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Research article

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Signs of Natural Renewal of Oil and Gas Reserves in Fields of the South Caspian Basin

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Abstract
Results are given of oil and gas production in the long-lived fields Bibieybat and Garadag of the Absheron Peninsula, South Caspian Basin (SCB). The analysis for the Bibieybat oil field covered the period from 1935 to 2018, and for the Garadag gas condensate field from 1955 to 1979. The development is the Productive Series (lower Pliocene) - main reservoir of the SCB. The intensive development of these fields leads to the disturbance of the natural dynamic equilibrium established in the reservoir over geological time. A sharp drop of formation pressure (significantly lower than hydrostatic) during field development contributes to the natural inflow of hydrocarbon fluids to the reservoir. The rate of natural oil replenishment calculated for 29 operating facilities of the Bibieybat field varies per well within 0.32-1.4 ton/day (averaging 0.76 ton/day) or about 277 ton/year. The rate of natural gas inflow at the Garadag gas condensate field is different for its various blocks, averaging 5.2 thousand m3/day per well. Stable oil and gas production and the equivalent rate of natural recharge are determined by the influence of a complex of factors, of which reservoir pressure, temperature and permeability of the reservoir rocks are dominant.

Key words: Oil, Gas, Long-Lived Field, Well Productivity, Pressure, Reservoir, Replenishment, South Caspian Basin

Introduction

For more than a century, hydrocarbon (HC) raw materials have been intensively used in our daily lives and continue to be the main source of energy for world civilization. However, since oil is a non-renewable resource and its reserves in the subsurface are limited, the consumer could not help but worry about the time to reach the peak of global oil production and the beginning of decline. In this regard, the world community has been actively discussing the prospects for oil production for many years.

The most well-known attempt to forecast the peak of oil production was made in 1956 by King Hubbert [1]. Studying the dynamics of growth in oil production in the United States, he predicted that the United States would have peak production between 1965 and 1970, after which production would inevitably decline. His calculations were confirmed in practice - after 1971, US oil production really began to decline. However, an attempt to predict the peak of world oil production was unsuccessful.

According to the US Energy Information Administration [2], world crude oil production hit a plateau in 2004 with a 2005 maximum of 73.71 million barrels per day, after which there has been a gradual decline until the recent advent of shale fracking. The Oil and Gas Peak Research Association (ASPO), founded by British geologist Colin Campbell, using modern information about known oil deposits, estimated future discoveries, growing oil demand and available technology, predicted that global production would peak around 2010 (Campbell, 2002) [3].

In a report by the British Council for Energy Research, which advises the UK government on global energy markets, the risk of reaching a critical point, the so-called oil peak, may occur by about 2020 [4]. According to the Institute of Petroleum Geology and Geophysics of the Siberian Branch of the Russian Academy of Sciences the peak of world oil production will fall between 2030-2040, when about 4.6-4.8 billion tons will be produced annually [5]. The International Energy Agency predicts the onset of the "oil peak" by 2030 [6]. Thus, there is currently no consensus on the expected date of the world peak of oil production and the beginning of its decline. Despite modern advances in oil and gas exploration geology, geophysics, and geochemistry, the development of their scientific and methodological foundations, an increase in investments in prospecting and exploration, a large-scale increase in oil reserves is not observed [2]. The future of oil production is associated with searches on continental shelves (including the Arctic) and in deep water, as well as the development of tar sands and shale oil. Alternative energy sources cannot yet be considered competitive in comparison with traditional resources.

In this situation, [7] put forward the idea that oil and gas fields are renewable sources of hydrocarbons. This statement aroused great interest among scientists and specialists in the oil and gas industry of Russia and served as an impetus for intensive research in order to verify the validity of the new oil and gas paradigm. The idea was sharply debated at all major conferences and meetings held in Russia. As a result, based on the example of a number of oil and gas fields being developed in Russia (Northern Caucasus, Western Kuban, Samara and Volga-Ural regions, Tatarstan and Western Siberia) to date many facts have accumulated confirming the existence of a replenishment process [8-16].

All suggest the existence of oil and gas supply centers and channels (fault and weakened zones) that are used to replenish reservoirs [17-22]. As a rule, high-flow-rate (so-called “abnormal”) wells are confined to these zones. After intensive development of readily available oil reserves, the proposal is to replenish oil reserves through rehabilitation cycles [16]. This problem is extremely important scientifically and practically and so requires the continuation and expansion of comprehensive studies. From this point of view, the South Caspian Basin (SCB), which is one of the oldest oil and gas provinces in the world where oil and gas fields have been developed since the beginning of the last century, is an excellent testing ground for such studies. This paper is based on an analysis of field data for the dynamics of oil and gas production at a number of long-term developed fields in the South Caspian Basin, a detailed study of the possibility of the self-filling process, and if it is possible to give a quantitative assessment of the rate of natural recharge by hydrocarbons.

