Geological and statistical modeling of oil recovery of carbonate formations

V Sh Mukhametshin, K T Tyncherov, N Rakhimov

Ufa State Petroleum Technological University, Branch of the University in the City of Oktyabrsky, 54a, Devonskaya St., Oktyabrsky, Republic of Bashkortostan, 452607, Russian Federation

E-mail: academic-mvd@mail.ru

Abstract. For the conditions of fourteen groups of low productivity, complex features in the carbonate reservoirs of the Volga-Ural oil and gas province were constructed geological and statistical modeling that allows predicting the ultimate oil recovery factor for deposits similar to those studied when solving various development tasks. Based on the consideration of cause-and-effect relationships between geological and technological parameters, the physical interpretation of the obtained models is given. It is established that the variety of oil deposits in carbonate reservoirs according to the conditions of occurrence, geological-physical and physical-chemical properties of reservoirs and their saturating fluids requires a differentiated approach when modeling and using models of the oil recovery process.

1. Introduction
A significant number of studies conducted both in our country and abroad have been devoted to the modeling problem of the oil recovery process using the experience of developing fields that have been in operation for a long time. The models created in this case allow solving a certain range of tasks in the design, analysis, control, and regulation of the development process [1-8].

The variety of proposed geological and statistical models indicates the presence of specific features of the oil recovery process in various geological and field conditions. Most of them are built for the conditions of deposits in terrigenous reservoirs developed with waterflood of production horizons, and only recently started to appear models based on the study of the development experience of relatively productive deposits in carbonate reservoirs. The lack of models that characterize the oil recovery process from low productivity objects in the carbonate reservoirs of the Volga-Ural oil and gas province is explained by the relatively insignificant service life of most of them and the insufficient volume of research conducted on them.

Significant oil reserves concentrated in these reservoirs allow us to consider them as a significant reserve in oil production and require the study of the oil recovery process based on complex modeling using all the information currently available on the objects under development.

2. Materials and methods
Among the three hundred and four development objects were identified fourteen groups that are similar in terms of the considered geological features (tectonic-stratigraphic confinement and parameters of objects are described in detail in [9]). Within each group of objects, the influence of geological and
technological parameters on the ultimate oil recovery factor during the development of deposits in the natural drive was studied. The number of objects in groups varied from seven to twenty-eight. The values of the ultimate oil recovery factor ($\eta$) for groups of objects are shown in the table.

Table 1. Values of the ultimate oil recovery factor for groups of development objects

| Group of objects | The ultimate oil recovery factor, % |
|------------------|-------------------------------------|
|                  | maximum | average | minimum |
| 1                | 15.6    | 2.4     | 0.2     |
| 2                | 31.5    | 11.6    | 2.5     |
| 3                | 33.8    | 9.2     | 0.2     |
| 4                | 25.1    | 9.8     | 1.0     |
| 5                | 31.1    | 18.7    | 3.9     |
| 6                | 24.0    | 5.0     | 0.4     |
| 7                | 38.9    | 24.7    | 13.9    |
| 8                | 31.0    | 18.7    | 4.6     |
| 9                | 41.0    | 33.7    | 20.0    |
| 10               | 18.5    | 6.3     | 2.2     |
| 11               | 31.6    | 9.2     | 1.8     |
| 12               | 23.7    | 6.9     | 0.3     |
| 13               | 8.7     | 3.8     | 0.3     |
| 14               | 4.7     | 1.0     | 0.2     |
| 1-14             | 41.0    | 10.1    | 0.2     |

As can be seen from the table, the values of oil recovery vary quite widely, which is explained by the influence of both natural factors and the difference in the technology of reservoir developments, namely, the difference in the pattern arrangement of development wells (for various objects at the time of analysis, it varied from 3 to 200 ha/sq.).

