The International Journal of Engineering and Science (IJES)
|| Volume || 7 || Issue || 1 || Pages || PP 73-80 || 2018 ||
ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805

SPATIAL CHANGES OF ROCK PROPERTIES IN DEPLETED PETROLEUM RESERVOIRS USED FOR UNDERGROUND GAS STORAGE (A CASE STUDY: GARADAG FIELD, AZERBAIJAN

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--*ABSTRACT*--

For the horizons VII–VIIa of the Productive Series (the Lower Pliocene) of the Garadag gas-condensate field (Azerbaijan) used for underground gas storage (UGS) the reservoir rock properties and gas saturation models are given.The models use the software package ‘ROXAR’ (IrapRMS). The purpose is to identify spatial changes of the rock properties of the productive stratum. The fluid saturation model of productive horizons clearly demonstrates the progress of water infiltration into the gas reservoir with the tendency towards fragmentation into isolated pillars due to the mosaic nature of the reservoir rock properties. The factors determined can enhance the efficiency of further exploitation of the Garadag UGS.

Keywords: depleted gas condensate field, reservoir properties of rocks, spatial heterogeneity, ‘ROXAR’(Irap RMS) software, underground gas storage, South Caspian basin.

Date of Submission: 15-01-2018 Date of acceptance: 05-02-2018

I. INTRODUCTION

Gas supply is characterized by considerable seasonal differences between supply and demand. This problem was solved using depleted petroleum fields and, later, also water-bearing beds, salt caverns and coal mines as underground gas storage (UGS) facilities. There are 688 UGS facilities around the world right now with a total active capacity of more than 377 bln m³. Moreover there are plans to create additionally 236 UGS (Cornot-Gandolphe, 2013.).

There are 2 UGS in Azerbaijan developed in 1974 and 1986 respectively (Figure 1) from the depleted Galmaz gas and Garadag gas-condensate fields.

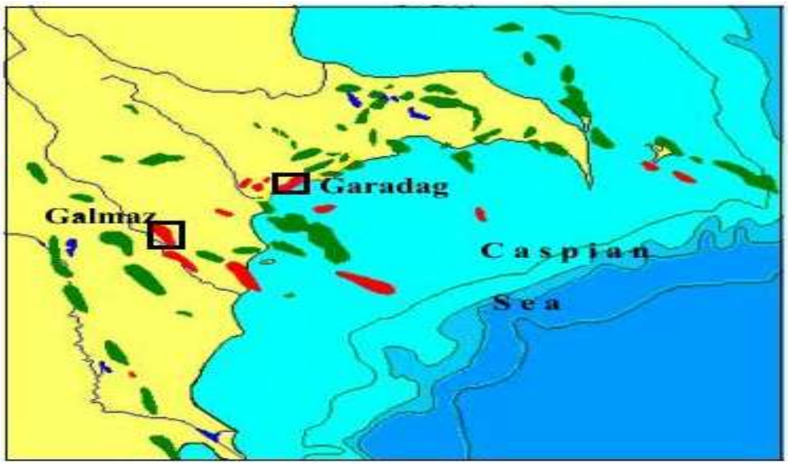

Figure 1. The Garadag and Galmaz fields/UGS (Azerbaijan) location scheme (red – gas/gas-condensate fields; green – oil fields)

The geological structures of the oil and gas fields are significant for the creation of UGS. The multiplicity of production variations is characterized by the spatial macro-and micro-heterogeneity of productive layers (Borisov et al., 1970; Dementyev, 1965; Obukhov, 1964; Pulkina and Zimina, 2012; Semin, 1962; Berman et al., 1983).

The heterogeneity of a reservoir is manifested by the spatial variability of its material constitution and petrophysical properties: grain size composition, porosity, permeability, carbonate content, specific electrical resistance, pore space texture, oil and water saturation, etc. (Pulkina and Zimina, 2012).

Analysis of the physical properties of reservoirs with laboratory and field-geophysical methods shows that even thick layers of sandstone (at first glance homogeneous) are substantially altered by area and section (Melik-Pashayev, 1979; Pulkina and Zimina, 2012).

