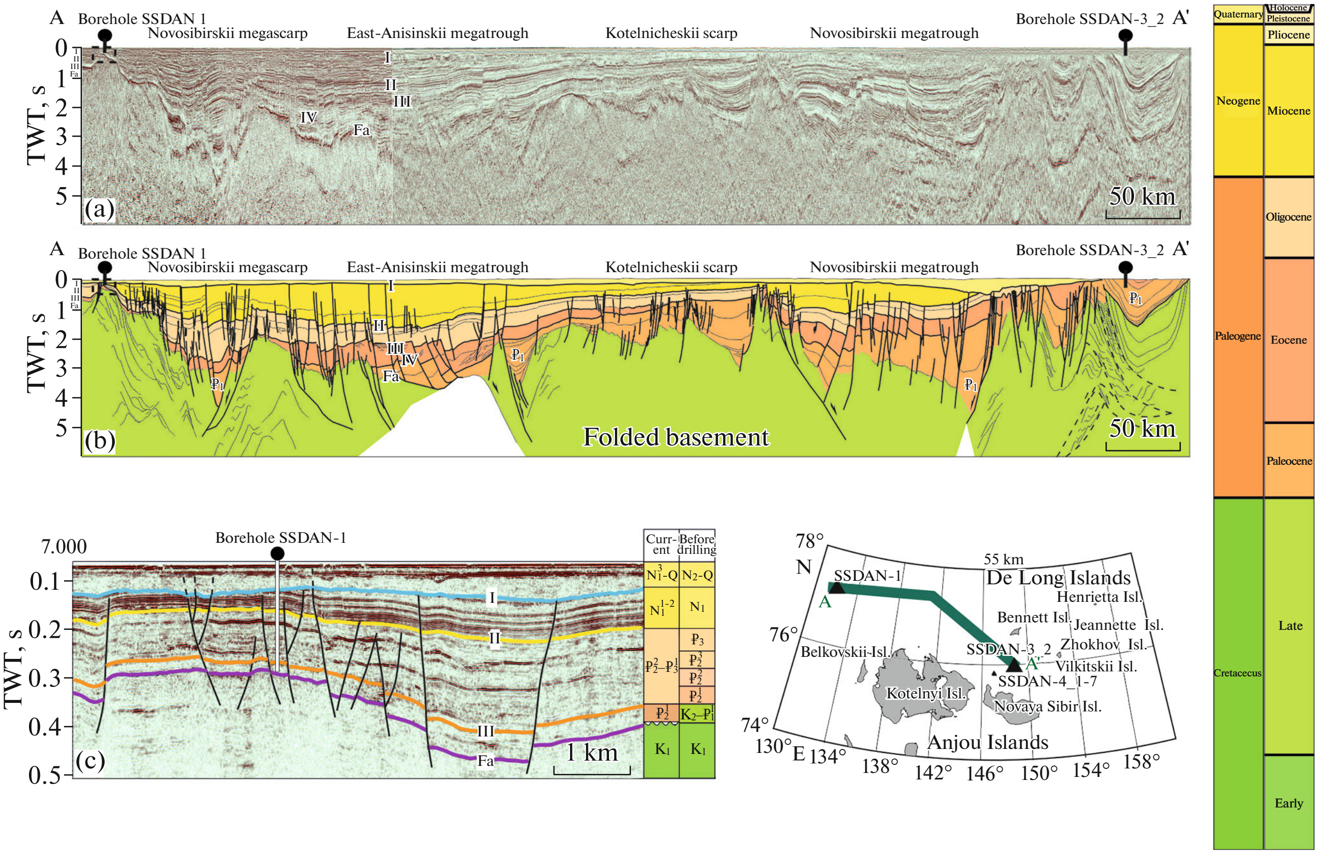

Fig. 5. (a) 2D CDPM time section along the line A–A', (b) seismogeological profile along the line A–A', (c) super-resolution seismic section through borehole SSDAN-1 (see location in the left-hand part of the seismogeological profile) with interpretation of the key reflecting horizons and their stratigraphic reference based on the current results of the analysis of shallow drilling data in comparison with the base model made before drilling (columns in the right-hand part of the figure).

ifer complex were established in the clayey-siltstone sediments. We conventionally accept the age of the SC as the Late Miocene (?)–Quaternary by its position in the section above the Lower Tortonian and sharply eroded surface at the base.

