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LITHOGENESIS ROLE IN FORMATION OF ZONES WITH IMPROVED RESERVOIR PROPERTIES OF SUBSALT CARBONATE SEDIMENTS OF VENDA AND LOWER CAMBRIAN (EASTERN SIBERIA)

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РОЛЬ ЛИТОГЕНЕЗА В ФОРМИРОВАНИИ ЗОН С УЛУЧШЕННЫМИ ФИЛЬТРАЦИОННО-ЕМКОСТНЫМИ СВОЙСТВАМИ ПОДСОЛЕВЫХ КАРБОНАТНЫХ ОТЛОЖЕНИЙ ВЕНДА И НИЖНЕГО КЕМБРИЯ (ВОСТОЧНАЯ СИБИРЬ)

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The object of research is pre-salt deposits of carbonate complexes from Vendian and Lower Cambrian Nepa-Botuobiya anteclise (NBA), located in the central part of the Siberian platform, administratively dedicated to the Irkutsk region.
The problems of fluid dynamics within the basement ledges are considered. Their role in the high productivity of overlying carbonate deposits is assessed. Reconstruction of sedimentation conditions and subsequent diagenesis and katagenesis of Nepa formation sediments is made that have the greatest impact on morphostructure of the sedimentary cover. Cuts of Vendian-Cambrian sediments before and after diagenesis and katagenesis are given. Detailed construction helped to establish antiform structure of the sedimentary cover deposition over the basement ledges, allowing visually see in retrospect a sediment`s restructuring and its influence on the formation of hydrocarbon traps. The information on the rising pore pressure within the ledges is provided, due to which there is a subvertical fluid migration through both sulfate-carbonate rocks and interformational mudstones which to the beginning of elysion processes in Nepa formation were also unlithified porous sediments. It is suggested that the most permeable zones in the sulfate-carbonate rocks were formed over the edge portions of the projections as the most deformed during compaction of sand and clay deposits Nepa formation and restructuring of the upper section of the sedimentary cover. It is suggested that the elysion stage of sedimentary basin development within ledges and arched structure of Vendian-Cambrian deposits leads to dissolution and mobilization by aqueous solutions of the sedimentary rocks substance at depth and their migration mostly up. The results outlined in this paper are supported by the core data analysis.

Ключевые слова:
Непско-Ботуобинская антеклиза, карбонатные отложения, Восточная Сибирь, венд, нижний кембрий, седиментация, диагенез, катагенез, коэффициент уплотнения, флюидомиграция, элизионная стадия, выступы фундамента, рассоливание, фильтрационно-емкостные свойства.

Объектом исследования являются подсолевые отложения карбонатных комплексов венда и нижнего кембрия Непско-Ботуобинской антеклизы, расположенной в центральной части Сибирской платформы, в административном отношении приуроченной к Иркутской области.
Рассмотрены вопросы флюидодинамики в пределах выступов фундамента. Оценена их роль в высокой продуктивности вышележащих карбонатных отложений. Выполнена реконструкция условий седиментации и последующего диагенеза и катагенеза отложений непской свиты, оказывающих наибольшее влияние на морфоструктуру осадочного чехла. Приведены разрезы венд-кембрийских отложений до и после диагенеза и катагенеза. Детальные построения помогли установить антиформное строение отложений осадочного чехла над выступами фундамента, позволяя наглядно увидеть в ретроспективе структурную перестройку осадочных отложений и влияние ее на формирование ловушек углеводородов. Приведена информация о нарастающем поровом давлении в пределах выступов, за счет которого происходит субвертикальная флюидомиграция сквозь как сульфатно-карбонатные породы, так и межформационные аргиллиты, которые к началу элизионных процессов в непской свите также являлись нелитифицированными пористыми отложениями. Предположено, что наиболее проницаемые зоны в сульфатно-карбонатных породах формировались над краевыми частями выступов как наиболее деформированных в процессе уплотнения песчано-глинистых отложений непской свиты и структурной перестройки верхней части разреза осадочного чехла. Сделано предположение, что элизионная стадия развития осадочного бассейна в пределах выступов и сводового строения венд-кембрийских отложений приводит к растворению и мобилизации водными растворами вещества осадочных пород на глубине и их миграции преимущественно вверх. Изложенные в настоящей работе результаты подкреплены анализом керновых данных.

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Introduction

The target of our survey are subsalt carbonate sediments of Vendian and Lower Cambrian sequences Nepa-Botuobiia Anteclise (NBA), located in the central part of the Siberian platform administratively assigned to the Irkutsk region. Geologically NBA belongs to Leno-Tungus oil and gas bearing province [1].

The geological exploration of the NBA territory was initiated in the second half on the 19th century. In 1940, core drilling was commenced in Turuk anticline. After the end of the Great Patriotic War, operations in the NBA territory were resumed to include core drilling starting in 1947 in the Ust-Kut district. In 1960s–1970s of the previous century, scientists of the Academy of Sciences of the Union of Soviet Socialist Republics and the Ministry of Geology of the USSR, geologists and geophysicists of the Irkutsk region and the Yakut Autonomous Soviet Socialist Republic proved that the exploration and prospecting works should have been focused on the NBA territory [2–6].

Currently the key productive horizons of the explored territory are subsalt carbonate sequences: Lower Cambrian – Osa horizon (B_1 and B_2 beds); Vendian-Lower Cambrian – Ust-Kut horizon ($B_{3–4}$, B_5 beds); Vendian – Preobrazhenskii horizon (B_{12} bed) and Yerbogachenskii horizon (B_{13} bed) [7].

In general, the subsalt sequences are characterized by a complex reservoir structure and high variability of reservoir rock properties both owing to the lithological changes and to the local salinization of their pore volume [7]. It is the salinization that to a large extent defines the reservoir properties (permeability and porosity) of the oil and gas bearing horizons.

