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A Sequence-Stratigraphic Analysis of the Upper Vendian of the Northeastern Part of the Nepa–Botuoba Anteclise of the Siberian Platform Based on the Study of Cores and Analysis of the GWL Data

A. V. Plyusnin[a] and L. F. Kopaevich[b, *]

[a] *LLC INK, Irkutsk, 664007 Russia*
[b] *Moscow State University, Moscow, 119991 Russia*
**e-mail: lfkopaevich@mail.ru*

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Abstract—The results of the analysis of the core and logs of the Upper Vendian sediments (Vilyuchansky, Nepsky, Tirsky, and Danilovsky horizons) of the northeastern part of the Nepa–Botuoba anteclise are presented. The regional sequence-stratigraphic analysis made it possible to identify six third-order sequences and stratigraphic unconformities confined to their boundaries. The system tracts are represented by proluvial, alluvial, lagoonal, and shallow-water–marine sediments, which successively replace each other. This is typical of the passive continental margin environments and the general subsidence of the Siberian Platform in the Vendian.

Keywords: Botuoba structural-facies zone, Nepa–Botuoba anteclise, Mirny uplift, Upper Vendian, facies analysis, sequence-stratigraphic analysis

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INTRODUCTION

The structure and sedimentation environments of Upper Vendian basal deposits (Nepa and Tirsky horizons) within the Nepa–Botuoba anteclise (South Siberian Platform) are of great interest in connection with their petroleum potential. These intervals have been studied for more than 1 decade. Problems of the lithological-facies structure and stratigraphy of some sites of the Nepa–Botuoba anteclise have been repeatedly discussed in the previous works. However, the age substantiation and correlation of Upper Vendian rocks are still not unambiguously interpreted due to a lack of the material (a low core recovery), the occurrence of hiatuses, and facies variability. That is the reason that the comprehensive study of the Upper Vendian deposits is still important and that the areal material characteristics of this stratigraphic interval, facies transitions, sequence-stratigraphic analysis, and paleogeographic reconstructions based on obtained data have gained particular importance. For this purpose, following the previous regional lithological-facies and sequence-stratigraphic studies within the Nepa–Botuoba anteclise (Plyusnin et al., 2019, 2020), we have performed the studies in the present paper. Seven borehole logs that exposed deposits of the Vilyuchansky (Khoronokh Formation), Nepsky (Kursovsky Formation), and Tirsky (Byuksky Formation) horizons have been studied. The borehole logs and the literature data on the studied stratigraphic interval have been studied as well.

MATERIALS AND METHODS

The ages are based on the complex of geological–geophysical data, including the materials of the layer-by-layer lithological description of the core and the results of the geophysical well logging (GWL), namely gamma-ray logging (GRL) and neutron gamma logging (NGL) of the Kubalakhskaya-705, Khaiskaya-702, Srednebotuobinskaya-99, Srednebotuobinskaya-32, Srednebotuobinskaya-69, Kurungskaya-1, and Khotogo-Murbaiskaya-730 boreholes, which were drilled in 1970–2010. The peculiarities of the lithological-facies structure of the section were studied based on core samples from the unique Kurungskaya-1 borehole with a core recovery of approximately 100%, in the intervals of the Kursovsky Formation, Lower Byuksky Subformation, and the lower part of the Upper Byuksky Subformation. These results were given in (Plyusnin, 2019a).

In addition, the following literature sources were analyzed (Fomin and Chernova, 1993; Lebedev et al., 2014; Shemin, 2007). The sequence-stratigraphic profile was constructed based on these boreholes, whose logs are composed of deposits of the Vilyuchansky, Nepsky, Tirsky, and Danilovsky horizons (from the basement surface up).

The results of the lithological-facies analysis of the core material of the Upper Vendian deposits were previously published in (Plyusnin, 2019b, 2019c). The main body of the present paper is devoted to the regional sequence-stratigraphic analysis of the Botuoba structural-facies zone (SFZ). A short set of the characteristics of the used terms, which are quite traditional, is given below.

A *sequence* is a relatively conformable succession of genetically interrelated beds, limited at the top and bottom by stratigraphic unconformities or corresponding conformable boundaries. It represents a succession of system tracts and is interpreted as a geological body formed in the period between peaks in the decrease of the relative sea level (Posamentier et al., 1999).

A *system tract* is a lateral set of synchronous depositional systems or facies (Catuneanu et al., 2011).

A *sedimentation system* is three-dimensional association of lithofacies, genetically associated with environments of sedimentation: delta, river, lagoon, a barrier island, shelf, etc. (Posamentier et al., 1988). A system tract is characterized by its position within a sequence, different types of sets of parasequences, certain geometry of reflecting surfaces on seismic profiles. The formation of a system tract was connected with a definite position of the sea level. It is reflected in the names of tracts: lowstand system tract (LST), transgressive system tract (TST), and the highstand system tract (HST); if the fall in sea level is insignificant, the marginal-shelf tract (MST) forms.