Based on all available information on the deposits obtained on the basis of geophysical, hydrodynamic and laboratory studies, we investigated the effect of the ratio of ultimate oil recovery for the following parameters: average values of efficiency and oil-saturated thickness within the object ($H_3$) and in the drilling out area ($H_5$), standard deviation ($\sigma_{H_3}$), variation coefficient ($W_{H_3}$), entropy ($\mathcal{E}_{H_3}$), relative entropy ($\mathcal{E}_{\bar{H}_3}$), parameter heterogeneity ($\Pi_{H_3}$) effective oil-saturated thickness; average value ($H_{\Pi}$), standard deviation ($\sigma_{H_{\Pi}}$), variation coefficient ($W_{H_{\Pi}}$), entropy ($\mathcal{E}_{H_{\Pi}}$), relative entropy ($\mathcal{E}_{\bar{H}_{\Pi}}$), the nonuniformity parameter ($\Pi_{H_{\Pi}}$) of the oil-saturated thickness of interlayer; the average values of permeability coefficients ($K_{\text{ипов}}$), the oil-saturation ($K_{H}$), porosity according to laboratory ($m_{\text{К}}$) and geophysical ($m_{\text{Г}}$) studies, the standard deviation ($\sigma_{m}$), variation coefficient ($W_{m}$), entropy ($\mathcal{E}_{m}$), nonuniformity parameter ($\Pi_{m}$) and porosity according to the geophysical researches; ruggedness ratio ($K_{R}$), fraction of reservoir rocks in the total formation thickness ($K_{\text{неод}}$), the complex index of heterogeneity ($K_{\text{неод}}$); viscosity ($\mu_{H}$), relative viscosity ($\mu_{\text{О}}$), density ($\rho_{H}$) of formation oil, formation gas-oil ratio ($G$), the oil-gas saturation pressure ($P_{\text{нас}}$), the initial formation pressure ($P_{\text{пл}}$), temperature ($t_{\text{пл}}$), formation depth ($H_{\text{зал}}$), the pattern arrangement of field well (S) [10-14].

Heterogeneity parameters were defined as the product of standard deviation, variation, entropy, and relative entropy,$K_{\text{неод}}$ and wells density grid as the area ratio of oil-bearing capacity to the number of all wells in operation.

One of the algorithms of the group method of data handling (GMDH) was used in the simulation. The choice of this algorithm is due to the following reasons:

+ lack of reliable a priori information about the most likely nature of the relationship between the oil recovery coefficient and the geological and technological parameters;
3. Results and discussion

The obtained models of the dependence of the ultimate oil recovery factor on the geological and technological parameters have the following form:

\[ \eta = 18.3 \Pi_m^{0.5} \Pi_{H_3}^{0.5} / S - 169 \Pi_{H_3}^{0.5} / S + 0.15 S / \Pi_m^{0.5} \Pi_{H_3} - 10.9 \Pi_m^{0.5} \Pi_{H_3} / H_3^{0.5} S \]  
(1)

(for objects of the first group);

\[ \eta = 18 \Pi_m^{0.5} \Pi_{H_3}^{0.5} \sigma_{H_3}^{0.5} / (2.2 \cdot 0.012 S)^{0.5} \]  
(2)

(for objects of the second group);

\[ \eta = 2680 K_p \sigma_m^{0.5} / S - 471 (\sigma_{H_3} H_3^{0.5} + 13.3 H_3^{0.5} / H_3^{0.5}) - 146 (K_p / S)^{0.5} + 136 (K_p H_3^{0.5} / \mu_i S)^{0.5} + 3380 P_{k_p_0}^{0.5} K_p^{0.5} / \Pi_{k_p}^{0.5} S^{0.5} - 19.9(0.5 \cdot 10^4 (K_p P_{k_p_0} / W_{k_p_0} S)^{0.5} \]  
(3)

(for objects of the third group);

\[ \eta = 44.1 \sigma_{H_3} P_{nac}^{0.5} / H_{H_3}^{0.5} S^{0.5} - 79.3 \sigma_{H_3}^{2} \sigma_m^{0.5} / W_{H_3}^{0.5} + 583 \sigma_{H_3} \sigma_m^{0.5} / H_{H_3}^{0.5} S^{0.5} + 604 P_m^{0.5} P_{k_p}^{0.5} / W_{k_p}^{0.5} \]  
(4)

(for objects of the fourth group);

\[ \eta = 910 \sigma_{H_3}^{0.5} / H_{H_3}^{0.5} S^{0.5} \sigma_m^{0.5} W_m^{0.5} - 78.1 H_3^{0.5} / P_{nac}^{0.5} \sigma_m^{0.5} W_m^{0.5} \]  
(5)

(for objects of the fifth group);

\[ \eta = 356 \sigma_m^{0.5} H_3^{0.5} / K_{nac}^{0.5} S^{0.5} \]  
(6)

(for objects of the sixth group);

\[ \eta = 5.83 G^{0.5} P_{nac}^{0.5} \sigma_{H_3}^{0.5} H_3^{0.5} / m_r^{0.5} \sigma_m^{0.5} \sigma_m^{0.5} S^{0.5} + 0.523 P_{k_p}^{0.5} P_{k_p}^{0.5} P_m^{0.5} / m_r^{0.5} m_p^{0.5} P_m^{0.5} \]  
(7)