The more complex the geological structure of the field and the more heterogeneous the object, the more difficult it is to choose a rational field development system. A simplified approach, based on perceptions of the reservoir as a homogeneous geological object, leads to an incorrect choice of the development system, a dramatic watering of the well production and reduction of oil recovery(Belozerov, 2011; Kochneva and Sedunova, 2013; Musikhin, 2016).

Clarification of the geological reasons for heterogeneity is a complex scientific challenge, the solution of which can contribute to more efficient exploitation of fields as well as the UGS created in depleted petroleum deposits (Pulkina and Zimina, 2012).

Over the last 30-40 years there has been a significant jump in computer technology that enabled the creation of 3D geological models of reservoirs. The use of such technologies is a good basis to enhance operational efficiency for existing as well as planned UGS. Currently, all design and technological documents are prepared using three-dimensional geological and hydrodynamic models of petroleum fields (Lifantyev, 2014).

The purpose of this article is a retrospective analysis of the spatial heterogeneity of the petrophysical properties of the VII horizon of the Productive Series (PS) of Lower Pliocene age in the depleted gas-condensate field of Garadag (Azerbaijan), used now as an UGS, and assessment on production.

II. METHODICAL BASIS OF RESEARCH

Methods for studying reservoir heterogeneity and its influence on the reservoir properties (RP) of rocks during operation of UGS have been considered by many researchers, from both the geological and technological points of view. Basically, one is reduced to constructing a geological, and lithological model of a natural reservoir (Berman, Neyman, 1972; Gaysina, 2015; Zubarev, 2010; Pulkina and Zimina, 2012; Semin, 1962; Stasenko and Klimushin, 1972; Berman et al., 1983; Hewett and Behrens, 1990).

Methods of mathematical modeling are often used to study the processes occurring in the development of hydrocarbon deposits. There is a wide range of programs for modeling the geology and development of oil and gas fields: such as Eclipse, Pertrel (developed by the Schlumberger company, France); IRAP, TempestMORE (Roxar, Norway); Tehschema (SurgutNIPIneft, Russia). These programs allow one to simulate both a single well and a field as a whole. Modeling with such software products is carried out after analysis and processing of experimental, laboratory and geophysical research results, as a result of which the reservoir properties are determined (Popov, 2007).

In this paper, the ROXAR (Irap RMS) software was used to study the change in the RP of the VII horizon of the Garadag gas condensate field.This software includes the most advanced technological developments in the field of geological, hydrodynamic modeling and planning of wells (Internet source, 1984; 2013; 2016).The software incorporates advanced solutions pertaining to geological and hydrodynamic modelling and well design.

Many specialists (Gaysina, 2015; Minlikayev, 2005; Internet source, 2008) consider IRAP RMS the best tool for 2D and 3D geomodelling, estimation of reserves, hydrodynamic calculations, risk analysis and well planning. This software is used in more than 20 countries (Internet source, 1984; 2015; Robinson et al., 2016).

The IrapRMS Petrophysical software package allows one to obtain consistent three-dimensional fields of porosity, permeability and initial saturation.

In the petrophysical model of VII horizon PS in the Garadag gas condensate field well logging (WL) was performed using the integrated WL data processing system PRIME (Remeev, 2005).

Currently used two-dimensional interpolation maps of reservoir parameters (created according to the analyses of well cores) are generally not quite correct because they use discrete data, vertically variable parameters, and also do not display the required detail of the variability in cross-borehole space.

III. Research results and discussion

Briefly about the Garadag field/UGS

The Garadag field/UGS is located on the southern wing of the asymmetrical anticline fold of the same name, as show by seismic exploration in the far southwest of the Absheron Peninsula, 30 km from Baku (see figure 1).For the PS sediments, the axis of the western part of the structure has a latitudinal strike. The eastern part of the fold tends to the south and passes into the near-median extension. The short northern wing of the fold has a declination of 30-35^0, while the southern wing has a declination of up to 60^0. The crest of the fold is complicated in the north by parallel faults of the thrust type. The amplitudes of the faults are 600-500 mon the western pericline, and decrease to 100 m on the eastern pericline.

