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Features of fluid dynamics in long-term heterogeneous gas reservoirs

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Abstract

Geological features are characterized by macro- and micro-heterogeneity, manifested by the spatial variability of material composition and lithophysical properties of rocks. This, in turn, determines the spatial and temporal variability of hydrocarbon (HC) fluid dynamics both during the reservoir formation and during its development and, subsequent operation as an underground gas storage facility (UGSF). The long-term operation of underground gas reservoirs at the Galmas and Garadagh areas in the South Caspian Basin (SCB), serving as a reservoir of commercial gas accumulations, and subsequent underground gas storage (UGSF) is characterized by significant peculiarities. Analysis of monitoring data on volumes of gas injection and extraction at the Galmas/Garadagh UGSF in the period of 2020–2021 showed their spatial variability, as well as the variability of wells deliverability during the gas reservoir development. This suggests the inherited nature of UGSF operation mode in relation to the gas reservoir development mode. The heterogeneous nature of spatial variability of these parameters is determined by the reservoir rock poroperm properties. A formation pressure drop during reservoir development is accompanied by decreasing rock permeability. When operating UGSF, the lithofacial properties of rocks determine the ratio of volumes of injected and extracted gas. In this regard, a necessary condition for selecting the optimal system of UGSF operation is to take into account the spatial heterogeneity of the underground reservoir. The irregular nature of variation of rock poroperm properties, the origination of isolated zones in the reservoir with considerable residual gas volumes, as well as unpredictable directions of fluid movement are the main reasons for decreased efficiency of field development and underground gas storage facility operation. In order to determine the optimal system of operation of UGSF in depleted underground oil and gas reservoirs, the features of the spacial variations resulting from the rocks poroperm properties need to be taken into account.

Keywords

underground gas storage facility, reservoir, rocks, reservoir poroperm properties, porosity, permeability, spatial heterogeneity, gas-condensate reservoir, fluid dynamics, South Caspian Basin

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ГЕОЛОГИЯ МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Научная статья

Особенности флюидодинамики в длительно эксплуатирующихся неоднородных газовых резервуарах

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Аннотация

Геологические объекты характеризуются макро- и микронеоднородностью, что проявляется изменчивостью в пространстве вещественного состава и литофизических свойств пород. Это, в свою очередь, определяет пространственно-временную изменчивость динамики углеводородных (УВ) флюидов как при формировании залежи, так и при ее разработке, а в последующем и эксплуатации в качестве подземного хранилища газа (ПХГ). Длительная эксплуатация подземных газовых резервуаров на площадях Галмас и Гарадаг в Южно-Каспийском бассейне (ЮКБ), служащих вместилищем промышленных скоплений газа, а в дальнейшем для подземного хранения газа (ПХГ) характеризуется существенными особенностями. Анализ данных мониторинга объемов закачки-отбора газа на ПХГ Галмас и Гарадаг в период 2020–2021 гг. показал изменчивость в пространстве их значений, так же, как и продуктивности скважин при разработке газового резервуара. Это позволяет предположить унаследованный с режимом разработки газового резервуара характер режима эксплуатации ПХГ. Неоднородный характер изменения в пространстве этих параметров определяется фильтрационно-емкостными свойствами пород. Падение пластового давления в процессе разработки залежи сопровождается снижением проницаемости пород, а при эксплуатации ПХГ литофациальные свойства пород определяют соотношение объемов закачиваемого и отбираемого газа. В связи с этим необходимым условием выбора оптимальной системы эксплуатации ПХГ является учет пространственной неоднородности подземного резервуара. Неравномерный характер изменения по площади фильтрационно-емкостных свойств горных пород (ФЕС), формирование изолированных зон в резервуаре со значительными остаточными объемами газа, а также непрогнозируемые направления движения флюидов являются основными причинами снижения эффективности разработки залежи и эксплуатации ПХГ. Для определения оптимальной системы эксплуатации ПХГ, созданных в истощенных подземных нефтегазовых резервуарах, необходимо учитывать особенности изменения в пространстве ФЕС слагающих его пород.

Ключевые слова

подземное хранилище газа, резервуар, горные породы, фильтрационно-емкостные свойства, пористость, проницаемость, пространственная неоднородность, газоконденсатная залежь, флюидододинамика, Южно-Каспийский бассейн

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Introduction

There are no absolutely homogeneous geological features in the natural environment. All are characterized by macro- and micro-heterogeneity, manifested by spatial variability of the material composition and lithophysical properties of rocks. This, in turn, determines the spatial and temporal variability of hydrocarbon (HC) fluid dynamics both during reservoir formation and during its development and, subsequent operation as an underground gas storage facility (UGSF).

Irreversible changes in the reservoir during the long-term development of fields are caused by a continuous drop in formation (reservoir) pressure connected with extraction of significant volumes of fluids (oil, gas, water) from the underground reservoir [1, 2]. In comparison with the change in porosity of rocks, the formation pressure drop leads to more significant irreversible changes in their permeability [3-6].

Compared with the mode of reservoir development, changes in the reservoir during UGSF operation are connected with repeated alternating stresses on the formation (reservoir) (cyclic variations of the effective pressure), caused by seasonal injection and extraction gas.

The study of the above processes by the example of gas field development in Galmas and Garadagh areas of SCB, as well as the long-term operation of UGSFs created in them is the main objective of this paper.

Brief description of the assets to be investigated

Galmas field / UGSF

Galmas oil and gas field / UGSF (underground gas storage facility) is located in the northern part of Nizhnekurinsky depression, 75 km from Baku (Fig. 1).

The depression is complicated by longitudinal and transverse faults and, as a consequence, has a block structure. The main fault within the fold is a longitudinal disruption, upon which an extinct mud volcano of the same name is located.

The Productive Strata consists of alternating clayey and sandy-silty interlayers, the proportion of which varies significantly depending on the depth and area of spreading.

Commercial gas inflows were obtained from wells which penetrate into the formations of the local Absheron sequence (Lower Anthropogen), Akchagyl (Upper Pliocene), and Productive Strata (PS, Lower Pliocene). The Galmas field was brought into commercial development in 1956.

Since 1976 the previously commercially gas-bearing I and II horizons of the PS have been used as Underground Gas Storage Facilities (UGSF). Gas in small volumes is also injected into the sand reservoir of the Absheron formation (strata).

