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HOW TO CONSIDER ROCK DENSITY IN FLUID FLOW MODEL OF OIL FIELDS DURING PERMEABILITY MODELLING

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ВОЗМОЖНОСТЬ УЧЕТА ПЛОТНОСТИ ПОРОДЫ ПРИ МОДЕЛИРОВАНИИ ПРОНИЦАЕМОСТИ В ГЕОЛОГО-ГИДРОДИНАМИЧЕСКОЙ МОДЕЛИ НЕФТЯНЫХ МЕСТОРОЖДЕНИЙ

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Key words:
core, porosity, density, permeability, linear discriminant function, three-dimensional hydrodynamic model, regression equation, porous reservoir, adaptation, well, oil production.

Data of experimental core study for a number of fields of Bashkirian dome is analyzed. Dependencies between parameters of porosity, bulk density and permeability of rocks are established. A representative series of core samples of Visean sandstone are divided into classes of tight formations (non-reservoirs), porous (granular) and super permeable reservoirs by linear discriminant analysis. Application of rock density parameter as an additional criterion to predict permeability values is justified. Each class of reservoirs was statistically analyzed. It is determined that permeability of tight formations (1st class) and super-permeable reservoirs (3rd class) is much less controlled by rock porosity and density than for porous reservoirs (2nd class), that is characterized by stable relationships between permeability coefficients with both porosity and density of rocks.

A suggested permeability prediction technique is implemented in construction of a fluid flow model of Visean formation at one of Bashkirian dome deposits where for each reservoir class, multidimensional regression equations were constructed to determine permeability based on integrated effect of porosity and density. A comparison of two calculations of fluid flow models is given. During first calculation permeability is determined by a conventional method. Second calculation is performed by a proposed method where permeability is a function of porosity and density of rocks.

Calculations showed a significant improvement in adaptation of a modified model in comparison with conventional approach. Proposed permeability modeling technique is recommended as an initial step in permeability tuning and adaptation of fluid flow model, which consider identified relationships between petrophysical characteristics of a formation.

Ключевые слова:
керн, пористость, плотность, проницаемость, линейная дискриминантная функция, трехмерная гидродинамическая модель, уравнение регрессии, поровый коллектор, адаптация, скважина, добыча нефти.

Выполнен анализ данных лабораторных исследований керна для ряда месторождений Башкирского свода. Установлены зависимости между параметрами пористости, объемной плотности и проницаемости горных пород. Представительная выборка образцов керна песчаника визейских пластов при помощи линейного дискриминантного анализа разделена на классы плотных пород (неколлекторов), поровых (гранулярных) коллекторов и коллекторов с аномально высокой проницаемостью. Представлено обоснование использования параметра плотности породы в качестве дополнительного критерия прогнозирования значений проницаемости.

Для каждого выделенного класса коллекторов выполнен статистический анализ, в результате которого установлено, что для плотных пород (1-й класс) и коллекторов с аномально высокими коллекторскими свойствами (3-й класс) проницаемость в значительно меньшей степени контролируется пористостью и плотностью пород, чем для порового коллектора (2-й класс), который характеризуется устойчивыми связями коэффициентов проницаемости не только с пористостью пород, но и с их плотностью.

Предложенная методика прогнозирования проницаемости реализована при построении фильтрационной модели визейского объекта на одном из месторождений Башкирского свода, где для каждого класса коллекторов построены многомерные уравнения регрессии для определения проницаемости на основе комплексного влияния показателей пористости и плотности. Приведено сравнение двух расчетов геолого-гидродинамических (фильтрационных) моделей: в первой реализации модели проницаемость определена стандартным методом, во второй – по предложенной методике рассчитана как функция от пористости и плотности пород.

Результаты сравнения расчетов показывают значительное улучшение адаптации модифицированной модели по сравнению со стандартным подходом. Предложенная методика моделирования проницаемости рекомендуется как начальный шаг при настройке проницаемости и адаптации фильтрационной модели, при котором комплексно учитываются выявленные связи между петрофизическими характеристиками эксплуатационного объекта.

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Introduction

Increase in the accuracy of determination of reservoir properties and their distribution in space between wells is an important task during building geological and fluid flow models. Laboratory, geophysical, hydrodynamic studies and their aggregate allow determining main formation characteristics. According to a number of researchers, reliable evaluation of permeability coefficient k is the main factor for good quality history matching in fluid flow model [1–3].

