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STUDY OF GEOLOGICAL AND TECHNOLOGICAL MODEL OF COMPLEX RESERVOIRS OF SAMOTLOR FIELD OIL AND GAS DEPOSITS

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ИССЛЕДОВАНИЕ ГЕОЛОГО-ТЕХНОЛОГИЧЕСКОЙ МОДЕЛИ СЛОЖНОПОСТРОЕННОГО КОЛЛЕКТОРА НЕФТЕГАЗОВОЙ ЗАЛЕЖИ САМОТЛОРСКОГО МЕСТОРОЖДЕНИЯ

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waterflooding, gasless oil flow rates, oil and gas deposits, reserves development, investigated object`s model, distribution of productive strata properties, petrophysical studies, barrier at the phase contact border, complex reservoirs, facies analysis, collector texture.

The achievement of project indicators of complex reservoirs` development through integrated management of oil and gas reserves` recovery requires the use of models that adequately reflect the geological structure of the medium, which determines the filtration flows direction during waterflooding. Their reliability increases based on the analysis of lithofacies features of productive part of the cut and enclosing sediments formation, reservoir features prediction in the inter-well space.
It is known that the heterogeneity of macro level (sand content, segmentation) plays a crucial role in the formation of primary directions of reservoir fluid`s filtration flows. Microinhomogeneity (anisotropy, lateral variability in the permeability) has an impact on the nature of mass transfer processes, the target fluid`s displacement indicators and the phase permeability changing.
Analyzing the the productive section of the AV_1^{1-2} reservoir, which is the most lithologically volatile in the Samotlor field, a special attention was given to textural characteristics (monolithicity and segmentation) of collectors. As a result, based on the ratio of two basic parameters Hef и αps, formation reservoirs were classified into three main classes: with massive texture, with thin-layered structure and with mixed texture.
As a result of detailed studies of the geological and physical characteristic`s features of structure and, taking into account the results of facies analysis for each of layers, criteria referring to a particular type were formed.
It was found that the productive strata gof the roup AB are characterized by a very complex facies formation environment, which occurred mainly in the coastal-marine conditions, in the areas of semi-enclosed sea gulfs and lagoons, deltaic subtraction of paleorivers. This affected both the nature of the various deposits types` distribution and their structure, and resulted in a significant heterogeneity of reservoir properties. The research results allowed to allocate within the considered layers zones with different facies.
It was found that the most effective barrier waterflooding is in the avandelta area. The influence of reservoir facies affiliation on the effectiveness of the barrier flooding associated with distribution characteristics of interlayers with different permeability and of reservoir segmentation degree was explained.
The recommendations for optimizing the barrier waterflooding techniques depending on the facial characteristics of the area were developed.

Ключевые слова:
заводнение, безгазовые дебиты нефти, нефтегазовая залежь, выработка запасов, модель исследуемого объекта, распределение свойств продуктивных пластов, петрофизические исследования, барьер на границе фазовых контактов, сложнопостроенный коллектор, фациальный анализ, текстура коллектора.

Достижение проектных показателей разработки сложнопостроенных коллекторов путем комплексного управления выработкой запасов нефти и газа требует применения моделей, адекватно отражающих геологическое строение среды, определяющей направление фильтрационных потоков при заводнении. Их достоверность повышается на основе анализа литолого-фациальных особенностей формирования продуктивной части разреза и вмещающих отложений, прогноза особенностей коллектора в межскважинном пространстве.
Известно, что неоднородность на макроуровне (песчанистость, расчлененность) играет определяющую роль в формировании преимущественных направлений фильтрационных потоков пластовых флюидов. Микронеоднородность (анизотропия, латеральная изменчивость проницаемости) оказывает влияние на характер массообменных процессов, показатели вытеснения целевого флюида и изменение фазовых проницаемостей.
При анализе продуктивного разреза пласта $АВ_1^{1-2}$, являющегося наиболее литологически изменчивым на Самотлорском месторождении, особое внимание уделялось текстурным особенностям (монолитности и расчлененности) коллекторов. В результате коллекторы пласта были классифицированы на три основных класса: с массивной текстурой, с тонкослоистой текстурой, со смешанной текстурой.
В результате детальных исследований особенностей геолого-физической характеристики строения и с учетом результатов фациального анализа для каждого из пластов были сформированы критерии отнесения к определенному типу.
Установлено, что продуктивные пласты группы АВ характеризуются весьма сложной фациальной обстановкой их формирования, которое происходило преимущественно в прибрежно-морских условиях, в зонах полузамкнутых морских заливов и лагун, дельтовых выносах палеорек. Это отразилось как на характере распределения отложений различных типов, так и на их строении и обусловило существенную неоднородность коллекторских свойств пород-коллекторов продуктивных пластов. Результаты исследований позволили выделить в пределах рассматриваемых пластов зоны с различной фациальной принадлежностью.
Установлено, что наибольшей эффективностью барьерное заводнение обладает в районе авандельты. Объяснен характер влияния фациальной принадлежности участка пласта на эффективность барьерного заводнения, связанный с особенностями распределения пропластков с различной проницаемостью и степенью расчлененности коллектора.
Разработаны рекомендации по оптимизации технологии барьерного заводнения в зависимости от фациальной характеристики участка.

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Introduction

The choice of technology for geologically complex oil and gas fields development is determined by the conditions of their associated occurrence in the formation, absence of impermeable discontinuities at the levels of gas-oil contact (GOC) and water-oil contact (WOC). In order to prevent dissipation of the integrated gas-hydrodynamic system of deposits, technologies for containment of formation fluids phase contact position shift are applied. For instance, one of them is barrier waterflooding, directed at dissociation of oil and gas reserves and their further independent development, prevention of gas breakthrough into the bottoms of producing wells, increase of gas-free oil production, preservation of pore pressure in the gas cap, and reduction of oil infiltration into the gas cap. To this end, according to the integrated development program of Samotlor field, barrier sequences of injection wells were formed for horizons AB_{1-3} and AB_{2-3}, which form an integrated hydrodynamically connected and uniquely massive reserve of oil and gas with common GOC and WOC. However, due to the low correlation between technology indicators and geological setting of the development target, partial dissipation of oil reserves occurred.