The complex structure of the voids and overall salinization of the Nepa-Botuobiia Anteclise carbonate productive sediments causes significant difficulties in location of wells at the stage of geological prospecting works in order to instigate their flow. In 2010–2012, resulting from the geological exploration of the PJSC Oil Company Rosneft license areas in the Irkutsk region and Krasnoyarsk Krai, 6 oilfields were discovered. In terms of geological structure, it became crucial to identify basement highs of assorted stretch. Their presence is a favorable sign for the forecast of productivity of the overlying carbonate reservoirs.

Basement highs as key prospecting indicator for areas with improved reservoir properties

The crystalline basement rocks in the territory of exploration are uncovered by all drilled wells. They consist of compositionally diverse metamorphic bodies (granites, gneissose granites, and magmatics), decompacted and highly weathered in the upper part of the basement. Virtually all wells have a weathering crust composed of grey-colored rock (from light grey to dark grey), highly crumbled, with inclusions of crystalline silica, glist, feldspar and at times splinters of granite with 1–4 m thickness. The highest penetrated thickness of the basement is 50 m.

Nepa suite stretches across the entire region where it overlies the basement rock with stratigraphic discordancy. The suite is overlapped by terrigenous-sulphate-carbonate rocks of Tira suite. Its thickness is highly variable, ranging from several to 120 m and consistently increasing from north-east to south-west.

Yerbogachenskii horizon (B_{13} bed) stands out from the Tira suite sequence and discordantly overlies the terrigenous deposits of the Nepa suite. The Tira suite deposits are not as pervasive, the thickest part located in the north-east part of the NBA. The Tira suite bottom surface reliably matches the subaerial erosion surface. Tira sequence in the explored wells drill sample can be provisionally separated into three units: terrigenous-sulphate-carbonate in the near-bottom part, primarily carbonate in the middle part and sulphate-carbonate in the upper part of the sequence. The basin genesis in Tira age is related to the inland advancement of the shoreline westward and basin deepening in the north-east part of the region under consideration.

Starting from Preobrazhenskii horizon, excluding B_1 bed, the studied territory is structurally regular. Structure of B_1 bed of Usolie suite is of special interest, namely the outstandingly complex geometry of a part of the territory of research, discovered over the recent years due to the analysis and integrated interpretation of materials of the detailed seismic survey by CDP-3D method. In the north-west part the sequence mainly consists of the thin biostromal buildups. The well sequences are dominated by the interbeds of horizontally laminated argillaceous dolomite. To the south-west, thickness of deposits steeply increases. Organogenic build-up with bulky formed elements is found in the drill sample. Its upper part was exposed to multiple erosions and karst formation. Judging by the wave train, in this area of variable thicknesses (from 18 to over 80 m) reef-like bioherm build-ups could form. Probably this area partially isolated the north-east part of the region.

As of today, the relation between the sedimentation environment, type of bioherm buildup and improved reservoir properties of the rocks overlying the basement highs hasn't been established. The 3D mineralogical model built based on geo information system (GIS) data suggests that the productive horizons deposits in the wells above the basement highs and beyond do not significantly differ either. The only exception is that the decrease of salt rock occurrence and increase of cavitation is observed in the wells overlying the basement highs.

Mineral composition of the principal productive horizons formed in Venda and Lower Cambrian age, drawing on the results of X-ray phase analysis, is the following: dolomite, calcite, anhydrite, clays, crystalline silica, salt rock. The 3D mineralogical model built based on X-ray phase analysis data suggests direct correlation between the age of deposits and content of dolomite in the rock. In Osa horizon, mean content of limestone is 13 %, while in the lower parts of the sequence it goes down to maximum 0.3 %. The proportion of rock salt dwindles from Osa to Yerbogachenskii horizon, being virtually absent from Preobrazhenskii and Yerbogachenskii horizons. Argillaceous minerals are present in all horizons in minor amounts, the mean value per bed being maximum 1 %. Crystalline silica content is stable throughout the sequence. Anhydrite content is the highest in Ust-Kut horizon. Upwards and downwards of the sequence, the anhydrite content decreases.

According to the reserves estimation guideline [8], for reservoir quality discrimination in absence of direct qualitative indicators (which is the case with the deposits under consideration) it is recommended to use quantitative criteria of reservoirs based on the statistical data.

Based on the experience of operations in the region, for wells located above the basement highs with cavitation even slightly over 5% in the productive horizons interval, oil inflow with tens of cubic meters per daily production rate was received. Generally the production rate from one bed can exceed 150 m^3 per day. Wells located exterior to the basement highs with 12–14 % rock cavitation appear to have no influx or be commercially unproductive in terms of hydrocarbons, judging by the results of formation testing in the closed well hole even after the acid treatment.

The deposits of interest are high-resistivity rocks; hence fluid content assessment based on the specific electrical resistivity data is complicated. The resistance range measured in the course of formation electrical resistivity evaluation in reservoir intervals with influx of both water and oil varies within 300 and 800 Ohm·m. This is evidence that the rocks resistivity does not solely depend on the fluid content, but also on the structure of voids and their hydrophobicity. Mixed wettability rocks simultaneously contain adsorption centers for oil and water phases; consequently, the specific electrical resistivity of the deposits is a complex function of their pattern within the voids and can be described by a percolating function [9]. It is highly relevant that the deposits in question display oil sweating on the drill samples throughout the area, which in its turn somewhat complicates the calculation of rock petroleum potential and inflow type evaluation [10].

The calculated K_{og} still might not explain the nature of inflow. In other words, unless the prospective site is tested using the basic logging suite, one can only extrapolate on the presence of a reservoir in the interval in question and on the nature of inflow. This phenomenon is characteristic of the well rocks situated both over the basement highs and away from them.