Background

The implementation was carried out on two long-term developed fields in the SCB: the Bibieybat oil field and the Garadag gas condensate field. The main development of the SCB is the Productive Series (PS), Lower Pliocene (Fig. 1).

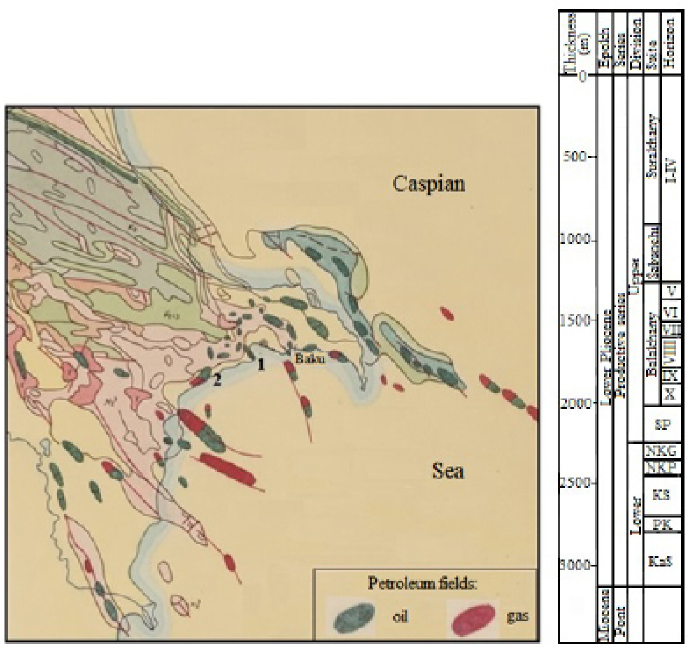

Fig 1: Locations of the studied fields of the SCB (1- Bibieybat; 2- Garadag) and the stratigraphic section of the Productive Series: SP- «Pereryva» suite; NKG- Overkirmaki clayey suite; NKP - Overkirmaki sandy suite; KS – Kirmaki suite; PK – Underkirmaki suite; KaS – Kala suite.

Bibieybat field

The Bibieybat petroleum field, one of the first fields in Azerbaijan, is located in the southwestern coastal part of the Absheron Peninsula, 2 km south of Baku. Since ancient times, oil production has taken place. In 1846, the first well in the world was drilled here, from which industrial oil inflows from PS were obtained. From then until the present day this area is an industrial oil development field. The Bibieybat field is a brachyanticline fold of northwestern strike with a gentle (25-30 °) northeast and relatively steeper southwest wings. A buried mud volcano is located at the crest of fold (Fig. 2).

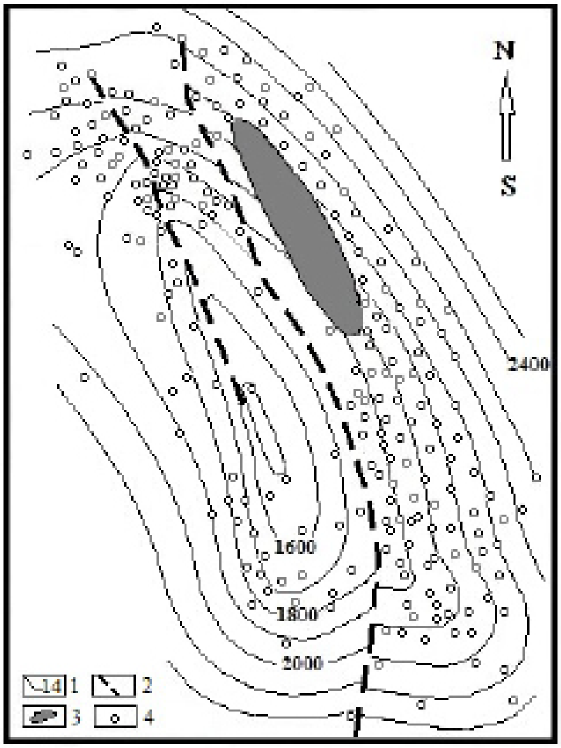

Fig. 2: Structural map of the Bibieybat deposit on the top of the PS: 1 - lines of tectonic faults; 2 - isolines of the top of structure; 3 - buried mud volcano.