Lyantor field does not include pure oil areas; water-oil zone contains 12 %, and water-oil-gas zone – 88 % of oil reserves. Dispersed 9-point pattern-type inverted water injection system is implemented. Apart from oil-saturated interlayers, injection wells uncover gas-saturated layer for creation of a dispersed waterflooding barrier and water rim at GOC. Analysis conducted by A.V. Makarov [1] indicated significant differences in reserves development for areas with varied geological structure, detected relatively low coverage of AC_{9-11} productive horizons, uneven recovery of reserves and water adown migration from initially gas-saturated intervals.

The examined fields are in the basic period of development (stage IV), when the previously unsolved problems are augmented by deficiencies in contour waterflooding and unsatisfactory implementation of the designed reservoir development systems. In the opinion of R.H. Muslimov [2], at this stage the main focus of attention should be directed at elaboration of targeted areas geology and differentiated description of the formation. N.N. Lisovskii and R.G. Shagiev [3] state that it is possible only with the advanced multidisciplinary basis of research containing data on properties and parameters of the productive strata. An explanation of physical essence of the production area is required, i.e. a valid model that would not contradict to various research data.

Thus, rational development of oil reserves in the oil and gas fields of Western Siberia (totaling in over 5 billion tons) is possible by means of improving the targeting of geological and production measures by means of productive strata properties detailing. It is topical to substantiate the selection of efficient development systems based on the detailed geological study of the target using special-purpose petrophysical research methods and calculation experiments drawing on the geological filtration models.

Applied tasks of rational hydrocarbon reserves development in multiphase formations were solved by M.T. Abasov, A.V. Afanasiev, Iu.E. Baturin, V.G. Griguletskii, S.N. Zakirov, I.S. Zakirov, B.A. Nikitin, A.N. Laperdin, M.N. Nikolaevskii, N.Ia. Medvedev, I.R. Mukminov, A.N. Shandrygin and other Russian researchers. As a result, it was established that the efficiency of multiphase reserves development systems application depends on the geological and physical structural features of the development target. Therefore, it is required to adapt the technologies tested at other fields to the identified specific geological structural features of the target, e.g. as a result of facies analysis. Reliable data is needed for correlation of development systems efficiency indicators, differentiated choice of technology for complex geology and physical conditions of various oil and gas reserves. A lot of attention was paid to the hydrodynamic substantiation for positioning of horizontal sidetracked wells, their profiles and production cycles. A task has been defined to create barriers at GOC level in order to prevent gas breakthroughs from the gas cap to horizontal parts of production wells draining the oil-saturated part of the reservoir. For some of the targets this measure will improve the efficiency of development systems and facilitate oil reserves recovery.

However, despite the significant amount of conducted scientific researches in this area, currently the problems of various waterflooding technologies selective use and efficiency improvement are not satisfactorily solved. Open sources barely reflect the results of research directed at analysis of geological features and well operation mode impact on forming of barriers at phase contact interfaces.

The achievement of project indicators of complex reservoirs` development through integrated management of oil and gas reserves` recovery requires the use of models that adequately reflect the geological structure of the medium, which determines the filtration flows direction during waterflooding. Their reliability increases based on the analysis of lithofacial features of productive part of the cut and enclosing sediments formation, reservoir features prediction in the inter-well space.

Research of Samotlor field $AB_{1–5}$ horizons development efficiency reduction causes

Analysis of development state for two areas (area 1 is located in the south-east part of the field, area 2 – in the north-west part) was performed. The areas have different waterflooding patterns but similar geological profile. Comparison of geological and physical parameters for these areas is provided in [4], presented in Table 1, and the characteristic for the implemented development systems – in Table 2.

Table 1

Geological and physical parameters comparison for areas 1 and 2

Horizon parameter	Horizon		
	$AB_1^{1–2}$	AB_1^3	$AB_{3–3}$
Permeability, 10^3 μm^2	25/4	99/137	344/190
Compartmentalization	6/6	2/2	6/9
Porosity	0.231/0.190	0.255/0.260	0.270/0.209
Sand fraction	0.66/0.69	0.61/0.69	0.42/0.52
Net thickness, m:			
Gas-saturated	18/18	7/5	8/8
Oil-saturated	0/0	1/2	14/13
Factor:			
Gas saturation	0.440/0.545	0.563/0.744	0.647/0.737
Oil saturation	0/0	0.626/0.326	0.700/0.643

Area 2 employs a massive modular enclosed system for limitation of gas breakthrough and oil immersion into gas-saturated intervals. High injected amount into the wells of external barrier sequence uncovering oil-saturated reserves of $AB_{2–3}$ horizon by 70 %, as well as unsteady gas extraction from gas wells shifted the pressure balance between the oil and gas parts of the reservoir, resulting in oil and water displacement into the gas part. Replacement of gas by water and oil in non-perforated horizons AB_1^3 and $AB_1^{1–2}$ had been already observed in the initial period of waterflooding. This phenomenon is mostly manifest in the areas adjacent to the barrier sequence wells.

Table 2

Key development indicators

Indicator	Area 1	Area 2
Well density, ha/well	11.3	12.5
Production/injection wells ratio	1:1	3:1
Oil thickness penetration degree, % in wells:		
production	51	60
injection	70	80
Gas thickness penetration degree, % in wells:		
production	70	49
injection	90	60
Initial recoverable reserves (IRR) of oil, million	10.4	16.4
Oil recovery factor (ORF):		
approved	0.480	0.480
current	0.360	0.430
estimated	0.451	0.482
Oil production per one well, thousand tons	47	68
Initial geological reserves (IGR) of natural gas, billion m^3	8.5	20.6
Production, % IGR	47	27
Natural gas production, thousand m^3/t oil	558	415
Mean (reduced) production, t/day:		
oil	25.5	23.8
fluid	220.5	132.4
Ratio between initial and current pore pressure *	164/184	164/164
Accumulation compensation, %	167	110
Cumulative water-oil factor (WOF)	8	5
Oil ingress (per pulsed neutron logging), year	1981	1989
Displaced volume in gas cap, %	63	41

Note: * – slash separates values for two horizons.

In area 2, along with barrier sequences, dispersed waterflooding system reinforced by focal injection wells is implemented. It ensured a significant improvement in oil production rate versus gas production rate. Overcompensation of production by injection increased water content in the producing wells, causing oil and water influx in the gas cap. Oil migration across the gas-saturated part of the overlying deposits was detected by well logging methods 8 years later than in the area 1 horizons. The main areas of water and oil influx are located in the areas adjacent to the inner barrier sequence wells in the absence of a continuous clay partition at GOC.

