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Conceptual Geological and Hydrodynamic Model of the Famennian-Tournaisian Reservoir as a Tool for Predicting the Effectiveness of the Reservoir Pressure Maintenance System, using the Example of the Sukhareva Field

Mikhail Iu. Riabchevskikh[1], **Aleksandr S. Nekrasov**[2]

[1]PermNIPIneft branch of LUKOIL-Engineering LLC in Perm (3a Permskaya st., Perm, 614015, Russian Federation)
[2]Perm National Research Polytechnic University (29 Komsomolskiy av., Perm, 614990, Russian Federation)

Концептуальная геолого-гидродинамическая модель фаменско-турнейской залежи как инструмент прогнозирования эффективности системы поддержания пластового давления на примере месторождения им. Сухарева

М.Ю. Рябчевских[1], **А.С. Некрасов**[2]

[1]Филиал ООО «ЛУКОЙЛ-Инжиниринг» «ПермНИПИнефть» в г. Перми (Россия, 614015, г. Пермь, ул. Пермская, 3а)
[2]Пермский национальный исследовательский политехнический университет (Россия, 614990, г. Пермь, ул. Комсомольский проспект, 29)

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Keywords:
organogenic reef structure, fractured-cavernous-pore type of reservoir, reservoir properties, 3D seismic survey, facies, conceptual geological model, multi-grid, geological base rescaling, geological-statistical section, “non-reservoir”, fracture coverage, dual porosity model and permeability, geological-hydrodynamic model, reservoir pressure maintenance system, adaptation, aquifer, Chen graphs, multivariate modeling, proxy model.

The paper outlines the technology for constructing a new conceptual geological model taking into account the structural features of the Famennian-Tournaisian deposit (T-Fm formation), which is represented by an organogenic reef structure of Late Devonian age, overlain by Paleozoic enclosing structures. This approach represents the distribution of a grid of layers of a geological model according to sedimentation processes.

Based on a three-dimensional digital geological model, a geological and hydrodynamic model was created and adjusted to actual development indicators. When adapting the model to the actual dynamics of reservoir pressure, zonal features associated with the distribution of filtration and reservoir properties were identified. The dynamics of water cut were adjusted based on the results of geological and field analysis, as a result of which the source of water cut was determined for each well.

Based on the geological and hydrodynamic model adjusted to the actual development indicators, forecast options were calculated: basic - at current levels of fluid production and taking into account geological and technical measures in accordance with the approved industry development program.

The author’s version was calculated with optimization of planned activities, which made it possible to stabilize the falling dynamics of reservoir pressure and obtain additional oil production.

The model construction technology is recommended for use in fields confined to organic reef structures of the Perm Kama region and adjacent regions of the Volga-Ural and Timan-Pechora oil and gas provinces.

Ключевые слова:
органогенная рифовая постройка, трещинно-кавернозно-поровый тип коллектора, фильтрационно-емкостные свойства, 3D-сейсморазведка, фация, концептуальная геологическая модель, мультисетка, ремасштабирование геологической основы, геолого-статистический разрез, «неколлектор», охват трещиноватостью, модель двойной пористости и проницаемости, геолого-гидродинамическая модель, система поддержания пластового давления, адаптация, аквифер, графики Чена, многовариантное моделирование, прокси-модель.

Изложена технология построения новой концептуальной геологической модели с учетом особенностей строения фаменско-турнейской залежи (пласт Т-Фм), которая представлена органогенной рифовой постройкой позднедевонского возраста, перекрытой палеозойскими структурами облегания. Данный подход представляет собой распределение сетки слоев геологической модели согласно процессам осадконакопления.

На основе трехмерной цифровой геологической модели создана и настроена на фактические показатели разработки геолого-гидродинамическая модель. При адаптации модели на фактическую динамику пластового давления выявлены зональные особенности, связанные с распределением фильтрационно-емкостных свойств. Настройка динамики обводненности осуществлялась по результатам проведения геолого-промыслового анализа, в результате чего определен источник обводнения для каждой скважины.

На основе настроенной на фактические показатели разработки геолого-гидродинамической модели рассчитаны прогнозные варианты: базовый – на текущих уровнях добычи жидкости и с учетом геолого-технических мероприятий согласно утвержденной отраслевой программе развития.

Также рассчитан авторский вариант с оптимизацией запланированных мероприятий, который позволил стабилизировать падающую динамику пластового давления и получить дополнительную добычу нефти.

Технология построения модели рекомендуется к использованию на месторождениях, приуроченных к органогенным рифовым постройкам Пермского Прикамья, сопредельных районов Волго-Уральской и Тимано-Печорской нефтегазоносных провинций.

© **Mikhail Iu. Riabchevskikh** (ORCID: 0009-0008-5725-8623) – Leading Engineer (tel.: +007 (912) 488 41 67, e-mail: Rjabchevskikh@gmail.com). The contact person for correspondence.
© **Aleksandr S. Nekrasov** (Author ID in Scopus: 57221645949) – Doctor of Geological and Mineralogical Sciences, Professor of the Basic Department of Oil and Gas Engineering (tel.: +007 (912) 070 25 88, e-mail: Aleksandr.Nekrasov@lukoil.com).

© **Рябчевских Михаил Юрьевич** (ORCID: 0009-0008-5725-8623) – ведущий инженер (тел.: +007 (912) 488 41 67, e-mail: Rjabchevskikh@gmail.com). Контактное лицо для переписки.
© **Некрасов Александр Сергеевич** (Author ID in Scopus: 57221645949) – доктор геолого-минералогических наук, профессор кафедры «Нефтегазовый инжиниринг» (тел.: +007 (912) 070 25 88, e-mail: Aleksandr.Nekrasov@lukoil.com).

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Introduction

The current project document (calculation of oil and gas reserves – 2014 and technological development scheme – 2015) provides for areal system of development of the object mainly by horizontal production wells (16 wells out of 19) with the use of intra-contour flooding (8 injection wells).

As of 01.01.2023, there is a tendency to decrease reservoir pressure with a natural increase in the level of fluid withdrawal (Fig. 1).

Figure 1 clearly shows two intervals of reservoir pressure decline: the first interval of slow decline to saturation pressure (11.98 MPa), probably conditioned by fracture deformation with the influence of the contour area and the current system of reservoir pressure maintenance (RPM), and the second interval of rapid decline after saturation pressure, probably associated with fracture deformation and no influence of the contour area. Bottomhole pressure decreased to 5–6 MPa and became 48–50 % lower than saturation pressure, which led to a 14.0 % deviation in oil production in 2022 (project – 146.9 thousand tons, actual – 170.6 thousand tons). Fluid production is 5.2 % higher than the design level (project – 176.2 thousand tons, actual – 185.3 thousand tons). Injection levels are significantly behind the design value, the deviation amounted to 43.3 % (project – 231.1 thousand m3, actual – 131.1 thousand m^3) due to the lag of the injection well stock (project – 7 wells; actual – 4 wells).

In order to preserve the energy potential of the deposit and for a more uniform development of reserves, it is necessary to implement a system of reservoir pressure maintenance [1, 2]. Obviously, the possibilities for a significant increase in oil production from operating wells have almost been exhausted, so the organization of the reservoir pressure maintenance system in the context of systematic "undercommissioning" of new wells (and even with the full design commissioning of new wells) will make it possible to approach the design levels of oil production in 2023–2024.

Prerequisites for the Creation of a Geological Model

A prerequisite for the creation of a new conceptual geological model is the problem of adjusting the geological and hydrodynamic model to the actual development indicators [3–6], which are associated with the features of the reservoir structure.

The T-Fm reservoir is an organogenic reef structure of Late Devonian age overlained by Palaeozoic encircling structures (Fig. 2). The oil-bearing stage is more than 300 m, the amount of geological reserves of hydrocarbons (HC) of AB1 category is 9.38 million tonnes, recoverable – 3.189 million tonnes. 78 wells have been drilled at the field, of which 771 metres of core were taken in 5 wells.

In the current implementation of the geological model (GM), the slicing of grid layers is typical for the reservoir (Fig. 3), without taking into account the peculiarities of the geological structure of the organogenic reef structure.