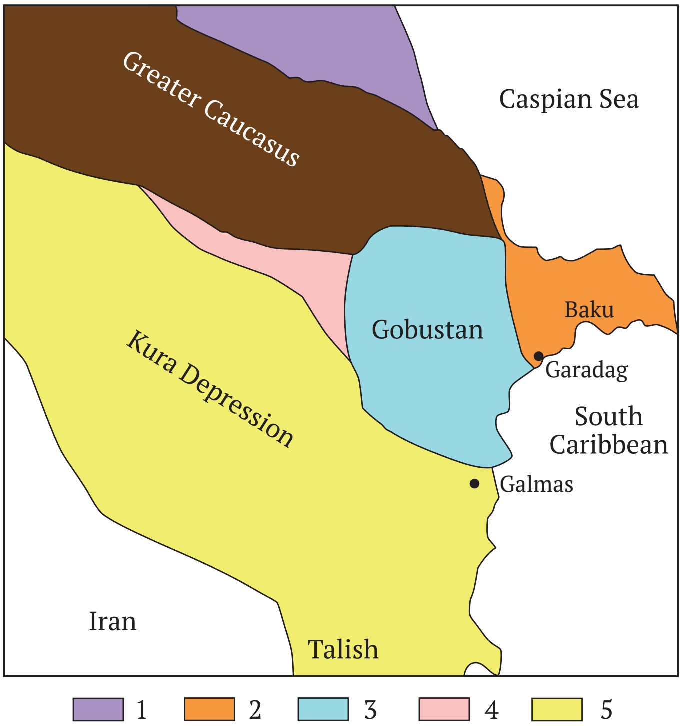

Fig. 1. Location of the Galmas and Garadagh fields / UGSFs and lithofacial types of the Productive Strata sediments: *1* – Pre-Caspian; *2* – Absheron; *3* – Gobustan; *4* – Geylar; *5* – Nizhnekurinsky

Garadagh field / UGSF

The Garadagh field/UGSF is located in the extreme southwestern part of the Absheron Peninsula, 30 km from Baku (see Fig. 1) and is confined to the southern flank of the asymmetric anticline with block structure [7].

The main targets of the Garadagh oil and gas field development are the I-VII horizons of the PS. A gas-condensate reservoir was identified in the VII-VIIa horizons of the PS (hereinafter the PS VII horizon). In the SE part of the southern limb they unite and form a single thick sandstone layer. The effective thickness of the VII horizon reaches 10–25 m in the northwest and 55–75 m in the southeast.

Exploitation of the PS VII horizon as a UGSF started in 1986.

Research techniques and factual material

Analysis of well productivity in the areas under study was performed for about 110 wells. The poroperm properties of rocks were studied in more than 150 core samples.

Gas injection/withdrawal dynamics analysis for Galmas and Garadagh UGSFs, covering the period of 2009–2011, was carried out based on the data of more than 100 and 60 wells, respectively.

The monitoring of formation pressure in the wells included more than 50 measurements.

The data processing and corresponding plotting were carried out using standard computer programs.

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Findings and Discussion

About the conditions of the PS rocks formation

Galmas and Garadagh fields / UGSFs, confined to the Lower Pliocene sediments, are located in different oil-gas bearing districts of SCB, Nizhnekurinsky and Absheron (see Fig. 1).

It is known that PS formation occurred within the South Caspian Sea, which was isolated from the Eastern Paratethys. PS formation covers the time interval from 5.5 million years ago to 3.5 million years ago, i.e. about 2 million years [8].

Sediments were accumulated under conditions of significant fluctuations of the Paleo-Caspian level, resulting in the origination of different types of paleo-conditions, from lacustrine to typically fluvial. The PS sequence is represented by rhythmic alternation of sand-silt-clay sediments, the thickness of which in the most submerged (buried) part of the basin reaches 7 km.

In connection with the fact that the sediments were brought to the basin simultaneously from several surrounding mountain groups, five lithofacial types of sediments were distinguished in the PS [8].

The Garadagh field / UGSF is located in the zone of PS Absheron facies. This is composed mainly of sediments brought by Paleo-Volga from the Russian platform. Other sources of the material midgration are of subordinate importance. The rocks of this facies are mostly sandy. The number of productive horizons in some fields reaches 40–50. The Absheron facies is the thickest in the South Absheron basin (up to 5 km). The mineralogical composition of the light fraction of the rocks is characterized be predominance of quartz, 95 %. Feldspars (up to 20 %) and rock fragments (up to 10 %) are also present.

