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Conceptual Geological Modelling based on Lithological and Petrographic Studies (The Case of the Permo-Carboniferous Deposit of the Usinskoye Field)

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Создание концептуальной геологической модели, основанной на литолого-петрографических исследованиях, на примере пермокарбоновой залежи Усинского месторождения

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The work intends to develop a conceptual model of the Permo-Carboniferous deposit of the Usinskoye field. In the furtherance of this goal, the authors have addressed the tasks of designing a specialised table format to describe thin sections of carbonate core samples and create a database based on the developed format for the subsequent analysis. The paper deals with studying the Permo-Carboniferous deposit of the Usinskoye field, located in the Komi Republic. A unique database of 1,710 described thin sections from 12 wells was created based on the developed format. The classification of carbonate rocks by R.J. Dunham supplemented by Embry and Kloven (based on the dominating fabric in limestone, type of cementing agent and their relationships in the rock) was used as a basis. According to rock material compositions and textural properties, the following nine rock lithotypes were identified: Mudstone, Wackestone, Packstone, Grainstone, Boundstone, Floatstone, Rudstone, Crystalline Carbonate (Dolomite), and Clayey Carbonate Silicite. By following the rock lithology type identification results and the seismic data, three main facies zones were determined in the section of the mid-Carboniferous and Lower Permian sediments: carbonate shoal (inner ramp zone), organogenic buildup (middle ramp zone) and shallow marine shelf plain (mid-ramp zone, partially outer ramp zone).
A moderately deep marine shelf plain facies (outer ramp zone) was provisionally defined.
Following the study results, two profiles of the Mid-Carboniferous and Lower Permian sediments of the Usinskoye field were plotted along two well lines. The presented sections support the conceptual model developed. Based on the core sample findings, the zone of organogenic build-ups stands out in the eastern part of the field, dating back predominantly to the Late Carboniferous and Early Permian periods. An inner ramp with the carbonate shoal facies supposedly exists in the field north-west.
The conducted work has resulted in the development of a conceptual model of the Permo-Carboniferous deposit of the Usinskoye field, which can be used for further development of more reliable 3D facies models, commercial-scale estimations of reserves and field development designs.

Рассматривается создание концептуальной модели пермокарбоновой залежи Усинского месторождения. Для достижения поставленной цели решаются задачи по разработке специализированного табличного формата описания шлифов керна карбонатных отложений, формирование базы данных на основе разработанного формата для последующего анализа. В качестве объекта исследования выбрана пермокарбоновая залежь Усинского месторождения, расположенного в Республики Коми. По разработанному формату сформирована уникальная база данных по 1710 описанным шлифам из 12 скважин. За основу принята классификация карбонатных пород по Р.Х. Данему с дополнениями Эмбри и Кловена (по преобладанию в известняке структурных компонентов, типу цементирующего вещества, а также их взаимоотношению в породе). На основе вещественного состава породы и структурного параметра выделено девять литотипов пород: мадстоун, вакстоун, пакстоун, грейнстоун, баундстоун, флаутстоун, рудстоун, кристаллический карбонат (доломит), глинисто-карбонатно-кремнистая порода. По результатам определенных литологических типов пород и данным сейсморазведки в разрезе среднекаменноугольно-нижнепермских отложений выделены три основных фациальных зоны: карбонатная отмель (зона внутреннего рампа); органогенная постройка (зона среднего рампа); мелководно-шельфовая равнина (зона среднего рампа, частично зона внешнего рампа).
Дополнительно выделена фация умеренно-глубоководной шельфовой равнины (зона внешнего рампа).
В результате проведенных исследований построены два профиля каменноугольно-нижнепермских отложений Усинского месторождения по двум линиям скважин. Представленные разрезы подтверждают построенную концептуальную модель. По данным исследования керна в восточной части месторождения хорошо выделяется зона органогенных построек, образование которых происходило преимущественно в позднекаменноугольное и раннепермское время. В северо-западной части месторождения предполагается существование внутреннего рампа с фациями карбонатной отмели.
В результате проведенной работы построена концептуальная модель пермокарбоновой залежи Усинского месторождения, которая может быть использована для последующего построения более достоверных трехмерных фациальных моделей, промышленного подсчета запасов и проектирования разработки месторождений.

