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Estimation of multistage hydraulic fracturing parameters using 4D simulation

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Abstract
At the present stage, most oil and gas condensate fields in the southern part of the East Siberian oil and gas province are characterized by an increasing proportion of difficult oil reserves in tight reservoirs. Multistage hydraulic fracturing (MHF) is proposed for the offshore Challenger Sea field (Southeast Dome). The implementation of this technique at a shelf will be a source of additional risks. For example, the properties of the RR-2 overlying seal have not been unambiguously assessed, and there are a number of geological uncertainties, such as the tectonic regime. However, there are a number of arguments in favor of MHF: heterogeneity of the reservoir; low permeability; low water cut of the field; sufficient thickness of the pay zone; and the overlying seal. One more positive factor is that sand ingress is not observed in the process of oil production. The selection of a principal well completion scheme on the eastern side of the RR-7 formation is aimed at effectively recovering the remaining reserves. The objectives of the study performed are: to create a geological and hydrodynamic model of the Challenger Sea (Southeast Dome); develop 1D and 3D geomechanical models; evaluate oil production forecasts based on fundamentally different well completion schemes; and determine the optimum parameters for multistage hydraulic fracturing. The research methods included: petrophysical methods; logging methods; core studies; drilling reports and formation testing data; and 3D, 4D geomechanical simulation. Other geophysical methods included acoustic logging, density logging, and gamma-ray logging. After building a geomechanical model of the reservoir at the beginning of drilling, a hydrodynamic calculation was performed. This established the reservoir pressures and saturations at certain points in time. The results made it possible for the principal stress directions, the values of effective and principal stresses, and the values of elastic strains to be determined. In order to assess MGF process efficiency, production forecasts were made using a hydrodynamic model for an exploration well with conventional completion (perforated liner) and with five-stage MGF. In the first case, the accumulated production was 144 kt over 15 years, and in the second case, 125 kt over 17 years. The difference in cumulative production is due to different initial well flow rates, as well as the rate of oil withdrawal during the first few years of development. Thereafter, the production and daily flow rate curves showed similar behavior. In order to select the most effective option, an economic analysis of the efficiency was performed.

Keywords
oil and gas condensate field, oil, well, core, porosity, geological model, geomechanical model, geological and hydrodynamic model (reservoir simulation model), acoustic logging, density logging

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СВОЙСТВА ГОРНЫХ ПОРОД. ГЕОМЕХАНИКА И ГЕОФИЗИКА

Научная статья

Оценка параметров многостадийного гидравлического разрыва пласта с помощью 4D моделирования

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Аннотация
На современном этапе большинство нефтегазоконденсатных месторождений южной части Восточно-Сибирской нефтегазоносной провинции характеризуется ростом доли трудноизвлекаемых запасов нефти в плотных коллекторах. В акватории моря на месторождении Челенджер-море (Юго-Вос-

точный купол) предлагается применить многостадийный гидравлический разрыв пласта (МГРП). Внедрение этой технологии на шельфе станет источником дополнительных рисков. Например, однозначно не оценены свойства покрышки RR-2, есть ряд геологических неопределенностей, например, тектонический режим. Однако есть ряд аргументов в пользу МГРП – неоднородность коллектора, небольшая проницаемость, низкая обводненность месторождения, достаточная мощность продуктивного пласта и покрышки. Также хорошим фактором является то, что в процессе добычи не наблюдается пескопроявлений. Выбор принципиальной схемы заканчивания скважин на восточном борту пласта RR-7 производится с целью эффективного извлечения остаточных запасов. Задачи проведенной работы заключаются в создании геолого-гидродинамической модели Челенджер-море (Юго-Восточный купол); разработке 1D и 3D геомеханических моделей; оценке прогнозов по добыче с использованием принципиально разных схем заканчивания скважин; определении оптимальных параметров многостадийного гидравлического разрыва пласта. Методы исследований включают в себя петрофизические методы; методы ГИС; керновые исследования; буровые сводки и данные об испытаниях пластов; 3, 4D геомеханическое моделирование; геофизические методы: акустический каротаж, плотностной каротаж, гамма-каротаж. После построения геомеханической модели пласта на начало бурения производится гидродинамический расчет, по итогам которого определены кубы пластовых давлений и насыщений на определенные моменты времени. Полученные результаты позволили определить направления главных напряжений, значения эффективных и главных напряжений, а также величины упругих деформаций. Для оценки технологической эффективности МГРП были произведены прогнозы добычи на гидродинамической модели по разведочной скважине с традиционным заканчиванием (перфорированный хвостовик) с пятью стадиями МГРП. В первом случае накопленная добыча составила 144 тыс. т за 15 лет, во втором – 125 тыс. т за 17 лет. Разница в накопленной добыче обусловлена разными стартовыми дебитами скважин, а также темпами отбора в первые несколько лет разработки, а в дальнейшем кривые добычи и суточных дебитов демонстрировали схожее поведение. Для выбора наиболее эффективного варианта выполнен экономический анализ эффективности.