The SC seismic pattern shows signs of low-amplitude displacements, as well as such indirect indicators of the fault dislocations as the anomalies, like gas chimneys above the faults of the underlying complexes, differences in amplitudes of seismic reflections on the walls of faults, the presence of anomalous landforms of the seafloor (neptunic structures?), etc.

It is interesting to note that some ultrahigh resolution profiles (Fig. 6, inset) show that rocks of the uppermost complex are involved in rather intense deformations, apparently of fold-and-thrust origin (Fig. 6c). In our opinion, these structures are paragenetic to the glacial dislocations known on Novaya Sibir Island and are associated with the largest Neopleostocene glaciation [14].

Thus, according to the results of stratigraphic drilling, the Paleocene age of the syntectonic filling of basins of the main most ancient rifting stage was established. Postrift sediments have overlain a system of grabens and horsts since the Early Eocene.

The second phase of extension has a younger Late Miocene (Messinian?) or Pliocene age. The time of its manifestation is determined by the established Oligocene–Tortonian age of the seismic complex between RHs II and I, which has been cut by young fault dislocations of the normal fault and transtension origin. Apparently, the poorly manifested deformations of the youngest seismic complex (RH I–seafloor) reflect the present day tectonic regime of sublatitudinal extension, expressed, in particular, in the increased seismicity of the region studied [15].

CONCLUSIONS

The deformed Lower Cretaceous (Upper Barremian–Lower Aptian) sequences are the most ancient of those recovered by boreholes. Rocks of this complex are the youngest formations involved in the regional Late Mesozoic (Late Jurassic–Neocomian) compressional deformations. Thus, they are part of the folded basement of the basin in the area studied by stratigraphic drilling. The Lower Paleocene–Pleistocene