Currently there is a reliable well logging method for determining the productive intervals in the researched deposits – that of nuclear magnetic logging (NML). Thus, based on an integrated series of laboratory drill sample analyses under the NMR-Injection-NMR schedule (where NMR is drill sample nuclear magnetic logging survey), it was established that the deposit water in the study area contains magnetic impurities and its signal in the transverse relaxation distribution (T_2) does not cross with the signal from light oil contained in the sequence [11]. Moreover, the drill sample research has shown that the values of highly mineralized water based drilling mud used for well drilling in form of mud filtrate (MF) when penetrating the reservoir, approximate the time of MF relaxation in the void space in the T_2 distribution [12, 13]. Since MF T_2 value in the void space exceeds the relaxation time of deposit water and oil in the NML distribution, signal occurrence in the incremental cavitation spectrum at time values exceeding oil relaxation period may signify that the interval contains an area of MF penetration into the oil-filled reservoir. This further suggests that the formation is productive. Based on this evidence, a sequence of algorithms was developed for interpretation of nuclear magnetic logging data in the interval of the deposits of interest, involving a calculation of bound water and oil proportions and dynamic cavitation, and an estimation of productivity and hydrodynamic permeability of the tested area was made [14, 15].

The results of X-ray tomography for the core drill sample of the well drilled from above the crystalline basement high have shown that the deposits contain narrow intervals of increased cavernous porosity (Figure 1). Apparently, this kind of an interbed acts as the main filtering channel for productive formations. It is notable that even within one meter these areas are oriented at multiple angles and azimuths. Based on the shape elements of these areas, it is fair to assume that they inherited this feature from the initial build-up forming the main carcass of the rocks. Samples selected based on the results of the X-ray tomography and oriented along the cavern generation development trend, manifest absolute gas permeability up to 10 D. The obtained results suggest that the process of drill sample collection for laboratory testing should be conducted thoroughly and taking into account the structure of the rock voids.

A visual representation of absence of sedimentological properties influence on the filtration characteristics of deposits is a comparison between absolute permeability to gas of two wells before and after desalting for B_5 bed, where one well is located above the basement high and another is outside of the basement high area (Figure 2).

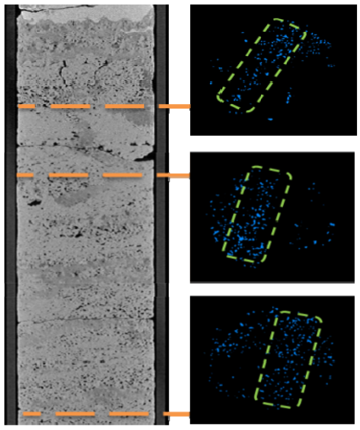


Figure 1. Intensive cavern formation areas from the results of X-ray tomography

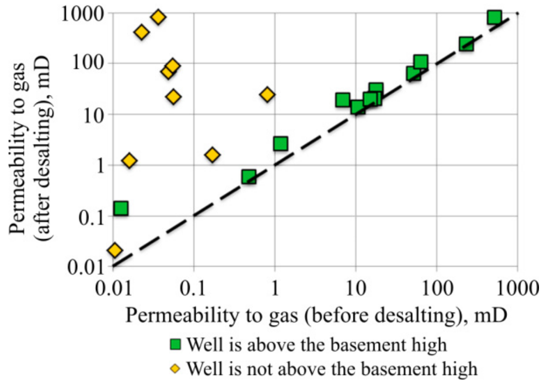


Figure 2. Comparison of absolute permeability to gas of two wells before and after desalting

From the comparison in Figure 2 it is apparent that for the well bored above the basement high, after salt rock removal from the samples their permeability grows insignificantly. Meanwhile, in the samples from the well bored outside of the basement high area, the average permeability growth constitutes from 0.14 to 160 mD.

Another special feature of the wells located above basement highs is consistent inflow from virtually all productive formations.

Concerning possible origin of areas with improved reservoir properties above the basement highs

It is still unclear in what way the basement highs formation process impacted the reservoir properties of the deposits. There are several views of the relation between basement heterogeneity and petroleum potential of the superposed sedimentary cover.

Within the territory of Kuyumba-Yurubchen-Tohomo area, the oil and gas accumulation zones are related to the intensity of decompactification of the Riphean dolomites on the interface with Archean-Lower Proterozoic basement [16]. This interface is a sizeable interval, although variable in thickness – a sequence of flat-lying plates alternating with crystalline rock plates [17, 18]. Basically, this is a hydrodynamically integrated, albeit a petrographically heterogeneous reservoir. Within seismic sequences of Kuyumba field there are subvertical pillarlike areas of Riphean dolomites decompactification and disintegrated granite highs [17]. This data significantly expands the diversity of complexly structured reservoir types formed by crystalline and carbonate rocks. Genesis of such oil and gas nearing reservoirs, in the opinion of A.E. Lukin, is ultimately caused by the Earth outgassing processes. Tight intertwining between hydro-acidulated and carbon outgassing branches in oil and gas bearing crystalline strata explains the existence of sustainable paragenesis of decompacted crystalline rocks and carbonate build-ups [16, 17].

Within NBA western slope, local highs of erosional origin occur in the basement, overlain by productive horizons of Venda-Cambrian deposits that have high permeability and porosity. The well testing results suggest high productivity for oil and gas. Some of the researchers believe that this is caused by a set of carbonate deposits sedimentation conditions immediately above the basement highs [19, 20]. According to these conditions, the study area could be described as a low angle monocline carbonate platform with prevalence of finely dispersed biochemical sedimentation arranged in locally distributed uplifted subsurface shallow water islands - shoals. These wave-built bodies have intense flow dynamics with accumulation of sediment washed free of fine material. The obligatory condition for development of such bodies is accumulation of material above the lower plain of wave action. Basement highs, in the authors' opinion, served as areas for highly porous rock accumulation, whereof they assume that a highly productive reservoir had developed in the area of the paleohigh and sharp decrease of porosity and permeability with increasing distance [19].