The thickness of the PS within this area reaches 1700-1800 m and is an ordinary terrigenous lithofacies, but with a slightly increased clay content. Within the Bibieybat field industrial oil and gas pools are confined to all sandy suites and horizons. The upper boundary of the industrial oil-gas content here is horizon II (Surakhany suite - the upper division of the PS), and the lower — the Underkirmaki suite (PK) of the lower division of the PS (see fig. 2). In the interval of the stratigraphic section from the top of the Kirmaki suite (KS) to the top of the Surakhany suite 17 sandy-silt oil and gas bearing layers are distinguished, which are separated by thin clayey sections. Trap fill factor is 0.47. The oil deposits of the upper division of the PS (up to the Nadkirmaki clayey suite - NKG) usually occupy the crest of fold. Starting from the Nadkirmaki sandy suite (NKP), oil pools are noticeably pushed to the wings, and gas caps are located on the fold arch. The largest initial oil reserves were established in horizons II and III of the Sabunchu suite (upper division of PS), and in the lower division of PS, the largest oil and gas reserves are characteristic for PK.

Garadag field

The Garadag field/UGS(Underground Gas Storage) 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°, while the southern wing has a declination of up to 60°. 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 m. on 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 [23-25]. The structural model of the field is shown in Figure 3.

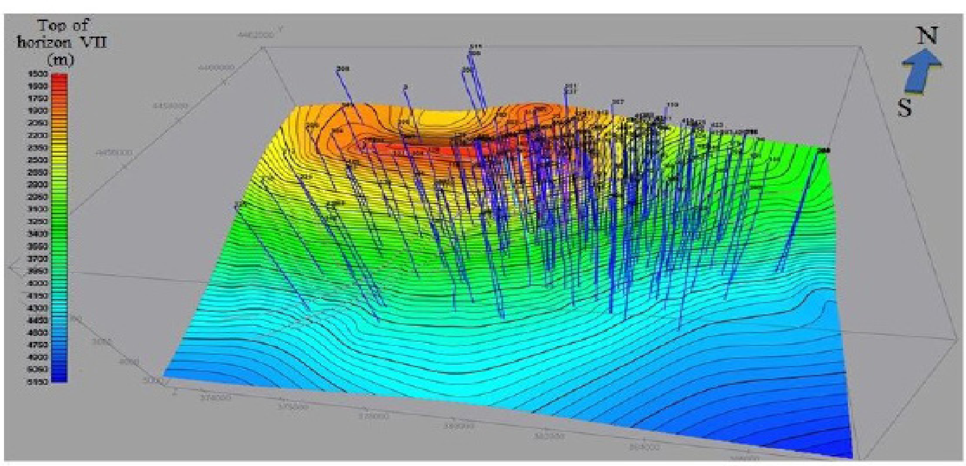

Fig. 3: Structural model of horizon VII of the Garadag field

The gas condensate pool of horizon VII of the PS is distinguished from others by high productivity. Three interval are distinguished in the section: the upper (VII) and lower (VIIa) horizons, separated by a clay layer 16-36 m thick. In the southeastern part of the southern wing, the VII horizon consists of 4-5 sandstone interbeds 5- 10 m, which are separated by clayey interlayers 2-4 m thick.

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

In the southeastern part of the southern wing horizons VII and VIIa combine and form a single thick sandstone layers. In the north-west direction, a decrease in the total effective thickness of horizons VII-VIIa is observed due to an increase in the number of clay layers. In the southeast, their total effective thickness is 55-75 m, and in the northwest 10-25 m.

Exploitation of the Garadagh field began in 1939 with the development of an oil and gas pool in the V horizon of the PS. The main facilities under development were horizons I-VII (upper part of division of PS), horizon VIII (according to the Garadag nomenclature, an analogue of the NKG suite of the lower division of PS in the Absheron nomenclature) and deposits of the Upper Miocene, with an average oil and gas bearing depth of 2750 m. A gas condensate pool with an oil rim in the VII-VIIa horizons was put into development in 1955. The depth of the VII horizon at the crest is 1900 m, and in the submerged part is 4250 m (average depth 3125 m). The productivity of the wells of the VII horizons varies. The wells located in the submerged SE part of the reservoir are more productive. The Garadag gas condensate field was developed without maintaining formation pressure and by the end of the 1980s pools in the VII-VIIa horizons were depleted. For the period from 1955 to 1978 more than 20.5 billion m3 of gas were produced from the VII-VIIa horizons. Horizons VII-VIIa were recommended for underground gas storage (UGS). From 1986 to the present the Garadag field has been so used.

Results

Bibieybat field

Figure 4 shows graphs of changes in the annual total oil production (4a) and the average production rate per well (4b) for the period from 1935 to 2018.