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Introduction

This work is intended to develop a conceptual geological model as illustrated by the Permo-Carboniferous deposit of the Usinskoye field using the lithological and petrographic findings. The model is based on the Dunham rock texture classification that reflects the rock deposition conditions.

Experimental Procedure

The studies deal with the Permo-Carboniferous deposit of the Usinskoye field, located in the Komi Republic. The deposit is unique in its size and properties (μ = 723.2 mPa·s). The oil-saturated layer exceeds 300 m, the volume of AB1 geological reserves is 747 million tonnes, and the recoverable reserves make up 247 million tonnes. More than 2,000 wells were drilled in the field, we chose 30 of them to select over 2,000 m of the core material, which was used to make approximately 9,000 standard and over 1,000 full-size core samples that were later used for laboratory tests. For the Usinskoye field reservoirs, it is of particular importance to conduct studies on both standard and full-diameter core samples, as they most accurately reflect flow patterns of reservoir processes [1-19]. Only laboratory-based core studies give an opportunity to directly obtain such information [20-22]. Furthermore, approximately 3,000 thin sections were made and described.

Description of sections is a specific and time-consuming process, while the description itself is presented in the form of a consecutive textual specification and, as it should be noted, the descriptions by various authors may differ in style and terminology, which complicates their further use for operational data analysis and statistical researches.

To address this issue and categorise the representation of descriptions of the carbonate sedimentary thin sections, a team of specialists from PermNIPIneft, the branch of OOO LUKOIL-Engineering, has developed a specialised table format with coding of the most relevant parameters determined in the thin sections. The key parameters included in the table were the rock family, presence of organic matter, grains, fabric, Dunham texture, predominant authigenous constituents affecting porosity and permeability, measured porosity of the thin section, the prevalent type of porosity, fracturing and stylization. The developed format made it possible to present all textual descriptions of the rock petrographic characteristics in the table form, which provides a range of advantages. Firstly, it is instrumental in the mathematical and statistical analysis of the thin section descriptions. Secondly, it offers a tool to create a database for analysis using findings of different authors, including images of thin sections. Thirdly, it enables us to analyse and compare the thin section parameters with other core sample findings.

By using the case of the Permo-Carboniferous deposit of the Usinskoye field, we created a unique database of 1,710 described thin sections from 12 wells based on the developed format.

For the subsequent lithologic facies analysis and the deposit conceptual geomodelling, the sediments were lithologically differentiated into classes. The structural-genetic classification of carbonate rocks by R.J. Dunham supplemented by Embry and Kloven (based on the dominating fabric in limestone, type of cementing agent and their relationships in the rock) was selected as the key parameter to define lithology of the studied sediments, in addition to the rock material composition). Based on the rock material composition and textural properties, the following nine rock lithotypes were identified: Mudstone, Wackestone, Packstone, Grainstone, Boundstone, Floatstone, Rudstone, Crystalline Carbonate (Dolomite), and Clayey Carbonate Silicite. Figure 1 shows images of the rock thin sections illustrating the facies deposition zones of the Permo-Carboniferous deposit of the Usinskoye field.

Figure 2 shows an analysis of lithotype distribution over a well that is the most typical of various facies zones.