This study suggests an alternative model of high quality reservoirs formation in productive horizons of carbonate sequences in the western part of NBA Nepa arch, based on inversion of sedimentation and lithogenesis conditions of sedimentary cover within the basement high area. For this purpose, sediment genesis is defined as the process of sedimentary deposits formation in the basin; lithogenesis – as the process of sediments transformation into sedimentary rocks undergoing the diagenesis, katagenesis and metagenesis stages.

The geological framework of the sedimentary cover deposits within the limits of erosion basement highs is such that certain stratigraphic units are absent from the sequence. This is related to the dimensions, particularly height, of the basement highs, and Venda-Cambrian overlying and distant deposits sedimentation conditions. Namely, within the projection of the basement high uncovered by well 3, Nepa, Tira and partially Katanga suite deposits are absent, including B_{12} productive horizon. The generic model of Venda-Cambrian deposits sedimentation within the western part of Nepa arch and Irkutsk license blocks is shown in the geological sequence (Figure 3).

The beginning of Venda deposits genesis within the study area is related to the regional transgression. Nepa suite deposits mostly consist of mudstone with thin interbeds of aleurolites and sandstones formed in conditions of initially shallow and eventually deep shelf. Thickness and structure of these deposits are related to the crystalline basement physiography. Tira suite deposits signify the transition from terrigenous to sulphate-carbonate process of sediment accumulation and form in littoral and sublittoral conditions.

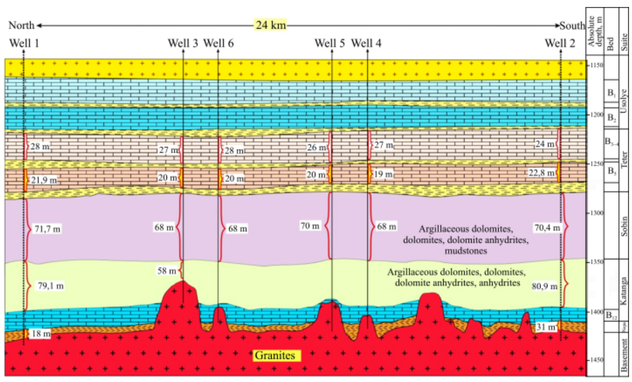


Figure 3. Geological section of Venda-Cambrian deposits sedimentation period in the territory of Severo-Danilovskaia area basement highs

Erosion basement highs in that period were islands, on top of which the above listed deposits were unable to accumulate or were washed away by underwater currents, if they were located below sea level. The most hypsometrically bulky highs are also lacking the Lower Katanga deposits. Further sulfate-carbonate sediment accumulation processes within basement highs area and outside result in leveling of the sedimentation base along the roof of Katanga suite. The final leveling of the roof occurs in the process of formation of clay-sulfate-carbonate deposits of Sobin suite, whereof the sedimentation took place in undisturbed environment of deep shelf or deep lagoon below the storm wave activity base level (facies belt 1, in Wilson's grading) [21].

This conclusion is based on the analysis of Venda sedimentation cover thickness within the study area (Table 1), and is visually presented in the geological section (Figure 3). Katanga suite is thinner above the erosion highs, while outside of the highs its thickness is even, constituting 79–80 m in the wells detached from on another by 24 km along the strike. Thickness of Sobin suite is 68–72 m depending on the position of the wells in the sequence. Thickness of productive deposits of B_5 bed varies from 19 to 22.8 m along the wells 1–3 profile, reducing insignificantly above the basement highs in comparison to the outside area. This difference is 2–4 m, i.e. there is no alluviation; on the contrary, the formation thickness reduces (see Table 1, Figure 3).

Table 1

Thickness analysis of Venda-Cambrian deposits uncovered by wells in Severo-Danilovskaia area

Suite, bed	Well		
	1	3	2
B_5	21.9	20	22.8
Teter suite	59.3	58.4	61.8
Sobin suite	71.7	68	70.4
Katanga suite	79.1	58	80.9
Nepa suite	18	Absent	31
Sobin suite base – Osa horizon roof	180	175.5	187.2

Thus in the sedimentation process a subhorizontal structure is formed, where thickness of Sobin suite deposits and B_5 productive horizon above the basement highs is less than out of their area. Overall, along the paths of wells 1–3, thickness of sedimentary deposits from Sobin suite base level to the roof of Osa Horizon is clearly related to the thickness of argillaceous deposits of Nepa suite (see Table 1). Reduced thickness of sedimentary cover sequence (175.5 m) is determined in well 3, where Nepa suite is absent; the thickest part uncovers in the well 1 (187.2 m), where Nepa suite thickness is 31 m. As will be shown below, this type of sedimentary cover structure can be explained by compaction (thickness reduction) of Nepa suite argillaceous deposits in the process of early diagenesis and sequence compensation by increasing thickness of sulfate-carbonate deposits. Therefore, basement highs buried under 150 m thick sulfate-carbonate deposits of Katanga and Sobin suites could not have influenced the sedimentation processes of productive horizon B_5 of Teter suite, as some of the authors have argued [19, 20]. It is even less probable that alluviated shoals would form exactly above the buried highs, wherein B_5 horizon thickness, conversely, reduces (see Table 1).

Meanwhile, seismic orthogonal cross sections display evident orthomorphic and arched structure of all Venda-Cambrian deposits within the area of basement highs up to the roof of Usolye suite, and not just of the productive horizons (Figure 4). In our opinion, the character of the entire Venda-Cambrian sequence is a consequence of compactification, metamorphoses of shape and thickness of sand-clay Nepa suite deposits around the highs in the process of diagenesis and katagenesis.