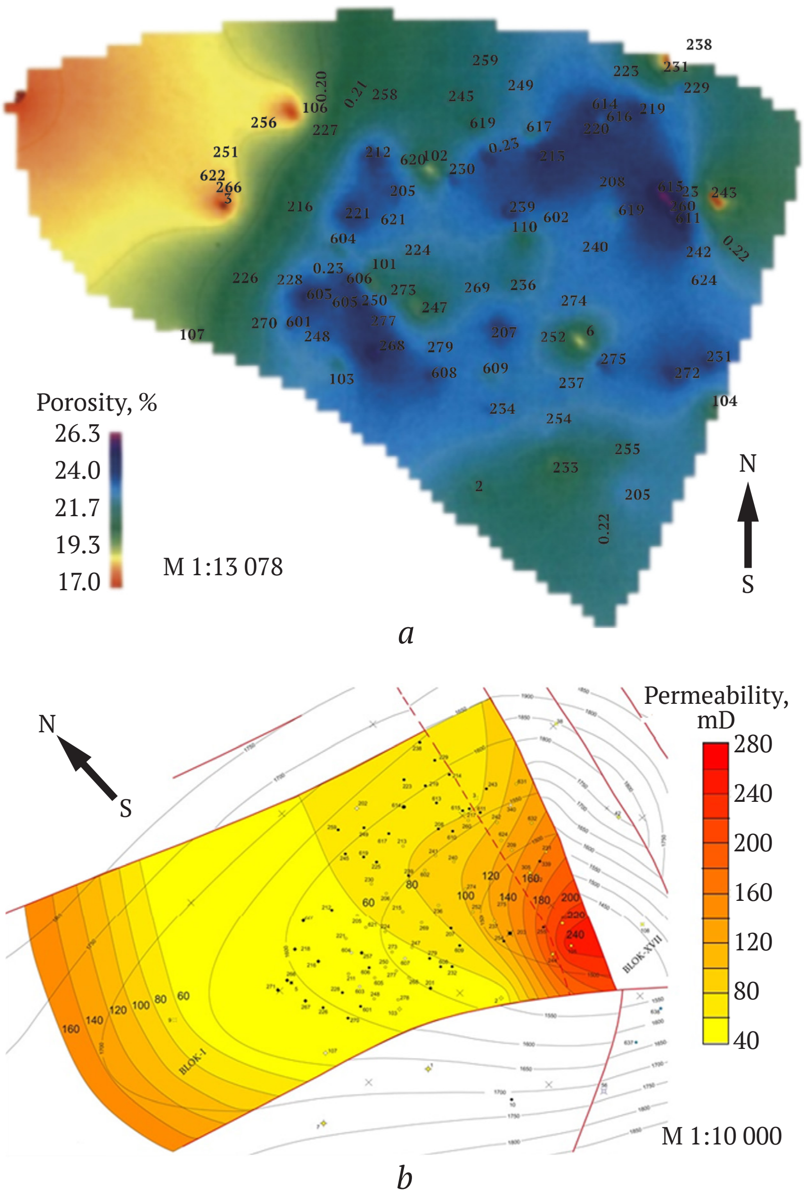


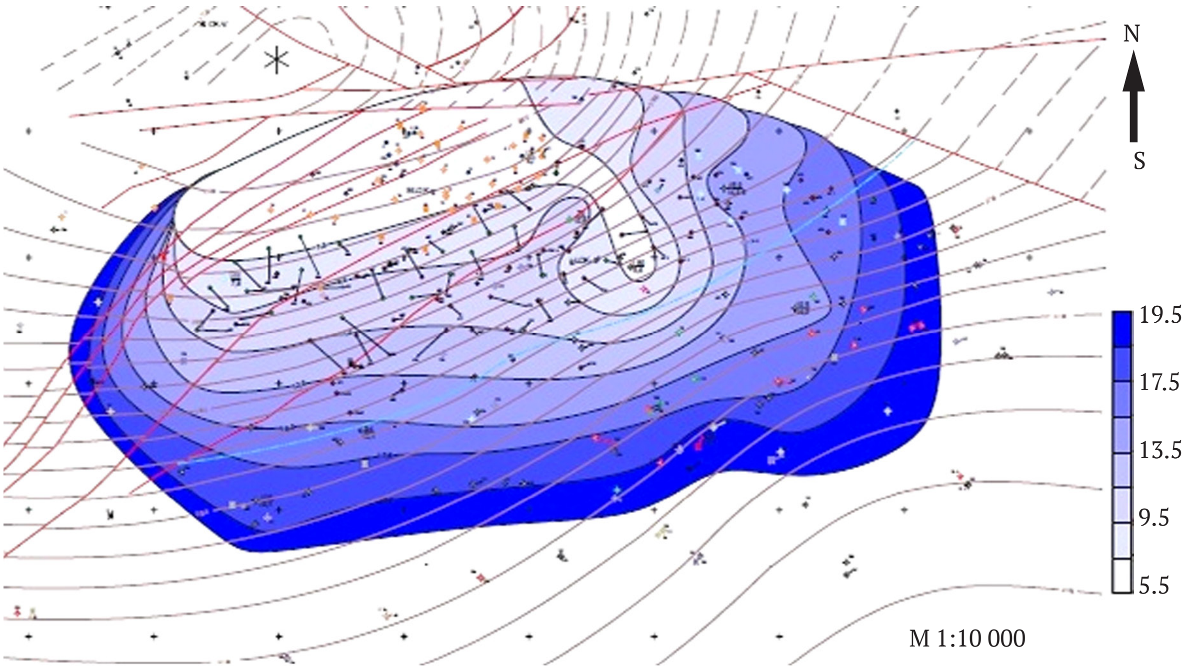
Fig. 2. Spatial variation of porosity (*a*) and permeability (*b*) of the rocks of the PS I horizon at the Galmas field

The PS rocks within the Galmas field/UGSF refer to the Nizhnekurinsky facies. During origination of this lithofacial type of PT, clastic material was brought to this part of the SCB mainly by the largest river. The Paleo-Kura, and the Paleo-Arax transported products of the erosion of the Kurinsky Lowland, the Great and Minor Caucasus, and the Talysh.

The total thickness of the sediments is 3,500–4,000 m. The sequence is represented by about 20 sand members, up to 20 m thick. The highest level of sandiness is observed in the upper 300–400 m, and the sand content decreases considerably down the sequence. The rocks of the Nizhnekurinsky facies differ from those of the Absheron facies by low quartz content and high feldspar content.

On spatial heterogeneity of gas reservoirs

Analysis shows that the Galmas and Garadagh underground gas reservoirs are characterized by geological heterogeneity (block structure, spatial variation of the material composition of rocks). This is also manifested in spatial variation of poroperm properties of the reservoir rocks (Fig. 2, 3).



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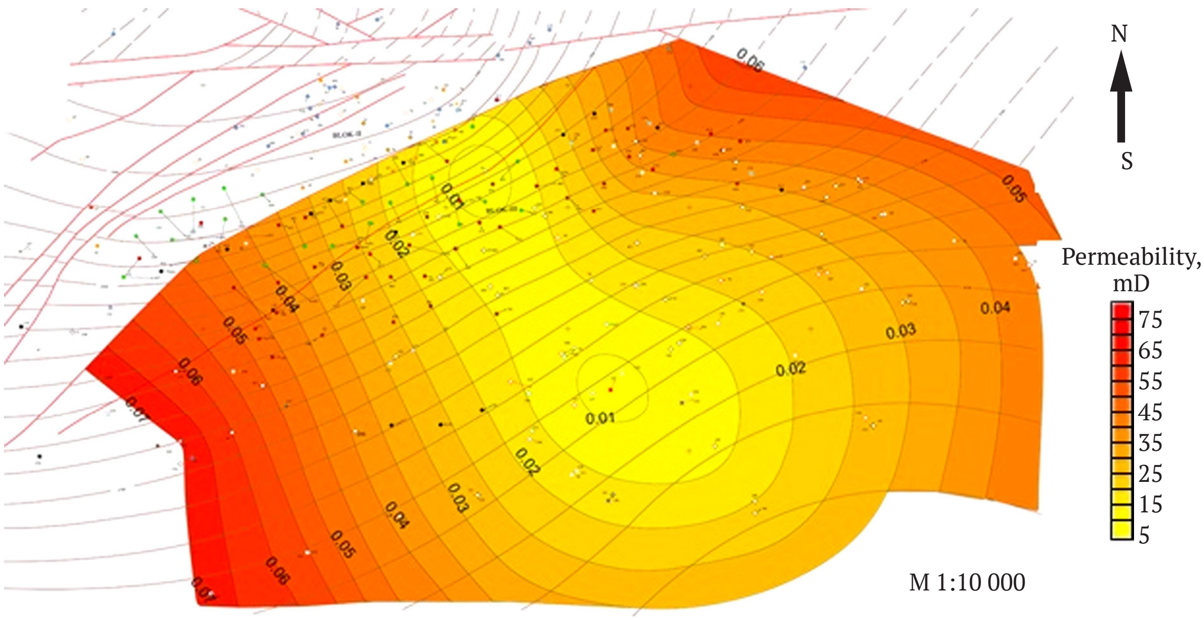

b

Fig. 3. Spatial variation of porosity (*a*) and permeability (*b*) of the rocks of the PS VII horizon at the Garadagh field

Spatial heterogeneity is also manifested in the productivity of wells at the Galmas and Garadagh fields, Fig. 4.