Well test data or petrophysical functions of porosity $k = f(K_p)$ are used during determination of k. Both methods have their pros and cons. For example, use of well test allows complete (in comparison with other methods) modelling reservoir operation regime, i.e. it takes into account its vertical and horizontal heterogeneity. But statistically representative and reliable results of well test for all the wells are presented on the object of study not always [4]. Weak correlation of petrophysical functions $k = f(K_p)$ is the main issue. In general, when applying both approaches convergence of comparison of actual and design development indicators does not always correspond to necessary requirements. One of important directions of scientific research is improvement of quality of modeling of reservoir flow properties [5–8].

As it was mentioned above there are objective issues arised often due to lack of tight link of parameters when assessing permeability through the petrophysical function $k = f(K_p)$. If the function $k = f(K_p)$ is exponential, it is impossible to substantiate various relationships between k and K_p at different ranges of K_p values.

Analysis of representative series of petrophysical data

In order to identify more significant links between reservoir petrophysical characteristics an analysis of laboratory data on 626 core samples of Visean deposits, represented by sandstone, was performed for a number of deposits in Perm Region, dedicated to the same tectonic element (Bashkir dome). At the same time, the effect of both porosity and rock density ρ on permeability was analyzed. Values of rock permeability, density and porosity, determined from laboratory core studies, are combined into a single statistical sample to enable development of a methodology necessary for description of k using integrated application of laboratory studies in particular when adding rock density to analysis.

Density of rocks depends on their mineral composition, structural and texture features, porosity, fracturing as well as on formation and bedding conditions. Use of this parameter in forecast of permeability will allow taking into account additional features of void space structure of rocks that belong to the same age.

Justification on separation of representative series into classes of porosity

Correlation fields between studied indicators are constructed based on an example of Visean sandstones of one of Bashkir dome deposits (Fig. 1, *a*-*c*). Practical application of a methodology developed in the article will be presented on this object.

Fig. 1 shows that correlation between K_p and ρ is inverse and fairly linear, while in a number of cases there is a wide range of values. Unlike the previous example, link between k and K_p and ρ in both cases is characterized by obvious nonlinearity. There are three sections of various parameter function are distinguished on the Fig. 1, a. In case if $K_p < 10$ %, porosity values have a significant range and k takes extremely low values. In case if $10 < K_p < 20$ % both K_p and k vary significantly and correlate with each other. In case if $K_p > 20$ %, the values of K_p vary slightly, whereas k has a very large change range. The dependence of k on ρ is characterized by an almost mirror image of the dependence of k on K_p.

In order to obtain more reliable analysis results data from a number of deposits of Bashkir dome was used.

For the entire series of data, a graph of change in pair correlation coefficient r was built for each parameter pair over the whole range of porosity values (from the minimum to the maximum set value of K_p) (Fig. 2).