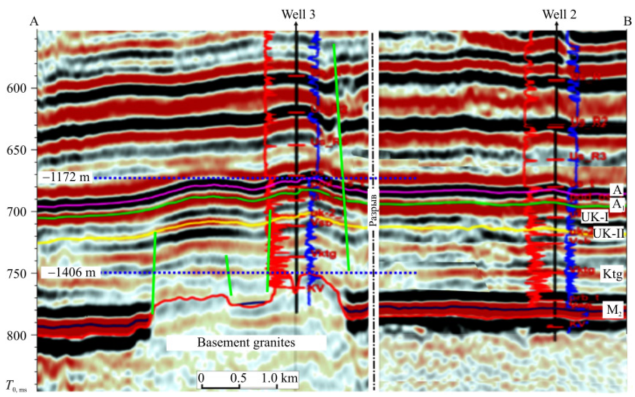


Figure 4. Wave field visualization of crystalline basement paleohigh time section (in the area of well 3): A – B_1 roof; A_1 – B_2 roof; UK-I – B_{3-4} roof; UK-II – B_5 roof; Ktg – Katanga suite roof; M_2 – Nepa suite roof

In order to define the morphostructural features of terrigenous and sulfate-carbonate deposits in the study area, an inversion of their sedimentation and further lithogenesis conditions was performed. Normally paleoreconstruction uses the entire sequence of sedimentary deposits [22]. In the studied sequence we are only considering the sand-clay deposits of Nepa suite with high compactification ratio and their diagenesis and katagenesis which results in significant metamorphoses in the structure of superposed sulfate-carbonate deposits of Tira, Katanga, Sobin and Usolye suites, including productive horizons (B_1, B_2, $B_{3–4}$, B_5, B_{12} and B_{13}).

Role of diagenesis and katagenesis in vertical fluid migration and formation of areas of improved reservoir properties

In our opinion, one of the main reasons of improved reservoir properties areas genesis in the productive horizons located above the basement highs is vertical fluid migration of water expelling stage of hydrodynamic system in the course of diagenesis and katagenesis of Nepa suite argillaceous deposits. In order to substantiate this model, we have conducted an inversion reconstruction of Nepa suite deposits sedimentation and lithogenesis conditions and considered fluid migration within the basement high areas in the process of Venda-Cambrian deposits and productive horizons genesis.

Terrigenous deposits' diagenesis and katagenesis processes are often used in petroleum industry to determine the structural profile of sedimentation mass and fluid dynamics in the process of lithogenesis, influence of these processes on reservoir properties of formations, authigenous mineral genesis etc.

It is well known that during lithification of sedimentary material in the process of subsidence the deposits undergo compactification, also known as gravitational consolidation [23]. This compactification starts from the time of their deposition in the basin of sediment accumulation and continues under the weight of later formations. Several models are proposed, featuring from two to four stages of compactification of sedimentary rocks [23]. So far a common regularity of sediments and argillaceous rocks compaction for all formations and sequences hasn't been established. Each region, formation and sequence, respective of its age, sediment accumulation rate, mineralogical composition of clays and geological history, has its own conditions of sedimentary deposits consolidation and individual compaction curves. At each stage of rock transformation, the compaction process can have its own pattern of development, depending on the environment (wet or dry), substance content, structure and size of fragmental grains, P-T-conditions of lithification etc. In particular, the research has shown that compactification is the fastest in carbonate rocks, and the longest in sandstones and aleurolites [24].

In order to provide a quantitative assessment of initial sediment thickness metamorphosis degree, many different factors apply. One of these is shrinkage factor (K_s), showing by how many times the thickness of enclosing rocks has decreased versus its initial value [25]. Other studies state that K_s of sand deposits is 1.1–1.3, i.e. their thickness decreases by a maximum of 10–30 %; argillaceous muds transform into mudstones with 3–4 times thickness decrease; carbonaceous mudstones and peat bogs decrease in thickness by 5 times and more [25–27]. For paleothickness reconstruction, S.I. Romanovskii [24] uses individual shrinkage factors for various lithological types of rock (Table 2).

Table 2

Classification of rocks by shrinkage factor after S.I. Romanovskii [24]

Shrinkage factor	Compaction type	Rock
Below 0.1	Virtually uncompactable rock	Large-grained and coarse-grained sandstones, gritstones etc.
0.1–0.3	Low compaction rock	Fine-grained sandstones
0.3–0.5	Moderate compaction rock	Large- and medium-grained aleurolites, with different degrees of clay content
0.5–0.7	High compaction rock	Fine-grained aleurolites with high clay content, mudstones etc.
Over 0.7	Extremely high compaction rock	Carbonaceous mudstones, coal (bod muck) etc.

Inversion of sedimentation mass compaction conditions and, in particular, determining the paleothicknesses of geologic horizons comprising the sedimentary cover are of a great interest for geologists and geophysicists engaged in problems of formation and metamorphosis of sedimentary deposits, accumulation of hydrocarbons and their migration, evaluation of size and reservoir quality of formations wherein the oil and gas deposits emerge [22]. Evaluation of initial thickness (decompactification method after M.R. Lider [28]) provides a basis for paleoreconstruction and sedimentological analysis of genetic types of sedimentary deposits, especially for localized areas where values of productive formations thickness and paleotopography amplitudes are below the seismic methods sensitivity threshold. Neglect of the initial thickness parameter inevitably leads to serious distortion in calculations and erroneous conclusions, which negatively impacts the efficiency of geological exploration [24]. Notably, the importance of paleoreconstruction application in substantiation of productive reservoirs US after lithification of Tumen suite is illustrated through several targets in West Siberia [29].

Inversion of Venda-Cambrian deposits origination and lithogenesis conditions in basement highs areas

In order to calculate Nepa suite deposits thickness, shrinkage factor K was used, as proposed by S.I. Romanovsky [24]. Initial thickness was calculated by the formula:

$$H^* = H/(1 - K),$$

where H – contemporary thickness of Nepa suite deposits, where K factor is individual for each lithological variety – mudstone and sandstone. All calculations are provided in Table 3. Mean shrinkage factor K_m for Nepa suite sand-clay deposits uncovered by the wells in the study area amounted to 2.64–2.77. Additionally, initial thickness reduction of argillaceous sediments (alluvium) (by 25–30 %) was taken into account, occurring after the first 8–10 m of subsidence (early diagenesis).