Three main facies zones were identified in the section of the Mid-Carboniferous and Lower Permian sediments, according to the rock lithology type definition results and the seismic data:
– carbonate shoal (inner ramp zone, Fig. 2, *a*)
– organogenic buildup (mid-ramp zone, Fig. 2, *b*)
– shallow marine shelf plain (mid-ramp zone, partially outer ramp zone Fig. 2, *c*)

Additionally, we can define such facies, as moderately deep marine shelf plain (outer ramp zone).
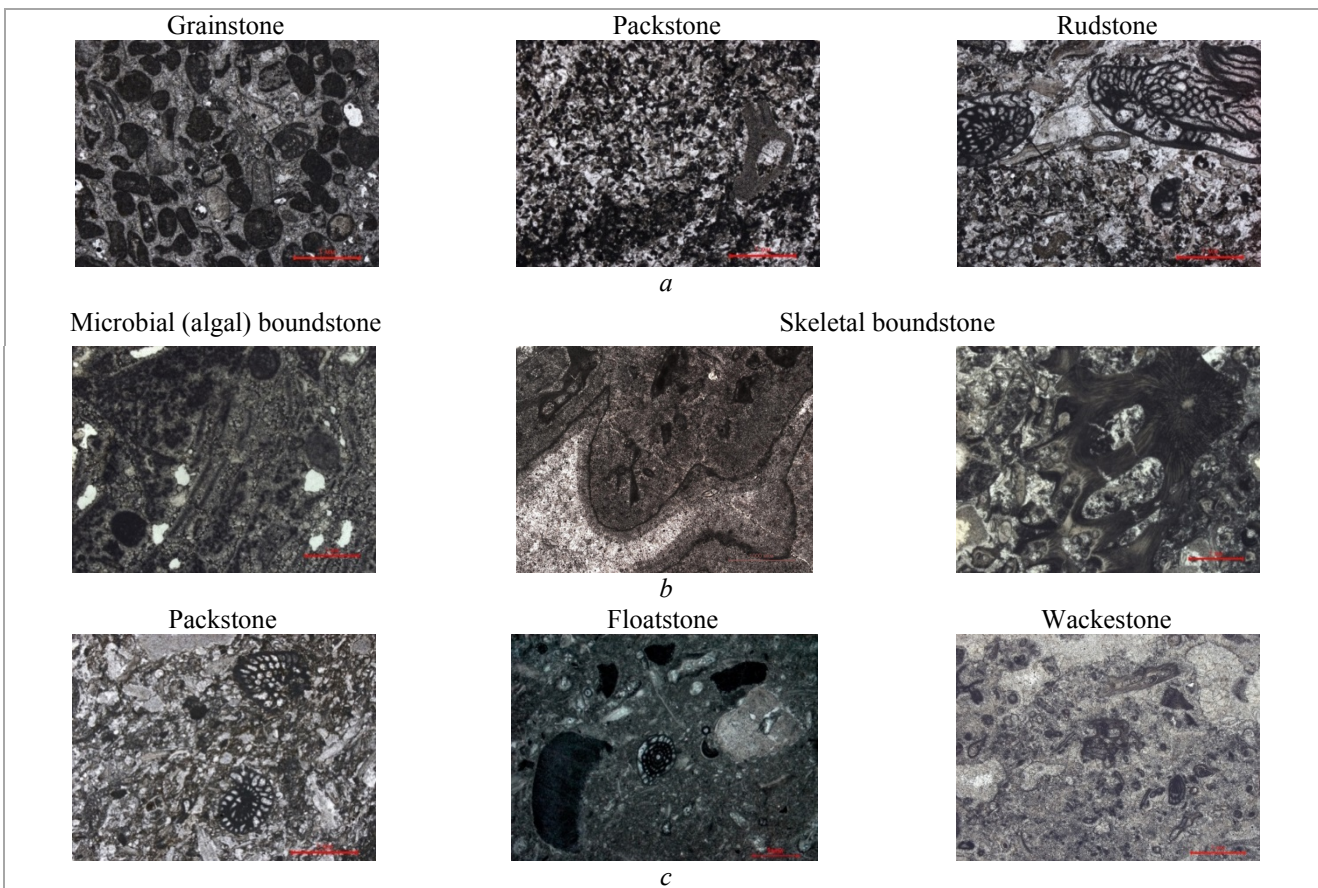
Fig. 1. Images of thin sections typical of facies zones: *a* is carbonate shoal facies zone; *b* is organogenic buildup facies zone (mid-ramp zone); *c* is shallow marine shelf plain facies zone (mid-ramp zone, partially outer ramp zone)
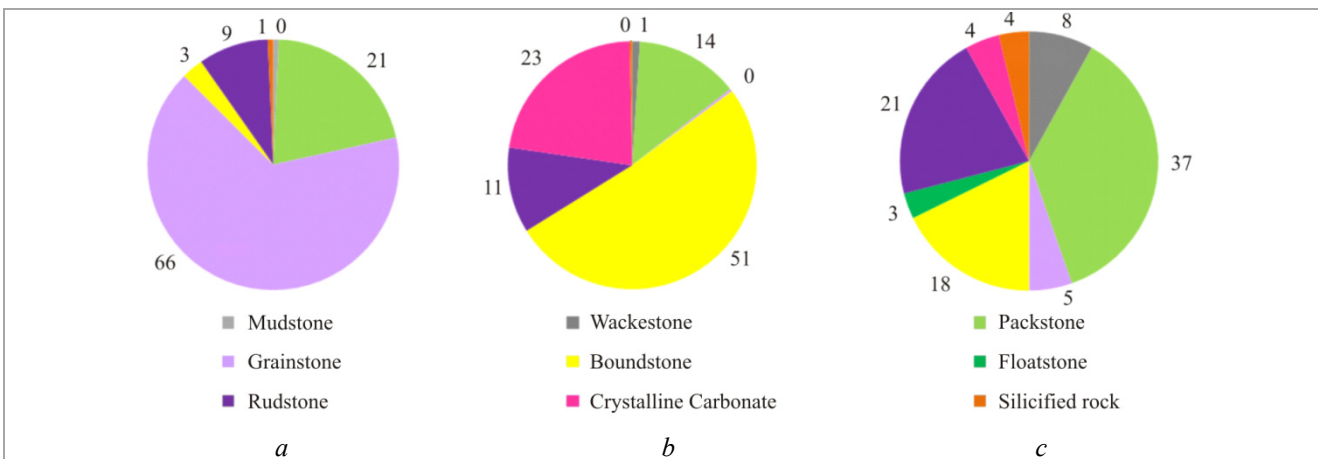