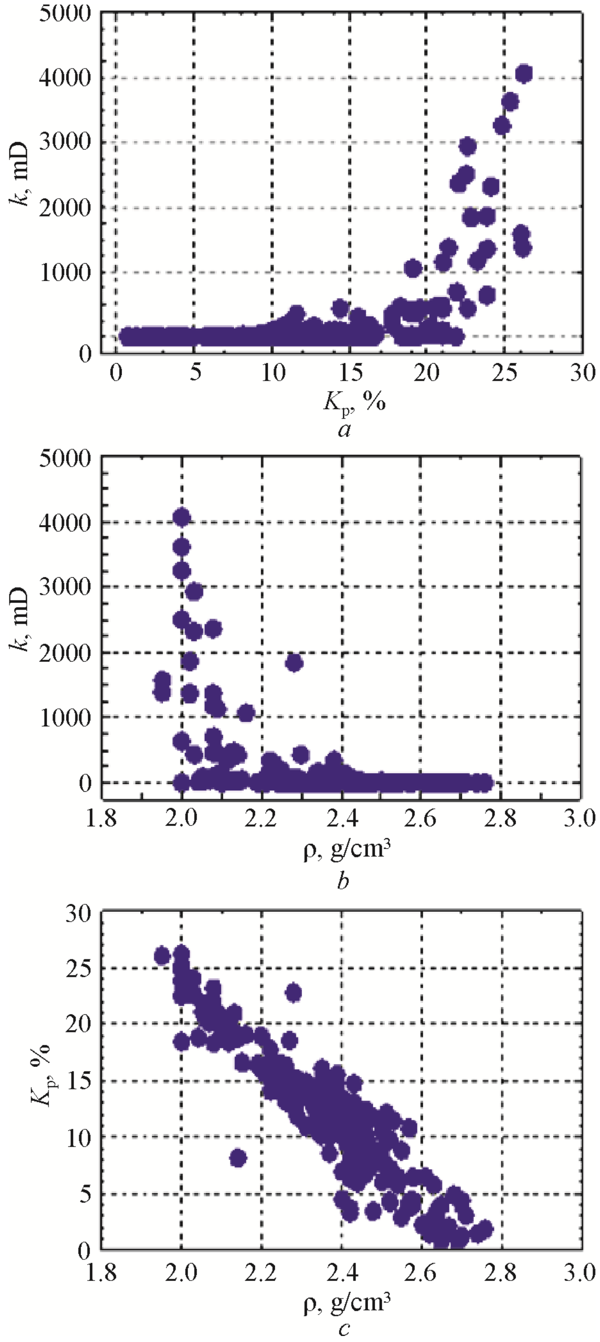

Fig. 1. Correlation fields: *a* – K_p and *k*; *b* – ρ and *k*; *c* – ρ and K_p for one of the fields of Bashkir dome

Analysis of this functions alows to say that values of *r* vary significantly depending on considered range of variation of K_p. That indicates a selective influence of the parameters on each other.

For a complex estimation of influence of values of K_p and ρ on *k*, according to visual analysis of correlation fields series was devided into three classes. The first class includes cores samples with low reservoir properties that are below

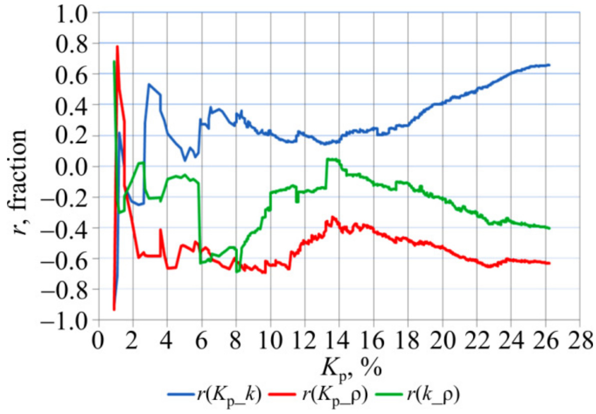

Fig. 2. Change in values of the pair correlation coefficient *r* between K_p and *k*; ρ and *k*; ρ and K_p for a number of fields of Bashkir dome

boundary values of flow (non-reservoir). The second class includes those values within correlation fields, where there is a significant connection between K_p and *k*, ρ and *k*. In this class values of K_p, ρ and *k* are significantly higher than in the first class. That reflects pore reservoir. The third class includes reservoirs with abnormally high values of reservoir properties ("super reservoirs").

Quantitative boundaries of distinguished classes are determined using linear discriminant analysis (LDA) [9-16]. The possibility of using LDA for solving similar problems is given in [17]. With help of visually selected areas linear discriminant functions are sequentially calculated, along which recognition is determined until the entire series is completely divided into classes. Discriminant analysis allows finding transformations of several variables into a single discriminant number. To solve this challenge two discriminant functions have been constructed, according to which the values of Z_1 and Z_2 are calculated. A ratio of Z_1 and Z_2 is shown in Fig. 3.

Class 1 differs from class 2 by values of Z_2. Class 2 differs from class 3 by values of Z_1. Thus, multidirectional values of K_p and ρ influence *k* (determined in laboratory) all the time and by different ways over the whole range of values.

According to results of classification, 35 definitions are assigned to the first class, 460 are assigned to the second class and 131 are assigned to the third. Average values of parameters in the allocated classes differ significantly from each other (Table 1).