The simplified approach to modelling an organogenic reef structure does not make possible to reproduce filtration processes typical for a massive deposit: formation of watering cones from the footwall and increase of the water-oil contact (WOC) level over the entire area.

Also, grid slicing can directly affect the correctness of property distribution in the interwell space, which, in turn, affects the amount of oil reserves (Fig. 4). Therefore, it was decided to consider in more detail the features of construction of the geological models of organogenic reef deposits.

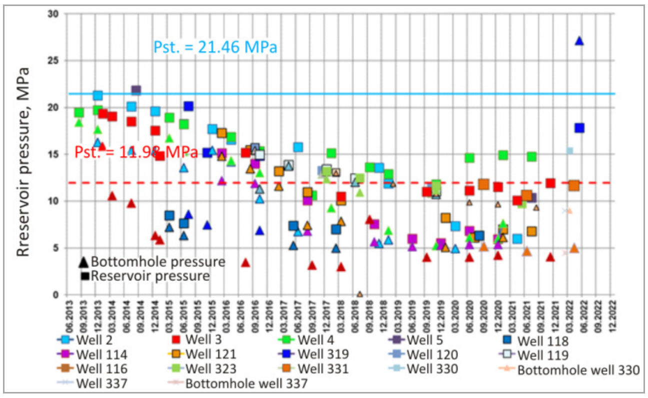


Fig. 1. Reservoir pressure dynamics.
Sukharev field. T-Fm formation

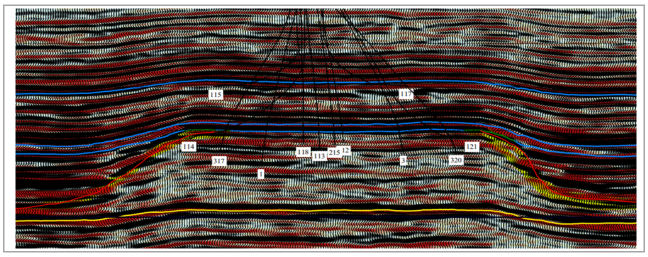


Fig. 2. Fragment of the vertical slice
of the cube from 3D seismic data

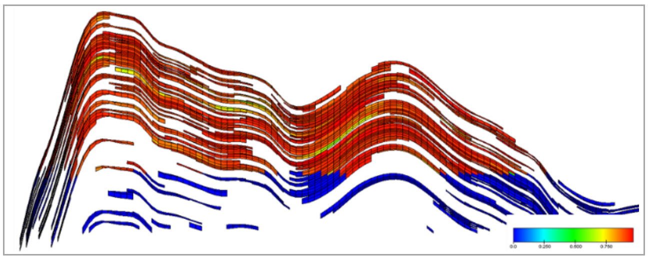


Fig. 3. Section from the geological and hydrodynamic model
by the example of oil saturation cube

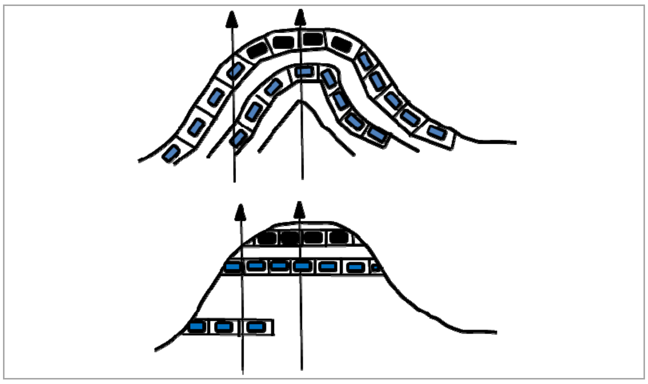


Fig. 4. Schematic representation of reservoir distribution
for reservoir and massive deposit

Principle of Choosing Layer Slicing for Geological Modeling of Organogenic Reef Structures

Review of peculiarities of 3D geological modelling in carbonate and fractured reservoirs, determined by K.E. Zakrevskiy (high oil saturation coefficients (K_s), hydrophobisation of rocks, absence of *Ks* increase when moving away from the surface of the WOC and lack of operability of the porosity-permeability relationship), allows us to state that the most optimal variant of layer slicing for organogenic reef massifs, according to

V.A. Zhemchugova, is the variant of proportional slicing, as it takes into account the different growth rate of the central and marginal parts of the reef structure for the same geological time [7–10] (Fig. 5).

However, this approach visually characterises the drapping structure rather than the organogenic structure, and creates difficulties in setting the reservoir pressure drop in the deposit because of the hydrodynamic connection between the upper layers and the lower water-saturated part of the formation [11, 12].

The approach with horizontal slicing [7], which is used with insufficient amount of core and incomplete well logging complex, is considered (Fig. 6). This approach visually better describes the filtration process in a carbonate deposit [13].

Under ideal conditions, for the breaking up an organogenic structure it is necessary to perform a detailed lithological correlation, where the layers are sliced according to stratigraphic boundaries, but taking into account the presence of unconformity surfaces, for example, when the roof of the reef structure rose above sea level or the structure collapsed on the flanks [11], as well as the directions of diagenetic processes [14–16]. This approach requires high labor costs and a sufficient amount of initial information.

Creation of a Three-Dimensional Geological Model

The initial data for the construction of the GM [17–20] were the results of interpretation of 3D seismic survey, drilling of 78 wells, data on reserves calculation, results of interpretation of well logging (WL) (stratigraphic boundaries of reservoir, boundaries of permeable interlayers, nature of reservoir saturation, quantitative determinations of filtration-capacity properties of reservoir rocks (FCP) (K_p – 0.08 decimal units, K_{pr} – 2 mD, K_{ov} – 0.09 decimal units), results of core studies, inclinometry data, altitudes and wellhead coordinates, petrophysical equations, and qualitative (descriptions) core studies, maps of effective and oil saturated thicknesses 2D (from the reserves estimation report). Summary tables of estimated parameters and HC reserves.

Definition of the Modelling Area

The modelling area was chosen to be the Famenno-Turnean reservoir within the Late Devonian reef structure, the thickness of which varies from 470 to 570 m in the central part according to 3D seismic data. The structural map (Fig. 7) shows the boundaries of the modelling area at the absolute mark of -1938 m (determined by experts), above which the structure starts a sharp increase in height.

Construction of a Structural Model

Fo modeling it was used the structural surface of the OGS^{II} (identified with the roof of the T-Fm reservoir) from the previously built GM [21–23] which was created using the Classic structure module by the Stratigraphic modelling method. For structural constructions, the size of cells along the lateral 50 by 50 m was chosen based on the size of the field and drilling of the structure.

Selection of Volume Mesh of Model Parameters

To create a geological model the Corner point grid type has been selected. This type of mesh is characterized by the fact that it is a flexible system where the size of the cells varies, well suited for modeling deposits with high amplitudes of structures [2, 7, 24].

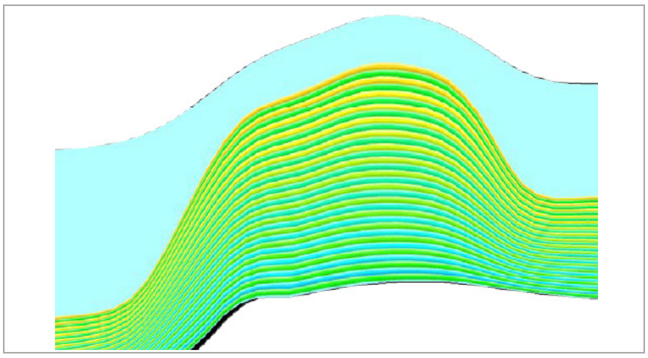


Fig. 5. Proportional scheme of layer slicing for organogenic reef structure [7]