Fig. 2. Most typical well distribution (%) of lithotypes for different facies zones:
a is carbonate shoal (inner ramp zone); *b* are organogenic buildups (mid-ramp zone);
c is shallow marine shelf plain (mid-ramp zone, partially outer ramp zone)

In the Carboniferous and Lower Permian period, the deposition of sediments in the region occurred in shallow marine shelves with the prevalent carbonate, clayey carbonate (less frequently) and sulphate carbonate (for the Mid-Carboniferous period) sedimentation.

According to the regional geological surveys of the Timan-Pechora region (works by V.A. Zhemchugova, N.I. Nikonov et al.), an extensive carbonate ramp gently descending eastwards was located within the Pechora Plate during the Carboniferous and Permian periods.

The Usinskoye field sediments were mainly formed in the inner and mid-ramp zone. Further to the seafloor paleosurface of that time, the fair-weather and storm-wave base actions were the primary factors affecting sedimentation. The sedimentation took place as deep as the first dozens of metres.

The carbonate shoal facies (inner ramp area) is above the fair-weather wave action level, where sediments accumulated from moving shallow waters. It is mainly composed of bioclastic oolitic limestone, sparitic cement (grainstone/rudstone/packstone), while the mud fraction of the sediments was washed away. The facies is defined for all the field locations of the Permo-Carboniferous deposit.

According to V.A. Zhemchugova, organogenic buildups of the Pechora basin, which are the Late Carboniferous and Early Permian by their morphology and environmental evolution, pertain to mounds (as termed by James, Bourque, 1992). Unlike classical reefs, they lack typical massive skeletal organisms, backshelves and foreshelves, their development has been completed at the pioneer stage of the paleo-ecological succession.