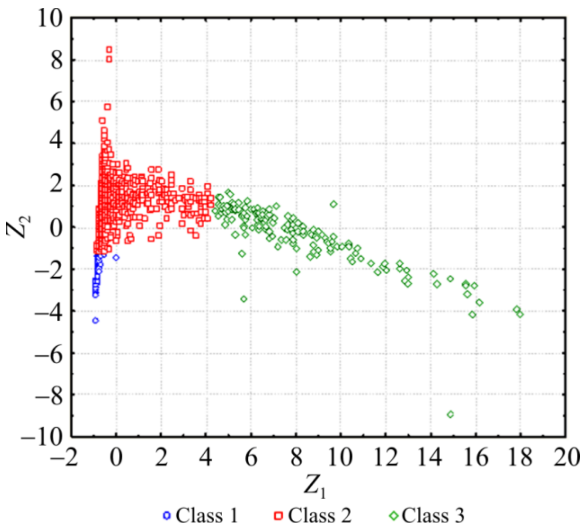

Fig. 3. Ratio of Z_1 and Z_2

Table 1

Statistical characteristics of values of k, K_p, ρ by classes (average values of indicators ± σ)

Indicator	Class 1	Class 2	Class 3
k, mD	0.97 ± 1.05	646 ± 316.6	1026.8 ± 770.8
K_p, %	4.1 ± 2.03	17 ± 4.32	21.2 ± 2.4
ρ, g/cm^3	2.55 ± 0.12	2.23 ± 0.19	2.15 ± 0.2

Table 2 shows correlation coefficients r between parameters for selected classes.

Table 2

Correlation matrix for selected classes

Indicator	k, mD	K_p, %	ρ, g/cm^3
k, mD	1.00 1.00 1.00	0.13 0.52 –0.01	–0.08 –0.52 0.06
K_p, %		1.00 1.00 1.00	–0.41 –0.55 –0.66
ρ, g/cm^3			1.00 1.00 1.00

Remarks: top line – class 1; middle line – class 2; bottom line – class 3.

Analysis of values of correlation coefficients shows that maximum influence of K_p and ρ on values of k is provided by data for class 2. Low values of r prove that there is minimal influence of K_p and ρ on k for classes 1 and 3.

Building of multidimensional models for Visean object for one of Bashkir dome field

For complex prediction of permeability estimation multiple regression method [18-26] was applied. Possibilities of a method for solving similar problems are considered in [27].

Multidimensional regression equations are constructed to predict permeability of each class:

class 1: $k = 13.9 + 4.3K_p - 9.34\rho$; $R = 0.287$,

class 2: $k = -493.4 + 48.9K_p - 42.2\rho$; $R = 0.685$,

class 3: $k = 1350.2 + 38.6K_p - 52.2\rho$; $R = 0.121$.

It is clear that for the class of dense rocks due to the absence of oil reserves in them, construction of prediction dependence of permeability estimation for tasks assigned is not so relevant. Evaluation of reservoir properties in terms of wells with anomalously high permeability is extremely important in describing such processes as premature watering, water breakthroughs or extremely high fluid and oil flow rates in single wells [28]. However, for the study area their fraction, according to [29], for pore-type reservoirs does not exceed 3 %. During three-dimensional modeling the type of a pore reservoir is predominant. Identification of relationships between parameters for that type is most significant in terms of development of a method for tuning a model in the space between wells. Development of reliable permeability estimation for pore-type reservoirs for majority of wells will significantly improve efficiency of geological and hydrodynamic modeling.

Application of the proposed method to build a fluid flow model of a field

Practical use of this technique was performed during building of geological and fluid flow models of the Tl-Bb object of one of the Bashkir dome fields.

During building a three-dimensional flow model of an object two calculations are performed which are as follow: the first case with the initial permeability cube, according to a standardized formula $\mathrm{Ln}(k) = 0.712K_p - 9.2516$ [30], the second case with a modified permeability cube from obtained regression equations for selected classes.

Study of statistical relationships of permeability of a Tl-Bb reservoir of one of the fields has been performed on 152 definitions of core values (*K*-core), according to well logging (*k*-WL), according to the developed methodology (k-K_p, ρ). A comparison of average permeability values determined by different methods is presented in Table 3.