The following model is applicable for the Upper Vendian of the Nepa–Botuoba anteclise: the basal member of the sequence—the lower part of the LST—a complex of submarine fans—the early part of the LST (Catuneanu, 2006). It is overlain by the upper part of the LST, an the association of slope deposits, represented by coarse sediments of the fluvial system and estuaries. The LST is characterized by a progradational set of parasequences. Higher in the succession, the TST occurs with a retrogradational set of parasequences. The proximal part is composed of coastal plain deposits, coastal marine sandstones, and shelf clayey deposits. The distal part often represents the condensed complex of shallow marine sediments formed at the stage of intensive rise of a sea level. The sequence section is crowned by the HST, which is characterized by progradational and aggradational sets of parasequences. The proximal part is composed of coastal plain deposits, coastal marine sandstones, and sandy–clayey shelf deposits. The distal part predominantly includes shelf and clayey slope deposits formed at the terminal stage of the rise and stabilization of a sea level. The sequence is terminated by a fall in sea level and the formation of the LST, from which a new sequence starts. In some cases, with an insignificant fall in sea level, the sequence section begins from the MST, represented by progradational and aggradational sets of parasequences; the sedimentation occurs in the supralittoral, littoral, and sublittoral environments (Posamentier et al., 1988).

There are two stages of constructing the profile.

The first stage. The lithological–sedimentological description of core samples and the construction of borehole logs occur, along with the mapping of the main boundaries (in particular, boundaries of sequences (Sb)), to which a subaerial stratigraphic unconformity may be confined; transgressive surface (ts) and maximum flooding surface (mfs) are distinguished based on the change of types of vertical successions of parasequences during one sedimentation cycle. The types and characters of parasequences (progradational, retrogradational or aggradational) are analyzed. The progradational set of parasequences is directed towards a basin and has a regressive character. The grain size in deposits increases from bottom to top along the section. The GRL values decrease from bottom to top; the curve is funnel-shaped (Vail et al., 1977). Moreover, the GRL values can decrease and increase. Due to this, the curve is semilunar. The retrogradational set of parasequences is directed to the opposite side and has a transgressive character. Detrital grains decrease in size from bottom to top along the section; the GRL values increase up the section. The curve is bell-shaped. The GRL data-based combination of progradation and retrogradation is characterized by the symmetrical shape of a curve. The aggradational set of parasequences is characterized by a stable position of the coastal line, the deposits more homogenous, with equidimensional grains. The GRL values are relatively consistent. The curve shape is cylindrical or peaked.

The second stage. Correlation occurs of the studied borehole logs with alignment at the base of the Danilov horizon, a regional benchmark that marked the onset of accumulation of predominantly carbonate rocks after the Late Tirsky–Early Danilov regional hiatus (Melnikov, 2018).

The boreholes in the profile are arranged inshore. The lateral facies sets of system tracts are shown by hatching. Thus, the constructed profile shows genetically related sedimentary systems separated by chronostratigraphic surfaces.

A SHORT GEOLOGICAL DESCRIPTION OF THE STUDY AREA

The Nepa–Botuoba syneclise, which is named after Nepa and Botuoba rivers, is located in the southeast of the Central Siberian Platform. It is elliptical in outline and extends in the northeastern direction from the upper reaches of the Nizhnyaya Tunguska River to