The spatial irregularity of gas saturation of an underground reservoir also defines spatial variability of the subvertical gas dispersion intensity. This is clearly seen by the example of the Galmas field. Here less contrasting halos of HC gas dispersion were identified in the north-north-western part of the reservoir with relatively low gas saturation of rocks, in comparison with its southern part (uplifted pool) with higher gas saturation (Fig. 5).

Peculiarities of fluid dynamics in the course of the development of the fields

During the development of the Galmas gas condensate field (from 1958 to 1962) about 3.8 billion m³ of gas were extracted from the underground reservoir. This led to 13.5 MPa (from 21.1 to 7.6 MPa) drop in the reservoir pressure, averaging about 0.3 MPa per month (Fig. 5, *a*).

The development of the Garadagh gas-condensate field, which began in 1955, was carried out without maintaining reservoir pressure. By the end of the 1980s it was depleted. About 21 billion m³ of gas was

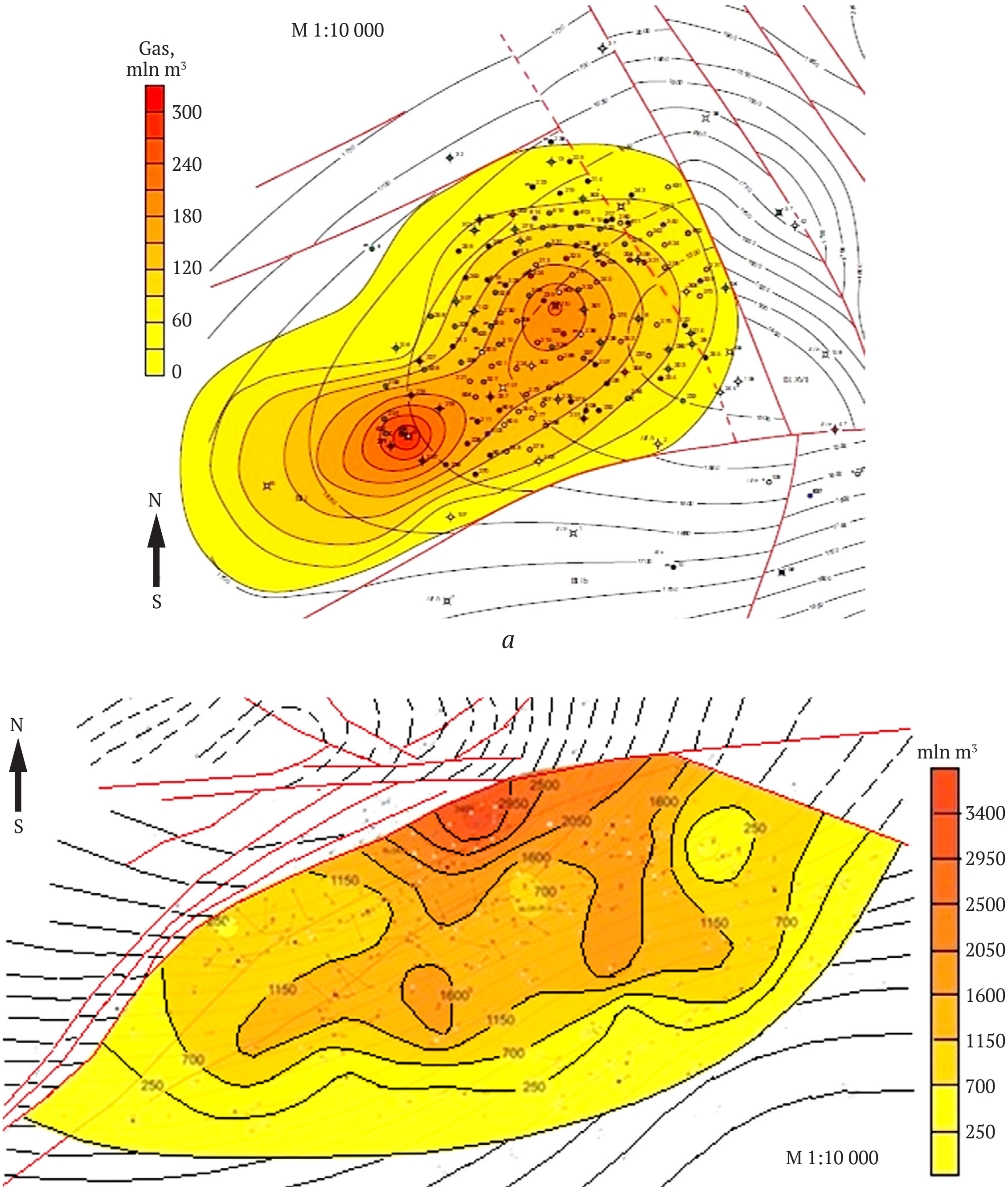

Fig. 4. Well productivity variation maps for the Galmas (*a*) and Garadagh (*b*) fields

withdrawn in total, leading to reservoir pressure drop from 39.8 to 3.6 MPa (Fig. 5, *b*)

The rate of reservoir pressure drop at the Galmas field is about 1.8 times higher than that at the Garadagh field. This is most likely due to the lower energy level of gas in the Galmas field due to its relatively smaller reserves compared to the Garadagh field.

The initial reservoir pressure in the wells within the Garadagh area exceeds hydrostatic pressure by an average of 1.2 times. Due to excess elastic energy of gas in the first 2 years of the field development, a permanent increase in production was observed accompanied by an insignificant drop in reservoir pressure (within the interval of 40-38 MPa). The cause-and-effect relationship between the two parameters during further reservoir development follows the exponential law, characterized by a steady decline in gas production and reservoir pressure drop (Fig. 7).

Based on the example of the Garadagh field, it was found that the value of the reservoir pressure drop change (from 2.4 to 11.7 MPa) was accompanied by decreased rock permeability (from 1.2 to 4.9 mD) (Fig. 8, Table 1). The permeability decline rate due to the reservoir pressure drop in the considered wells is equatable, except for wells 124 and 132, located in the near-fault zone. In these wells the permeability decline rate is relatively higher.