Table 3

Comparison of mean values of *k* determined in different ways

Average value of indicators			Statistical characteristics of indicators	
k-core, mD	*k*-WL, mD	k-K_p, ρ, mD	*t* between *k*-WL and k-K_p ρ	*t* between *k*-core and k-K_p ρ
476.9 ± ± 239.1	605.7 ± ± 556.9	462.9 ± ± 196.4	2.62 0.009	0.15 0.539

Comparison of average values of *k*-core and k-K_p, ρ showed that they are statistically indistinguishable. The correlation coefficient between *k*-core and *k*-WL is 0.41, correlation coefficient between *k*-core and k-K_p ρ is 0.75.

During modeling of rock density in three-dimensional space of a geological and fluid flow model a high correlation coefficient between K_p and ρ for the field under study is taken into account. Density is determined as a function of K_p and calculated for each cell of fluid flow model: $\rho = 2.616 - 0.0247\ K_p$, $R^2 = 0.907$.

Parameter *k* was calculated based on regression equations for each porosity class in a three-dimensional fluid flow model of a Tl-Bb object of a studied field. When *k* was distributed according to the proposed procedure (k-K_p, ρ) there was the best convergence obtained in a fluid flow model between calculated and actual data on oil production (Fig. 4) with respect to calculation with *k*, determined by well logging (*k*-WL). Permeability distribution was performed as the initial step of history matching without additional tuning of each well configuration.

Comparison of *k*-WL with k-K_p, ρ shows that there is a smaller spread of values of the parameter obtained by the presented method (Fig. 4). This allowed not to set high permeability values in a fluid flow model and to exclude unjustified inhomogeneity in the distribution of the parameter in space between wells.

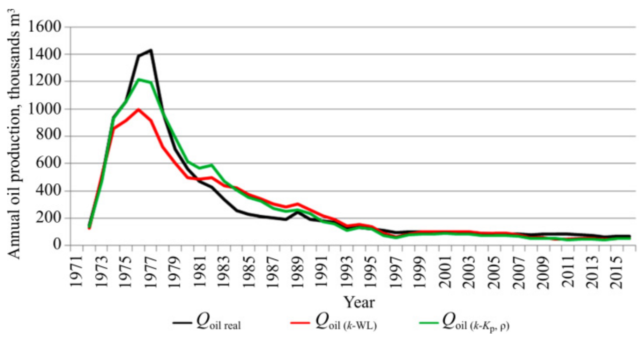

Fig. 4. Comparison of real and estimated annual oil production for an entire object

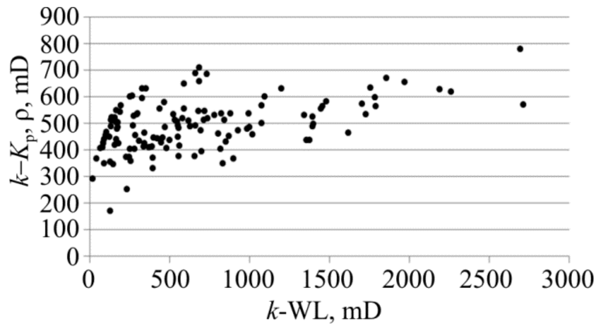

Fig. 5. Comparison of permeability by wells according to well logging (*k*-WL) and calculated by the proposed method (k-K_p, ρ)

There are calculations of annual oil production for a number of high production wells below operating at the initial period of development of a Visean object of the studied field (Fig. 6).

It should be noted that the best convergence of calculated and real oil production rates by the proposed method was obtained at the initial moment of field development (see Fig. 4, 6). Ususally this period is characterized by no water in well production. So, there is a flow of one fluid. That flow tells about the absolute permeability of a rock (the one that is directly determined by petrophysical studies). During further development of the field two-phase fluid flow is described and controled by phase permeability. The most adequate value of *k* in the late stages of field development is determined by results of well test, but this definition of permeability can rather be attributed to dynamic characterization of a reservoir, since this value can change over time as a result of ongoing geological and technical measures and a change in state of a bottomhole formation zone.