Development of oil part of both areas implied gas production from the gas cap and injected water production, whereby the gas factor in the initial development stage of area 1 equal to 700–400 m^3/t exceeded this value obtained for area 2 in the same development period by 1.5–2.0 times.

The cumulative water-oil factor (WOF) for area 1 is higher than for area 2 (see Table 2). At similar geological features, the implemented development system for area 2, balanced operation modes of production and injection wells have provided for a more efficient recovery. The volume of initially gas-saturated formation displaced by oil and water, according to the comprehensive assessment, totals in 41 % for area 2 and 63 % for area 1. Comparison of a massive under gas-cap zone development results in Samotlor field areas with different waterflooding patterns has shown that modular development system implementation using focal selective waterflooding is more effective and ensures comparatively high oil production rates with reduced gas breakthrough volumes.

For all development targets, development systems were implemented to varying degrees. Target AB_1^{1-2} employs a dispersed 7-point inverse system with two barrier sequences in the delta front area. In the rest of the “Ryabchik” territory, an outer barrier sequence is formed. For horizon AB_1^3 in gas-oil part of the reserve, next to the internal GOC, circular waterflooding system is implemented. Target AB_{2-3} employs a circular waterflooding system consisting of outer and inner barrier sequences in the gas-oil area. Individual sections of GOC use dispersed 7-point system. Gas-oil area of horizon AB_{4-5} uses a modular waterflooding system.

Overall for AB_{1-5} horizons three circular systems are formed: at the inner GOC – AB_1^3, inner and outer GOC – AB_{2-3}. Width of areas between the rings varies from 1.3 to 6.5 km.

Gas and gas-oil zones of AB_{2-3} horizon host 185 wells (outer sequence – 115, inner sequence – 70). A massive under gas-cap zone allowed implementing a dispersed system of treatment including separate development modules, which ensured sufficiently effective oil displacement. The received oil production rates from under the gas cap in the basic development period exceeded the breakthrough gas production rate from the gas cap.

After 2003 a process of well conversion from the system of barrier waterflooding had started. Current compensation has stabilized at the level of 90–100 %, water content in production wells remains high. Currently gas production from the gas cap of the reservoir constitutes approximately 70 %; combined production of oil and gas by the well stock continues. Barrier sequences of the formation are mostly decommissioned, dispersed injection systems are being optimized to displace the residual volumes of oil from under the gas cap. The development product has high water content; gas factor depends on the distribution of the current reserve structure across the reservoir area and constitutes 150–420 m^3/t. Currently due to the development system implementation using barrier waterflooding at the main highly productive horizon AB_{2-3} nearly 80 % of gas-saturated thickness is displaced by water and oil. The current structure of reserves is most of all caused by the unstable gas production and horizon waterflooding.

Nevertheless, barrier waterflooding arrangement, in tandem with a massive dispersed system allowed increasing the gas and oil reservoir zone efficiency. Oil production from under the gas cap amounted to 72 % of the initial recoverable reserves (IRR).

In horizon AB_{1-3}, where barrier sequence consists of 137 wells located perimeter-wise between the inner gas bearing contours, narrow under gas-cap zone (from 3.5 to 0.6 km) impedes creation of an efficient dispersed injection system, similar to horizon AB_{2-3}. Out of all the 268 wells of the horizon that took part in the gas production from gas cap, only in 40 (15 %) only gas production was performed (with gas lift purpose), while in the rest of them liquid fluids and gas were production jointly.

Gas factor of oil producing wells in the basic development period remained high (1800–3500 m^3/t), signifying the presence of constant gas flow from the gas cap to oil-saturated part of the horizon in a number of complexly structured areas, despite the growing water injection volume into the barrier wells. Breakthrough gas historical production rates were high. Current gas production from gas cap amounts to 63 % of IGR, oil – 54 % IRR. In the course of barrier waterflooding implementation in the horizon AB_{1-3} the combination of production and injection wells became 1:2, which resulted in a significant overcompensation, gas displacement, oil and water ingress in the gas cap, replacement of 74 % gas-saturated thickness. In the present time, the structure of gas reserves in the horizon is mainly determined by waterflooding, as well as active development of the lower productive stratum AB_{2-3}, interlayer water and oil migration.

In this regard, it might be reasonable to conduct a research of oil reserves recovery from reservoirs of clay interlayers in the course of development of the horizon by vertical wells. To this end, hydrodynamic model is used [5]. Let us assume that at the model input (injection well) pressure $1.5p_0$ and water saturation $Sw = 1$ are given. At the model output (production well) – pressure $0.5p_0$, where p_0 – initial pore pressure. The rest of the conditions and parameters of the task repeat the conditions considered in the research by I.I. Vladimirov, E.V. Zadorozhnyi [6]. Dependence of clay interlayers permeability on the injected water content in the reservoir is exponential $f(Ss) = \exp(-d\cdot(S-S_0))$, where d – parameter characterizing intensity of well permeability decrease; S and S_0 – current and initial water saturation values of the reservoir.

Figure 1, *a*–*c* presents the dynamics of pressure fields and water saturation for options with various values of clay interlayers permeability decrease indicator: option 1 – $d = 0.0$; option 2 – $d = 10.0$; option 3 – $d = 20.0$.

Obviously, water injection per option 1 ($d = 0$), where reservoir permeability change does not occur, results in frontal displacement of oil by water, which is concordant with common ideas of oil displacement from a homogeneous reservoir.

Clay interlayers permeability variation in the course of waterflooding by fresh water significantly affects the displacement front. Due to the selective permeability decrease, the residual oil reserves are concentrated in clay interlayers. The higher parameter d is, the more unextracted oil remains in these interlayers (see Figure 1, *b*, *c*).

Certain studies [7, 8] explore the influence of horizontal wells (HW) and vertical wells (VW) on the nature of waterflooding of a layered horizon with clay interlayers. The results of HW and VW application in the course of reserves recovery are ambiguous.