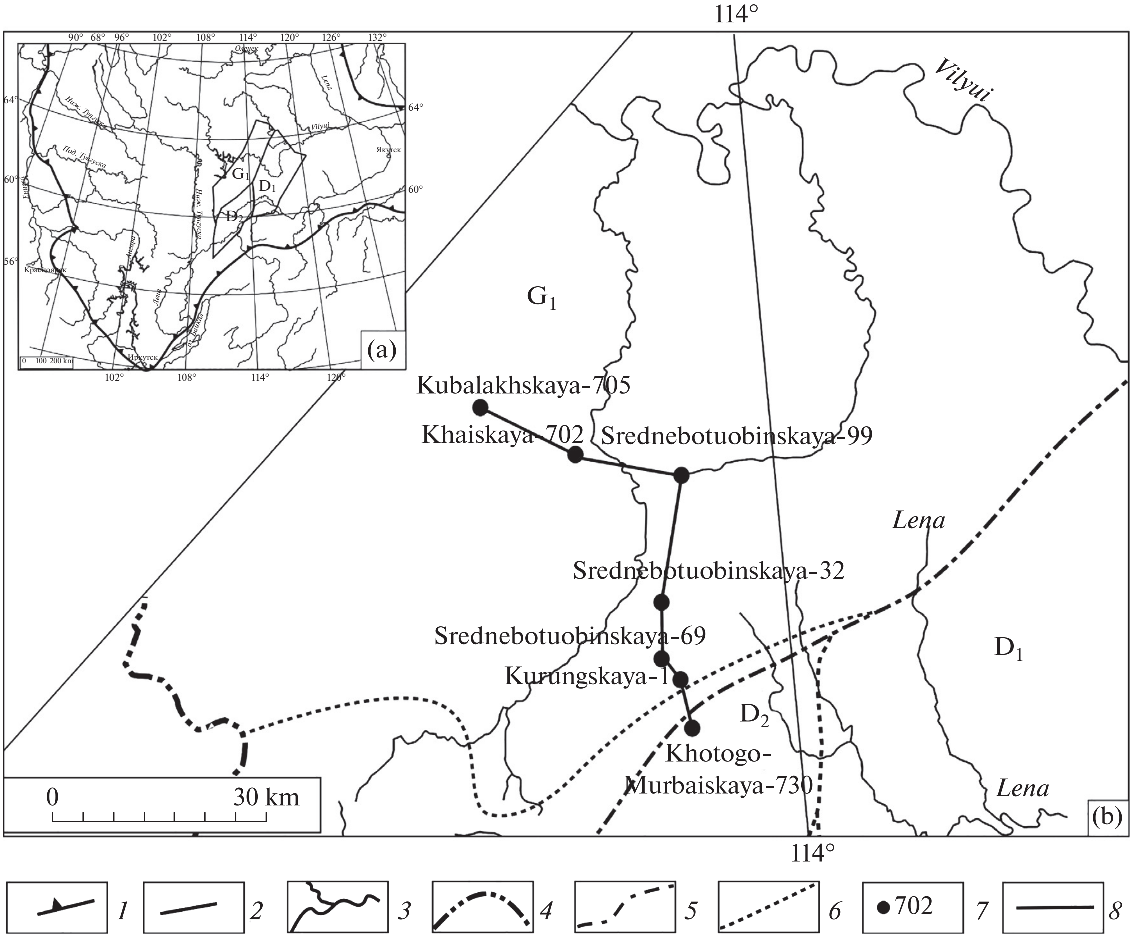

Fig. 1. The study area (A) and the locality of the studied boreholes (B) on the structural-facies zonation scheme of the Siberian Platform, after (Lebedev et al., 2014): G, Syugdzher–Nepa area: G1, Botuoba Zone; D, Cis-Patom–Vilyui area: D1, Vilyuchinsk-Ygyattin Zone; D2, Peleduy Zone;

(*1*) Margins of the Siberian Platform; (*2*) boundaries of facies zones; (*3*) river network; (*4*) the border of the Republic of Sakha (Yakutia); (*5*) boundaries of structural-facies areas; (*6*) boundaries of structural-facies zones; (*7*) locality of the studied boreholes; (*8*) the sequence-stratigraphic profile.

the Vilyui River basin. The anteclise is complicated by two positive structures, that is, the Nepa swell and Mirny uplift (Fig. 1A) and is bounded by the Cis-Patom Foredeep in the southeast.

The studied Botuoba structural-facies zone (SFZ) is confirmed to the Syugdzher–Nepa area. The constructed profile crosses the SFZ from northwest to southeast and partially enters the Peleduy SFZ of the Cis-Patom–Vilyui area (Khotogo-Murbaiskaya-730 borehole) (Melnikov, 2018; *Resheniya*..., 1989; Shemin, 2007) (Fig. 1b).

According to the regional stratigraphic scheme developed for inner zones of the Siberian Platform (Melnikov, 2018), the following subdivisions are distinguished in the Botuoba SFZ (Fig. 2):

(i) *Kursovsky Formation of the Nepa* horizon overlies unconformably the crystalline basement. Based on the lithological data, three units are distinguished. The lower part (from bottom to top) is represented by a gradual transition from gravelites to sandstones and siltstones. Sandstones and gravelites represent the Talakh productive horizon (Srednebotuobinskaya-99, -32, -69, Kurungskaya-1, Khotogo-Murbaiskaya-730 boreholes). The middle unit is composed of mudstones and siltstones with interbeds of dolomites and marls. The Arylakh productive horizon is represented by carbonate rocks (Srednebotuobinskaya-32, -69, Kurungskaya-1 boreholes). The upper unit is composed of sandstones, followed by siltstones with single interbeds of carbonate rocks. The Khamakin productive horizon is confined to sandstones (the Srednebotuobinskaya-32, -69, Kurungskaya-1, and Khotogo-Murbaiskaya-730 boreholes). The thickness varies from 3–5 to 120 m;

(ii) *Byuksky Formation of the Tirsky horizon* lies unconformably on deposits of the Kursovsky Formation and is subdivided into two subformations. The Lower Byuksky Subformation represents a gradual

<table>
<tr><td colspan="9">PROTEROZOIC</td><td>Acrotherm</td><td colspan="2" rowspan="4">GSS</td></tr>
<tr><td colspan="9">Upper Proterozoic</td><td>Eonothem</td></tr>
<tr><td colspan="9">Vendian</td><td>System</td></tr>
<tr><td colspan="9">Upper</td><td>Division</td></tr>
<tr><td>Vilyuchansky</td><td colspan="4">Nepsky</td><td colspan="3">Tirsky</td><td>Danilovsky</td><td>Horizon</td><td colspan="2" rowspan="2">RSS</td></tr>
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<tr><td></td><td colspan="4">Kursovsky</td><td colspan="3">Byuksky</td><td>Uspunsky</td><td>Formation</td><td rowspan="2">G_1</td><td rowspan="4">LSS</td></tr>
<tr><td></td><td colspan="4"></td><td colspan="2">Lower</td><td>Upper</td><td></td><td>Subformation</td></tr>
<tr><td>Khoronokh</td><td>Talakh</td><td colspan="5">Parshinskaya</td><td>Byuksky</td><td>Uspun</td><td>Formation</td><td rowspan="2">D_2</td></tr>
<tr><td></td><td></td><td colspan="2">Lower</td><td colspan="3">Upper</td><td></td><td></td><td>Subformation</td></tr>
</table>