Fig. 4. The Bibieybat field. Dynamics of changes in total

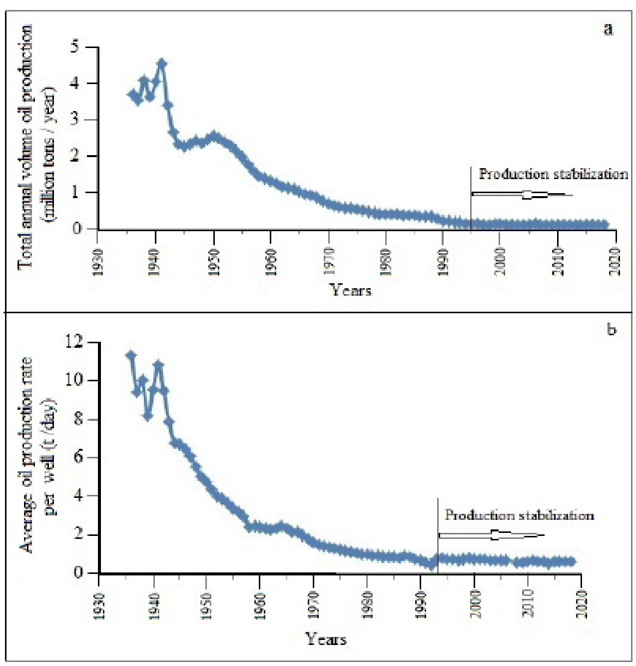

Fig. 4. The Bibieybat field. Dynamics of changes in total annual oil production (a) and average oil production rate per well (b). As can be seen from fig.4, from the beginning of development (since 1935) after a short period (up to about 5 years from the beginning of de-

velopment), a continuous decline in oil production was observed at the Bibieybat field, especially intense in the first 30 years. However, since about 1995, stabilization of production has been observed. The stable average daily oil production per well established at the late stage of field development varies between 0.32-0.89 tons (average 0.71 tons) for productive facilities in the upper division of PS and 0.88 -1.4 tons (average 1.0 tons) .in the lower division of PS The drop of oil production in the process of intensive development of field is accompanied by a steady drop in formation pressure, despite the artificial pressure maintenance in the reservoir by pumping water.

Initial reservoir pressures vary with depth close to hydrostatic pressure. However, during the development process, this pattern is violated, and the values of the current reservoir pressures fall significantly below the hydrostatic level, forming abnormally low formation pressures [26, 27]. According to [28], activities to maintain formation pressure by injecting water into the reservoir and other methods used at many fields in the world can restore pressure (and as a result, a corresponding increase in productivity) by no more than 10%. Such is also confirmed by the oldest Balakhany-Sabunchu-Ramany field on the Absheron Peninsula of the SCB. Here, during the development of the VI horizon of the PS from 1935 to 2001 formation pressure dropped 10 times. Horizon productivity over the same period decreased by almost 4 times in comparison with the peak value. Injection of water in order to maintain pressure increased oil production to only 9% of the peak value, increasing water production to a greater degree.

The nature and level of pressure drop in the productive objects of the upper and lower divisions of the PS differ noticeably (Fig. 5).

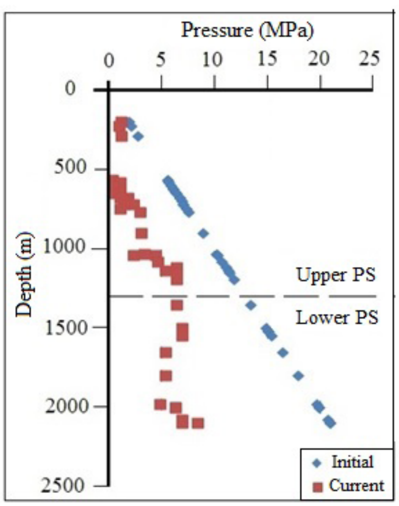

Fig. 5. Initial and current values of formation pressures vs. depth at Bibieybat field

Garadag field

The dynamics of gas production and the condensate contained in it at the Garadag field for the period from the beginning of development (1955) to its completion (1979) is shown in Figure 6.