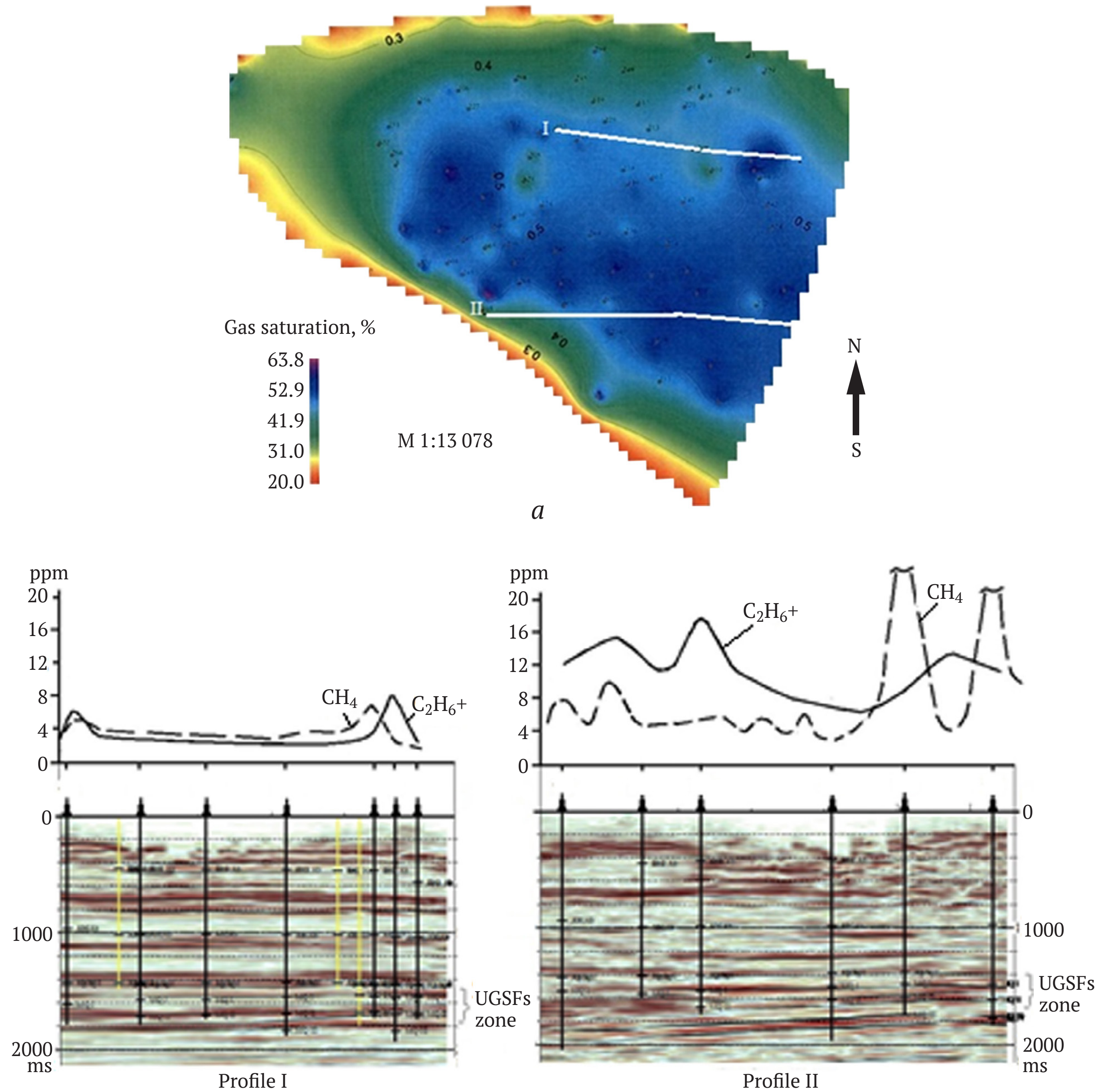

Fig. 5. Galmas field/UGSF: a – spatial variability of gas saturation of the PS I horizon rocks and location of gas survey profiles; b – distribution of HC gas concentrations in near-surface sediments (depth of about 1.2 m) along profiles I and II

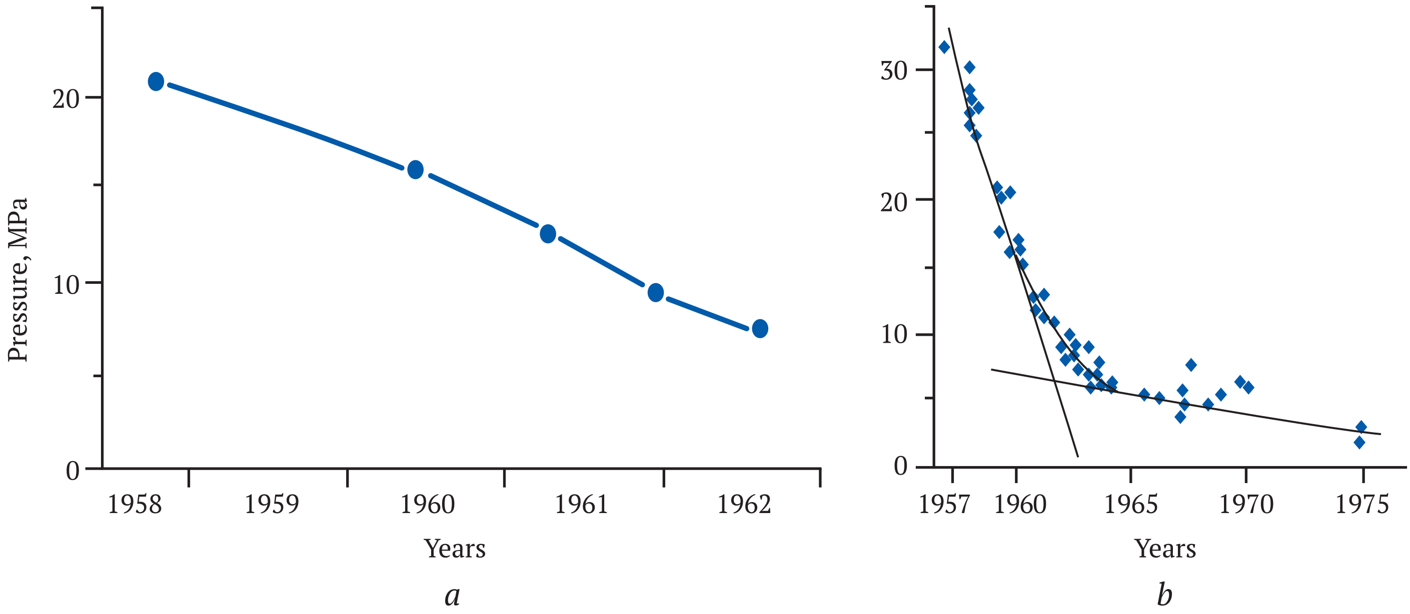

Fig. 6. Plots showing reservoir pressure drop rate during development of the Galmas (*a*) and Garadagh (*b*) fields (1)