Fig. 2. The correlation scheme of the Upper Vendian of the General Stratigraphic Scale of Russia (GSS), Regional Stratigraphic Scale (RSS) of inner areas of the Siberian Platform with local stratigraphic schemes (LSS) of the Botuoba Zone of the Syugdzher–Nepa area (G1) and Peleduy Zone of the Cis-Patom–Vilyui area (D2), after (Lebedev et al., 2014; Melnikov, 2018).

transition from pelite–siltstone (at the bottom) to psephitic–sandy (at the top) deposits. The Botuoba productive horizon is confined to sandstones (the Srednebotuobinskaya-99, -32, -69, Kurungskaya-1 boreholes). The thickness varies from a few meters to 30 m. The Upper Byuksky Subformation is composed of clayey–sulfate–carbonate deposits. The lower part of the subformation is represented by magnesite–anhydrite–dolomite rocks with a relic microbial texture. Higher in the section, they are followed by fine-grained, bedded and massive, irregularly clayey and sulfatized dolomites. The upper part of the subformation is composed of clayey marls and dolomites, which are replaced up the section by irregularly sulfatized dolomites. The thickness of this subformation reaches 170 m. The total thickness of the formation is 200 m.

The Byuksky Formation of the Tirsky horizon is overlain with a stratigraphic hiatus by Upper Vendian dolomites of the Danilov horizon, which is stable in thickness.

It was previously noted that the profile enters the Peleduy SFZ; this has the Vilyuchansky horizon at the base of the sedimentary cover section, which is overlain by the Nepsky and Tirsky horizons (Fig. 2).

The Vilyuchansky horizon is widespread in the Vilyuchansk–Ygyattin and Peleduy zones of the Cis-Patom–Vilyui area, where the stratotype sections of the Betinchin and Khoronokh formations are exposed (Fig. 1B). The Khotogo-Murbaiskaya-730 borehole log, drilled in the transition zone between Botuoba and Peleduy zones, was studied. The basal *Khoronokh Formation* rests on the basement rocks. It is represented by a stratum of medium- to fine-grained sandstones at the base, gradually replaced by aleurosandstones and siltstones in the upper part of the section. The exposed thickness is 85 m.

RESULTS AND DISCUSSION

A 175 km sequence-stratigraphic profile oriented from northwest to southeast was constructed based on studying the Kubalakhskaya-705, Khaiskaya-702, Srednebotuobinskaya-99, -32, -69, Kurungskaya-1, and Khotogo-Murbaiskaya-730 borehole logs. The results we obtained have shown that the bottom of the sedimentary basin slopes southeasterly in modern coordinates that determined a sedimentation trend. Borehole logs were put into alignment at the base of the Danilovsky horizon (Fig. 2).

Sequence SQ0 (Khoronokh Formation of the Vilyuchansky horizon). Due to the limited distribution, the sequence was distinguished in the Khotogo-Murbaiskaya-730 borehole log (Fig. 3). The sequence bottom corresponds to the stratigraphic unconformity surface. The LST coarse fan deposits overlie the basement rocks. Based on the values, which decrease from the bottom up and funnel-shaped GRL and GNL curves, a progradational set of parasequences is assumed.

The transgressive surface is marked by a change of the progradational set of parasequences to a retrogradational one. The TST section gradually changes from the bottom to top to clayey–sandy coastal plain deposits. The GRL values increase from the bottom upwards; the curve is bell-shaped. The GNL values are consistent and even; the curve is cylindrical.

The surface of maximum flooding is marked by the peak on the GRL curve and the change of the retro-