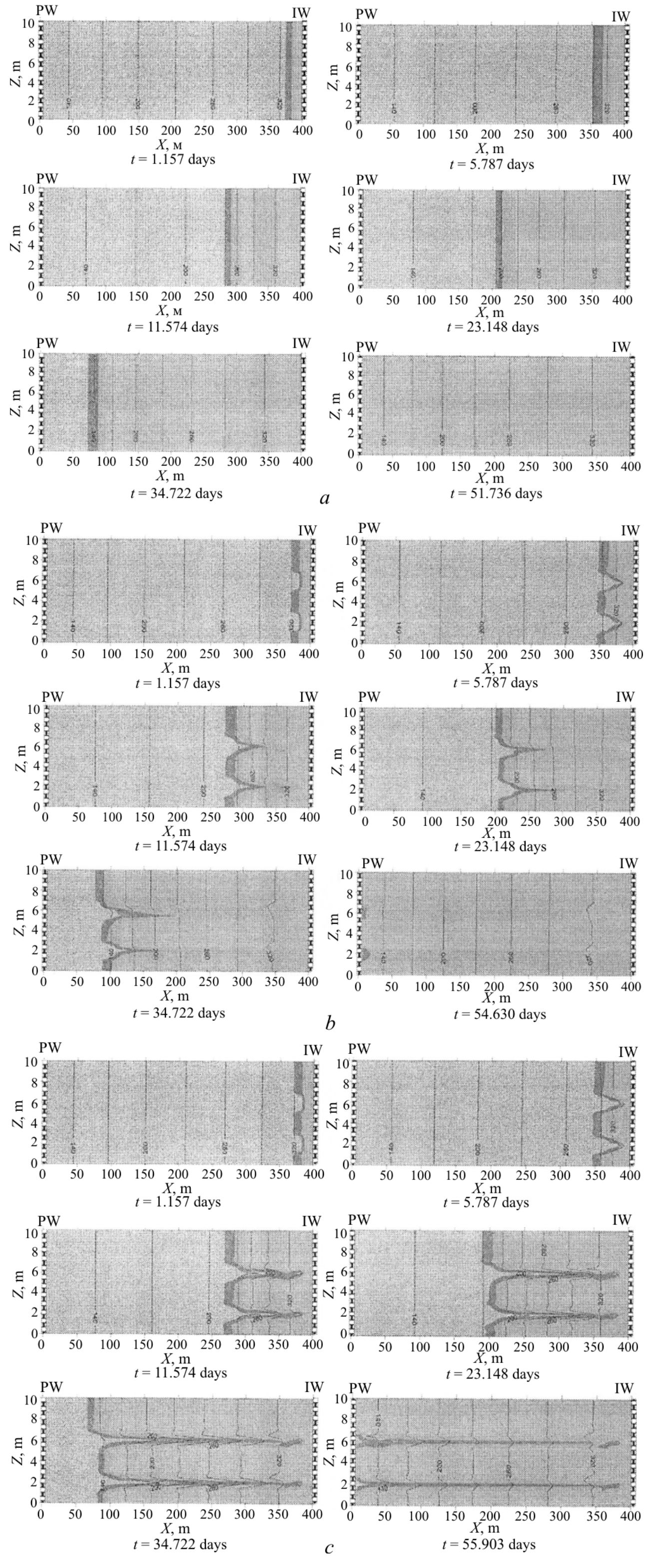

Figure 1. Pressure fields dynamics (isolines) and water saturation (color) for a homogeneous horizon with clay interlayers in the course of development by vertical wells: *a* – d = 0.0; *b* – d = 20.0; *c* – d = 10.0. Z, m – depth; X, m – width; t – time after well startup; PW – production well, IW – injection well

Comparing the oil production ratio in the course of HW or VW well development using a simple 2D-model it is fair only to discuss nature of waterflooding or oil reserves recovery across the horizon section. If permeability of clay interlayers does not decrease, than the final ORF for 2D model of the reservoir insignificantly depends on the type of the applied well and HW shaft position in the reservoir thickness. If parameter *d* increases, the efficiency of waterflooding across the horizon section significantly decreases for a vertical well and less so – for a horizontal well. The most efficient option of injection horizontal well shaft location is at the horizon base (option 1 of study [7]). However, with further increase of parameter *d* part of the oil reserves are cut off due to the decrease of clay interlayers permeability and disruption of hydrodynamic connection between the oil saturated layers. In these conditions the efficiency of HW falls dramatically and it becomes more reasonable to use VW that enable extraction of oil from all sand interlayers isolated from one another by clay interlayers that have become impenetrable.

E.V. Zadorozhnyi [9] performed improvement of oil residual reserves recovery technology from inhomogeneous layers of clay-containing AB_1^{1-2} horizon reservoirs in Samotlor field based on theoretical research and subsequent trials in the production sites. In cooperation with I.V. Vladimirov, N.I. Khisamutdinov et al. [10] he established that the procedure of vertical and horizontal well performance indicators comparison for this purpose requires correction.

The performed analysis established the following:

1. The scheme of barrier sequences installation and operation implemented in Samotlor field to a large extent facilitated mitigation of gas breakthroughs and stabilization of gas factor. However, 80 % of gas from the gas cap was production by the well stock from under the gas cap.

2. The main disadvantages of the implemented development schemes for AB_{1-3} horizons using barrier waterflooding are partial involvement of narrow under-gas areas in oil recovery, high water content in the product at early stages of development, production of massive volumes of breakthrough gas, waterflooding of gas-saturated formations.

3. Gas reserves localization zones in the gas cap of unreplaced volume of gas-saturated thickness are 50 % by integrated estimation and have complex geometry.

4. Organization of dispersed and focal selective waterflooding in combination with barrier sequences formation in AB_{2-3} horizon facilitated the development efficiency increase, but not entirely due to consistently high water content of the producing wells. Operation of inner barrier sequence of AB_{2-3} horizon caused gas displacement to the oil part of the reservoir, which complicated the formation development.

5. In the course of development of layered inhomogeneous reservoirs with anisotropic permeability field, efficiency of the development system using wells that uncover all oil-saturated interlayers of the horizon depends on the extent of hydrodynamic connection. It is necessary to research the dependence between efficiency of oil and gas reservoir waterflooding and field wells profile.