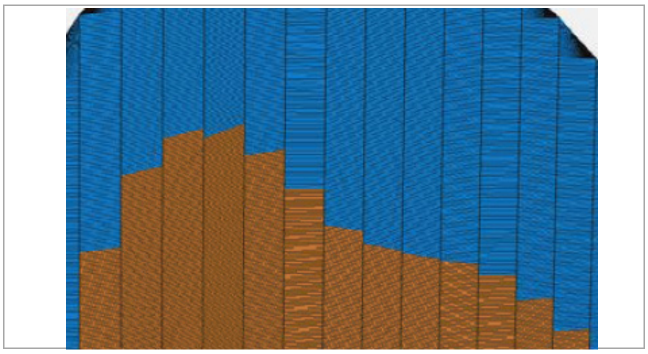


Fig. 6. Horizontal scheme of layer slicing for organogenic reef structure [7]

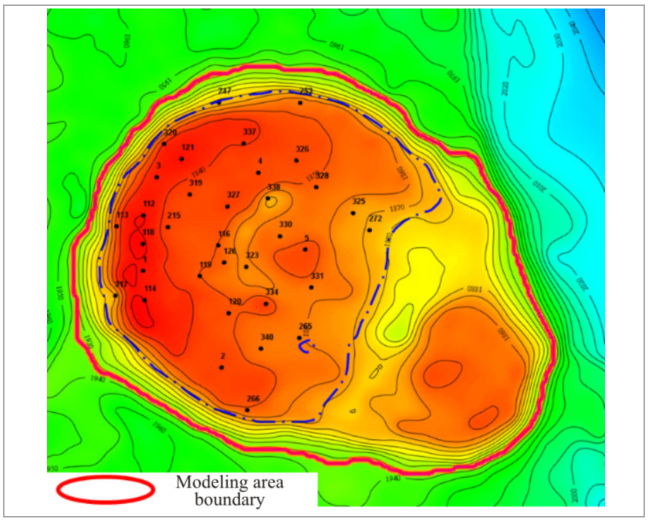


Fig. 7. Structural map of the T-Fm reservoir roof with the highlighted modelling area

It should be noted that the previously constructed geological model was created without dividing into Tournaisian and Famennian reservoirs. At the same time, according to core studies of wells 1–5 in the arched part of the reef the deposit of the Tournaisian stage are represented by rocks of the Korvinsky horizon with a thickness from1 to 5 m. Table 1 provides information on the thickness of the Tournaisian reservoir.

The complex structure of the pore space of carbonate rocks, which is a consequence of the variability of thermobaric conditions that existed at different stages of sediment-rock transformation, as well as tectonic movements of the Earth's crust, is particularly clearly reflected in the close relationship between the

Table 1

Total and effective thickness of the Tournaisian reservoir

Well number	Interval, m	Total thickness, m	Effective thickness, m
1	2171.84 – 2175.87	4.0	0.7
2	2832.50 – 2837.50	5.0	1.0
3	2432.00 – 2435.00	3.0	0.0
4	2621.50 – 2623.00	1.5	0.0
5	2683.50 – 2684.50	1.0	0.0

Table 2

Description of three-dimensional grids of productive reservoirs

Reservoir	Grid type	Cell size by area, m	Number of layers	Cell size by thickness, m	Number of active cells
T FM	Corner point	50 × 50	146 610	0.5	9 586 205

permeability of rocks and their porosity [19, 25–28]. The correlation between the permeability of carbonate rocks and their open porosity is significant but rather weak (Fig. 8, *b*). The correlation coefficient varies from 0.408 to 0.544. This uncertain correlation is caused by the different pore space structures. At the same time the dependence of gas permeability on the value of open porosity (Fig. 8, *a*) for carbonate rocks of Turnean age with pore space structure type is characterised by the correlation coefficient equal to 0.898 [29–31]. Due to the different genesis of the Tournai and Famena reservoirs [32, 33], it was decided to separate them by creating a multigrid. At the same time, the Famena reservoir should be built as a body of organogenic structure with parallel slicing of layers from the bottom of the reservoir, and the Tournaisian reservoir – by the draping structure parallel to the roof of OG IIP. Both subgrids with a constant layer size of 0.5 m. Grids description for reservoirs is given in Table 1, 2. The section along the created volumetric multigrid is shown in Fig. 9.

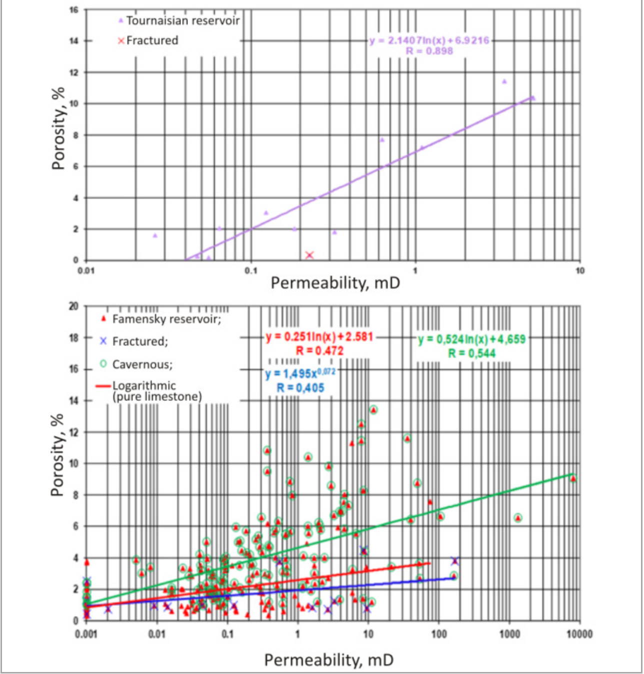


Fig. 8. Dependence of porosity and permeability coefficients for carbonate rocks of formations T (*a*) and Fm (*b*) for well No. 1

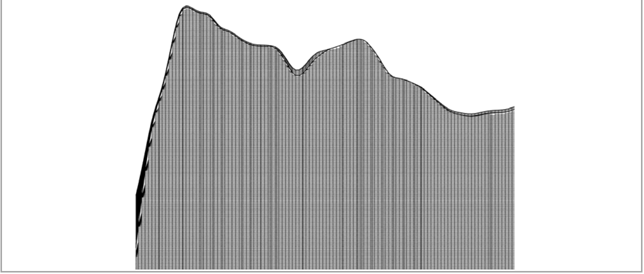


Fig. 9. Section on the created volumetric multigrid

Well Data Averaging

Well data averaging refers to the transfer of well information to 3D grid cells, which then serves as the basis for lithological and petrophysical modelling. Well data in a format suitable for use in IRAP RMS contains a stratigraphy curve (new_log), a discrete saturation curve (XN), porosity, oil saturation, and permeability curves (K_P, K_N, K_{PR}), continuous and discrete lithology curves (DEFINTERV, new_LITO).

When distributing the lithology parameter to the geological grid, the stochastic method of RMS Indicators (SIS Sequential Indicator Simulation) was used to obtain a discrete cube of the reservoir distribution based on the probability distribution of a particular facies using variogram data for each facie. In this case, the distribution of the reservoir facie (code "1") was performed, and the host facie was non-collector (code "0").

It is possible to analyse (Fig. 10) the correspondence between the distribution of the reservoir fraction in the geological grid and the averaged well data by comparing geological and statistical sections (GSS).