(for objects of the seventh group);

\[ \eta = 21.3 \Pi_{H_3}^{0.5} \sigma_{H_3}^{0.5} / W_m^{0.5} S^{0.5} + 0.508 K_{nac}^{0.5} \Pi_{H_3}^{0.5} / S^{0.5} - 0.125 H_{H_3}^{0.5} \]  
(8)

(for objects of the eighth group);

\[ \eta = 0.15 \Pi_m^{0.5} m_l^{0.5} \sigma_{H_3}^{0.5} - 10.4 W_{H_3} \sigma_m^{0.5} + 12.3 \Pi_m^{0.5} / W_{H_3}^{0.5} H_3^{0.5} \]  
(9)

(for objects of the ninth group);

\[ \eta = 6.29 G^{0.5} \sigma_{H_3}^{0.5} H_3^{0.5} / W_{H_3}^{0.5} \sigma_{H_3}^{0.5} S^{0.5} - 22.8 H_3^{0.5} / \sigma_{H_3}^{0.5} S^{0.5} + 1.26 \Pi_{k_p}^{0.5} P_{k_p}^{0.5} P_{k_p}^{0.5} / P_{k_p}^{0.5} P_{k_p}^{0.5} S^{0.5} \]  
(10)

(for objects of the tenth group);

\[ \eta = 0.322 \Pi_{H_3}^{0.5} H_3^{0.5} G^{0.5} \sigma_m^{0.5} \sigma_{H_3}^{0.5} / K_{nac}^{0.5} S^{0.5} + 0.123 \Pi_m^{0.5} \sigma_{H_3}^{0.5} H_3^{0.5} / S^{0.5} / \Pi_{H_3}^{0.5} \sigma_m^{0.5} + 0.068 G^{0.5} P_{k_p}^{0.5} P_{k_p}^{0.5} P_m^{0.5} / W_m^{0.5} H_3^{0.5} P_{k_p}^{0.5} / S^{0.5} - 3.79 \sigma_{H_3}^{0.5} - 10^2 P_{k_p}^{0.5} P_{k_p}^{0.5} G^{0.5} P_m^{0.5} / P_{k_p}^{0.5} P_{k_p}^{0.5} P_{k_p}^{0.5} / \Pi_{k_p}^{0.5} \]  
(11)

(for objects of the eleventh group);

\[ \eta = 30.4 \Pi_{H_3}^{0.5} H_3^{0.5} / S + 2.46 \sigma_{H_3}^{0.5} H_3^{0.5} \sigma_{H_3}^{0.5} W_{H_3}^{0.5} H_3^{0.5} / S^{0.5} \]  
(12)

(for objects of the twelfth group);

\[ \eta = 0.48 \Pi_{H_3}^{0.5} \sigma_m^{0.5} - 0.38 \cdot 10^{-3} \sigma_{H_3}^{0.5} \]  
(13)

(for objects of the thirteenth group);

\[ \eta = 2.1 \cdot 10^2 \Pi_{H_3}^{0.5} G^{0.5} \sigma_{nac}^{0.5} / \mu_o^{0.5} - 3 \cdot 10^{-4} \Pi_{H_3}^{0.5} G^{0.5} P_{nac}^{0.5} \]  
(14)

(for objects of the fourteenth group);
$$\eta = 7.86 \cdot 10^{-4} t_{\text{th}}^{0.5} H_{\text{eff}}^{0.5} \sigma_{H_{\text{ij}}}^{0.5} / K_{P_{\text{P}}}^{0.5} +$$
$$+ 9.54 \beta \cdot 10^{-6} t_{\text{P}_{\text{P}}}^{2} p_{\text{k}_{P} p_{\text{P}}}^{0.5} W_{P_{\text{k}_{P} p_{\text{P}}}}^{0.5} / m_{P_{\text{P}}}^{0.5} S^{0.5} - 20.8 \Pi_{\text{k}_{P} p_{\text{P}}}^{0.5} t_{\text{P}_{\text{P}}}^{0.5} +$$
$$+ 24.4 P_{\text{P}_{\text{P}}}^{0.5} p_{\text{k}_{P} p_{\text{P}}}^{0.5} P_{\text{P}_{\text{k}_{P} p_{\text{P}}}}^{0.5} \Pi_{\text{k}_{P} p_{\text{P}}}^{0.5}$$
(15)
(on all objects).

The values of correlation relations change from 0.729 to 0.998. The relative errors for equations (1-14) vary from 3.1 to 26.3 %, and on average they are 11.2 %. The relative error in equation (15) is 29.5 %, which indicates the need for a differentiated approach when modeling the oil recovery process and using the obtained models.