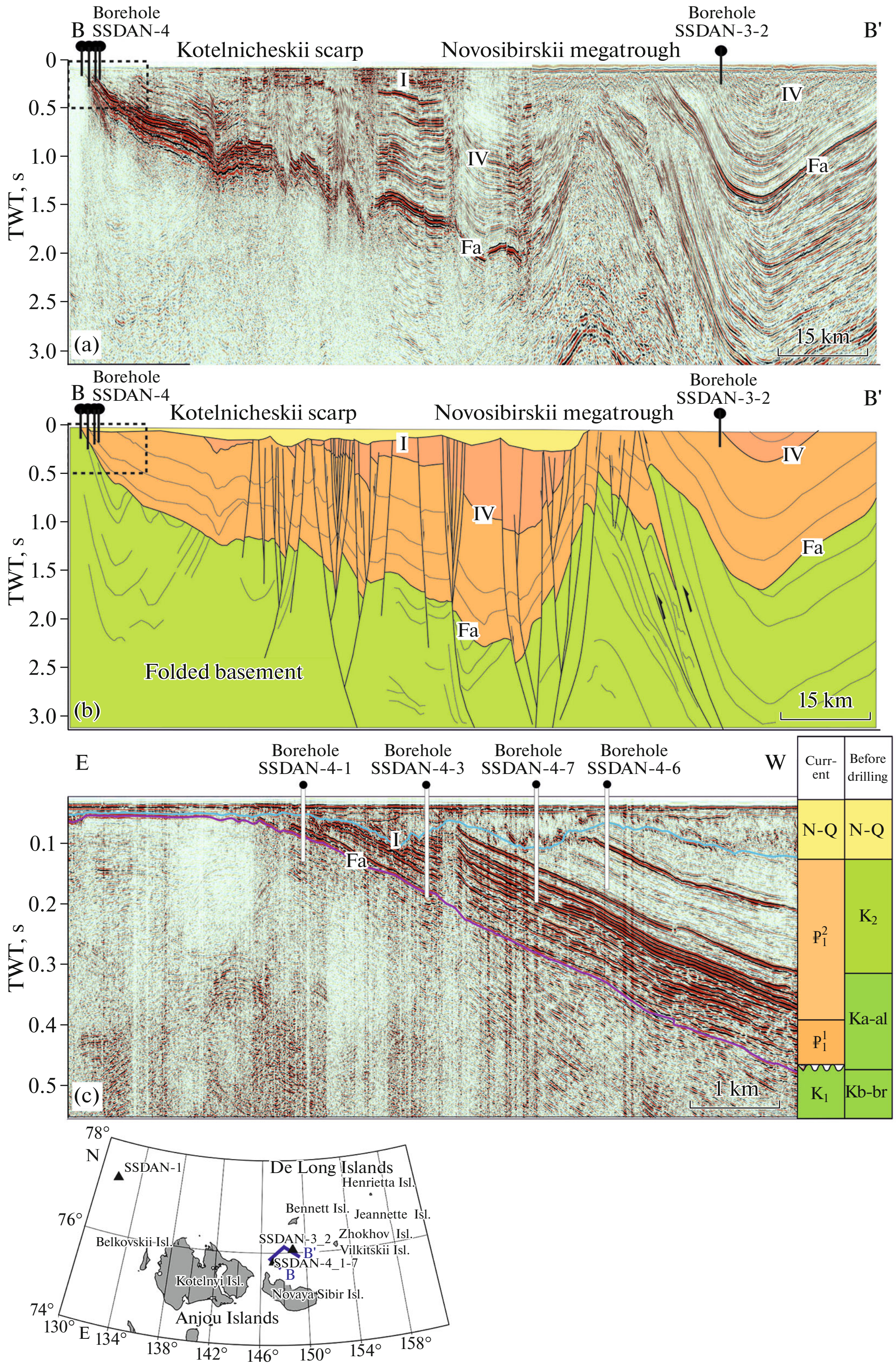

Fig. 6. (a) 2D CDPM time section along the B-B' line, (b) seismogeological profile along the B-B' line, (c) super-resolution seismic section through boreholes SSDAN-4_1, SSDAN-4_3, SSDAN-4_7, and SSDAN-4_6 (see location in the left-hand part of the seismogeological profile) with interpretation of the key reflecting horizons and their stratigraphic reference based on the current results of the analysis of the shallow drilling data in comparison with the base model made before drilling (columns in the right part of the figure).

complex of the sedimentary cover lie with angular unconformity on the Lower Cretaceous rocks with the Late Aptian–Maastrichtian hiatus.

For the first time, the extension of the complexes of the Late Mesozoic folded basement to the north of the New Siberian Archipelago was confirmed and the age limits of its formation were clarified. The data obtained indicate the completion of the final phase of collision in the New Siberian–Chukotka fold-and-thrust system in the Early Aptian.

According to the results of age definition of seismostratigraphic boundaries, the extension phase of the eastern part of the Laptev Sea was dated by direct biostratigraphic methods. The synrift complex of the oldest phase is the Paleocene, while the postrift complex formed since the Early Eocene. The second phase of intensive extension was manifested in the interval of the Messinian–Pliocene time.

Hiatuses in sedimentation are recorded from the most part of the Early Eocene to the lower part of the Middle Eocene and from the upper part of the Late Oligocene to the lower part of the Early Miocene (Fig. 4). The stratigraphic range of the youngest hiatus occurs within the Messinian–Pliocene interval and needs further clarification.

Stratigraphic drilling did not show the presence of sediments older than the Upper Barremian–Lower Aptian in the section. It is not excluded that the older (Upper Jurassic–Hauterivian?) sediments, known in the New Siberian Islands [16] and Chukotka [7], underlie the Upper Barremian–Lower Aptian sediments, because the seismic sections do not show angular unconformities older than the Paleocene basement. However, the regional seismic data do not exclude the possibility of identifying post-folding sedimentary complexes in the deeper submerged western parts of the Laptev Sea shelf (Aptian–Albian and/or Upper Cretaceous?) that are older than the Early Paleocene complexes dated in the stratigraphic boreholes. This key question of regional geology will be the subject of a separate integrated study, taking into consideration the obtained drilling data and detailed seismic stratigraphic subdivision of the sedimentary cover of the Laptev Sea shelf.

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CONFLICT OF INTEREST

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

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