By their paleo-ecological formation features and composition, there are two types of buildups: microbial (mud, algal) mounds and skeletal mounds.

The skeletal mounds are mainly formed on seafloor small elevations, with currents and waves washing out fine mud sediments from the buildups. Such organogenic buildups are composed mostly of crinoid bryozoan, bryozoan crinoid, algal crinoid, algal paleo-aplesine boundstone and the accompanying bioclastic rocks formed from the boundstone destruction.

Affected by waves on both sides of the buildup, interbioherm and shelf sediments containing the multisized bioclastic material (polybioclastic limestone) were accumulated.

Microbial (mud) mounds, mainly formed by phylloid algal, cyanobacterial algal bindstone (boundstone) and polybioclastic biocementolite, are able to expand in zones different in sea bottom topography and hydrodynamics.

At the Usinskoye field, the facies of organogenic buildups is determined in the Late Carboniferous and Lower Permian sediments. Its distribution area gravitates towards to the tops of the paleo-uplifts of the Usinskoye structure and is oriented to the north-west. The deposits of the facies of organogenic buildups exhibit increased thicknesses.

The facies of the shallow marine shelf plain is determined on a provisional basis. The sediments were formed in the mid-ramp zone, with weak hydrodynamics, below the fair-weather wave action level. The sediments are dominated by bioclastic, bioclastic micritic and micritic bioclastic limestone (packstone/floatstone/wackestone), with possible interlayers of grainstone/rudstone.

The facies of the moderately deep marine shelf plain is represented by clayey micritic limestone with rare bioclast (wackestone/mudstone) and argillite. Following the core sample analysis data, the rocks of this facies can be found only in few samples. The facies are clearly mappable by low thicknesses, mostly low porosity and permeability.

The rocks classified as crystalline carbonate lithotype, represented by dolomite, are defined in the section. The secondary dolomites are micro-fine and fine grained, calcareous, generally defined in the Mid-Carboniferous depositions. The primary fabric of the rocks is mostly undefined.

The rock dolomitization resulted from the impact of magniferous water on limestone, its calcite turning into dolomite until limestone is completely substituted by dolomite. Observed is the dolomitization of two generations: diagenetic and epigenetic. During the diagenetic dolomitization, dolomite is present as separate rhombohedral and irregular rhombohedral crystals immersed in the rock substrate. In this case, dolomitization has no significant impact on porosity and permeability of the rocks. During epigenetic and metasomatic dolomitization, dolomite significantly or completely replaces primary rocks, forming secondary dolomites, often accompanied by a complete rearrangement of the rock fabric and resulting in significant intercrystalline and dissolution porosity, thus improving the rock porosity and permeability.

Silification zones are observed along detritic limestone in the core samples of wells. Carbonate of organic remains is replaced by silica: the coarse-grained calcite or dolomite is usually replaced by coarser crystalline quartz, while the fine-grained calcite or dolomite is usually replaced by finer crystalline quartz, accordingly.