Analysis of models and consideration of cause-and-effect relationships between geological and technological parameters within the selected groups of objects allowed us to give a physical interpretation of the oil recovery process.

Within practically all groups of objects observed effect of wells density grid on the value $S$ (except for objects of group 9, which $S$ ranges from 3 to 7 ha/scr.), moreover, the link between these parameters is determined by the geological facilities features. The influence of geological parameters within the groups varies in size, and sometimes in sign, which is a reflection of the specific features of the structure of reservoirs and the associated oil recovery process.

Objects with higher values of effective oil-saturated thickness, the thickness of oil-saturated layers, the share of reservoir rocks in the total formation thickness, permeability coefficients and containing less viscous and dense oil are characterized by higher oil recovery coefficients, which corresponds to the classical ideas about the influence of these parameters on the process of oil reserves recovery.

With the increase of growth parameters, reflecting the geological heterogeneity at the effective oil-saturated thickness ($\sigma_{H_{\text{ij}}}, W_{H_{\text{ij}}}, \Theta_{H_{\text{ij}}}, \delta_{H_{\text{ij}}}, \Pi_{H_{\text{ij}}}$) and the thickness of oil-saturated interlayers ($\sigma_{H_{\text{ij}}}, W_{H_{\text{ij}}}, \Theta_{H_{\text{ij}}}, \delta_{H_{\text{ij}}}, \Pi_{H_{\text{ij}}}$) in some groups of objects (groups 1, 2, 3, 8). These parameters are associated with effective oil-saturated thickness and deposits productivity which quite an effect of the oil recovery process. At the same time, the greater the productivity, the greater the oil-saturated thickness and indicators reflecting the heterogeneity of $H_{\text{ij}}$ and $H_{\text{ij}}$.

With an increase in porosity in general for all objects (equation 15) is observed a decrease. This is because with a decrease in porosity, the degree of fracturing increases, permeability, and productivity increase, which contributes to the better oil reserves recovery. In the conditions of the most fractured reservoirs of objects of groups 5 and 7, this effect is most noticeable. However, at values of porosity coefficients greater than 0.09, the fracturing of reservoir rocks ceases to affect and increases with further increase in porosity in the conditions of individual groups.

Within the groups of analyzed objects, an increase in the average porosity (except for fractured Famennian limestones of group 7 and, to a lesser extent, fractured reservoirs of the Tournaissian stage of group 5) is accompanied by an increase in heterogeneity in this parameter ($\sigma_{H_{\text{ij}}}, W_{H_{\text{ij}}}, \Theta_{H_{\text{ij}}}, \delta_{H_{\text{ij}}}, \Pi_{H_{\text{ij}}}$). With increasing porosity (starting from 0.09), the object's productivity increases, and the degree of reserve production increases. This explains the nature of the influence of parameters reflecting the porosity heterogeneity on the oil recovery factor. Within the objects of groups 5 and 7, the decrease in porosity is accompanied by a decrease in the values spread of its relative average value, while the fracturing of reservoir rocks increases, productivity increases and the value increases accordingly $S$.

An increase in the separation coefficient leads to an increase in the oil recovery factor. The objects that have a large dissection are confined to zones of increased effective oil-saturated thicknesses. These zones, as a rule, have a better reservoir characteristic, which leads to an increase in oil recovery in the absence of water injection into the reservoir. Naturally, with the growth of the complex index of heterogeneity, the conditions for reserve production deteriorate, which leads to a decrease in the oil recovery factor.

The growth of the initial formation pressure and temperature of deposits occurs with an increase in the depth of the formations. At the same time, the viscosity and density of formation oil are reduced,
and due to compaction of reservoir rocks, fracturing and productivity increase. This explains the increase of formation pressure, formation temperature, and formation depth.

Within the considered groups of objects, the gas factor and saturation pressure increase with oil viscosity reduction, g and P\text{sat} therefore, in some models, the oil recovery factor increases with an increase in the parameter values.

4. Conclusion
1. For the conditions of fourteen groups of low productivity, complex features in the carbonate reservoirs of the Volga-Ural oil and gas province were constructed geological and statistical modeling that allows predicting the ultimate oil recovery factor for deposits similar to those studied when solving various development tasks.
2. Based on the consideration of cause-and-effect relationships between geological and technological parameters, the physical interpretation of the obtained models is given.
3. The variety of oil deposits in carbonate reservoirs according to the conditions of occurrence, geological-physical and physical-chemical properties of reservoirs and their saturating fluids requires a differentiated approach when modeling and using models of the oil recovery process.