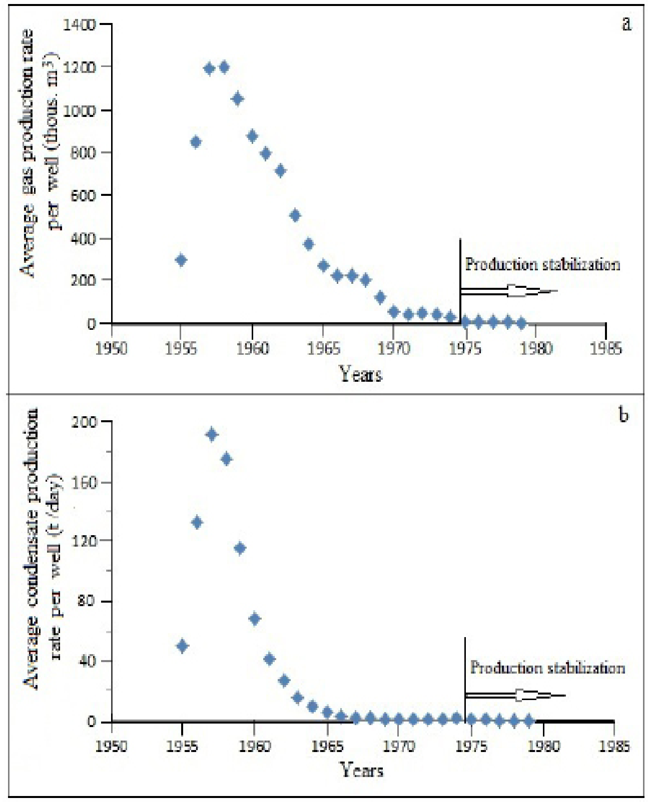

Fig. 6: Garadag field. The dynamics of the average daily production of gas (a) and condensate (b) per well. From figure 6, the peak in gas production, due to its intensive extraction, was reached about 2-3 years after the start of field development, and then followed a steady decline in production. The average daily production per well stabilized approximately 5-6 years before the completion of the development of the pool. Field development in the depletion mode (without maintaining formation pressure) contributed to a high rate of reservoir pressure drop (Table).

Table . Rate of pressure drop in wells of the Garadag field

Well	Time interval between measurements (month)	Total pressure drop (MPa)	Monthly average pressure drop (MPa
70	15.0	7.4	0.49
134	14.8	6.5	0.44
132	15.7	5.2	0.33
182	15.7	5.2	0.30
Average			0.39

The initial formation pressure equal to 39.7 MPa, by the end of field development has decreased by more than 10 times, amounting to 3.6 MPa. A particularly intense rate of pressure drop was observed in the first 5-6 years of field development (Fig. 7).

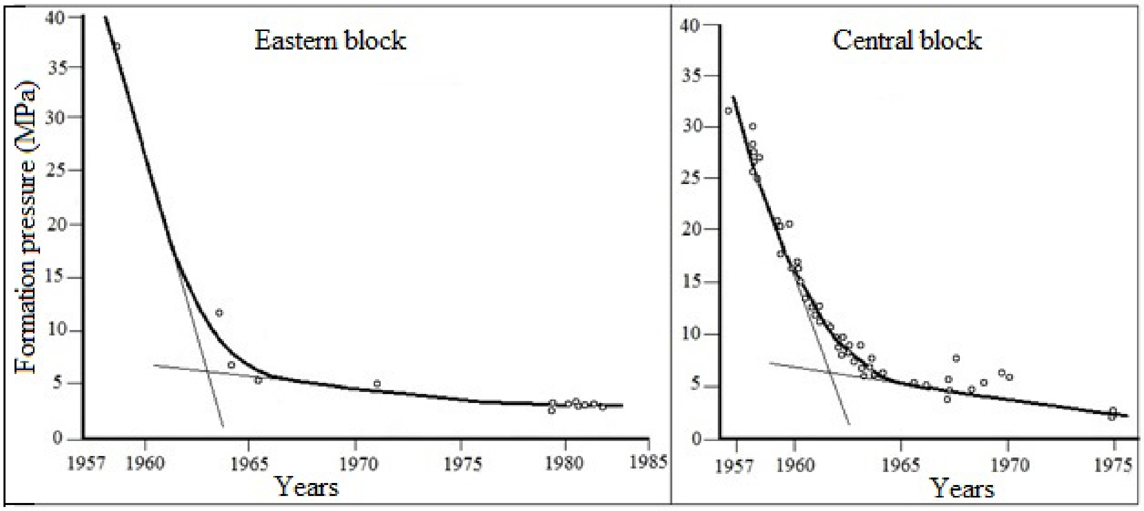

Fig. 7. Change in reservoir pressure during the development of the Garadag field

Discussion

The formation of an industrial accumulation of HCs in the subsurface occurs over a long geological time. Even for the relatively young fields in the Lower Pliocene sediments of the SCB, formation took about 1-2 million years. This process is completed with the establishment of a natural dynamic equilibrium in the rock-fluid system. Human activities associated with the development of oil and gas fields and intensive extraction of fluids (oil, gas, water) from the reservoir for a very short (compared to geological time) period of time, accompanied by a continuous drop in reservoir pressure, leads to a sharp violation of this equilibrium contributing to the development of irreversible deformation processes in the reservoir and to a decrease in the reservoir quality.