According to exploration and development data, the gas reservoir in the VII, VIIa horizons has a block structure (Chernomordinov et al., 1964; Karger et al., 2013; Panakhov and Agayev, 1985).

The structural model of the field is shown in Figure 2.

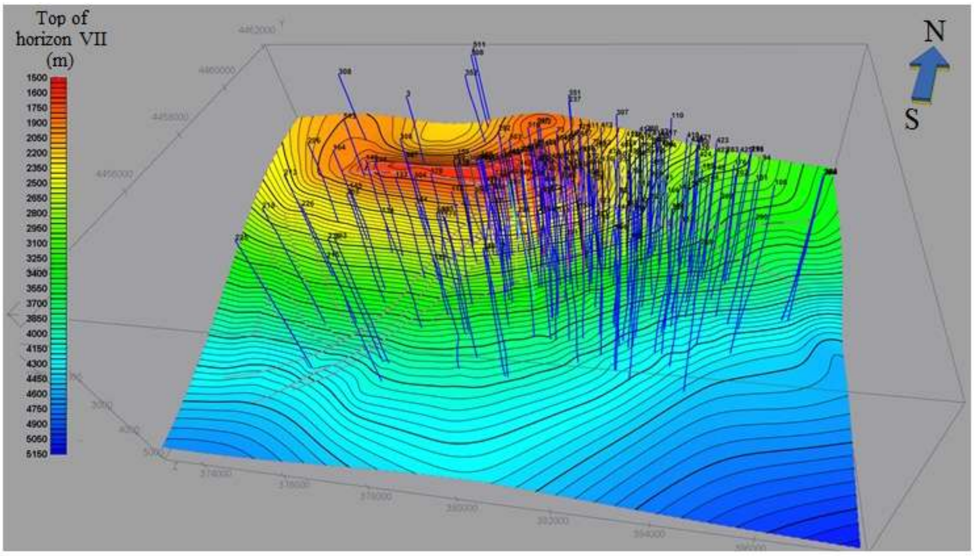

Figure 2. Structural model of horizon VII of the Garadag field

The gas-condensate deposit of the VII horizon of the PS differs from others deposits by high productivity. Two intervals are distinguished in section: the upper (VII hor.) and the lower (VIIa hor.) reservoirs, separated by a clay layer with thickness 16-36 m. In the south-eastern part of the southern wing of the fold the VII horizon consists of 4-5 sandstone layers with thickness 5 -10 m. These layers are separated by clayey interlayers with thickness 2-4 m.

In the section VIIa of the horizon, two sandstones layers are distinguished, separated by a clayey layer with thickness 5 m. The thickness of the upper sand layer is 10 m, the lower layer - 15 m, reaching up to 20-25 m in the submerged part of the southern wing of fold. The total thickness of the horizon VIIa is 21-52 m.

In the south-eastern part of the southern wing of the fold the VII and VIIa horizons join and form a single thick layer of sandstone. In the northwestern direction, a decrease in the total thickness of VII-VIIa horizons leads to a decrease in effective thickness. The effective thickness of the VII-VIIa horizons in the north-west is 10-25 m, and in the southeast - 55-75 m.Towards the western and north-western part and to the crest of structure, the effective thickness of the VII horizon is reduced at the expense of clay strata increase.

The exploitation of the Garadag field was started in 1939 with the development of an oil and gas deposit in the V horizon of the PS. The main developed objects were horizons I-VII (upper division of the PS), VIII horizon (lower division of the PS), and the Upper Miocene sediments, with an average depth of petroleum bearing reservoirs at 2750 m.

The gas-condensate pool with the oil fringe in the VII-VIIa horizons has been in operation since 1955. The depth of the VII horizon at the crest of the structure is 1900 m, the submerged part is at 4250 m (average depth 3125 m).

The productivity of the wells drilled into horizon VII is spatially uneven (Table 1). The more productive wells are located in the submerged SE part of the pool.