Table 3

Calculation of Nepa suite sand-clay deposits paleothicknesses for the period of sediment genesis

Well	Deposits	Thickness	Compaction factor K	Compaction factor K (weighted average for the entire suite)	Current suite thickness h_3, m	Thickness of initial uncompacted sediment of suite deposits h_1, m	Fold (shrinkage factor K_s)
1	Sandstones, aleurolites	1.7	0.4	0.64	18	50	2.77
	Mudstones	16.3	0.7				
2	Sandstones, aleurolites	8.1	0.4	0.62	31	82	2.64
	Mudstones	22.9	0.7				

So, in case of Well 1, initial thickness of Nepa suite deposits (before diagenesis and katagenesis amounted to 50 m at contemporary thickness equal to 18 m, while in Well 2 initial thickness was 82 m at contemporary thickness 31 m. Correctness of calculations is confirmed by reconstruction of geological sequence by the well paths, wherein the application of decompactification method resulted in leveling of Nepa suite deposits roof by the end of its formation in the marine sedimentation conditions (Figure 5).

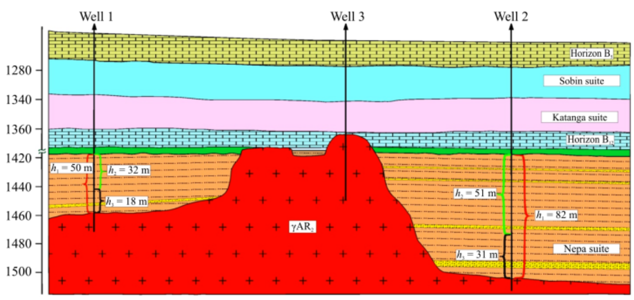


Figure 5. Geological profile of Venda-Cambrian deposits within Archean crystalline basement high (γAR$_2$) until diagenesis of sand-clay sediments of Nepa suite: h_1 – sediment thickness before compactification; h_2 – loss of thickness during compaction; h_3 – contemporary thickness

According to the geological profile presented in Figure 5, Nepa suite deposits composed mainly of mudstone were formed in the conditions of deep shelf. Basement and erosion highs were submerged in water; therefore Nepa suite is almost free of rudaceous rock of exogenous superficial weathering type. Further, during transition to carbonate sedimentation type, marine conditions subsist, resulting in formation of subhorizontal Venda-Cambrian sedimentary structure.

First sulfate-carbonate deposits of Tira suite accumulated in the period when predominantly argillaceous sediments of Nepa suite occurred in the condition of flow or plastic rock. Further compaction of Nepa suite deposits depended on the rate of accumulation of the entire Venda-Cambrian sedimentation sequence. According to the diagram of N.V. Logvinenko [30], transition of argillaceous sediments to lithified mudstones occurs within 5 stages of diagenesis and katagenesis with gradual metamorphosis of state and properties of deposits (Table 4). As for the Nepa suite deposits, the transition from argillaceous sediments to lithified mudstones occurred not earlier than at their subsidence to the depth of 1000–1200 m, i.e. after genesis of the entire Usolye suite of Cambrian age, or perhaps later. So, unconsolidated scarcely lithified deposits occur at a depth of up to 2 km.

Thus, the Nepa suite lithification process is synchronous to and dependent on the rate and conditions of sedimentation of the overlying Venda-Cambrian deposits. Gradual compaction and bending of Nepa suite deposits in the proximity of the basement highs and absence of this process immediately above the highs (absence of Nepa suite argillaceous deposits) result in orthomorphic and antiform structure of overlying sulfate-carbonate deposits and even evaporates, based on the seismic data and contemporary

Table 4

Physical properties of argillaceous deposits in the conditions of diagenesis-katagenesis based on the data of N.V. Logvinenko [30]

Stage	Depth, m	State	Clay particles orientation
I. Diagenesis	10–50	Fluid	Sparsely oriented or chaotic
II. Diagenesis	Ends at 50–200	Transfer to plastic state, moisture by 10–15 % higher than moisture at the plasticity limit	Stays chaotic
III. Transition from diagenesis to katagenesis	250–300	Bottom interface – transition to semi-solid state	Oriented in the stratification plane
IV. Katagenesis	600–700	Solid	Intense particles orientation in the stratification plane
V. Katagenesis	1000–1255	Solid, compaction and dehydration slow down	–

geological sequence (see Figure 4). Schematic visualization of rock compaction in the proximity of the basement high, providing an explanation for the seismic field wave train, is presented on the geological profile reflecting the modern sequence of Venda-Cambrian deposits (Figure 6).

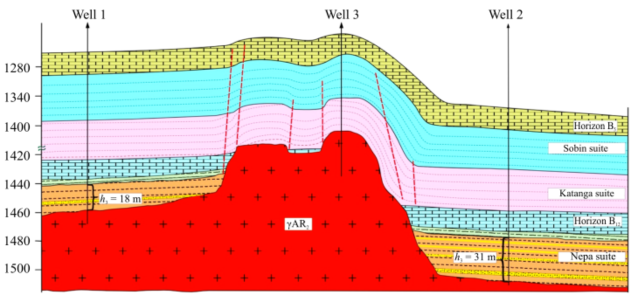
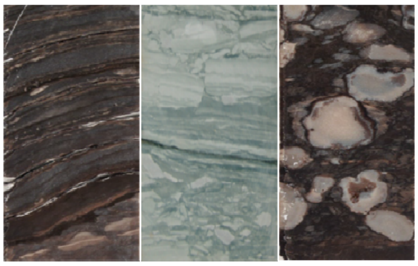


Figure 6. Contemporary geological sequence of Venda-Cambrian deposits within Daniovskaia area after katagenesis of Nepa suite sand-clay deposits