Thus, the results of experimental studies of two sandstone samples under conditions as close as possible to the real reservoir conditions showed that a decrease in reservoir pressure from 110 MPa to 10 MPa was accompanied by a decrease in their permeability, by 15% and 50%, respectively, under constant all-round pressure [29].

The experiments carried out by using rock samples from fields in the Gulf of Mexico also led him to conclude that inelastic deformation associated with HC production could lead to irreversible loss of porosity and permeability [30]. Moreover, a relative decrease in rock permeability is more significant in comparison with a decrease in porosity: a decrease in rock porosity by 10% is often accompanied by a decrease in permeability by about 70% from the initial value. The results of other studies led to the same conclusion. For example, according to estimates by [31], a decrease in the porosity of rocks from 23% to 21% is accompanied by a decrease in permeability from 230 mD to 50-140 mD. According to other experimental studies [32], with a decrease in formation pressure and, consequently, an increase in effective pressure by 20 MPa, a relative decrease in porosity and permeability occurs, respectively, by 13% and 80% for fractured rocks, and by 2% and 60% for granular rocks.

A decrease in the reservoir properties of rocks associated with a decrease in reservoir pressure occurs most intensively at the initial stage of development of HC pools [32, 33]. At the late stage of field development, a new technogenic-natural equilibrium occurs in the reservoir, due to the fact that the steady low volume of the extracted HC fluid comes into line with the rate of natural recharge. The extracted volume of HCs is compensated by the volume of natural replenishment of the reservoir. Based on the analysis of production dynamics at the Bibieybat field, the estimated rate of natural well replenishment with oil at various production facilities varies over a wide range: 0.32-1.4 t/day (fig. 8).

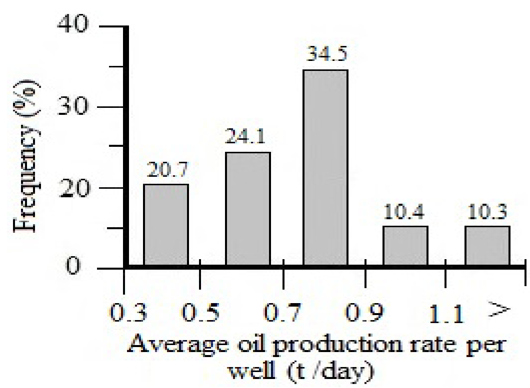

Fig. 8: Histogram of the distribution of steady-state daily average oil production per well for various productive facilities at a late stage in the development of the Bibieybat field.

The modal value of the steady low, but stable, oil production from 29 production facilities in the section of PS at the Bibieybat oil field, which is supposedly equivalent to the rate of natural inflow into the oil reservoir, is in the range of 0.7-0.9 t/day, averaging 0.76 t/day. The rate of natural daily recharge of wells at the Garadag field as a whole is estimated at about 5.2 thousand m3 of gas and 0.9 tons of condensate, although the rate differs for various blocks. The wide range of times and levels of onset of stable oil and gas production aredetermined by the influence of complex factors. Such factors are most likely to be reservoir pressure and temperature, as well as rock permeability, which correlate well with oil and gas production (Fig. 9-11).

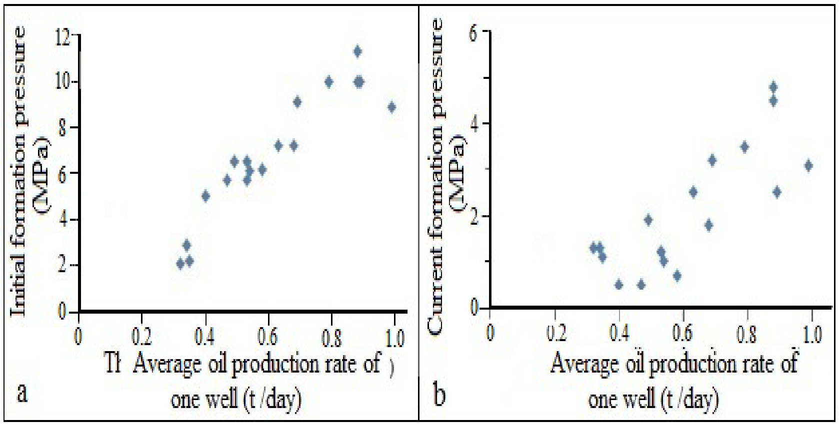

Fig. 9: The Bibieybat field showing the average daily oil production per well versus initial (a) and current (b) formation pressures.