Figure 3 shows a detailed conceptual model of the structure of the Carboniferous and Lower Permian sediments of the Usinskoye fields, which reflects the deposit formation genesis.
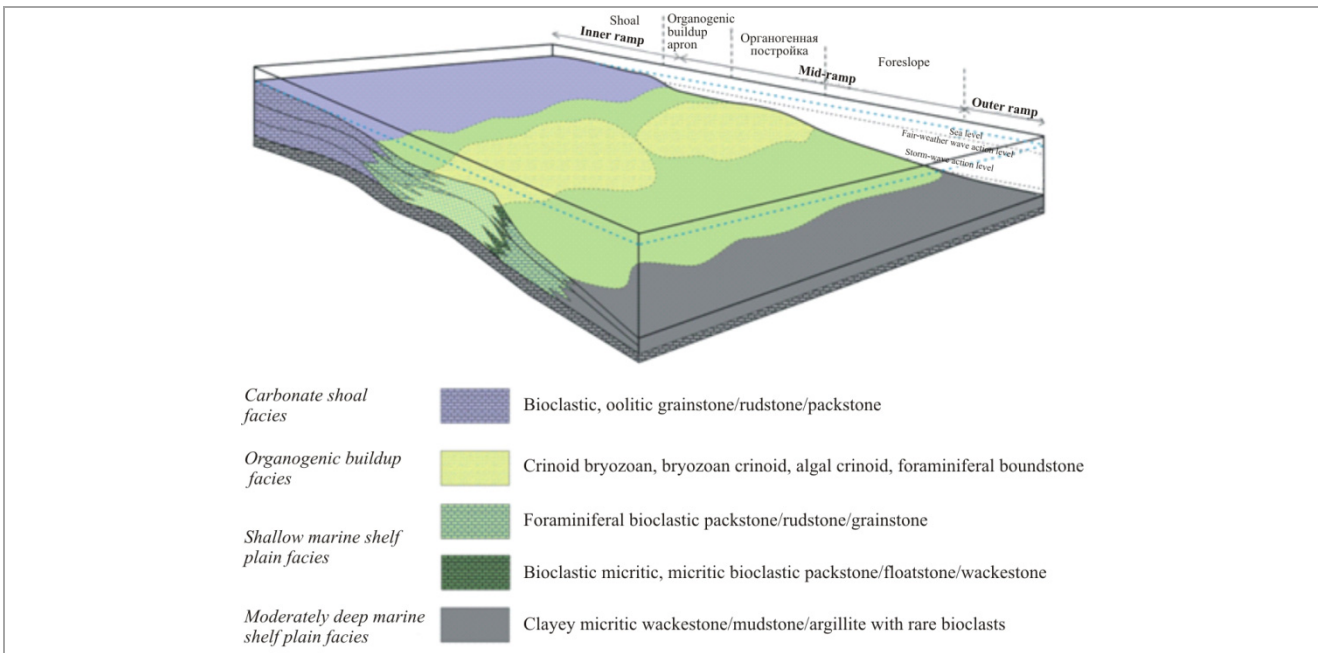
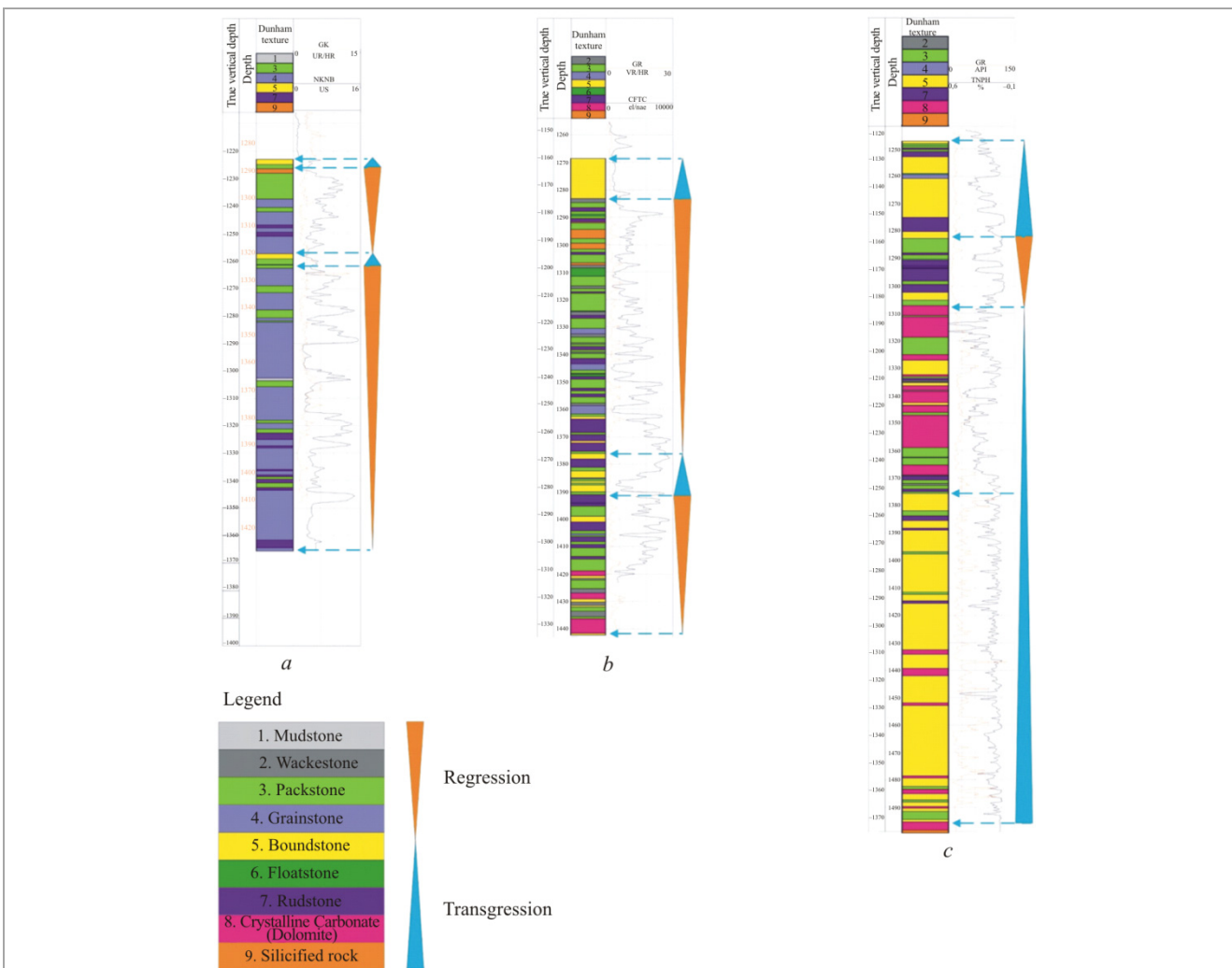Fig. 3. Conceptual structural model of the Carboniferous and Lower Permian deposits of the Usinskoye field