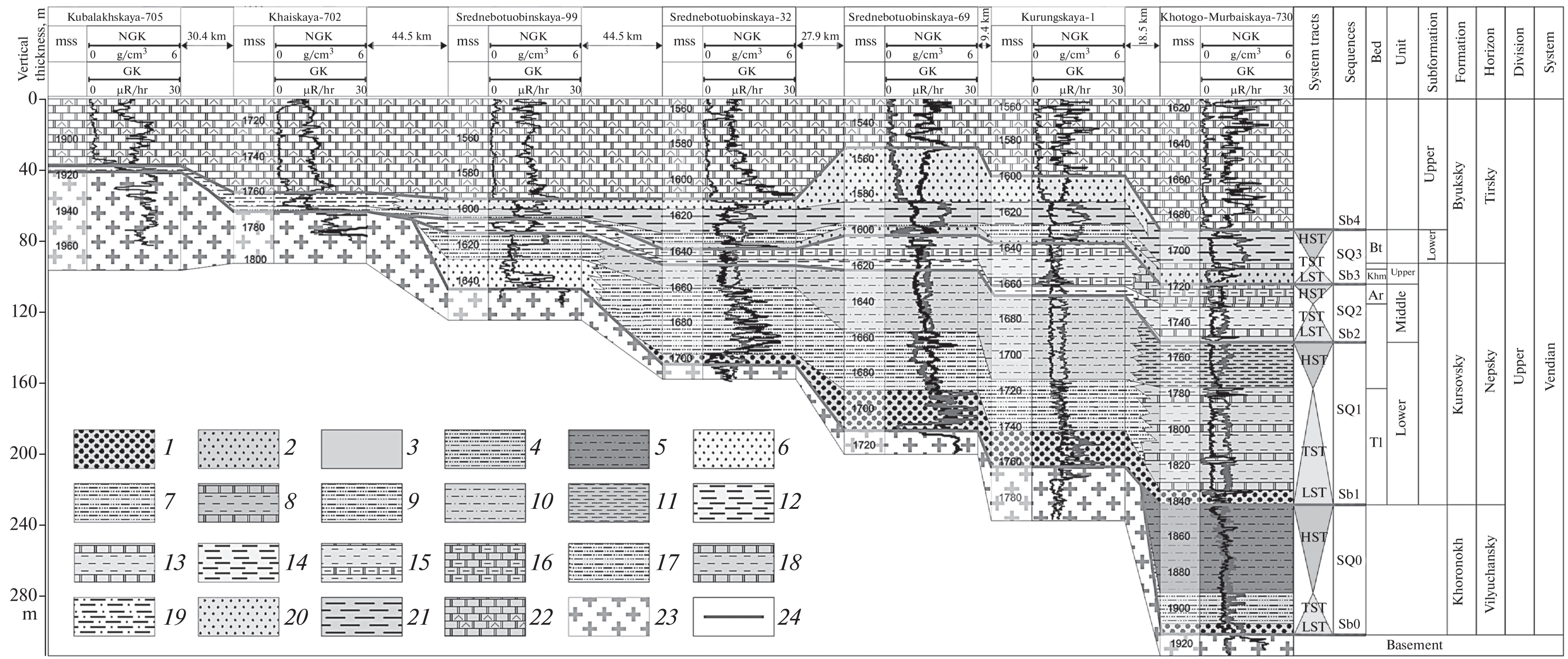

Fig. 3. The NW-SE sequence-stratigraphic profile across the Mirny uplift: LST deposits: (*1*) coarse fan deposits; (*2*) channel sandy deposits; (*3*) sandy submarine fan deposits. *Sequence SQ0* (Khoronokh Formation of the Vilyuchinsky horizon), TST: (*4*) clayey–sandy deposits of the coastal plain; HST: (*5*) sandy–clayey coastal-marine deposits. *Sequence SQ1* (the lower unit of the Kursovsky Formation), the TST facies set: (*6*) sandy deposits of the coastal plain, (*7*) sandy–clayey coastal plain and shallow-water deposits, (*8*) carbonate-clayey shelf deposits; the HST facies set: (*9*) sandy–clayey deposits of the coastal plain, (*10*) sandy–clayey coastal marine deposits, (*11*) clayey sublittoral deposits. *Sequence SQ2*) (the middle unit of the Kursovsky Formation), the TST facies set: (*12*) clayey lagoonal deposits, (*13*) carbonate-clayey shelf deposits; the HST facies set: (*14*) clayey lagoonal deposits, (*15*) carbonate-clayey shelf-lagoonal deposits, (*16*) shelf carbonate deposits. *Sequence SQ3*) (the upper unit of the Kursovsky Formation–Lower Byuksky Subformation of the Byuksky Formation), the TST facies set: (*17*) clayey–sandy littoral deposits, (*18*) carbonate-clayey shelf deposits; the HST facies set: (*19*) clayey–sandy deposits of the coastal plain, (*20*) sandy deltaic and shallow-water deposits, (*21*) clayey prodeltaic and littoral deposits, (*22*) dolomites of the Upper Byuksky Subformation, (*23*) basement; (*24*) boundary of sequences. Abbreviations: NGL, neutron gamma logging; GRL, gamma-ray logging; SQ, sequence, Sb, sequence-stratigraphic boundary. Productive horizons: Tl, Talakh; Ar, Arylakh; Khm, Khamakin; Bt, Botuoba

gradational set of parasequences to the aggradational–progradational one. The HST is represented by coastal marine sandy–clayey deposits. Based on the GRL and GNL curves, the homogenous sandy–clayey composition is assumed in the lower part and the predominance of clayey–sandy sedimentary formations, caused apparently by progradation of a deltaic complex, in the upper part.

Thus, the SQ0 sequence corresponds to the Vilyuchansky stage of sedimentation. Intensive weathering of the basement rocks occurred within the Botuoba SFZ. Simultaneously, the sedimentation occurred only in the most subsided zones: along the southeastern margin of the Nepa–Botuoba anteclise and mainly in the Cis-Patom Foredeep, where the terrigenous material from upstanding areas of the northwestern part of the studied region was accumulated.

The SQ1 Sequence (the lower unit of the Kursovsky Formation) was distinguished in the Srednebotuobinskaya-99, -32 and -69, Kurungskaya-1, Khotogo-Murbaiskaya-730 boreholes (Fig. 3). The lower boundary of the sequence corresponds to the well-defined surface of a stratigraphic unconformity, which is clearly distinguished in core samples (an erosional contact between coarse deposits and underlying basement rocks). The LST is characterized by a progradational structure and is represented by coarse fan deposits (alluvial fans). These are widespread and overlie the basement rocks in the Srednebotuobinskaya-32 and -69, Kurungskaya-1 borehole logs. In the Khotogo-Murbaiskaya-730 borehole log, they rest erosively on clayey–sandy deposits of the HST SQ0. Based on the GWL data, a gradual decrease in GRL and GNL occurs upward; the curves are funnel-shaped. The GRL peaks are connected with the presence of gravelites, which bear fragments of radioactive felsic rocks in the section.