Impact of geological and physical properties of AB group horizons on oil reserves recovery in Samotlor gas field

Russian researchers have been studying the relation between efficiency of development of multifacies terrigenous reservoirs and their particle size distribution (macroinhomogeneity) and orientation of sandstones grain mass in the interlayers (microinhomogeneity). As a result of research of the influence of sediment accumulation conditions on the production conditions at the reservoir and performance of the wells conducted by S.B. Denisov, G.M. Zoloeva, I.V. Evdokimov, R.M. Kuramshin, R.H. Muslimov, S.V. Nikiforov et al., it was established that:

– sand package geometry can be justified based on sedimentation conditions analysis;

– initial porosity and permeability value is defined by sedimentation processes;

– final distribution of porosity and permeability is justified by diagenesis processes;

– presence of linear sand bodies can cause high lateral anisotropy of rock properties, with axes of anisotropy of improved porosity and permeability directed along the lines of filtration flows.

These conclusions should be taken into account when designing waterflooding, reservoir pressure maintenance systems (RPM) and enhanced oil recovery methods.

It is well known that macrolevel inhomogeneity (grittiness, compartmentalization) plays a defining role in formation of prevailing directions of reservoir fluids filtration flows. Microlevel inhomogeneity (anisotropy, lateral permeability variability) influences the nature of mass exchanging processes, target fluid displacement indicators and phase permeability variation.

In the research conducted by R.G. Sarvaret-dinov et al. [11, 12] six lithotypes of rock were identified in each of the 5 interlayers of AB_1^{1-2} horizon structure. The research of reservoir fluids filtration mechanisms has shown that the proportion of fluid inflow to each of the interlayers varies significantly. This can be explained by the type of reservoir structure, varying porosity and permeability and interlayers thickness.

Based on the representations by A.V. Khaba-rov et al., J.O. Amaefile et al. [13, 14], lithological classification of rocks in the studied sequence allows segregating individual groups of rocks that deposited in similar sedimentation conditions and were exposed to similar diagenetic meta-morphoses. The results of research are instrumental in attributing the unique permeability correlations (k_{per}) and porosity correlations (K_{por}) to the groups, as well as capillary pressure profiles and shapes of phase permeability curves.

In the process of analysis of particle size distribution, pore measurement data, results of designated core samples research in cooperation with A.V. Khabarov and other specialists of "Tyumen oil research center" LLC, 3 types of reservoirs were determined: 1) the most highly permeable (homogeneous large pore sandstone); 2) standard; 3) variations with high clay content (both disperse and layered).

For determining the fluid content and oil and gas saturation factor (K_{og}), a comprehensive method by Ya.E. Volokitin and A.V. Khabarov and capillary saturation model [15] where used to augment and verify the electrical model. Adequacy of electrical model is confirmed by high reproducibility of results against data received with the aid of capillary model.

It has been established that electrical resistance of layered rock is an anisotropic parameter. As a rule, the vertical resistance is higher than horizontal resistance along the layers, i.e. in the same horizon the horizontal well resistance will be higher than in the vertical well. Failure to take into account this phenomenon results in inadequately high calculated values of K_{og} in horizontal wells.

Based on the comparison of specific electrical resistance values (SER) of rocks in pilot subvertical and main subhorizontal wellbores, SER of horizontal wells is 1.3–1.5 times higher than that of the subvertical ones. The received correlation allows correcting SER value taking into account the electrical anisotropy of rocks and, as a result, verify K_{og} in the wells with outstandingly high values of vertical deviation.

It is well known that in order to estimate permeability, it is crucial to take into account lithological properties and pore space structure. In the absence of fractured and cavernous rock, there must be a correlation between porosity/permeability based on geophysical and hydrodynamic research, and actual wells productivity.

The obtained permeability model demonstrated a distinct correlation with hydrodynamic logging (HDL) data (Figure 2) and allows identifying highly permeable interlayers in the nonhomogeneous reservoirs interval.

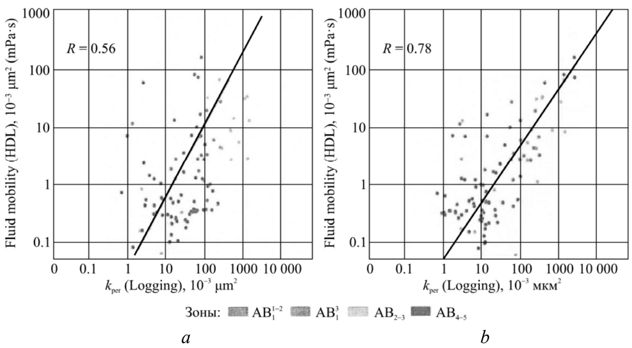

Figure 2. Comparison of fluid mobility by logging data and fluid mobility by HDL data for the old (*a*) and new (*b*) model

Facies analysis has established that during formation of AB_{4-5} horizon deposits there was an intense ingress of fragmentary material with a high proportion of sand fraction. Sedimentation process was accompanied by activation of tectonic processes; against their background, delta front and delta deposits prograded from south-east to north-west. Sand bodies are represented by such facies as delta front (amalgamated sandstones), deltoid channels and stream-mouth bars. Since the ingress of sandy material was abundant, hydrodynamic connection in lateral direction is pervasive. Vertically, the hydrodynamic connection is less seamless due to the presence of focal clay interlayers. Sedimentation activity significantly decreased by the end of $AB_{4–5}$ horizon formation period, during which an extensive delta plain was developed in the territory, crossed by rare but powerful, most probably subaerial, deltoid channels.

$AB_{2–3}$ horizon deposits are related with intensive sediment accumulation in conditions of delta plain where deposits consist of facies of shoestring sandy delta channels and bars, as well as facies of thin-layer structures occurring between the shoestring bodies. Sand content in the sequence is relatively high; therefore, vertical and horizontal continuity is present, though with varying degrees of seamlessness.

AB_1^3 horizon deposits consist of intermediate facies that were formed during immersion of the sea basin, decrease of sand fractions share in the incoming fragmentary material, activation of tectonic displacement that formed the drag folds of the north-west stretch.

The processes of sea basin immersion and tectonic displacement most of all impacted the formation of $AB_1^{1–2}$ horizon deposits. Argillaceous sandstones of this area are represented by facies of blanket deposits. Massive sand bodies in the east of the field were formed at the final stage of $AB_1^{1–2}$ horizon formation as a result of avalanche-type sedimentation.