Fig. 4. Section of wells with defined facies zones: *a* is carbonate shoal facies zone (inner ramp zone); *b* - shallow marine shelf plain facies zone (organogenic buildup apron); *c* - organogenic buildups facies zone (mid-ramp zone)

As a result of the conducted studies, two geological profiles of the Carboniferous and Lower Permian deposits of the Usinskoye field were developed, aligned to the regional reference *benchmark* R4 corresponding to the top of the field bench of the 3rd Moscovian stage.

The presented sections confirm the developed conceptual model. Figure 4 shows the well section, most typical of the defined facies zones. Following the core sample findings, a zone of organogenic buildups is well distinguished in the east of the field; such build-ups were formed largely in the Mid-Late Carboniferous and Early Permian periods. It is supposed that in the north-west of the field, there is an inner ramp with carbonate shoal facies.

Sedimentation during the Carboniferous and Early Permian periods occurred with slight sea level fluctuations. Based on the core study results, up to two second-order sequences in the carboniferous Middle and Upper Carboniferous deposits and one sequence in the Lower Permian deposits can be defined. The sequences consist of a transgressive system tract and highstand system tract. The sediments of a lowstand system tract are not common in the sections under study.

During a relative rise and high stand of the sea level, organogenic buildups were formed and growing, which corresponds to the stage of stabilisation and accumulation.

While an organogenic buildup was moved to the sea level, when the sea level stabilised or slightly lowered, the buildup was destroyed, and organogenic clastic sediments were formed (destruction stage).

The ideal sequence consists of sediments from shallow marine shelf plains passing into carbonate shoal sediments, and then into facies of organogenic buildups. The section is ended by sediments of subaerial exposition (breccia, paleokarst, etc.).

Application of Section Analysis in 3D Modelling

As part of the development of a digital 3D geological model of the Permo-Carboniferous deposit, a conceptual model of the Usinskoye field was built using a data set based on the results of the core sample analysis, geophysical studies of wells and interpretation of 3D seismic data [23]. The earlier conceptual model reflects essential geological principles of the productive sediment structure. Thus, now we have everything needed

for the conceptual model development using 3D modelling [24].