The transgressive surface can be drawn at the bottom tidal flat complex, where the progradational set of parasequences is replaced by the retrogradational one. The retrogradational character of parasequences is confirmed by the following TST succession: clayey shelf deposits can be replaced laterally from the southeast to northwest (in modern coordinates) by sandy–clayey coastal plain shallow-water deposits, and then by the coastal plain deposits (Fig. 3). Based on the GWL data, a gradual increase in GRL values occurs upward, the curve is bell-shaped. The GNL values gradually decrease up the section. The curve is from cylindrical to funnel-shaped in shape. Thus, the transgression was spread to the area of the Srednebotuobinskaya-32 borehole. In the Kurungskaya-1 borehole log, the TST represents a complex of littoral deposits. They belong to the tidal flat channel and tidal flat facies. Parasequences are characterized by a decrease in a grain size up the section.

The maximum flooding sequence is drawn based on the peak on GRL curve and the change of the retrogradational set of parasequences by the aggradational-progradational one. The HST facies set forms the following succession: clayey deposits of the sublittoral, followed by coastal-marine sandy–clayey deposits, then, sandy–clayey deposits of the coastal plain (Fig. 3). The GRL values, which are consistent at the base, increase gradually upward; the curve is cylindrical. The NGL values increase up the section; the curve is bell-shaped.

At this stage of the development of the territory, the transgression spread to the area of the Srednebotuobinskaya-99 borehole. In the Kurungskaya-1 borehole log, the HST is represented by sedimentary formations of the tidal flat and transition zones. The term "transitive zone" was accepted to characterize the littoral's wide transition facies zone (Plyusnin, 2019a). The facies is as far offshore as possible and is transitive to shelf facies (sublittoral and deep sublittoral). The upper part of the complex is characterized by an irregular alternation of sediments of the prefrontal beach zone, sometimes with a shelf lagoon and a superimposed sabkha plain.

The SQ1 sequence corresponds to the volume of the first unit of the Kursovsky Formation. Simultaneously, the sedimentation was spread in the northwestern direction towards the Srednebotuobinskaya-99 borehole. The terrigenous material was transported from the northwestern part of the study area. The Talakh productive horizon is confined to the LST and TST deposits. The sequence corresponds to the volume of the lower unit of the Kursovsky Formation.

The SQ2 Sequence (middle unit of the Kursovsky Formation) was distinguished in the Srednebotuobinskaya-99, -32, and -69, Kurungskaya-1, Khotogo-Murbaiskaya-730 borehole logs (Fig. 3). The sequence lower boundary is the stratigraphic unconformity surface. The LST deposits were distinguished in the Khotogo-Murbaiskaya-730 borehole log. The development of progradational sandy fans that formed within the shelf zone is assumed (Fig. 3). The GRL curve is funnel shaped.

The transgressive surface throughout the most of the territory is drawn based on the SQ2 lower boundary and in the area of the Khotogo-Murbaiskaya-730 borehole, based on the change of the progradational set of parasequences to the retrogradational one. The retrogradational structure is confirmed by the following succession along the strike: carbonate–clayey shelf deposits, followed by clayey lagoonal deposits (Fig. 3). According to the GWL data, a gradual increase in the GRL data and a decrease in the NGL data (a bell-shaped curve) are noted from the bottom up. Thus, the transgression spread to the area of the Srednebotuobinskaya-32 borehole. In the Kurungskaya-1 borehole log, the TST is represented by the following facies succession from bottom to top: a shelf lagoon, followed by a shelf lagoon with a high degree of salinity of the littoral and sabkha plain.

The maximum flooding surface is drawn based on the peak on the GRL curve and the change of the sets of parasequences. The HST was distinguished above this surface. It is characterized by an aggradational–progradational structure of sets of parasequences, forming the following succession along the strike: carbonate shelf deposits, followed by carbonate–clayey deposits of the shelf lagoon, then lagoonal clayey deposits. The limited space of accumulation, which was shrinking as the lagoon was filled with sediments, and a tendency to insufficient water circulation in the shallow-water zone provided ideal conditions for the formation of the sabkha plain. The penetration of salty waters into the upper lithified zone of dolomites and marls resulted in the epigenetic alteration of rocks by gypsum rocks. The latter were transformed into anhydrites. According to the GWL data (from the bottom up), peaks varying in frequency and amplitude are observed on the GRL and NGL curves. These peaks show a general trend to increase the clay content of the section upwards. The GRL curve is bell-shaped; the NGL curve is cylindrical and peaked. The transgression was propagating to the area of the Srednebotuobinskaya-99 borehole. In the Kurungskaya-1 borehole log, the HST is represented by the following succession from the bottom to top: sedimentary deposits of the shelf lagoon and the supralittoral sabkha plain.

The SQ2 sequence corresponds to the middle unit of the Kursovsky Formation (the second stage of sedimentation). At this time, the sedimentation occurred within the previous outlines. Sandy shelf fans formed during the LST, carbonate-clayey shelf lagoon deposits, and carbonate shelf deposits formed during the TST and HST. The deposits are very shallow water. The first microbial buildups appear. The Arylakh productive horizon is confined to fractured intervals.