Drawing on the available materials of seismic survey, drill sampling and logging data, there is a high degree of confidence that antiform structure captured by seismic data above the basement highs (see Figure 4), is characteristic of the entire Venda-Cambrian sedimentation sequence, and not merely for B_5, $B_{3–4}$ productive horizons, being related to a lengthy process of Nepa suite argillaceous deposits lithification. Processes of compaction of Tira and partially Katanga suite sulfate-carbonate deposits absent above the basement highs also make a minor contribution in the Venda-Cambrian sequence structural metamorphosis. Thickness reduction of Sobin suite, B_5 productive horizon and the entire sequence starting from the roof of Katanga suite and ending with the roof of Osa productive horizon immediately above the basement highs (see Table 1, Figure 3) is a consequence of carbonate accumulation compensation against the compaction and thickness reduction of Nepa suite argillaceous deposits away from the basement highs. Therefore the antiform structure of B_5 bed above the basement high and its reduced thickness are not due to the “alluviation” process in the latter [19], but to the undercompensation of the sequence or, conversely, on the washing out of the deposits.

Plastic deformation areas, brecciation areas and diagenetic fractures form in the Nepa suite deposits and superimposed sulfate-carbonate deposits during the continuous transition to solid state (Figure 7).

Figure 7 shows that the primary foliation of Sobin suite argillaceous deposits bends above the basement highs.



a *b* *c*

Figure 7. Deformations and brecciation in argillaceous and carbonate-argillaceous deposits of Sobin suite (*a*) and Teter suite (*b*); “agate” texture of secondary anhydrite in dolomites of horizon $B_{3–4}$ above the basement highs (*c*)

Besides, in many wells areas of plastic deformation, brecciation, indifferent lithification of carbonate rocks and argillaceous deposits occur (Figure 7, *b*). Presumably maximum brecciation and deformation form at the borders of basement highs. The vicinity of basement highs appears to have increased fracture porosity and decompaction of rocks traceable through to the productive horizons.

Fluid dynamics within the area of the basement highs

Considering the fluid dynamics in the immediate vicinity of the basement highs, it is fair to believe that the key processes here are related to the water expelling hydrodynamic systems conditioned by the above mentioned compaction processes in the Nepa suite deposits. Fluid dynamics means migration of fluids and gases of various compositions, temperatures and genesis (water expelling, infiltration etc.) in the three-dimensional space both vertically and laterally within the limits of specific geological blocks forming diverse anomalies in physical and geological fields [31–33]. Fluid dynamics allows estimating the nature of migration and discharge of fluids and accompanying processes (desalination, mineral forming etc.). It is important to determine the fluid conducting areas (fractures) that control fluid ingress, define reservoir quality, forming and retaining of hydrocarbons in the sedimentation cover.

According to the calculations described above, the shrinkage factor of Nepa suite sand-clay deposits (wells 1 and 2) constitutes an average of 2.7. Change of initial thickness from 50 and 82 m to 18 and 31 m, respectively, means that in the process of diagenesis and katagenesis of Nepa suite deposits the porosity of argillaceous deposits reduces from 60 to 10–15 % and further down to 5–7 %, respectively; a “pillar” of available ground water is expelled, its height reaching up to 50 m. Thus during submersion of sedimentary masses the water expelling stage of the background lithogenesis occurs, influenced by lithostatic pressure [34]. The water expelling stage of fluid emigration lasts from the initial diagenesis stage to early katagenesis as the Nepa suite argillaceous rocks subside down to the depth of 1 km. There is no doubt that the lithogenesis of argillaceous sediments is rather languid, taking, as it seems, several million years (not than until the end of Usolie suite deposits formation). Still, this process is crucial for fluid dynamics in the immediate vicinity of the basement highs, which is not only true for Nepa suite sand-clay deposits but also for superimposed sulfate-carbonate rocks of Tira, Katanga, Sobin, Teter and Usolie suites, including productive horizons B_5, $B_{3–4}$, B_2 and B_1.

A simplified approach to the directions of deep fluid trajectories within the basement high areas is as follows (we are not considering the rock pressure accretion rate in the process of sedimentation of later deposits, correlations between filtration resistance values in the sand-clay Nepa suite and superimposed carbonate deposits etc.). Fluid migration occurs normally to the surfaces with equal pressures according to the local threshold pressure gradient (from higher to lower pressure). In a simplified representation for the studied point of depth it can be expressed as

$$P_{\text{rock}} = g\sum_{i=0}^{H}\rho_i \cdot h_i,$$

where g – gravity factor, m/s^2; H – depth for calculation of rock pressure; ρ_i – rock bulk density, kg/m^3, for depth point i; h_i – depth sampling interval.

In the sedimentation cover rocks above the basement highs the rock pressure will be less in comparison to the areas where basement highs are absent, but Nepa suite water-filled argillaceous deposits mass is present. Within the limits of the largest highs, pressure on the Nepa suite deposits will be minimal due to its low thickness or equal to zero in the areas where there are no deposits (well 5). Therefore the fluids motion in the process of water expelling will be lateral and directed towards the basement highs, thus creating localized "water collectors" around them. The water collection area depends on the diameter and height of the highs. As the argillaceous deposits compactify, water is compressed in permeable sandy interbeds where fluid motion will also be directed towards the highs due to their geomorphic nature (see Figure 6).

Within the immediate limits of the highs, the increasing porous pressure will result in subvertical fluid migration through both sulfate-carbonate rocks and interformational mudstones that, by the beginning of water expelling processes in the Nepa suite, have also turned into unlithified porous deposits. Only salt deposits solve as covers at this point. It is assumed that the most permeable areas in the sulfate-carbonate rocks are formed above the edge parts of the basement highs due to their highest degree of deformation in the process of compaction of sand-clay Nepa suite deposits and structural metamorphosis of the upper part of the sedimentation cover (see Figure 6).