Table 1.The values of initial gas-condensate ratio (GCR) and the condensate yield for various parts of the Garadag structure

Well Location	Well number	Depth interval, m	GCR, m^3/t	Condensate Yield, g/cm^3
Near the crest of structure	140	2945	7631	131
« …»	155	2646-2661		145
« …»	212	3092-3129		136

Central part	120	3310-3410	7000	143
SE part	105	3850-3944	5225	191
« …»	130	3993-4033		136
« …»	78	3815-3823	5200	192

The Garadag gas-condensate field was developed without reservoir pressure maintenance and so the deposits of the VII–VIIa horizons were depleted by the late 1980s. More than 20.5 bn m^3 were extracted from the horizons VII–VIIa during 1955–1978. The formation pressure dropped from 9MPa to 3.5MPa. As of 1 January1976 the state of the depleted reservoir was assessd as: (Panakhov and Agayev, 1985)

– approximately 2 bn m^3 of non-recoverable gas resources;
– about 2 mln tonnes of liquid condensate resulting from retrograde processes;
– about 8 mln tonnes of residual crude oil.

One of the possible factors controlling the change in the area of well productivity of the Garadag field is the macro- and micro-inhomogeneity of the reservoir.

The macro-inhomogeneity of the formation is expressed by the presence of several productive horizons in the section, changes in the area of their thicknesses, the presence of pinched out zones and the substitution of reservoir rocks spatially.

The micro-inhomogeneity is manifested by the considerable variability of petrophysical properties of rocks of the VII horizon of the PS (according to analysis of more than 90 well core samples): porosity - from 3.3 to 24.5%, permeability - from 0.001 µm^{2}to 0.527 µm^2, carbonate content - from 5.7 to 26%.

The change in the properties of the reservoir rocks over the area and section reflects the maps of change of porosity and permeability of rocks constructed for the upper and lower parts of VII and VIIa horizons of the PS using the RMS Petrophysical program (Figures 3 and 4).

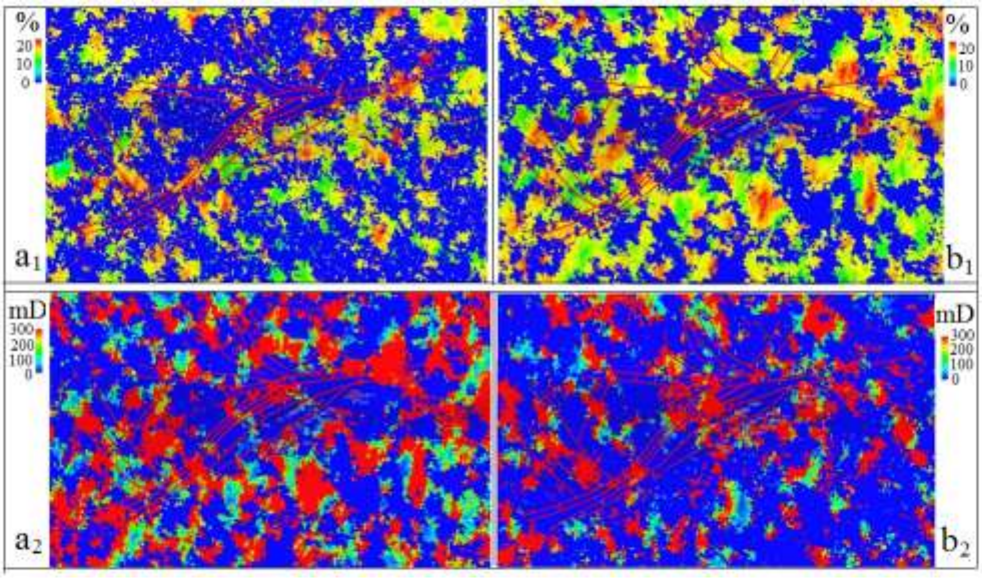

Figure 3. The change of porosity (%) and permeability (mD) of rocks in the upper (figure 3a$_1$ and 3b$_1$) and the lower (figure 3a$_2$ and 3b$_2$) portions of horizon VII of the PS over the area and section on the Garadag field/UGS

According to these maps, the changes in porosity and permeability of rocks are of a mosaic nature. Moreover, there is a difference in the structure of the petrophysical properties of the rocks, not only between VII and VIIa horizons, but also between the top and bottom parts of these horizons.