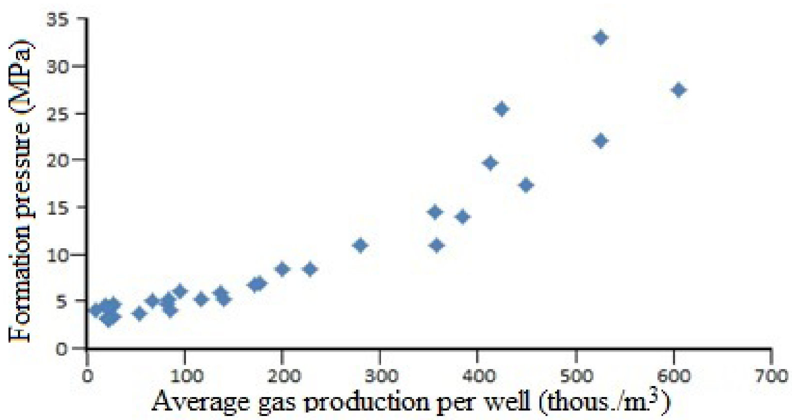

Fig. 10: Garadag field. Average daily gas production per well vs. formation pressure

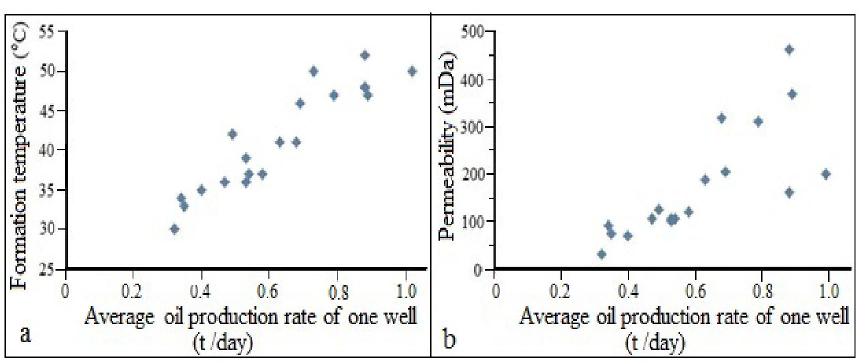

Fig. 11: The Bibieybat field. Average daily oil production per well versus. formation temperature (a) and rock permeability (b).

No relationship is observed between oil production and reservoir parameters such as its effective (oil-saturated) thickness and porosity of rocks for the Bibieybat field. The direct relationship between the volume of oil production and reservoir temperature, according to [34], may be associated with a decrease in oil density as a result of an increase in reservoir temperature.

Other things being equal (permeability and temperature), a sharp drop in formation pressure in the reservoir during its development enhances the inflow of HCs from the outside. Naturally, there must be HC supply channels, the role of which can be played by tectonic faults [23] and, under the conditions of the SCB, also channels of mud volcanoes. With the dominant epigenetic concept of the formation of HC fields in the SCB and their young age (formation does not exceed 2 million years) most HC mass transfer from the source to the reservoir likely occurred due to filtration (subvertical migration along deep faults, channels of mud volcanoes) [35-39].

Most likely, these channels serve as pathways of the enhanced (recovered) HC migration into the reservoir as a result of long-term exploitation of field. The presence of such zones of localization of highly productive wells is also seen in the example of oil fields: Guneshli (Fig. 12) and Galmas (Fig. 13) in the SCB [40-41].

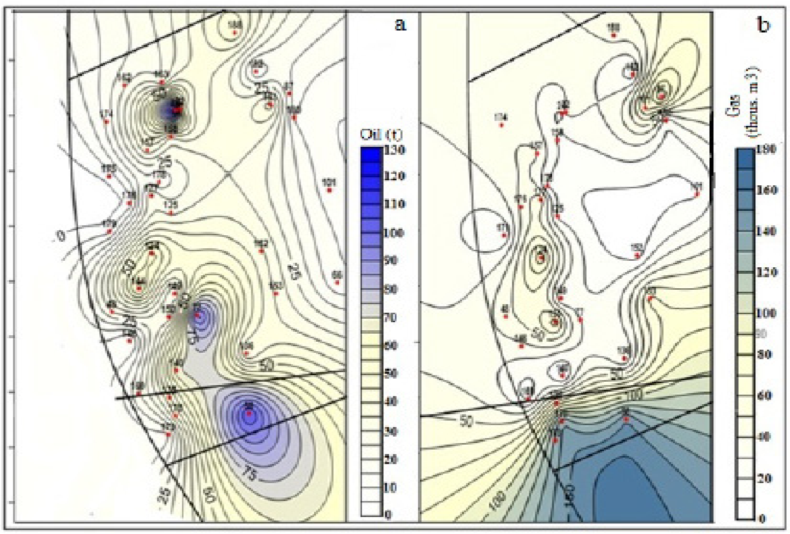

Fig. 12: Guneshli field. Distribution of the initial average daily production rates of oil (a) and dissolved gas (b) in the first 30 days of well operation of the "Pereryva Suite" (SP)