Comparison of GSS by lithology is performed only in the area of further modeling (oil-saturated + water-saturated parts of the section 15 m below the WOC). The lithological modeling is followed by the petrophysical modeling stage, the purpose of which is to determine the values of petrophysical parameters of productive formations. The porosity coefficient cube K_P of productive formations C1t-D3fm (T-Fm reservoir) was calculated by the Petrophysical Modelling module within the lithology cube defined as reservoir, using the stochastic distribution

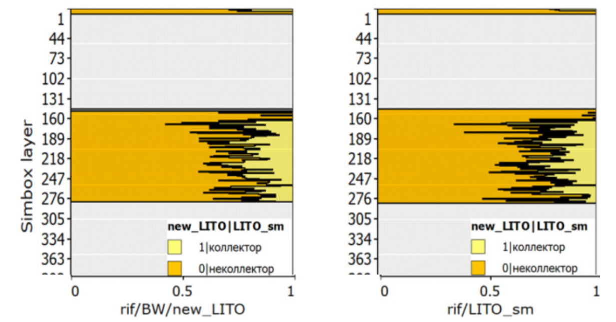


Fig. 10. Comparison of geologic and statistical sections in terms of reservoir fraction of BW well data and cube lithology in the geologic model

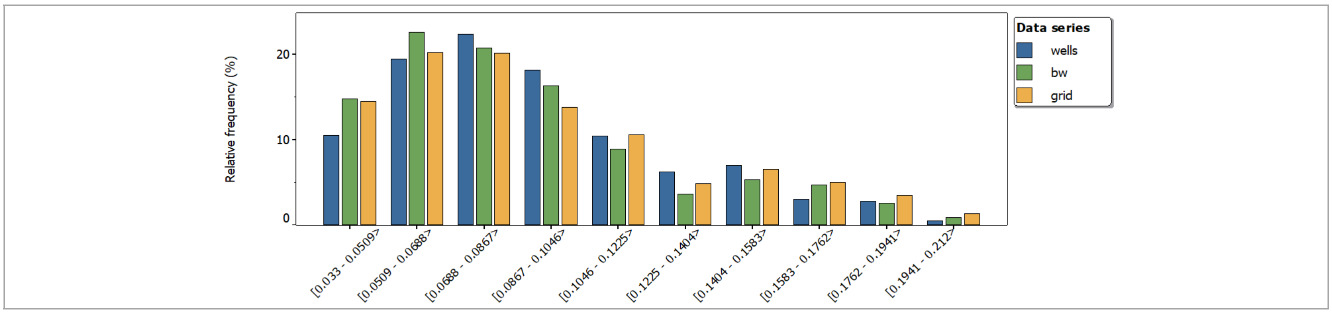


Fig. 11. Histogram of distribution by porosity coefficient of reservoir rocks of the T-Fm formation

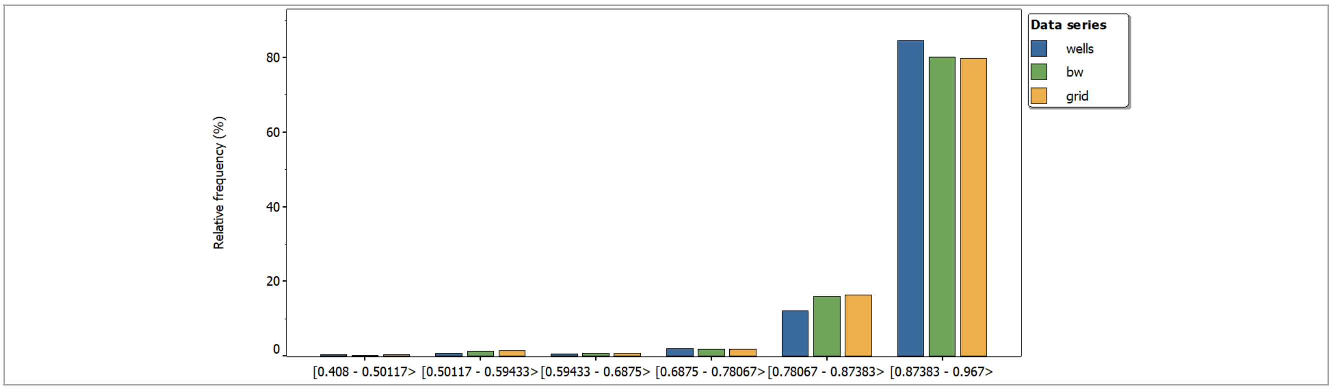


Fig. 12. Histogram of reservoir rock distribution by oil saturation factor of the T-Fm formation

Table 3

Petrophysical dependence of gas permeability on porosity for T-Fm formation

$K_p = f(K_{pmg})$	Variation range K_{pr}, mD / average parameter value
$K_{pm} = 0.02e^{0,5549 \cdot Kp}$	0.12–413.90/38

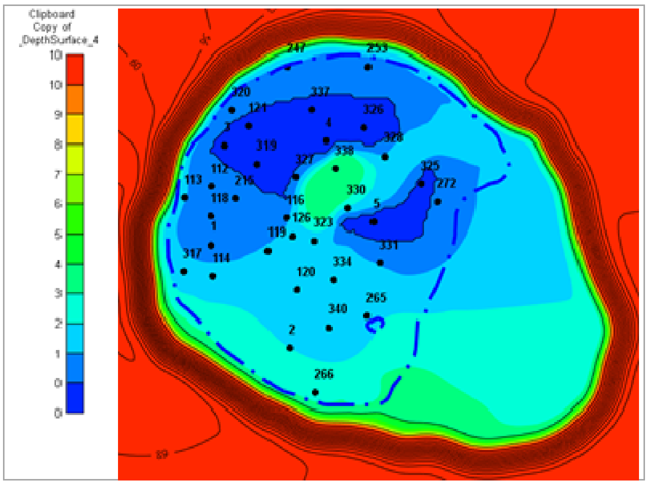


Fig. 13. Map of total thicknesses of sediments of Turnean age

algorithm Simulation (SGS subgrid scales). Figures 11, 12 show histograms of the distribution of porosity and oil saturation ratios from WLIR, averaged data and 3D parameter data.

In general, the distribution of parameters from WLIR data, averaged data and 3D data has satisfactory convergence. The main deviations are related to the fact that the entire well stock was used in the calculation, including horizontal wells, which may result in averaging errors.

The absolute gas permeability coefficient is distributed according to petrophysical dependences on open porosity within the rocks designated as reservoir $K_p = f(K_{pmg})$. The obtained values of permeability coefficient are given in Table 3.

To analyse the separately created region of the Tournaisian reservoir, a map of total thicknesses was constructed (Fig. 13). In the vaulted parts of the deposit either no sediments or thicknesses not exceeding 1 m are noted. As the reef height decreases, the thickness of the Tournaisian reservoir increases to 5 m or more. Beyond the oil-bearing contour on the reef slopes, the thickness of Tournaisian sediments is expected to increase up to 60 m (obtained by extrapolation due to the absence of wells outside the organogenic reef structure).

Table 4 presents a comparison of the estimated parameters and geological reserve values obtained during the reserves estimation process and on the GM.

Compared to the original GM the oil saturated thickness decreased by 2.4 % and, as a consequence, the geological oil reserves decreased by 4 %. The changes were caused by the change in the type of grid slicing shape, which in turn affected the distribution of the lithology parameter over the area and section.

Rescaling of Geological Base

In order to carry out the stage of works on creation of GHDM it is necessary to rescale the geological base due to a significant number of active cells (611 thousand), even taking into account only the study area (oil saturated + water saturated parts at 15 m below WOC). Calculation of GHDM on the geological base with the number of active cells over 150 thousand requires high production capacity and a significant time resource.

Remassescaling was performed automatically using a plug-in in Irap RMS. Figure 14 shows the GSS by porosity coefficient to analyse the preservation of geological heterogeneity along the section.

The number of active cells according to the rescaling results was 123 thousand active cells, which satisfies the requirements for continuing the next stage of work to create the GHDM.

Table 4

Parameters and values of geological reserves obtained in the process of reserves estimation at the GM

Parameter	RC (2014)	GM 2022	GM with regard to otganogenic structure	Deviation from GM 2022, %
Kp, dec.units	0.08	0.10	0.10	0.0
Ks, dec.units	0.91	0.91	0.91	0.0
Heff.s, m	10.1	8.3	8.1	2.4↓
Area, th.m^2	16 502	16 734	16 681	0.0
Reserves, th.t.	8 927	9 364	8 988	4.0↓

Creation of the Geological-Hydrodynamic Model

Calculations for GHDM were performed in the Tempest more 2022.2 software package by AspenTech company.

The current GHDM of the object under study was made as part of the updating of the GM in 2022, was configured to meet the requirements of integrated modeling and has good convergence with the actual development indicators. Due to the fact that within the framework of contractual obligations, almost all GGDM created by specialists have a satisfactory adjustment in terms of integral indicators, however, in the absence of a detailed study of the geological features of the deposit, the processes of oil displacement are reproduced inaccurately

As an example, let's consider the current GGDM, the rise in the level of WOC is typical for reservoir deposits (Fig. 15), although the deposit itself is an organogenic reef structure, which is watered from the bottom.