Due to the tectonic sedimentation processes, an integrated hydrodynamic system has formed for horizons $AB_{1–5}$, with one WOC and one GOC. The reservoir's integrity is ensured by low thickness or even absence of clay interlayers between the horizons. Presence of a gas cap was confirmed by multiple production data and geophysical materials based on which the GOC can with a high degree of confidence be established on the elevation mark of 1611 m. Group AB productive strata are characterized by an extremely complex facies environment of development, which occurred predominantly in coastal-marine conditions, areas of semi-closed sea gulfs and lagoons, deltoid paleoriver carry-overs. These conditions influenced both the nature of various deposits distribution and their structure, causing the existing inhomogeneity of productive strata rocks reservoir properties. AB horizons sand bodies were formed in conditions of shallow sea with abundant ingress of fragmentary material. Actually Samotlor field area in that period was an extensive delta-front flatland with facies of deltoid channels, stream-mouth bars with shoestring sand bodies and facies of interchannel fillers consisting of inhomogeneous alternations of sandstones, aleurolites, mudstones, and clays.

In the course of $AB_1^{1–2}$ horizon productive section analysis as the most lithologically variable in Samotlor field, special attention was paid to the textural features (consolidation and compartmentalization) of reservoirs. As a result, the horizon reservoirs were classified into three groups: with massive texture (MT), with thin-layer texture (TLT), and mixed texture (MT + TLT). Thus, for all of the studies horizons, three types of sections were defined (Figure 3, exemplified by horizon $AB_1^{1–2}$):

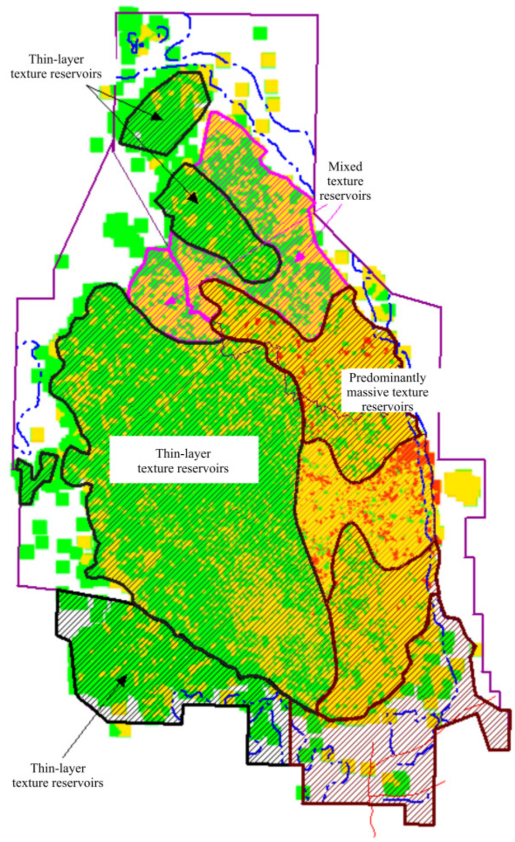

Figure 3. Schematic borders of various textures in horizon $AB_1^{1–2}$

– Structure type I – composed of reservoirs with massive texture (MT);

– Structure type II – composed of reservoirs with thin-layer texture (TLT);

– Structure type III – mixed, where the horizon consists of reservoirs with different texture (MT + TLT).

Drawing on the detailed study of geological and physical structural properties and the results of facies analysis, criteria of categorization were determined for each of the horizons (Table 3, exemplified by horizon AB_1^3).

Table 3

Porosity and permeability of reservoirs per AB_1^3 horizon structural types

Parameter	MT	TCT	MT + TCT
Porosity factor, fraction unit	0.27	0.25	0.26
Permeability factor, mD	319.5	110.28	310.72
Oil saturation, fraction unit	0.66	0.56	0.62

Geological and hydrodynamic target model improvement

In 2007–2008, in order to manage the field development, a geological-hydrodynamic model for $AB_{1–5}$ horizons group was created. Problems of target area modeling caused by the structural features of the horizons, its size (50×80 km), development duration and a high amount of wells are described in [16]. However, during the study of combined development of the gas cap and oil rim it was identified that in the course of model adaptation to the development history the volume of unproductive injection was estimated at 15–20 % (material balance method), whereby a decision was made not to reproduce the injection in the model in its full scope. Gas cap pressure level is assumed to be by 1.0–1.5 MPa lower than actual (it is a significant level of uncertainty for the gas cap in the course of assessment of gas production and volume of fluid invading the gas cap). The oil and gas carbohydrate deposits in West Siberian oil and gas province are known to have a high content of relict (residual) oil in the gas-saturated part of horizons. N.N. Mikhailov research school [17–19] established that the reserves of residual oil are a complex dynamic structure consisting of several individual varieties with their distinct properties and degree of mobility. It has been shown that a significant residual oil distribution inhomogeneity forms in the inter-well space. The applied systems for deployment and well density significantly influence the displacement factor. Waterflooding of the horizons allows displacing residual oil, but the degree of displacement depends on the correlation between reservoir properties of the intervals represented by rocks with distinct variability.

Residual gas saturation structure in the course of gas displacement with water or oil approximates the structure of residual oil saturation. This is confirmed by comparative experimental studies with oil and gas displacement by water, e.g. those in the research of M.W. Legatski [20]. The difference is that in the initially gas-saturated reservoir the hydrophobic parts of the pore surface are mostly wetted with gas (excluding the parts wetted by relict oil). In the event of oil ingress in the gas-saturated reservoir, residual oil saturation is determined only by capillary entrapped oil, since gas in reservoir conditions is more hydrophobia-inducing than oil, so oil wetting of surface is unlikely.

In the course of 2008 model adaptation, a simulation was performed based on the example of $AB_1^{1–2}$ horizon. It was established that the input assumptions of the vertical reservoir coherence adopted in the model (for horizon $AB_1^{1–2}$ the relation between vertical and horizontal permeability is set as 1/1000, for the rest – 1/100) did not reflect the real flow distribution between the horizons. For a more adequate modeling of vertical coherence it was decided to recalculate the vertical permeability of enlarged cells (vertical size – 2.6–10.0 m) accounting for the presence of clay interlayers in them. To set the residual oil- and gas saturation, their values were correlated with initial saturation of the reservoir by oil or gas. As a rule, to determine the residual oil saturation, correlation between its values and reservoir permeability is used; however it is applicable only for peak saturation, and its use for transition area considerably underestimates mobile oil reserves. Russian researchers [21] have established that residual oil saturation is primarily determined by the initial saturation of the reservoir. This is confirmed by an isolated core research (Figure 4).