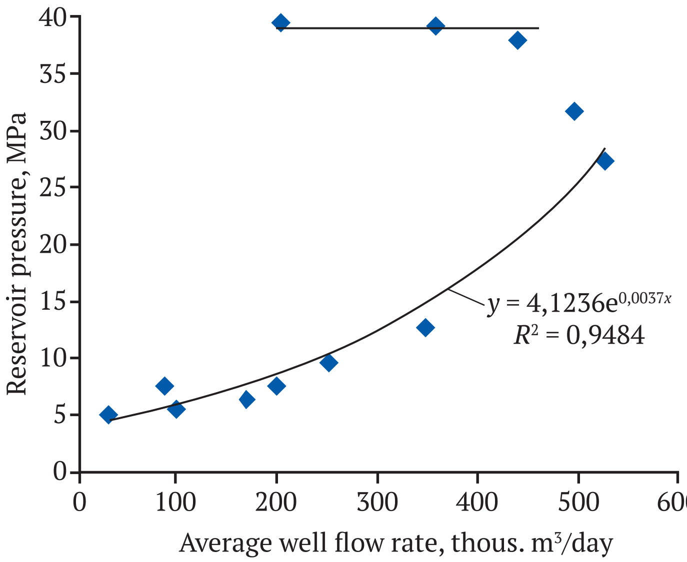

Fig. 7. Relationship between the reservoir pressure and the well flow rate at the Garadagh field

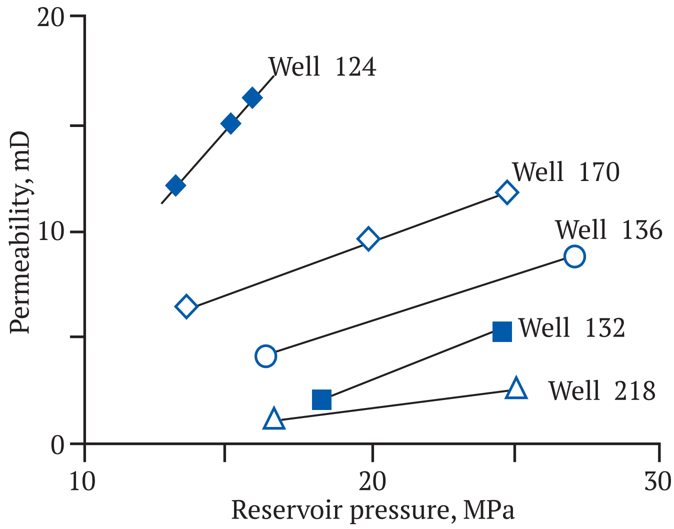

Fig. 8. Graphs of the PS rock permeability changes vs. the reservoir pressure drop at the Garadagh field. Well 124 is located near a fault

Table 1

Graphs of the PS rock permeability changes vs. the reservoir pressure drop during the Garadagh field development

Hole ID	Porosity, %	Measuring period, months	Pressure drop, MPa	Rock permeability decline, %
136	18.0	25	11	47
132 (close to fault)	18.5	15	3	56
218	17.4	14	1	44
170	16.7	13	5	41

Features of UGSF operation

Analysis of the monitoring data on the volumes of gas injected and extracted at the Galmas UGSF and Garadagh UGSF in 2020–2021 showed a spatial variability in their values (Fig. 9 and Fig. 10). A similar variability was demonstrated by productivity of the wells during the corresponding gas reservoir development (see Fig. 4). This suggests an inherited nature of UGSF operation in relation to the gas reservoir development mode. This is also confirmed by the positive correlation between the total volumes of gas extracted from individual wells since the beginning of the Galmas field development, and volumes extracted during operation of the UGSF created in the same reservoir (Fig. 11).

It is important to note that operating wells at the UGSF differ in terms of the ratio of injected and extracted gas volumes. This may be due to the influence of both technical and geological factors.