Therefore, there are situations when the predicted values for GHDM are not confirmed. In the current implementation of the model according to the basic scenario, there is a sharp drop in fluid production levels (Fig. 16). In this case, we can assume an incorrect setting of the energy state.

Preparation of Initial Information

Preparation of initial information for the creation of GHDM is one of the most important stages requiring the competence of a modeling specialist in related fields, necessary for data analysis and verification. To create the GHDM, the following is used:

- Geological basis after rescaling: geological grid, distribution cubes: reservoir fraction, porosity coefficient, oil saturation coefficient, permeability coefficient. This information has been downloaded from the GM created as a part of the work;
- Data on the initial properties of the reservoir: PVT properties, RPP curves, data on reservoir anisotropy, compressibility of pore space, GSS. All information is used from the current GHDM;
- Information on actual development indicators: flow rates of liquid, oil, dissolved gas, measurements of reservoir and bottomhole pressures. All information is used from the current GHDM and the history for the period 01.09.2022 – 01.03.2023 has been added.

Rejection of the Dual Porosity and Permeability Model

To create a model of double porosity and permeability [33–36], significant computing power is required due to the increase in the counting rate at the cost of grid doubling (all properties are specified for both pore and fractured reservoirs). There is high uncertainty of the initial data:

– distribution of fracture coverage over the area and section (special core and GIS studies – 6 studies performed);

– determination of the sigma parameter (matrix-fracture relationship);

– determination of fracture permeability values and fracture direction.

A variant of this model creation was implemented, the calculation time was 72 h, however, further works on model adjustment were stopped due to its inexpediency.

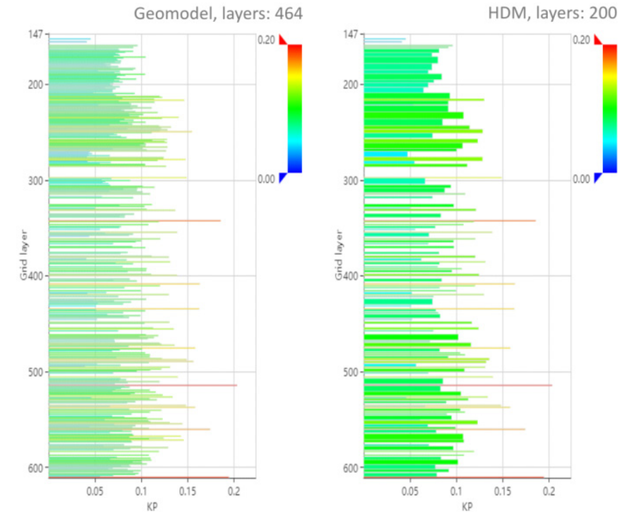


Fig. 14. Geological and statistical section by porosity coefficient

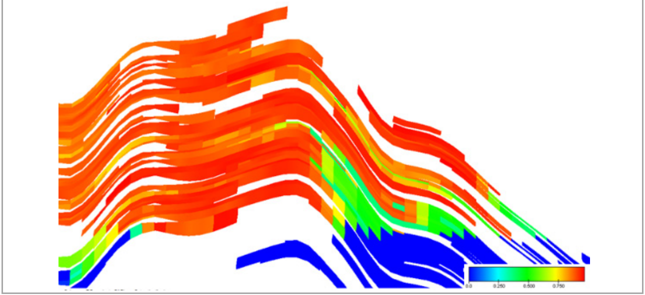


Fig. 15. The oil saturation cube section in the operating HDM of T-Fm facility

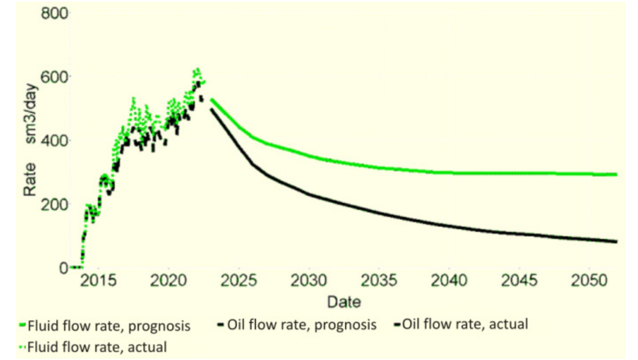


Fig. 16. Graph of liquid/oil flow rate dynamics. Actual + Basic Option

Table 5

Conditions for dense “non-collector” layers

Parameters	Collector's share, dec.units	K_p, dec. units	K_{pm}, mD	K_s, dec.units	K_{op}, dec.units	K_{vyt}, dec. units
Conditions	0.09	0.01	0.5	0.904	0.700	0.226

Table 6

Comparison of geological oil reserves derived from reserves calculation and geological model

Ralative to		Balance (CR 2014)	GM (2022)
Change in geological reserves of oil,	th.t.	+149	–288
	%	+1.6	–3.2

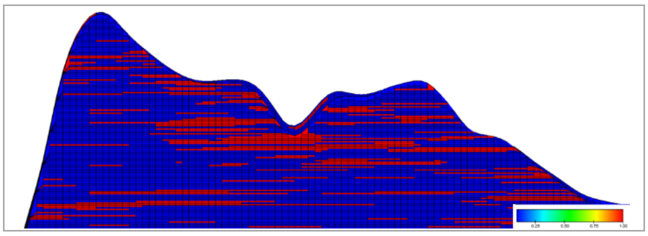


Fig. 17. Section of GHDM by the example of cube distribution of collector’ share (NTG)

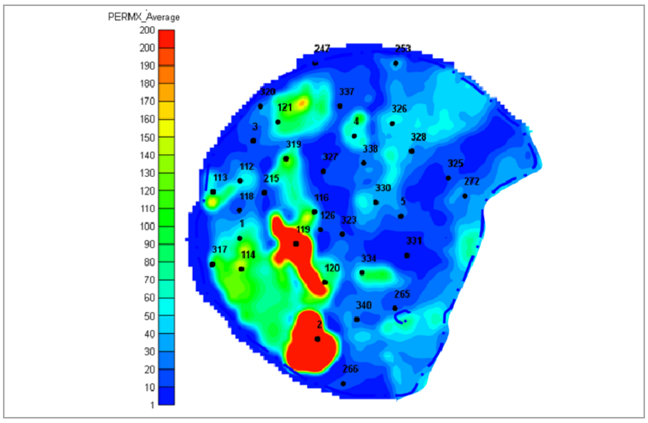


Fig. 18. Map of permeability distribution based on the results of the T-Fm reservoir GFDM adaptation

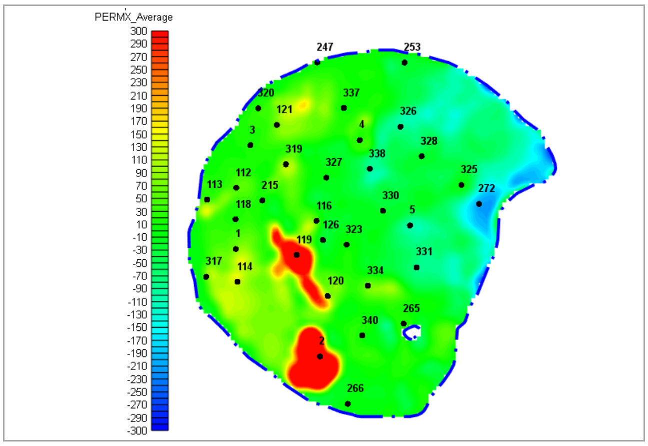


Fig. 19. Map of permeability distribution difference in the GM and final GHDM of the T-Fm reservoir

Consideration of the Presence of Dense Interlayers ("Non-Collectors")

The investigated object has a high coefficient of dismemberment (geological and physical characteristics – 12.6) and a complex type of reservoir with the presence of both pore and fractured components of the pore space [34–37]. Thus, the filtration process can involve not only the isolated reservoir formations according to well logging, limited by the subjective boundary value of porosity (for T-FM – 3 %), but also the rest of the deposit. The presence of permeable interlayers below the porosity limit is confirmed by core data (K_{pm} up to 200 mD).