After processing the data obtained by S.V. Dvorak et al. [22] as well as our own experimental data for Samotlor field, we were able to show that reservoir oil saturation above the GOC should be defined taking into account the distance to the GOC, α_{sp} values and relict oil saturation.

Residual oil and water saturation were determined separately for horizon $AB_l^{1–2}$ and other horizons. Residual oil saturation in the oil reservoir

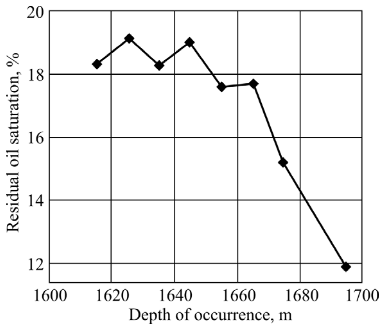

Figure 4. Dependence of residual oil saturation (determined by the sealed core sample) from true vertical depth for horizons AB_{1-5} of Samotlor field (porosity is 24–28 %, true vertical depth of gas-oil contact – 1611 m)

was determined based on displacement factor (K_{dis}), defined for each reservoir class by correlations obtained from processing of experimental data,

$$K_{dis} = \left(1 + \frac{1}{\alpha + \beta k_{per}}\right)^{-1},$$

where α, β – factors [21]; k_{per} – permeability factor.

In order to determine phase permeability values for gas, oil and water at critical saturation values correlations with reservoir permeability and porosity were used (based on the theoretical regularities defined by Iu.E. Baturina, N.Ia. Medvedeva et al. [23]), received by way of processing of experimental relative phase permeability values. To account for the vertical inhomogeneity of AB_{1-5} horizons group in the model, a method of vertical permeability cube construction was used, based on parameters of the initial geological model.

Thus, drawing on the aforementioned provisions, the model was amended as follows:

1. In AB_{1-5} horizons saturation model, based on the results of drill samples examination, geophysical and literary data, the initial (relict) oil saturation of gas cap was introduces depending on the height above the gas-oil contact and porosity (mean saturation amounted to 5 %).

2. Residual oil saturation of gas cap depending on porosity, initial oil and gas saturation was set at the level by 3–5 % higher than relict oil saturation (based on the research of conditions of residual oil saturation formation in polymictic reservoirs of the West Siberia).

3. Residual gas saturation of the gas cap as a function of porosity and permeability, as well as initial gas saturation of the reservoir (based on core samples examination and data provided in literary sources) is assumed as equal to 23–29 %.

4. Residual oil saturation in initially oil-saturated area of the horizons is set depending on the porosity, permeability and initial oil saturation (based on the research of residual oil saturation formation conditions in polymictic reservoirs of the West Siberia).

5. Based on the laboratory research results and literary data, correlations were received for dependency of end points of phase permeability values on porosity and permeability of reservoirs with subsequent scaling of phase curves in each active cell of the model.

6. Vertical permeability cube calculated based on geological model data with use of anisotropy factor dependence on self-potential method indicator α_{sp} was introduced in the hydrodynamic model.

Increase of physical informative potential of the model improved adaptation quality in terms of the main process parameters of development and reliability of oil and gas production forecasting. As a result of the amendments, it became possible to reproduce the current reservoir pressure distribution in the gas cap volume, and to eliminate discrepancy between actual and calculated injection data.

Waterflooding technology trial after adaptation to the determined specific geological and physical features

To assess the efficiency of barrier waterflooding with the use of hydrodynamic model of AB_{1-5} horizons group, a version of AB_{1-5} horizons group development was calculated as if it were absent in the historic period. The calculation results were compared to the basic version concordant to the history of AB horizons development reproduced in the model.

Each of the AB_{1-5} horizons group is officially considered an independent target of development, but in fact there is a connection between the horizons conditioned by several geological reasons and man-induced factors.

Comparison of calculation results for the basic version and version without barrier waterflooding was performed for each of the horizons and for AB_{1-5} group as a whole. The main calculation indicators for the comparison were oil and free gas production indicators dynamics, fluid volumes migrating through GOC in the process of development: oil and water ingress in the gas cap, current gas reserves in the gas cap.

Overall the arrangement of barrier waterflooding facilitated the reduction of breakthrough gas volumes from gas cap to the production wells and, to a certain extent, prevented the oil from entering the gas caps, however this process was not completely overcome and in subsequent years there were sporadic migrations of oil into gas caps and ingress of free gas into the oil part.

Comparison of accumulated volumes dynamics for oil and water ingress in the gas cap for individual horizons and $AB_{1–5}$ group in general, for free gas ingress in the oil are, in case of presence and absence of barrier waterflooding based on results of hydrodynamic modeling is presented in Figure 5.

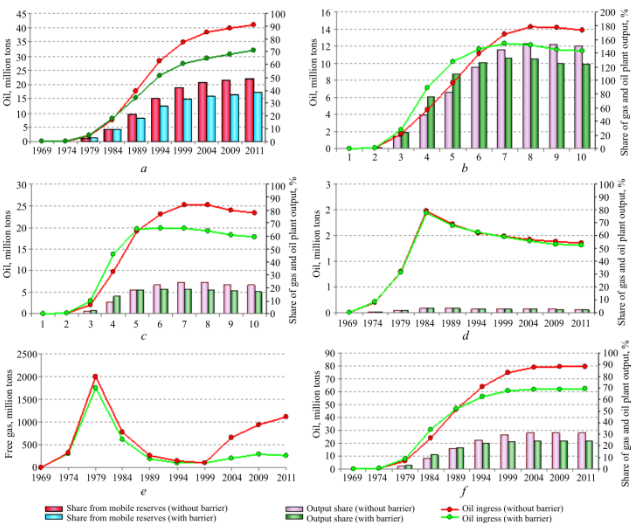

Figure 5. Dynamics of accumulated ingress volumes of oil into the gas cap and free gas into the oil zone: *a* – oil ingress into the gas cap, horizon $AB_1^{1–2}$; *b* – oil ingress into the gas cap, horizon AB_1^3; *c* – oil ingress into the gas cap, horizon $AB_{2–3}$; *d* – oil ingress into the gas cap, horizon $AB_{4–5}$; *e* – free gas volume below GOC, million m^3; *f* – oil ingress into the gas cap, horizon $AB_{1–5}$

Based on the accumulated volumes of free gas ingress in the oil part of the reservoirs, a difference was identified between the versions received in the period of 2000–2010, when due to the active commissioning into development of producing wells of the gas and oil area, production of fluid and oil was increased. It was established that the reason of gas migration increase in the version without barrier waterflooding was the presence of horizon junction windows, resulting in the ingress of massive free gas volumes into the oil are of the reservoir. As of the date of assessment, the ingress volume of free gas under the version without barrier waterflooding amounted to 1.1 billion m^3, which is 5 times more than in the version with use of barrier waterflooding (0.26 billion m^3).