The SQ3 sequence (the upper unit of the Kursovsky Formation–Lower Byuksky Subformation) was distinguished in all boreholes (Fig. 3). The sequence bottom corresponds to the well-defined surface of the stratigraphic unconformity. The LST bottom is well defined in the core material and traced based on the GWL data (a sharp decrease in GRL values and an increase in NGL ones). Deposits have a progradational character and are represented by channel sandy deposits, discharged as deltas in the southeast (Lebedev and Chernov, 1996). The Khamakin productive horizon is confined to these deposits. According to the GWL data, the following succession is noted from bottom to top: a gradual decrease, an increase in GRL values (a semilunar curve), and a decrease in NGL values (a funnel-shaped curve). In the Kurungskaya-1 borehole log, the LST is represented by consertal sandstones, with differently oriented oblique bedding, with siltstone intraclasts at the bottom, which represent deposits of fluvial channels.

The transgressive surface is drawn based on the change of the progradational set of parasequences by the retrogradational one. The character of the TST parasequences is confirmed by the following succession along the strike: clayey–sandy deposits of the littoral are gradually overlain by carbonate-clayey shelf deposits. According to the GWL, an increase in the GRL values (a bell-shaped curve) and low, consistent NGL values (cylindrical and peaked curves) are noted in this interval. The transgression was spreading to the area of the Khaiskaya-702 borehole. In the Kurungskaya-1 borehole log the TST is represented by clayey shallow-water shelf and prodeltaic deposits.

The maximum flooding surface is drawn based on the GRL peak and the change from the retrogradational set of parasequences to the aggradational–progradational one. The HST facies series has the following succession along the strike: clayey–sandy coastal plain deposits pass into bar-deltaic and shallow coastal sandy deposits.

The Botuoba productive horizon is confined to sandstones. Based on the GWL data, the decrease in GRL values (a funnel-shaped curve) and increase in the NGL values (a bell-shaped curve) are noted.

In the Srednebotuobinskaya-32, -69 and Kurungskaya-1 borehole logs, the HST is represented by fluvial/wave deltaic deposits. The following facies succession occurs from bottom to top: prodelta, the lower part of the delta front slope, the upper part of the delta front slope, including mouth bars, and a distribution channel.

The SQ3 sequence corresponds to Late Kursovsky–Early Byuksky stage of sedimentation.

It includes the interval of the upper unit of the Kursovsky Formation and Lower Byuksky Subformation. The LST is composed of the channel and deltaic sandy deposits, to which the Khamakin productive horizon is confined. The TST in the study area represents the shallow marine shelf. The HST was characterized by progradation of sandy deposits, forming the Botuoba productive horizon; the bar-deltaic genesis was discussed in detail in (Plyusnin, 2019b).

The SQ4 sequence (the lower part of the Upper Byuksky Subformation) was distinguished in all boreholes based on the GWL data and the core data from the Kurungskaya-1 borehole (Fig. 4). The sequence base represents the surface of stratigraphic unconformity. The LST deposits are distinguished on the funnel-shaped GRL curve and bell-shaped NGL in the Khotogo-Murbaiskaya-730 borehole. The formation of sandy fans with the progradational structure in the shelf zone is assumed here.

The transgressive surface throughout the most part of the territory is drawn based on the fourth-order sequence bottom, whereas in the Khotogo-Murbaiskaya-730 borehole area it is drawn based on the change of the progradational set of parasequences to the retrogradational one. The character of TST parasequences is confirmed by the following succession along the strike: clayey–sulfate–carbonate sublittoral