At the same time, if the lower part of the VII horizon is characterized by a relatively better porosity (Figure 3b$_1$), then there is relatively more favorable permeability of rocks in the upper part (Figure 3a$_2$). Horizon VIIa (Fig. 4b$_1$ and Fig. 4a$_2$) shows similar, but even more contrasting, changes in the rock properties.

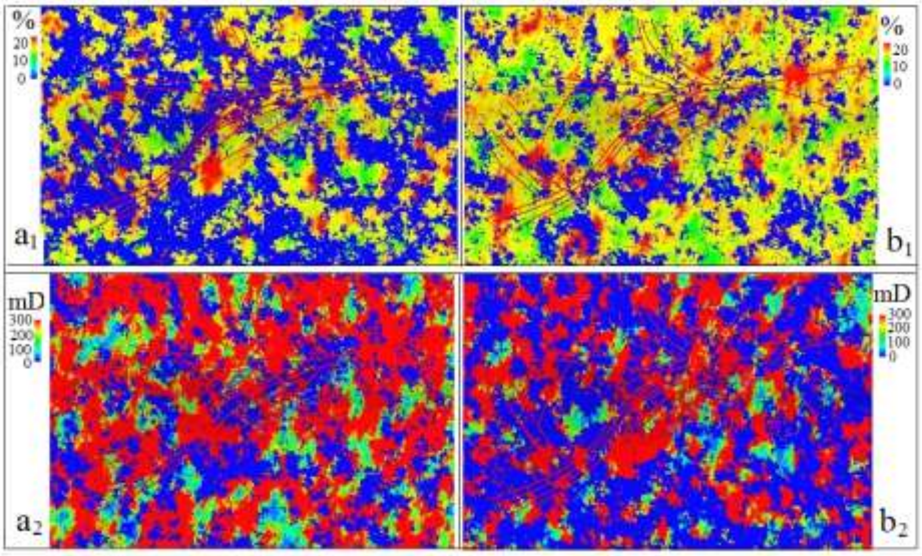

Figure 4. The change of porosity (%) and permeability (mD) of rocks in the upper (figure 4a_1 and 4b_1) and the lower (figure 4a_2 and 4b_2) portions of horizon VIIa of the PS over the area and section on the Garadag field/UGS

In agreement with the spatial structure of the reservoir rock properties of the VII and VIIa horizons the mosaic nature also has gas-saturation of rocks (Figure 5). It is important to note that some gas bearing parts of the reservoir communicate with water content of the structure. This character of the water saturation of the productive part of the reservoir led to its fragmentation into separate gas pillars, as is typical for three of the four models of gas saturation of rocks presented on Figure 5. The more favorable (less fragmented) nature of gas saturation is inherent only in the upper part of the horizon (Fig. 5a_2).