The problem of interaction between specialists from different scientific disciplines in the creation of project technological documents has been described in paper [2]. To solve these problems, it is necessary to create a multidisciplinary teams including experienced generalists. It is also argued that there is a need to move from the traditional concept of absolute (abstract) pore space (APS), based on classical differential equations, to a new concept of effective pore space (EPS). The EPS concept involves consideration of "non-reservoirs" in geological and hydrodynamic modeling [7]. In this model, a "non-collector" is defined in all cells with a porosity below the 3 % boundary value (Fig. 17).

Table 1. 5 shows the conditions specified for the "reservoir-non-reservoir".

Geological oil reserves in the "non-reservoir" amount to 88 thousand tons, which is equal to 1% of the geological oil reserves in the deposits, while recoverable reserves are 20 thousand tons, which, in turn, does not exceed 0.4 % of the recoverable oil reserves as a whole. Thus, the volume of inventories, taking into account the "non-collector", does not exceed the limit of 5% relative to the requirements of the temporary regulations for the acceptance of design and technological documents (Table 6).

At the same time, the "non-collector" does not effect on the displacement factor, but increases the oil recovery factor (ORF) due to better coupling of permeable layers, which increases the coverage ratio.

GHDM Adaptation

Adjusting the GGDM to the actual development indicators has many tools, but understanding the need to use certain options requires a geological and field analysis and knowledge of the features of fluid filtration processes in the reservoir [38–41].

One of the authors' main guidelines for adjusting wells to actual development indicators was minimal interference in the change in the well-to-reservoir communication parameter [42–46]. This option was created to simulate the degradation of the bottomhole zone of the formation, but is often used as a tool for closing certain intervals to obtain better convergence with actual indicators [47, 48].

At the first stage, the dynamics of reservoir pressure and fluid extraction was adjusted by two main tools – an acquifer (tuning the activity of the influence of the contour region) and a modification of the permeability cube. In the course of tuning, the southwestern part of the reservoir in the area of well No 2, 119 underwent the largest modifications upwards (Fig. 18, 19). This area is characterized by the best productivity of production wells.

Relative to the value adopted for the design, the permeability is increased by 26 times, and the original GM cube is increased by 2 times (Table 7).

In the course of reservoir pressure adjustment three areas with different dynamics were identified, which is largely associated with the zonal heterogeneity of the permeability distribution, both fractured and pore. Fig. 20 shows a map of isobars showing the accumulated liquid withdrawals and selected areas.

Area № 1

Geographically, area No 1 is the western part of the deposit, according to the 2014 seismic facies analysis, it belongs to the reef ridge facies. It has a high percentage of extraction from the accumulated oil production – 39 %, which is 447 thousand tons. It is characterized by complex dynamics of reservoir pressure for tuning in GHDM (Fig. 21).

The area is characterized by a sharp rate of reservoir pressure drop from the beginning of development to 2020 with stabilization at 6 MPa, which is 5 MPa below the saturation pressure and 15.5 MPa below the initial pressure. Probably, the fracture component is involved in filtration up to 2020, and from 2020 to the present moment, after the fractures close, it is involved the pore component [49, 50]. This process is modeled using the KVSP option, which represents the dependence of permeability on formation pressure. The dependence is obtained as a result of multivariate calculations until the necessary dynamics is obtained (Fig. 22).

Analyzing the graph of permeability multiplier dependence on reservoir pressure, we can conclude that the fracture component participating in the filtration process of the area No.1 is 90 %. It is also necessary to mention the absence or weak influence of the contour area.

Area № 2

Located in the central part of the deposit, according to the 2014 seismofacial analysis, it is represented by clastic sediments of the intra-reef plume, which accounts for the bulk of oil production, 57 %, or 616,000 tons. Actual measurements of reservoir pressure have linear dynamics of decline (Fig. 23), which indicates the presence of a connection with the contour area and the influence of the RPM system, better reservoir quality than in Area 1 (probably, less fracture component). Only in this area there are wells with water cut above 10 % – wells No. 4, 116 (Fig. 24). Well No. 319, which was watered out as a result of poor-quality hydraulic fracturing, was removed from consideration. The geological and field analysis revealed that the source of watering of well No. 4 was a cone of bottom water. The injection front reached the bottomhole of well No. 116 from injection well No. 319. These assumptions are confirmed by Chen's plots (Fig. 25, 26), which represent the dependence of the water-oil factor and the derivative of this dependence in logarithmic coordinates on time.

Area № 3

This area has been developed since 2020 with four wells, two of which are injection wells. Cumulative oil production as of 01.01.2023 amounts to 51 thousand tons, which is 4 % of the total. The graph of reservoir pressure dynamics is shown in Fig. 27.

Table 7

Comparison of GM and HDM permeability

Parameter	GFH	GM	GHDM	Deviation from GM, %
Permeability, mD	2	38	83	54

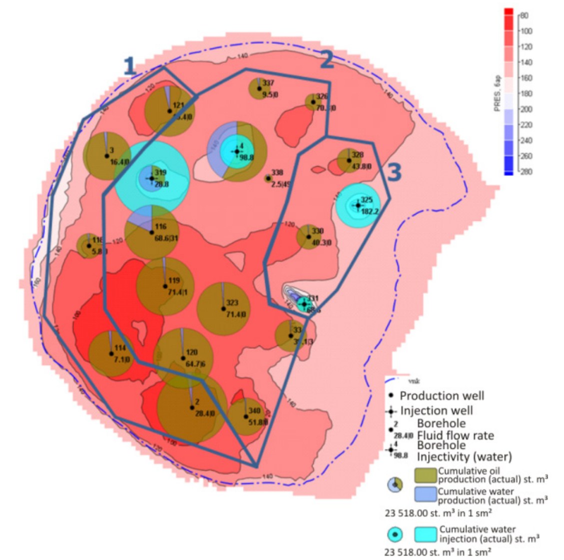


Fig. 20. Isobar map (GHDM) + accumulated samples for the T-Fm formation

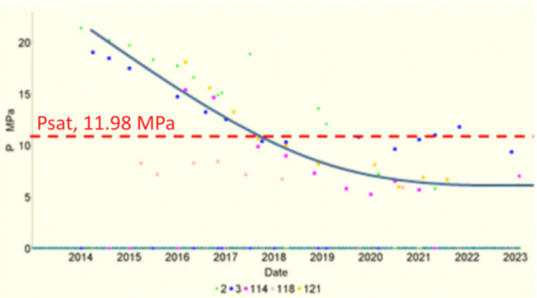


Fig. 21. Graph of reservoir pressure dynamics. Area No. 1. T-Fm reservoir

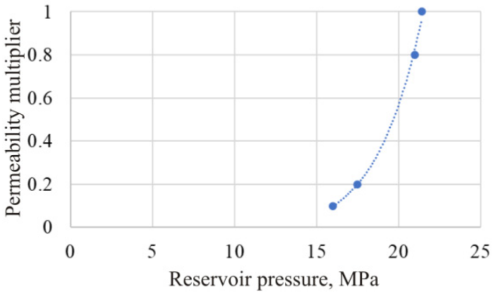


Fig. 22. The graph of dependence of permeability multiplier on reservoir pressure. T-Fm reservoir