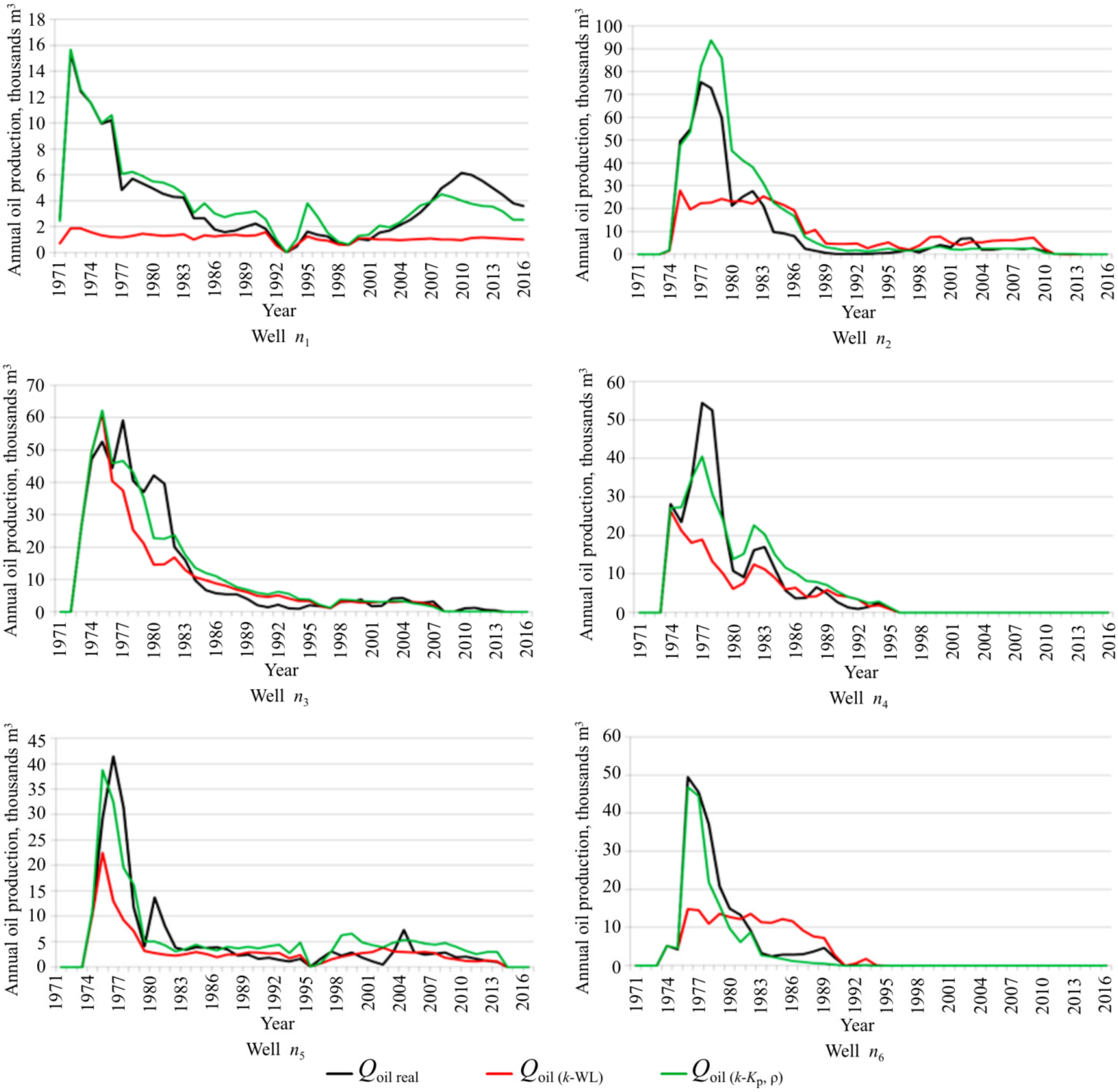

Fig. 6. Comparison of real and estimated annual oil production by wells n_1–n_6

Sometimes determination of k by well test is not enought for a correct distribution of k over an area and section of a field. During building of a three-dimensional fluid flow model of a field it is most important to determine absolute permeability of a reservoir (static parameter).

Conclusion

The paper shows that in a number of porous reservoirs permeability largely depends on density of rock among other things. As a result, the methodology for taking into account rock density with a permeability prediction was proposed for the first time. It significantly increases reliability of permeability evaluation in comparison with a logarithmic function on porosity. Influence of rock density in determination of permeability was not taken into account previously.

The proposed approach of predicting permeability has a much better convergence of a fluid flow model with development history, especially at initial period of time. First, this makes a geological and fluid flow model more reliable. Secondly, it can significantly reduce time of permeability tuning when adapting a fluid flow model. So, there is no need of manual permeability adjustment that is always subjective and has no geological justification.

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