The composition of formation water that is gradually squeezed out in the process of clays compaction influences the fluid filtering properties that depend on the difference of charges, ionic and molecular radii of hydrated fluids. The filtration process results in formation of a) migrating filtering water with low salinity; b) retained water with high salinity [28]. Both groups of water can take part in the diagenetic reactions. As of today, the content of expelled water squeezed out of Nepa suite deposits is unknown. This question can be answered by laboratory study on determination of gas and liquid inclusions in authigenic minerals. Extrapolating from other regions, it can be assumed that waters expelled from clay rocks can contain calcium chloride (expelled water of diagenesis area) and sodium hydrocarbonate (expelled water of katagenesis area). The assumption is that Nepa suite expelled water mineralization profile was characterized by low salinity, i.e. the waters were not saturated enough to the point when salts, sulfates and carbonates deposit out of solutions [35].

Water expelling stage of sedimentation basin evolution within the limits of basement highs and arched structure of Venda-Cambrian deposits results in dissolution and mobilization of deep sedimentation matter with water solutions and their predominantly upward migration. Deposition of carried-away components occurs in higher horizons of sedimentation rocks. Thus substance redeposits up-section.

In the immediate vicinity of basement highs, undersaturated fluids pressed out of Nepa suite argillaceous deposits dissolve sulfate-carbonate rocks of Katanga and Sobin suite. It is notable that anhydrite is much less soluble than rock salt, but much more soluble than limestone and dolomite. Numerically anhydrite is 160 times more soluble, and rock salt is 25 000 times more soluble than calcite in distilled water at 20 °C. When temperature decreases, a relatively large amount of calcium sulfate deposits out of the saturated solution. For example, temperature decrease from 10 to 0 °C causes deposition of approximately 0.2 g/l anhydrite, i.e. at temperature decrease by even 1 °C about 20 mg/l of anhydrite forms.

Thus in migration "pillars" zone sequence is formed. So, reaching the level of productive horizons and cooling down, the solutions "discharge" Ca^{2+} in form of anhydrite and become undersaturated and more aggressive again. An instance of secondary anhydrite formation is given in Figure 7, *c*. In the productive dolomite areas above this geochemical barrier desalination and leaching occur, resulting in genesis of reservoirs with high porosity and permeability. In the presence of local barriers, ponding of solutions occurs with further lateral migration and forming of tabular types of reservoirs.

Drawing on the aforementioned, it is fair to believe that the development of reservoirs in Venda-Cambrian deposits above the basement highs can be explained by water expelling processes in the period of compaction in the course of diagenesis and katagenesis of Nepa suite argillaceous sediments.

Discussion of results

The conducted survey of the sedimentation cover geological profile has shown that the development of productive horizon B_5 reservoirs with high porosity and permeability above the erosion basement highs (probably other horizons as well) is a result of desalination of carbonate rocks of the horizon in the process of fluid migration caused by water expelling as it is squeezed out of the rock in the process of diagenesis and katagenesis of Nepa suite argillaceous deposits.

Carbonate rock of B_5 horizon in the upper part of the sequence consist of algal boundstones of biogerm buildup, superimposed by argillaceous dolomites and alternations of mudstone, anhydrites and dolomites of supralittoral or shallow lagoon facial area (probably evaporates) up the stratigraphy. By the end of sedimentation period, the deposits of B_5 horizon and superimposed rocks were not lithified and contained a significant amount of seawater with high salinity. Carbonate deposits lithification rate considerably surpasses the rate of argillaceous sediments compaction. Therefore, when Nepa suite argillaceous deposits were still in the second stage of diagenetic metamorphosis, the overlying carbonate deposits of B_5 horizon were lithified and contained a high amount of devitrified salt rock. Forming of salts and anhydrite at the stage of carbonate deposits early diagenesis is described in [36].

Salinization of B_5 productive horizon is regional in scope and is related to the shallowing of the territory and formation of a halogenic basing above the deposition horizon. For instance, in the upper part of B_5 horizon (well 7) content of salt rock in dolomites reaches 29 %.

Desalination of B_5 horizon carbonate deposits, on the contrary, is selective. So, above the basement highs the desalination can occur under the influence of subvertical desalted fluids from water expelling stage of diagenesis and katagenesis of Nepa suite argillaceous deposits. Simultaneously leaching of carbonate deposits occurs, but it is the desalination that causes the development of high quality reservoirs. Similar processes occur above other structural irregularities of the basement: fluvial channels, fractures, especially along the interface between granitoids and enclosing rocks.

Summary

The study proposes an approach to the explanation of high porosity and permeability areas in the productive horizons interval of the wells located above the basement highs. The approach enables an explanation of lack of relation between sedimentology and reservoir properties of the rocks, the decrease of salt rock proportion in the voids and high cavernous porosity of deposits.

Thus, the obtained results can serve as criteria to identify and forecast the location of high quality reservoirs in Venda-Cambrian carbonate deposits of Nepa arch western slope. The study does not cover the matters carbohydrates fluid migration, which probably also have water expelling origins. However, if carbohydrate migration is related to the superimposed allochtonous processes, the water expelling stage of carbonate rocks metamorphosis and high porosity and permeability will be a precursor of oil and gas accumulation forming.

In the future, in order to substantiate the hypothesis, laboratory research aimed at the study of vertical variability of rock mineralogical content, trace contaminants in the key rock-forming minerals, gas-fluid inclusions in carbonate deposits and authigenic minerals is required. In case of confirmation and determination of vertical fluid migration properties other opportunities will emerge for geological targeting of carbohydrate reservoirs in Nepa-Botuobiia Anteclise.

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Роль литогенеза в формировании зон с улучшенными фильтрационно-емкостными свойствами подсолевых карбонатных отложений венда и нижнего кембрия (Восточная Сибирь) / Н.Ф. Каячев, В.А. Колесов, С.К. Квачко, Р.А. Мусин // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2016. – Т. 15, № 20. – С. 216–231. DOI: 10.15593/2224-9923/2016.20.2