The accumulated volumes of water ingress in the gas cap were assessed as 328.4 million m^3. This is 22 % more than in the version without barrier waterflooding in the historic period (269.5 million m^3), which constitutes 15.2 and 12.5 % respectively from the pore volume of the gas bearing part of $AB_{1–5}$ horizons group.

Barrier sequences arrangement in horizons $AB_1^{1–2}$, AB_1^3 and $AB_{2–3}$ according to the calculations allowed reducing the volumes of oil ingress into the gas caps by 17 million tons (or by 27 %).

Implementation of barrier waterflooding also facilitated the migration of massive water volumes into the gas cap. Significant water injection volumes into the barrier wells promoted water breakthrough to the production wells of the gas and oil area adjacent to the barrier sequences from the outer side, and their quick waterflooding. Injection of high volumes of water in the barrier wells of $AB_{2–3}$ horizon caused significant migration of fluids between the targets, and first of all the fluid migration from $AB_{2–3}$ target into the gas part of AB_1^3 through the large junction windows. The inner barrier sequence of $AB_{2–3}$ horizon was proposed to be decommissioned.

Therefore in under-the-cap area of AB_1^3 horizon, taking into account the existing gas reserves structure, presence of displaced volume of the gas cap ad minor residual gas reserves localization areas, barrier waterflooding is not necessary. In this area it is required to improve efficiency of dispersed and focal selective development systems, along with purely oil area of the reservoir. Moreover, gas production has to be arranged in the local areas using the gas stock wells together with $AB_1^{1–2}$ horizon where the main reserves of gas are concentrated.

In this context, a research was conducted in cooperation with K.M. Fedorov on the operation of horizontal wells with low-angle and sinusoidal wellbore profile, which are known to be less dependent on the vertical inflow component and allow increasing the vertical drainage area [24].

A comparative analysis was performed for the well productivity with horizontal, low angle and sinusoidal wellbore profile using sectoral geological and hydrodynamic model of AB_1^{1-2} horizon consisting of three equally thick interlayers (2.5 m each) with different horizontal permeability factor value (8; 12; 17 mD). Intervals of low angle and sinusoidal part are replaced with sectional horizontal parts uncovering the horizon. Horizontal wellbore length is L = 500 m, pressure sink – 10 MPa. Let us assume that one can neglect the motional friction of formation fluid in the wellbore.

To solve this task, it is required to know the drainage radius of the well. A common method for horizontal well drainage area calculation [25] is considering it as a total of the areas of two halves of the circle with radius b and area of rectangle $2bL$. Let us assume that radius b is equal to drainage radius of vertical well $r_в$, and drainage area can be expressed as

$$S = \pi r_в^2 + 2Lr_в.$$

As a rule, $r_в$ is assumed to be a semi-distance between the wells which for this sector of horizon AB_1^{1-2} constitutes 300 m. Therefore, it is possible to calculate drainage area for each separate segment of the low angle or sinusoidal well taking into account the length of horizontal wellbores in this interlayer.

Based on the calculation results it was established that the value of the low-angle well production output exceeds the horizontal well production output by 2.2 times, while the sinusoidal profile well production output exceeds the low-angle well production output by 1.4 times.

To verify the estimations, calculations were performed in the sector model of AB_1^{1-2} horizon with application of three-phase hydrodynamic model of the area, constructed with Eclipse simulator. To take into account possible degassing of oil in the wellbore area, gas phase was introduced into the model. Forecast calculations were performed for the period of 15 years ahead, on condition that bottom-hole pressure will remain the same during the entire time of operation and will be equal to 6 MPa. Skin factor was assumed as zero. Wellbore length of nominally horizontal part was 500 m. Horizontal, low-angle and vertical profiles were studied. In all options, the wellbore was located in the upper half of AB_1^{1-2} horizon, since its base part is less oil saturated.

It was established that the horizontal part of the well was the least efficient. The cumulative oil production amounted to 41.2 thousand tons at cumulative fluid production of 176.6 thousand tons. Cumulative oil production in a well with low angle wellbore profile is higher than that of the well with a horizontal profile by 40 %. Sinusoidal bore profile is the most efficient one. Cumulative oil production exceeds one for the low angle wellbore profile by 17.8 %.

The above mentioned results allowed substantiating the key points in assessment of horizontal drain efficiency. However, all the conclusions relate to a horizon with homogeneous or nominally homogeneous permeability. Research [26] considers an example of zonally inhomogeneous permeability horizon, where RPM system has been formed. The area of reduced permeability is uncovered by the well where a hydraulic fracture is created to induce productivity of the well or a horizontal sidetrack is constructed.

Based on the displacement features application, a conclusion was made that the operation of horizontal wellbores in low permeability area of the horizon distanced from the injection wells sequence is a more attractive option in terms of process efficiency, providing a more impressive oil production rate and lower water production increase.

Summary

1. Drawing on the analysis of reservoir textural features in each of the studied productive horizons, three types of sequences were determined: reservoirs with massive, thin layer and mixed texture. For these types of reservoirs, identification criteria and distinctive features were established.

2. It was determined that group AB productive horizons have an extremely complicated facies environment of development, which occurred predominantly in coastal-marine conditions, areas of semi-closed sea gulfs and lagoons, deltoid paleoriver carry-overs. These conditions influenced both the nature of various deposits distribution and their structure, causing the considerable inhomogeneity of productive strata rocks reservoir properties. The research results permit to distinguish areas with varying facies attribution within the studied horizons.

3. It was established that barrier waterflooding has the highest efficiency in delta front areas. An explanation was provided for the influence of facies attribution of a horizon area upon efficiency of barrier waterflooding, related to the distribution of interlayers with different permeability, as well as to the reservoir compartmentalization.

4. Recommendations were developed in view of optimization of the barrier waterflooding technology depending on the facies features of the area.

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