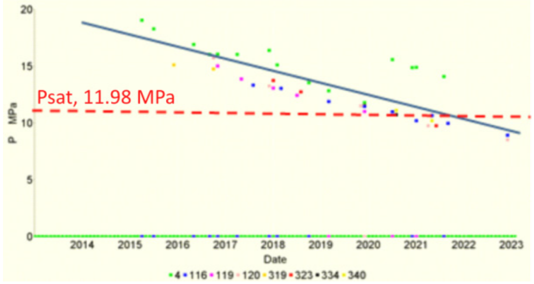


Fig. 23. Graph of reservoir pressure dynamics. Area No. 2. T-Fm reservoir

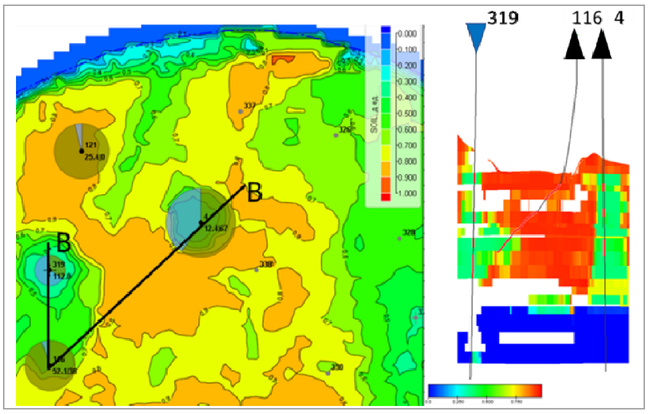


Fig. 24. Map and section of current oil saturation as of 01.2020. T-Fm reservoir

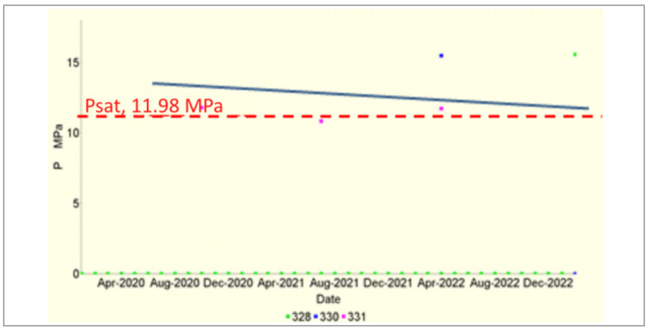
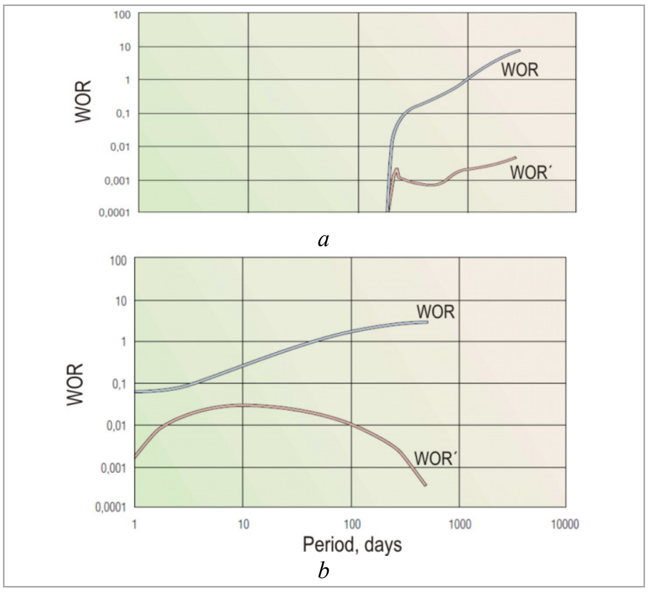


Fig. 27. Graph of reservoir pressure dynamics. Area No. 3. T-Fm reservoir



a

b

Fig. 25. Chen's theoretical diagram characterizing water breakthrough: *a* – from injection to production well; *b* – as a result of cone formation

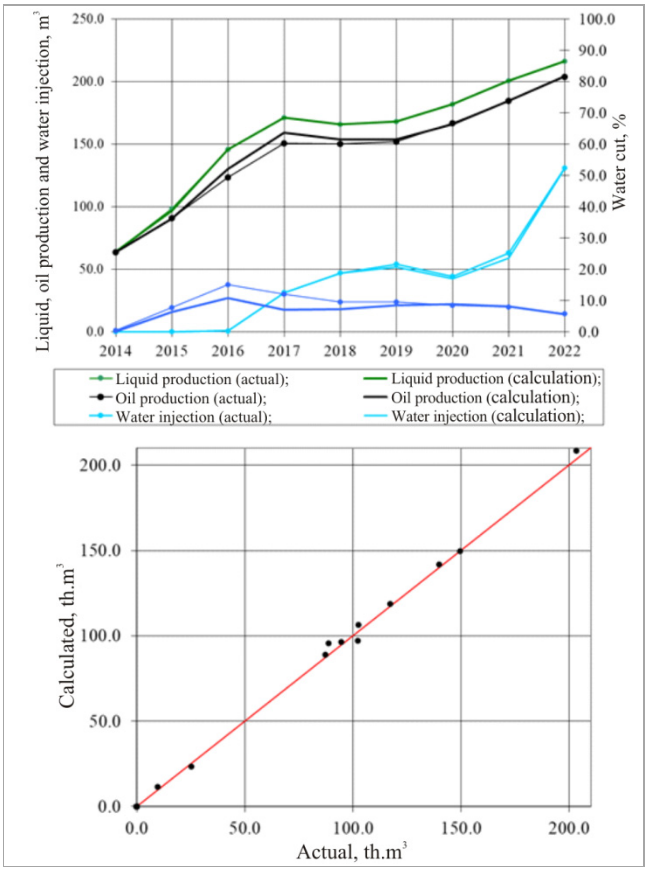
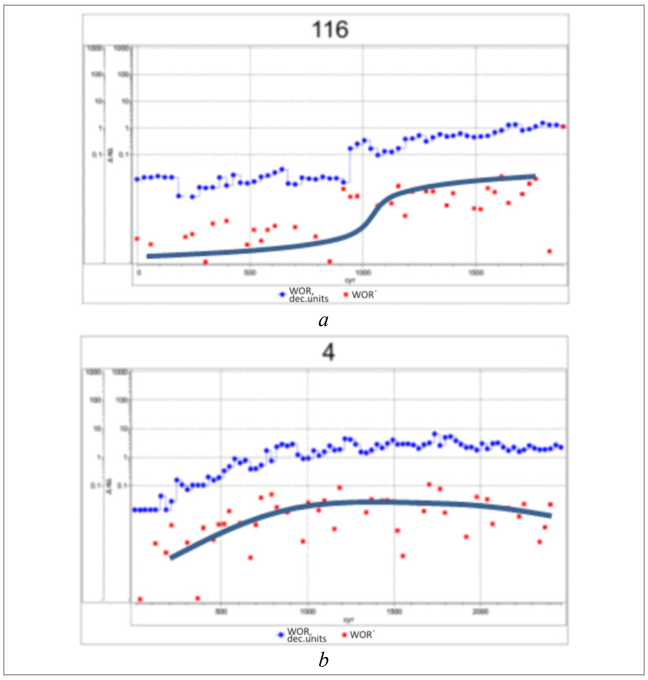


Fig. 28. Graph of adaptation results and crossplot on cumulative oil production by wells. T-Fm reservoir



a

b

Fig. 26. Chen’s diagram: *a* – on the well №116. Reservoir T-Fm; *b* – on the well №4. Reservoir T-Fm

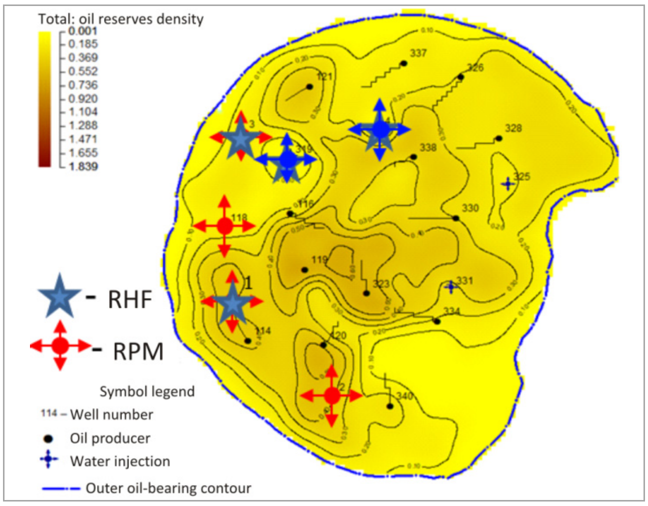


Fig. 29. Map of mobile oil reserves density as of 01.01.2023. IDP variant

Table 8

Activities of the IDP

Well №	The year of the event	GTA
2	2024	Transfer for injection
118	2025	Transfer for injection
319	2024	RHF
1	2027	Introduction of new injection well + RHF
3	2029	RHF
4	2033	RHF

Table 9

Adjusted program of recommended IDP

Well	Year	Workover Actions	Optimization
2	2024	Transfer for injection	+ Increase in injection up to 160 m3/day
118	2025	Transfer for injection	Failure
319	2024	RHF	Failure + shutdown in 2024.
1	2027	Introduction of new injection well. + RHF	+ Transfer to 2025 + increase of injection to 150 m3/day
3	2029	Transfer for injection + RHF	+ Transfer to 2024 .
4	2033	RHF	Failure
325	2024	–	RHF + Increase in injection up to 220 m^3/day

Due to the short period of development of this area, to analyze the dynamics of reservoir pressure is not possible, but initial measurements in the range from 12–16 MPa indicate that the organogenic reef massif is a unified hydrodynamic system.