The following kinds of data were input into the geomodelling software system as a base for the conceptual model development:

– boundaries of the facies zones identified during the interpretation of 3D seismic data (identified for four main formations)

– lithotypes identified as per the Dunham classification for 12 wells located in the Permo-Carboniferous deposit

– constructional surfaces of reflecting horizons.

Subject to the seismic surface analysis, a reference structural tectonic model the Permo-Carboniferous sediments was built, which consists of four layers.

Based on the structural and tectonic framework of the four layers, a 3D grid with a lateral cell size of 100×100 m was built for conceptual modelling. A grid was selected with an even cell width [25-27]. For each formation within a 3D grid, a discrete parameter was obtained on distribution of the facies zones defined based on the 3D seismic data interpretation results. A unique discrete index was assigned to each facies zone. Since the boundaries of the facies zones are determined laterally only, it was chosen to use Indicators Belts method for the uniform, realistic vertical change in the boundaries of the defined facies zones. The result of the facies zone distribution is a 3D facies parameter (Facies) that most accurately reflects the form and nature of distribution of the facies types in question.

The initial lithotypes data were input in Las file format as the well information. The lithotypes were transferred to the grid cell using the well data averaging function, which allowed us to obtain values of lithotypes in the cube within the well path. Further, using stochastic modelling, discrete lithotype values were distributed across the wells within each facies zone. The final parameter of the 3D distribution of lithotypes in the interwell space subject to the facies zones was obtained (Fig. 5), reflecting the general concept of sedimentation.

The data in Figure 5 illustrate the change of different types of sections, controlled by the change of facies zones and represented by characteristic combinations of lithotypes.

The resulting 3D cube of lithotypes can be used at further stages of three-dimensional modelling of porosity and permeability properties
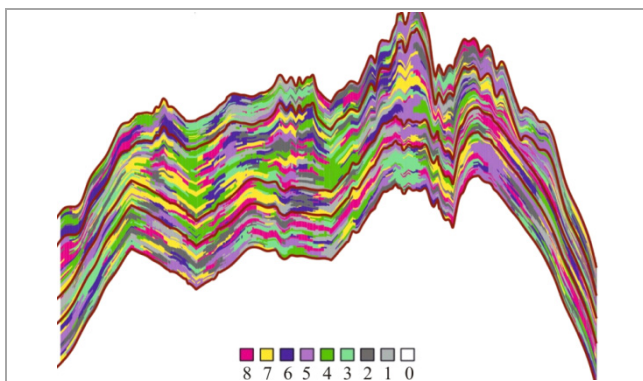
Fig. 5. Final distribution of lithotypes in the 3D grid of the Permo-Carboniferous deposit of the Usinskoye field: *0* is the buildup outside the formation; *1* is Mudstone; *2* is Wackestone, *3* is Packstone, *4* is Grainstone, *5* is Boundstone, *6* is Floatstone, *7* is Rudstone, *8* is Crystalline Carbonate

of reservoir rocks, specifically, as an additional parameter in the distribution of the oil saturation factor of the Permo-Carboniferous deposit.

Conclusions

A database of thin section descriptions of the Permo-Carboniferous deposit of the Usinskoye field has been generated in a specialized format. The generated database was used as a database for a comprehensive analysis of the thin sections of the Permo-Carboniferous deposit of the Usinskoye field aimed at building more reliable three-dimensional models, commercial-scale estimations of reserves and field development designs.

A detailed conceptual model of the structure of the Carboniferous and Lower Permian deposits of the Usinskoye field was built based on 1,710 thin section descriptions, well logging and 3D seismic data.

The applied approach to creating the 3D conceptual model of the Permo-Carboniferous deposit of the Usinskoye field was based on the generalised geological and geophysical data subject to lithotypes identified as per the Dunham classification.

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