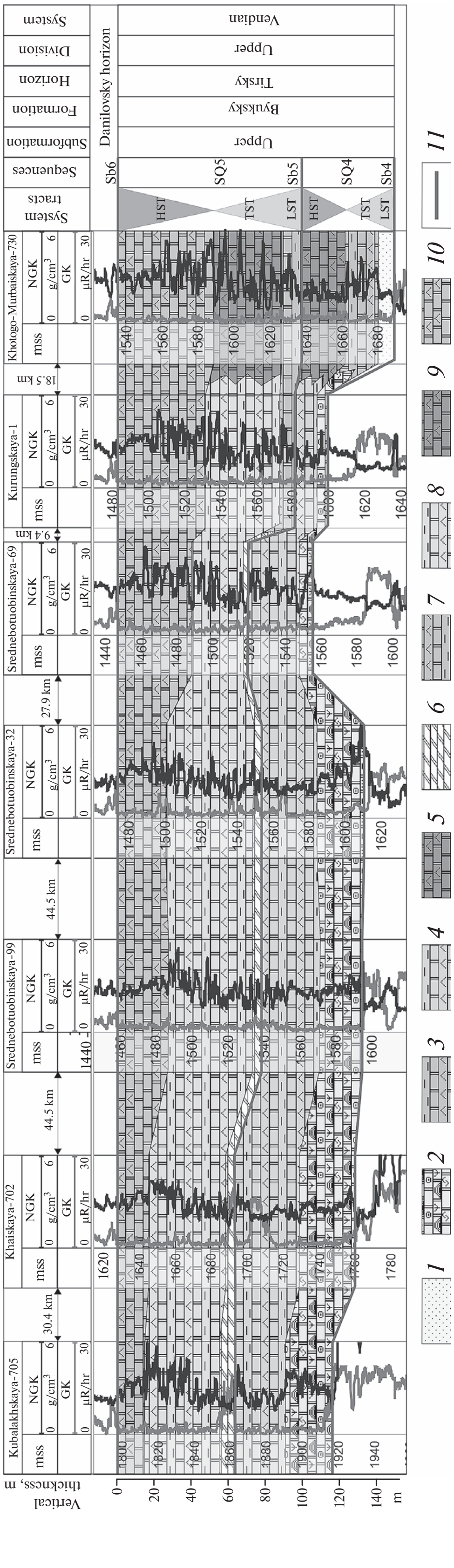

Fig. 4. The sequence-stratigraphic profile (NW–SE) across the Mirny uplift. *Sequence SQ4* (the lower part of the Upper Byuksky Subformation), LST: (*1*) sandy shelf fan deposits; TST: (*2*) organogenic carbonate littoral deposits, (*3*) clayey-sulfate-carbonate sublittoral deposits; HST: (*4*) clayey-sulfate-carbonate sublittoral deposits, (*5*) sulfate-carbonate shelf deposits. *Sequence SQ5* (upper part of the Upper Byuksky Subformation), MST: (*6*) clayey-carbonate supralittoral and upper littoral deposits, (*7*) sulfate-carbonate-clayey sublittoral deposits; TST: (*8*) clayey-sulfate-carbonate littoral and sublittoral deposits, (*9*) sulfate-carbonate shelf deposits; HST: (*10*) sulfate-carbonate shelf deposits. See other abbreviations in Fig. 3.

deposits, which are followed by carbonate organogenic shallow-water littoral deposits. Based on the GWL, funnel-shaped GRL and NGL curves are recorded in this interval. The transgression covered the study area of the Botuoba SFZ. In the Kurungskaya-1 borehole log, the TST transgressive surface is clearly distinguished in core samples from the contact between quartz sandstones and oolitic and lithoclastic sandstones, followed up the section by stromatolitic dolomites with the terrigenous filling. The nonlithified sandy deposits were eroded by intensive wave action and repeatedly redeposited within the littoral zone. As the sea level rose, they were settled by benthic microbial communities, forming stromatolitic dolomites with a terrigenous-carbonate filling, which indicates intensive wave activity.

The maximum flooding surface was identified based on the peak on the GRL curve, a decrease in NGL values, and the change of sets of parasequences. The HST is distinguished above this surface. It is characterized by the aggradational–progradational structure of sets of parasequences. It forms the following succession along the strike: sulfate–carbonate shelf deposits, followed by clayey–sulfate–carbonate deposits of the sublittoral. Based on the GWL data, the GRL curve in this interval is cylindrical with rare peaks in the interval of clayey varieties, and the NGL curve is peaked.

The SQ4 sequence corresponds to the early late Byuksky, the final transition from terrigenous to carbonate sedimentation. During this time, a shallow marine basin covered the area of the Botuoba SFZ. The carbonate rocks of the Upper Byuksky Subformation are irregularly sulfatized due to increased aridization of the climate during the Tirsky time and secondary processes of mineral genesis.

The SQ5 sequence (the upper part of the Upper Byuksky Subformation) was distinguished in all boreholes based on the GWL data and the core data from the Kurungskaya-1 borehole (Fig. 4). The sequence bottom represents the surface of the stratigraphic unconformity. The MST deposits form the progradational–aggradational succession along the strike: clayey–carbonate sublittoral and upper littoral deposits, followed by sulfate–carbonate–clayey deposits of sublittoral. Based on the GWL data, the GRL curve in this interval is funnel-shaped and the NGL curve is bell-shaped.

The transgressive surface is drawn based on the change of the set of parasequences to the retrogradational type. The character of the TST parasequences is confirmed by the following succession along the strike: sulfate–carbonate shelf deposits, followed by clayey–sulfate–carbonate littoral and sublittoral deposits. Based on the GWL data, the GRL curve in this interval has a cylindrical shape, and the NGL curve has a peaked shape, which gradually increases upsection.

The maximum flooding surface is drawn based on the peak on the GRL curve, a decrease in NGL, and the change of sets of parasequences to the aggradational–progradational structure of the HST, represented by sulfate–carbonate shelf deposits. Based on the GWL curves, the GRL curve in this interval is cylindrical and the NGL curve is funnel-shaped.

The SQ5 sequence (the upper part of the Upper Byuksky Subformation) corresponds to the terminal Late Byuksky. The marine shelf zone was intensively spread in the northwestern direction.

CONCLUSIONS

A new variant of correlation of the Nepa and Tirsky horizons, based on the areal tracing of sequence boundaries, has been proposed. For the first time, six third-order independent sequences have been distinguished. The previously established stratigraphic unconformities were confirmed. The stratigraphic unconformities were distinguished for the first time: at the base of the Middle Kursovsky Unit (sequence SQ2), at the base of the lower (sequence SQ4) and upper (sequence SQ5) parts of the Upper Byuksky Subformation.

Thus, the regional sequence–stratigraphic analysis makes it possible to distinguish and trace the third-order sequences in the interval of the Kursovsky Formation of the Nepa horizon and Byuksky Formation of the Tirsky horizon of the Botuoba SFZ. The succession of sedimentation was reconstructed and clarified. The sediments of this stratigraphic interval were accumulated at the passive continental margin under the conditions of cyclically replacing alluvial and fluvial with lagoonal and shallow-marine environments. The general marine transgression covered the south of the Siberian Platform in the Late Vendian, with a peak in the Late Tirsky. The main productive horizons are confined to the LST (Talakh and Khamakin) and the HST (Arylakh and Botuoba) deposits.

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