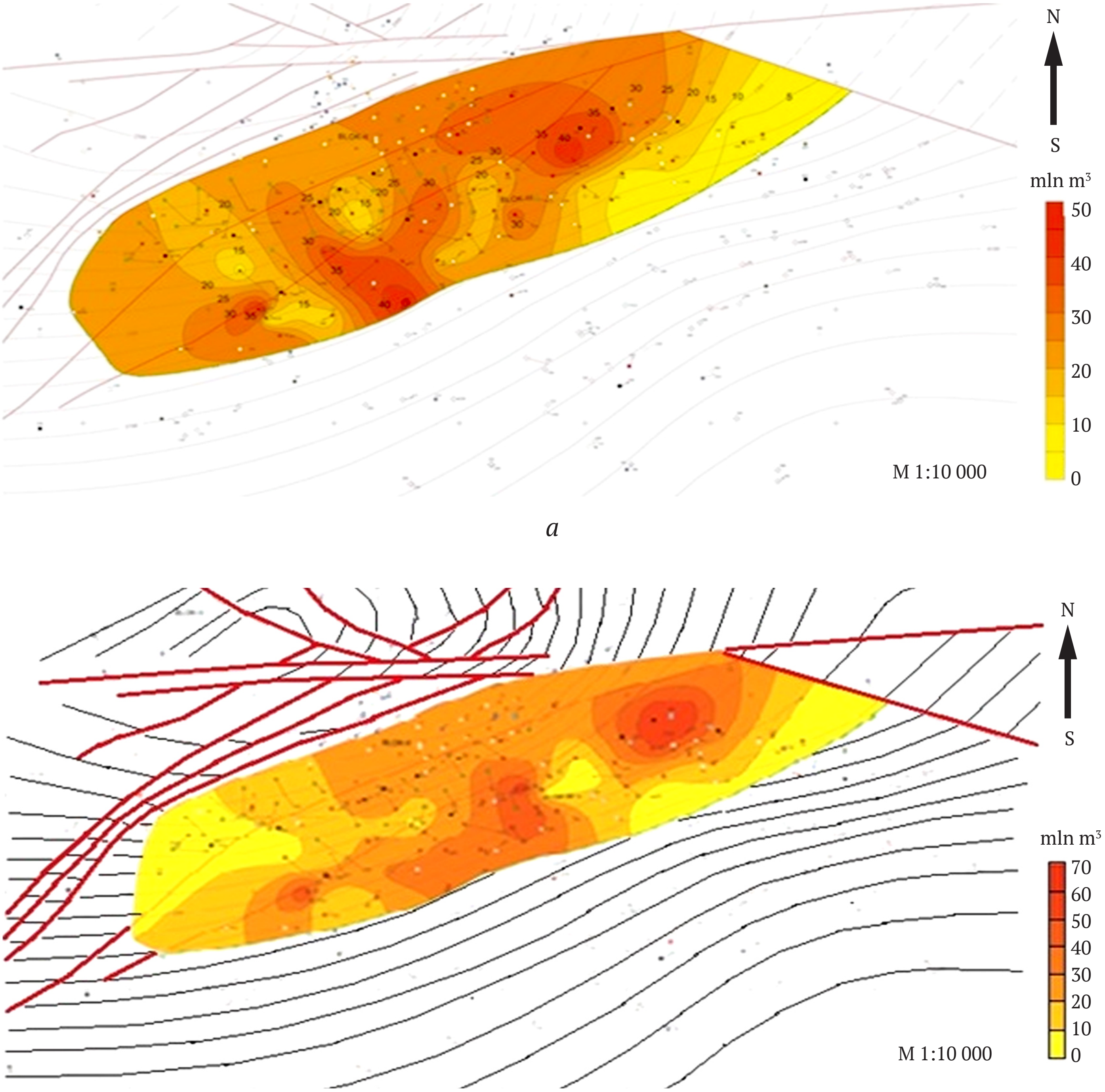

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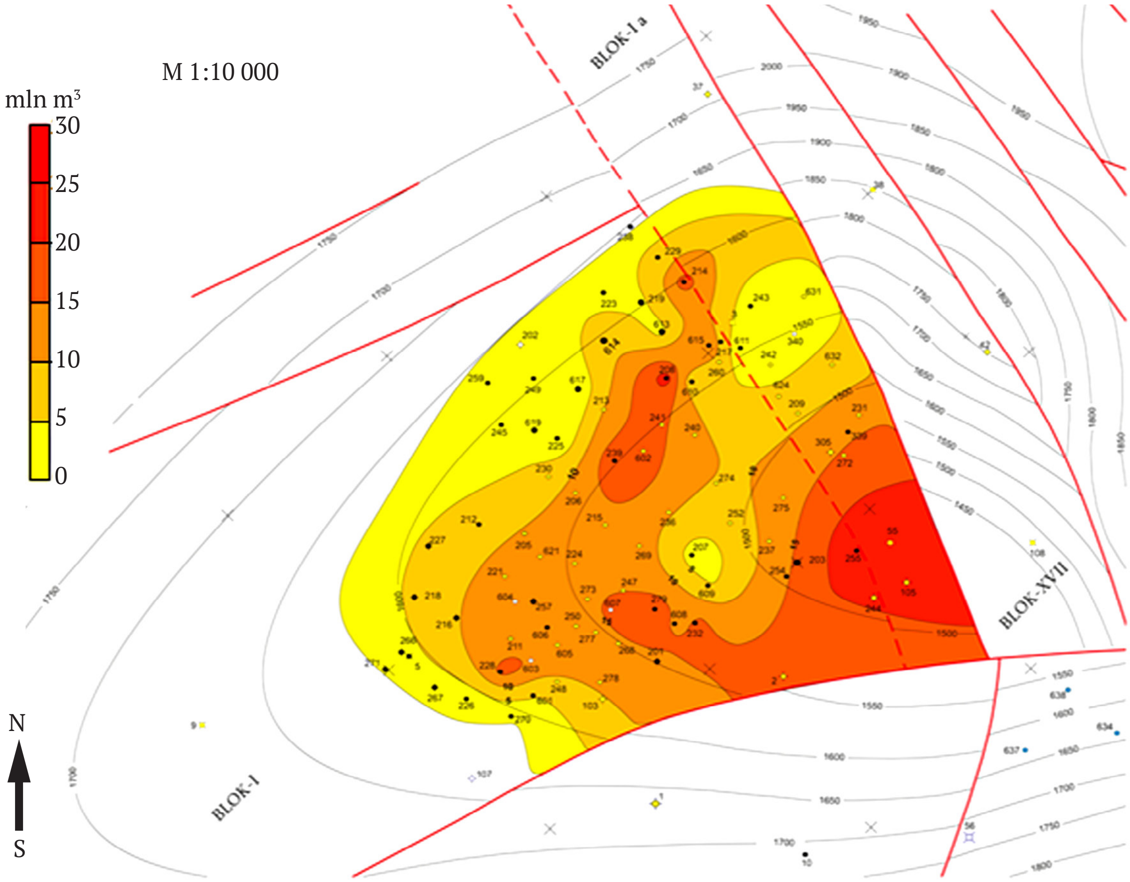
Fig. 9. Maps of spatial variation of the volumes of injected (*a*) and withdrawn (*b*) gas at the Garadagh UGSF for the period of 2020–2021



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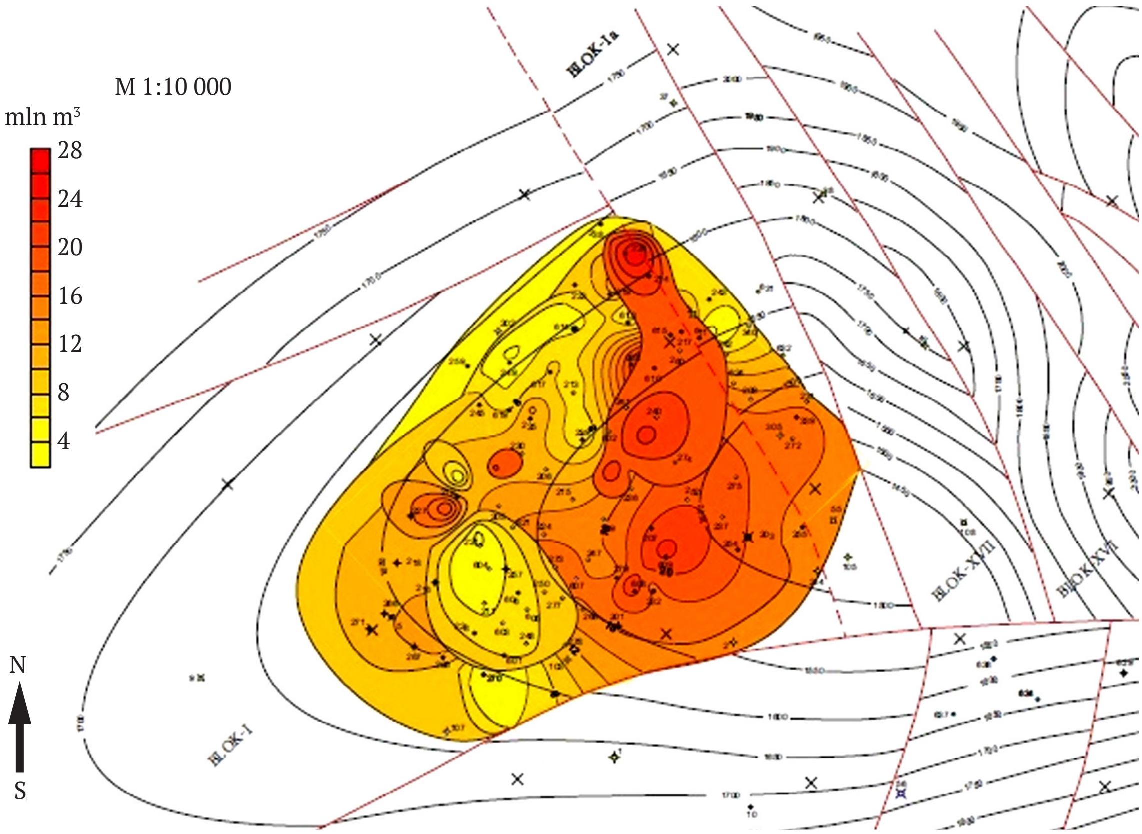