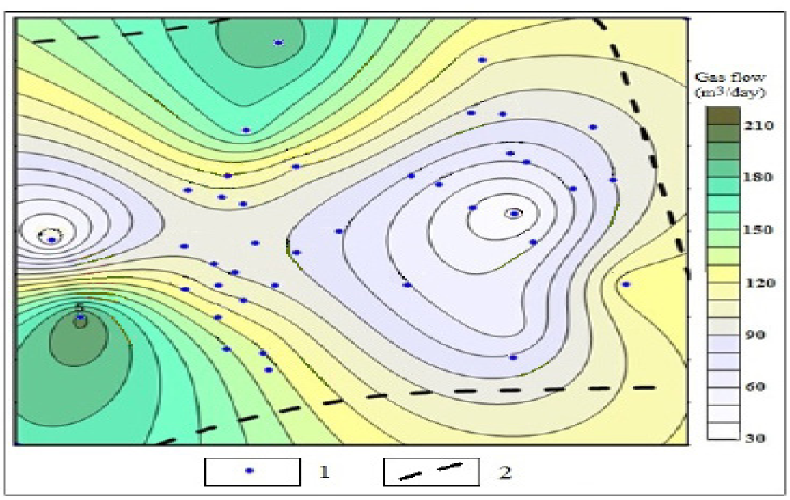

Fig. 13: The spatial distribution of gas productivity of wells on the Galmas field: 1-well; 2- tectonic faults

At present, methodological approaches to identifying HC inflow zones have been developed [9], based on the identification of highly productive (abnormal) wells, as well as a complex of geochemical studies of dissolved oils and gases. The above data indicate that the migration of HC fluids in the sedimentary section occurs at a much higher rate than previously assumed and continuously ongoing to date. A real-time example of modern fluid dynamics in SCB are natural gas manifestations and mud volcanoes that continuously emit gas (mainly methane), and some periodically discharge large volumes of gas into the atmosphere during their eruptions (Fig. 14).

Fig. 14: SCB. Absheron Peninsula. "Yanardag" burning natural gas discharge (at the left) and the eruption of the Lokbatan mud volcano. The intensity of natural gas manifestation and the frequency of eruptions of each individual mud volcano are determined by the rate of replenishment of the deep source (reservoir) with gas. During the eruption of a mud volcano, as well as in the fields, the flow of HCs is enhanced by a sharp drop in pressure in the deep source caused by the natural discharge into the atmosphere (and at the field by intensive technogenic extraction) of large volumes of gas.

Conclusion

An analysis of the dynamics of oil and gas production in combination with other field data, performed on the long-lived fields Bibieybat and Garadag in SCB, allows us to conclude the following:- the formation of the SCB fields, which takes about 2 million years, leads to the establishment of dynamic equilibrium in the rock-fluid system;- forced extraction of fluids (oil, gas and water) during field operation, accompanied by a sharp drop in reservoir pressure (significantly lower than hydrostatic), violates the established natural balance in the reservoir and so causes a natural inflow of HC fluids that, at a late stage of development, begins to compensate for the amount extracted leading to the emergence of a new natural-technogenic equilibrium in the reservoir;- estimates of the rate of natural oil inflow to each individual well, performed on 29 productive objects at Bibieybat field, vary within the range of 0.32-1.4 t/day, averaging 0.76 t/day or about 277 t/yea, in good agreement with previous estimates. According to which the rate of oil accumulation in traps is from 12 to 700 t/ year, and the duration of the formation of oil deposits is 1-12 million years;- values of the rate of natural recharge of wells in the Garadag gas condensate field for its various blocks are different, amounting to an average of 5.2 thousand m3/day of gas and 0.9 tons per day of condensate;-there are a wide range of times and levels of occurrence of stable oil and gas production and the equivalent rate of natural recharge, determined by complex factors, of which are reservoir pressure and temperature, as well as rock permeability, are dominant. In summary oil and gas fields can be exploited more efficiently and for a very long time if HC production is carried out on the basis of a balance of recharged and extracted volumes [42].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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