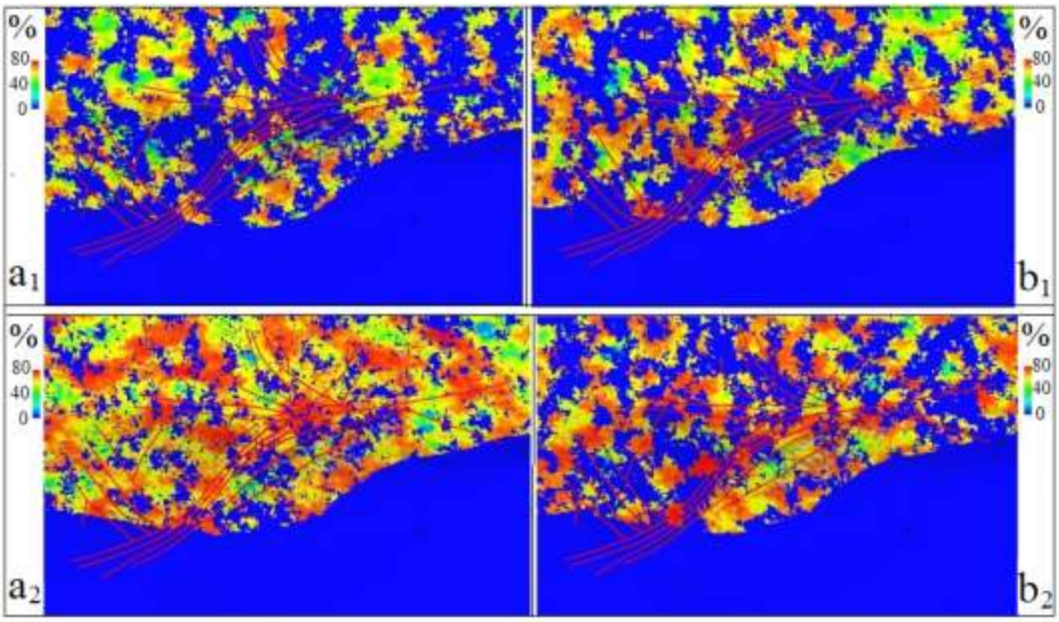

Figure 5. Change of gas saturation of rocks (%) of horizon VII (the upper part –a_1 and the lower part –b_1) and horizon VIIa (the upper part – a_2 and the lower part –b_2) of the PS in the Garadag field/UGS (the blue colored zone is the water portion of the reservoir)

An attempt t expand the gas-bearing area of horizon VIIa due to the water-saturated part of the reservoir was unsuccessful because the water of this horizon is more highly pressured than that in the VII horizon. As a result, all the wells drilled to a depth of 3,000 m gushed water and an attempt to block by injection of gas with a pressure of 16 MPa failed. Perhaps, a more powerful compressor would be needed to accomplish this task.

The unevenness of the gas saturation of rocks over the area, due to the variability of their reservoir properties, is consistent with the uneven gas saturation of rocks along the section of the VII horizon, revealed from gas logging data. According to the averaged gas logging curves shown on figure 6, a section of well 473 (located in a zone with relatively favorable reservoir features) is characterized by a higher content of hydrocarbon (HC) gases, compared to well 474 (located in a relatively low reservoir quality zone).

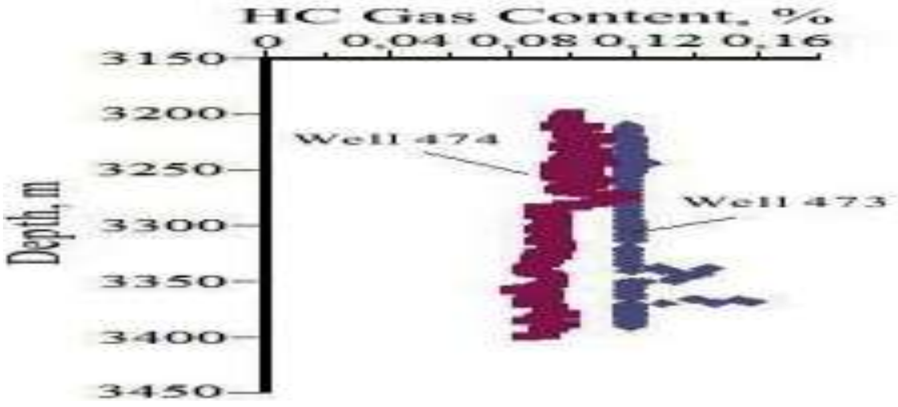

Figure 6. Change of hydrocarbon gas content along the section of horizon VII (based on gas logging data) in well 473 (located in the zone with favorable reservoir properties) and well 474 (located in a zone with relatively low reservoir quality)

Operation of the Garadag UGS (in VII-VIIa horizons) was started in 1986. The gas-bearing area of the VIIa horizon at the beginning of its development was the largest. However, during the transfer of this horizon for use as an UGS facility, most was water flooded and at present only a small part is used for injection and extraction of gas.