Results of GHDM Adaptation

The result of this stage is a customized GHDM based on a new conceptual geological model taking into account the filtration features of the deposit. The results of the GHDM adaptation are presented in Fig. 28.

The deviation of cumulative oil production from actual production is 1.5 %. This GHDM allows to perform correct calculation of expected variants.

Calculation of Expected Variants

Due to the fact that the last design document for the field was executed in 2015 and the placement of design wells does not coincide with the actual one, the calculation of expected variants are based on the plan of geological and technical measures according to the program of the Industry Development Program (IDP) for 2024–2033 (Table 8).

It should be noted that all planned activities are aimed at strengthening the existing RPM system.

Limitations for calculations of forecast variants under conditions of falling oil production by operating wells and already actual drop in reservoir pressure below saturation:

- operating wells:

– released liquid flow rate (maximum historical liquid flow rate - as a capacity constraint);

– average depression for the last 3 months;

- injection wells:

– average injectivity over the last 3 months;

- bottomhole pressure at the level of auto-RHF pressure (45 MPa).

The forecast is made for a medium-term perspective for 30 years, starting from 01.01.2023.

At the first stage calculations of the base variant under current development conditions and the IDP variant were performed (Fig. 29). According to the results of the calculation, the increase in cumulative oil production in the IDP variant as compared to the base variant amounted to 381 thousand tons of oil. It should be noted that from 2040, after stabilization of reservoir pressure, a group control (VREP) on injection at the compensation level of 100 % is set to exclude premature watering of

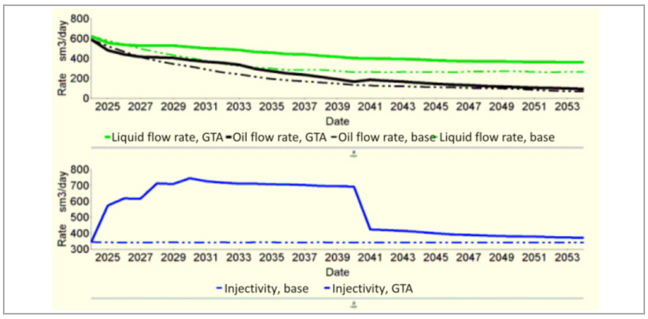


Fig. 30. Graph of main indicators of T-Fm reservoir development

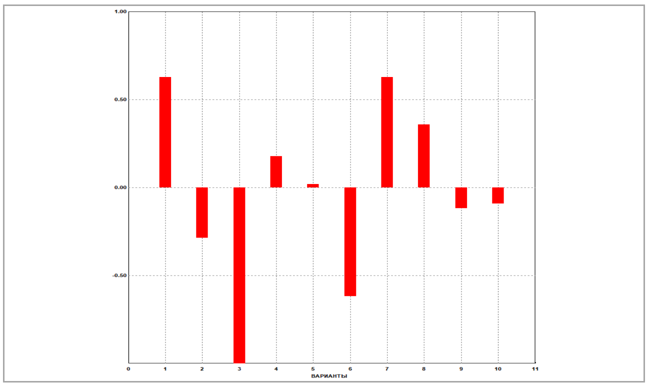


Fig. 31. Tornado diagram of cumulative oil production

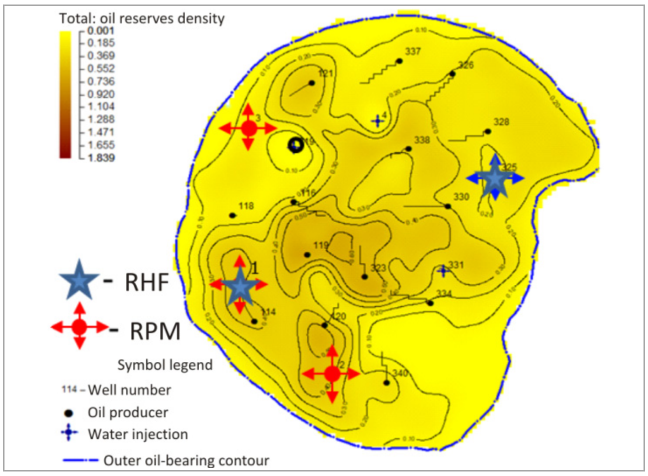


Fig. 32. Density map of mobile oil reserves as of 01.01.2023. formation T-Fm. Optimization variant

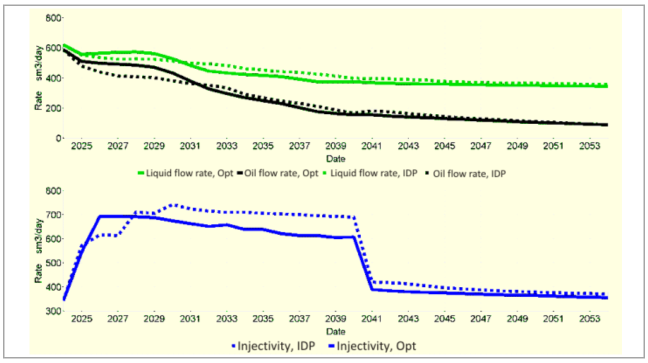


Fig. 33. Graph of comparison of the basic indicators of the optimization and IDP variants development

the producing stock and growth of reservoir pressure above the initial pressure (Fig. 30).

At the second stage of works using ResView program complex on the basis of IDP variant, multivariate calculations (10 variants) were performed on the proxy model in order to find the optimal injection for each well. According to the tornado-diagram, the best variant in terms of cumulative oil production was selected (Fig. 31). However, when calculated on a full-fledged GHDM, the effect of these measures was not revealed. Therefore, it was decided to form the variant by adjusting the measures in the industry development program.

At the third stage, considering the analysis of the existing injection stock and filtration peculiarities, the ID program was corrected (Table 9, Fig. 32).

The area of wells No. 1 and 2 has the worst energy condition, therefore it is recommended to increase the planned injection for two wells, as well as earlier transfer of well No. 1 to injection in 2025.

Rejection of transferring well No. 118 to RPM is associated with the fact that at the moment, at a low reservoir pressure of 5 MPa, the water cut of production is 0 %. If injection is organized at well No. 1 by 2030, the pressure in well No. 118 will be stabilized and an additional 10.000 tons of oil will be withdrawn.

Hydrofracturing of well No. 319 was canceled due to the fact that the water front reached the bottom of well No. 116, and this measure will aggravate the situation.

Taking into account the transfer of well No. 3 to injection, it is recommended to shut down injection well No. 319 in 2024.

In addition, it is recommended to strengthen injection in the eastern part of the deposit by hydraulic fracturing of well No. 325, which will make it possible to take an additional 16.000 tons of oil from well No. 328.

In general, the cumulative production of the optimization variant is 5 thousand tons higher than the IDP variant, but due to the reduced number of measures (one transfer and one hydraulic fracturing), plus a better rate of withdrawal until 2031, the calculation of economic indicators will increase the positive effect.

Based on the results of calculation it has been plotted a graph comparing the optimization and IDP variants (Fig. 33).

Conclusion

The result of this work is a new conceptual geological model of the Famenno-Tournaisian deposit, taking into account the features of sedimentation and fluid filtration during development.

On the basis of the conceptual GM, the GHDM was created and adjusted to the actual development indicators. There were carried out predictive calculations taking into account measures for optimization of the reservoir pressure maintenance system and prepared recommendations.

This approach is recommended for modeling and designing the development of oil deposits confined to the organogenic reef structures of the Perm Kama region and the adjacent areas of the Volga-Ural and Timan-Pechora oil and gas provinces.

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