References
[1] Bou-Mikael S, Asmadi F, Marwoto D, and Cease C 2000 Minas Surfactant Field Trial Tests Two Newly Designed Surfactants with High EOR Potential SPE Asia Pacific Oil and Gas Conference and Exhibition (Brisbane, Australia, 16-18 October 2000) 12 p DOI: 10.2118/64288-MS
[2] Rogachev M.K., and Mukhametshin V.V. 2018 Control and Regulation of the Hydrochloric Acid Treatment of the Bottom-Hole Zone Based on Field-Geological Data Journal of Mining Institute 231 275-280 DOI: 10.25515/PMI.2018.3.275.
[3] Alvarado V, Reich E-M, Yunfeng Yi, and Potsch K 2006 Integration of a Risk Management Tool and an Analytical Simulator for Assisted Decision-Making in IOR SPE Europe/EAGE Annual Conference and Exhibition (Vienna, Austria, 12-15 June 2006) 6 p DOI: 10.2118/100217-MS
[4] Mukhametshin V.V. and Kuleshova L.S. 2019 Justification of Low-Productive Oil Deposits Flooding Systems in the Conditions of Limited Information Amount SOCAR Proceedings 2 pp 16–22 DOI: 10.5510/OGP20190200384
[5] Andreev A V, Mukhametshin V Sh, Kotenev Yu A 2016 Deposit Productivity Forecast in Carbonate Reservoirs with Hard to Recover Reserves SOCAR Proceedings 3 40-45 DOI: 10.5510/OGP20160300287
[6] Rogachev M K, Mukhametshin V V and Kuleshova L S 2019 Improving the efficiency of using resource base of liquid hydrocarbons in Jurassic deposits of Western Siberia Journal of Mining Institute 240 711-715 DOI: 10.31897/PMI.2019.6.711
[7] Alvarado V, Stirpe M, La Roque C, Ponce R, and Farias M 2002 Streamline Simulation for Enhanced-Oil Recovery: Review and Laboratory Tests Proceedings of INGEPET, EXPL-4-VA-84
[8] Akhmetov R.T., Kuleshova L.S. and Mukhametshin V.V. 2019 Application of the Brooks-Corey Model in the Conditions of Lower Cretaceous Deposits in Terrigenous Reservoirs of Western Siberia IOP Conference Series: Materials Science and Engineering (MEACS 2018 – International Conference on Mechanical Engineering, Automation and Control Systems) 560(1) 012004 1–4 DOI: 10.1088/1757-899X/560/1/012004
[9] Kuleshova L.S., Kadyrov R.R., Mukhametshin V.V. and Safiullina A.R. 2019 Design Changes of Injection and Supply Wellhead Fittings Operating in Winter Conditions IOP Conference Series: Materials Science and Engineering (MEACS 2018 – International Conference on Mechanical Engineering, Automation and Control Systems) 560(1) 012072 pp 1-5 DOI: 10.1088/1757-899X/560/1/012072
[10] Kuleshova L.S., Kadyrov R.R., Mukhametshin V.V. and Akhmetov R.T 2019 Auxiliary Equipment
for Downhole Fittings of Injection Wells and Water Supply Lines Used to Improve Their Performance in Winter IOP Conference Series: Materials Science and Engineering (MEACS 2018 – International Conference on Mechanical Engineering, Automation and Control Systems) 560(1) 012071 pp 1-6 DOI: 10.1088/1757-899X/560/1/012071

[11] Webb KJ, Black C J J, and Tjetland G 2005 A Laboratory Study Investigating Methods for Improving Oil Recovery in Carbonates International Petroleum Technology Conference (Doha, Qatar, 21-23 November 2005) 7 p DOI: 10.2523/IPTC-10506-MS

[12] Mukhametshin V V, and Andreev V E 2018 Increasing the efficiency of assessing the performance of techniques aimed at expanding the use of resource potential of oilfields with hard-to-recover reserves Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering 329 (8) 30–36

[13] Tyncherov K T, Mukhametshin V Sh, Paderin M G, Selivanova M V, Shokurov I V, Almukhametova E M 2018 Thermoacoustic inductor for heavy oil extraction IOP Conference Series: Materials Science and Engineering (MEACS 2017 – International Conference on Mechanical Engineering, Automation and Control Systems) 327 (4) (042111) 1–8 DOI:10.1088/1757-899X/327/4/042111

[14] Akhmetov R T, Mukhametshin V V, Andreev A V, and Sultanov Sh Kh 2017 Some Testing Results of Productive Strata Wettability Index Forecasting Technique SOCAR Proceedings 4 83–87 DOI: 10.5510/OGP20170400334