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Fig. 10. Maps of spatial variation of the volumes of injected (*a*) and withdrawn (*b*) gas at the Galmas UGSF for the period of 2020–2021

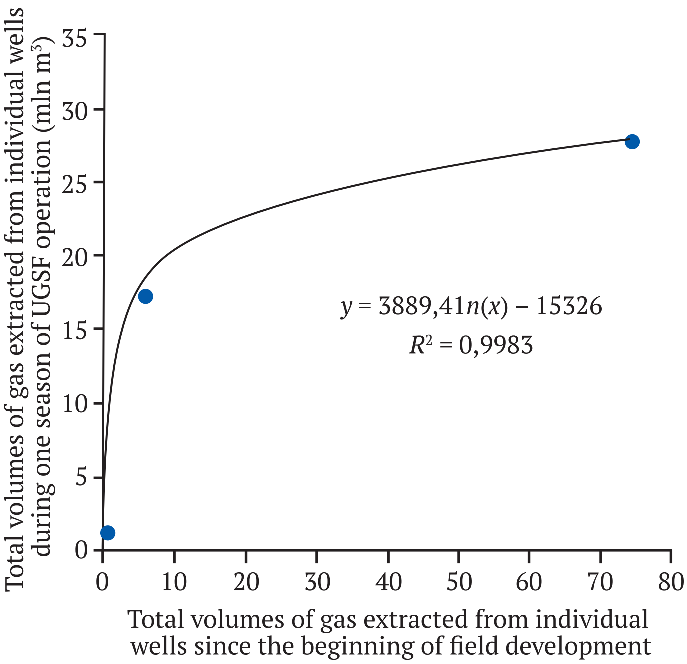

Fig. 11. Galmas Field/UGSF. Relationship between the total volumes of gas extracted from individual wells since the beginning of field development and during one season of UGSF operation

The analysis showed that in the wells with low rock poroperm properties the volumes of injected and withdrawn gas are close to the optimum (Garadagh UGSF), or the volumes of withdrawn gas exceed the volumes of injected gas (Galmas UGSF) (Fig. 12). In wells with relatively high rock poroperm properties, as a rule, the volumes of injected gas are greater than the volumes extracted (Table 2). A possible explanation for this phenomenon may be that rocks with relatively low rock poroperm properties are better at accumulating and retaining injected gas due to the low filtration properties and high adsorption properties of the rocks. Gas injection into relatively more permeable rocks with favorable fluid dynamics properties probably contributes to the dispersion (loss) in space of the injected gas.

Table 2

Galmas and Garadagh UGSFs. The ratio of extracted and injected volumes of gas for the wells with different rock poroperm properties

Well ID	Rock porosity, %	Rock permeability, μm²	Volumetric ratio of extracted and injected gas
Galmas UGSF			
240	27.8	0.130	0.7
252	29.2	0.145	0.7
275	29.3	0.183	0.8
624	27.5	0.198	0.9
273	24.8	0.065	1.3
219	25.6	0.068	4.1
606	24.7	0.084	1.3
277	24.5	0.069	1.4
Garadagh UGSF			
453	15	0.083	1.2
458	8.8	0.026	1.2
467	11.5	0.036	1.4
471	13.8	0.073	1.2
450	9.6	0.015	0.6
459	9.2	0.025	0.6
464	8.2	0.022	0.7
465	8.4	0.008	0.8

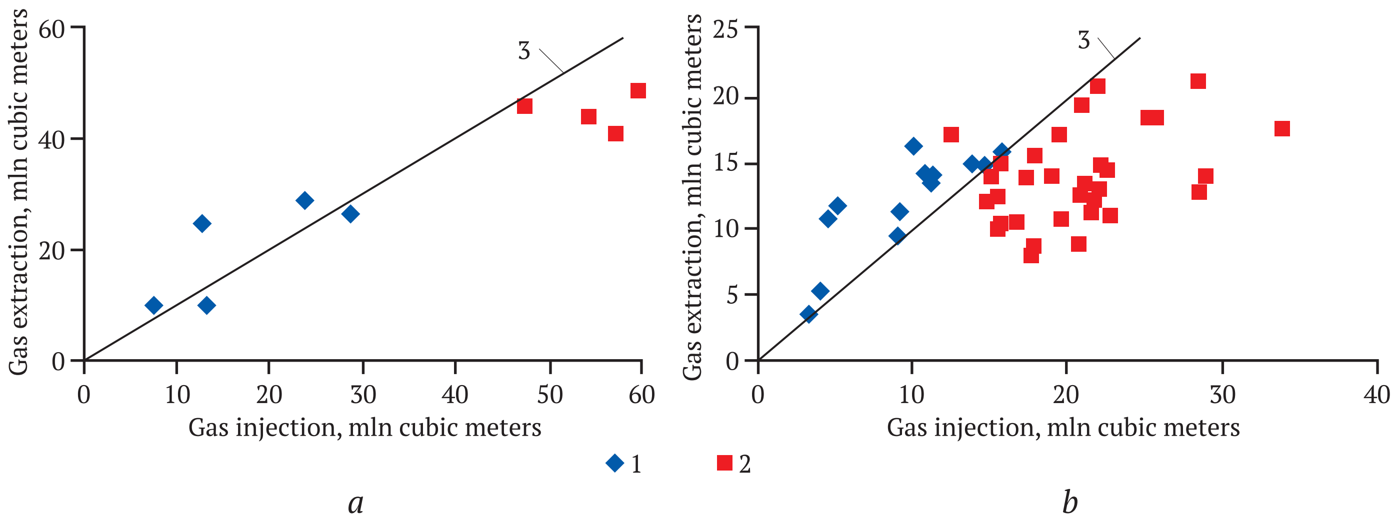

Fig. 12. Relationship between gas injection and extraction volumes at Garadagh (*a*) and Galmas (*b*) UGSFs:
1, *2* – wells with low and high rock poroperm properties, correspondingly;
3 – the line of equal values of gas injection and extraction volumes

Conclusion

Based on the example of the Garadagh and Galmas fields in the SCB, it was established that one of the main geological factors determining the mode of well operation both during the field development and in the course of UGSF operation is reservoir heterogeneity, as manifested in spatial variability of its geological structure and petrophysical properties of rocks.

The main reasons for decreased efficiency of field development and underground gas storage facility operation are: the irregular nature of variation of rock poroperm properties; origination of isolated zones in the reservoir with considerable residual gas volumes; as well as unpredictable directions of fluid movement.

In order to determine the optimal system of operation of UGSF in depleted underground oil and gas reservoirs, the features of the spacial variations resulting from the rocks poroperm properties need to be taken into account.

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