After the UGS was placed in operation, it worked for 2 years in the injection regime, after which it was transferred to the cyclic injection/extraction regime, with a gradual increase in pressure and the volume of injected gas. Since 2005 the operation of UGS is monitored on a regular and systematic basis.

Table 2. Volume of injection and extraction of gas at the Garadag UGS during 2010–2012 (depending on the reservoir rock properties)

Areas/Wells	**Volume of injected and extracted gas, thousands m^3**			
	Season 2010□2011		**Season 2011□2012**	
	Injection	**Extraction**	**Injection**	**Extraction**
With low reservoir rock properties:				
Well. 453	28698	26703	33768	34632
Well 458	23666	29301	30724	35129
Well 467	12783	24982	29199	34460
Well 470	7766	9915	11412	10584
Well 471	13212	10146	27136	26852
Average:	**17225**	**20209**	**26448**	**28331**
With high reservoir rock properties:				
Well 450	59567	48508	59035	60876
Well 456	25725	33621	45512	56604
Well 459	47483	45703	55544	49788
Well 464	57196	41043	58066	54157
Well 465	54066	44157	60528	52264
Average:	**48807**	**42606**	**55737**	**54738**

It was experimentally established that the rock strength with a dynamic pulsating load is reduced by 40-50%. As a result, after a small number of cycles of varying loads in the rock, micro-cracks appear, leading to the destruction of the rock skeleton and intensive sand lifting during the gas extraction from the UGS (Kolchitskaya and Mikhaylov, 2000; Kalinichenko, 2009). Evik et al. (2009) noted that during 34 cycles of injection and extraction of gas from the Shelkovskoe UGS (Russia), no well was observed that could not lift the solid phase, which is the product of reservoir destruction.

This phenomenon is also observed at the Garadag UGS where at the end of each season about 25-30 tons of sand precipitates in the separator and in the reservoir for liquid. This result is an obvious indicator of the destruction of underground reservoir rocks, leading to irreversible changes in the reservoir properties of rocks. Note that the greatest sand lifting is observed in wells in which the volume of extracted gas is greater than the volume of injected gas.

One of the possible causes of the destruction of the skeleton of productive reservoir rocks of UGS is uncontrolled loss of buffer gas in the process of cyclic injection and extraction, which leads to an increase in the amplitude of reservoir pressure fluctuations. To minimize the destruction of the reservoir it is recommended to reduce the volume of the active gas or increase the volume of the buffer gas, that is reduce the ratio of active to buffer gases (Yakovleva et al., 2004).

IV. CONCLUSION

The modelling of the spatial variability in reservoir rock properties and gas saturation of the productive formation (VII-VIIa horizons of the PS) of the Garadag gas condensate field/gas storage, using the software product ROXAR (Irap RMS), confirmed its effectiveness.

The spatial heterogeneity of the petrophysical features of the VII-VIIa horizons is established, as shown in the mosaic nature of the spatial changes of the reservoir properties and gas saturation.

The uneven nature of the change in the area of the reservoir properties of rocks, the formation of isolated zones in the reservoir, as well as the unpredictable directions of fluid movement are the main reasons for the decrease in operation efficiency of the Garadag field/UGS.

Thus, one has established that the volumes of injection and extraction gases at Garadag UGS are controlled by reservoir properties. In addition, in the fluid-saturation model of the reservoir, the development is seen of the process of water intrusion into the productive zone with a tendency to break into isolated gas pillars. These facts should be taken into account in the further operation of the UGS.

To monitor the dynamics of water movement, it is advisable to use the software package 'ROXAR' (Irap RMS).

The pressure difference in the reservoir during the cyclic injection/extraction of gas into the Garadag UGS is more than 10 MPa, which contributes to rock destruction. This effect is manifested by precipitation in the separator and in the reservoir for the liquid at the end of each season of about 25-30 tons of sand. The greatest sand lifting removal is noted in wells where the volume of extracted gas, as a rule, exceeds the volume of injected gas.

The results obtained in the present study can contribute significantly to increasing the operational efficiency of the Garadag UGS.

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