Ключевые слова

нефтегазоконденсатное месторождение, нефть, скважина, керн, пористость, геологическая модель, геомеханическая модель, геолого-гидродинамическая модель, акустический каротаж, плотностной каротаж

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Introduction

At the present stage, most oil and gas condensate fields in the southern part of the East Siberian oil and gas province are characterized by an increasing number of difficult oil reserves in tight reservoirs [1, 2].

Multistage hydraulic fracturing (MHF) is an effective method of enhancing oil recovery and production in terrigenous sediments all over the world [3, 4].

In the offshore area of the Challenger Sea field (Southeast Dome), the application of MHF is proposed. The implementation of this technique at a shelf will be a source of additional risks. For example, the properties of the RR-2 overlying seal have not been unambiguously assessed, and there are a number of geological uncertainties, such as the tectonic regime. However, there are arguments in favor of MHF: heterogeneity of the reservoir [7, 8]; low permeability; low water cut of the field; sufficient thickness of the productive formation and the overlying seal. Another positive factor is that sand ingress is not observed in the process of oil production.

General information about the field

The Challenger Sea oil and gas condensate field (Southeast Dome) is located in the territory of Stoykovsky District of Primorsky Region, 40 km southeast of the town of Serov on the Southeast Stoykovsky shelf, at a latitude of the southern end of the Starkovsky Bay.

The Challenger Sea field was discovered in 2011. The field is multilayer and contains gas-condensate and oil-gas-condensate pools of different types, such as lithological, and layer-arch. In terms of structure, the field is very complex, and large in terms of the size of its reserves [11, 12].

Geographically, the area under consideration is confined to the southern range of the East Siberian ridge. The terrain is hilly, the landscape is partly forested and partly marshy. The maximum altitude does not exceed 200 m above sea level. The bottom relief in the area of the field is poorly dissected. The climate of the area is typical of Primorye: winters are harsh, snowy, windy, with frequent snowstorms.

Tectonically, the Challenger Sea field (Southeast Dome) is confined to a large megantycline located in the northern part of the eponymous anticlinal zone, extending for more than 200 km on the shelf of the East Siberian Ridge in the northwestern direction [13, 14].

The southeastern shelf sequence is composed of Mesozoic and Cenozoic sediments, forming two structural levels. The lower level, basement, is composed of faulted and folded metamorphic rocks of Cretaceous age. The sedimentary cover (section) consists exclusively of Cenozoic sediments of Neogene age. In the sedimentary section, Ust-Davydovsky and Prikhankaisky horizons can be found. The latter, in turn, is subdivided into Lower Prikhankaisky and Upper Prikhankaisky subhorizons. The thickness of the Prikhankaisky horizon ranges 2000 to 3000 m, increasing from northeast to southwest. The Lower Prikhankaisky horizon is composed of gray sandstone, often silty and clayey, with interlayers of siltstone and clay. The Upper Prikhankaisky horizon is composed of sandstone and siltstone in the lower part, and loose sands with interlayers of clays in the upper part.

The productive (pay) oil and gas reservoirs are confined to the Upper Prikhankaisky subhorizon. The main productive formations in the Challenger Sea field (Southeast Dome) are RR-2, RRI-1, RRI-2 formations.

Research techniques

The research methods and information sources included petrophysical methods: logging methods; core studies; drilling reports and formation testing data; and 3D, 4D geomechanical simulation. The geophysical methods included acoustic logging, density logging, gamma-ray logging.

Technical part

The research was conducted with the RR-2 formation. The pay formation is characterized by lateral heterogeneity. The permeability and porosity at the eastern edge are significantly worse than those at the western edge, so an MHF option was considered for effective recovery of residual oil reserves.

Construction of a 3D geomechanical model of the Challenger Sea field (Southeast Dome)

Core Studies. The core is the only direct source of information about a pay zone and an overlying seal used in both geological-and-hydrodynamic and geomechanical simulations [15, 16]. Special studies were carried out on core samples from wells drilled at the Challenger Sea field (Southeast Dome). Aimed at clarifying the mechanical properties of rocks and to build a reliable geomechanical model.

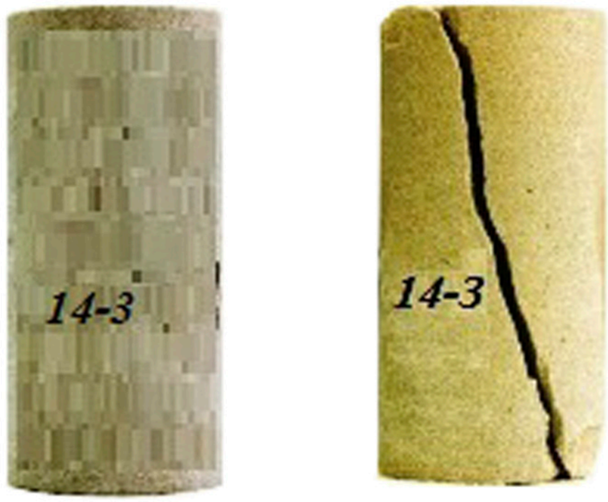

Fig. 1. Cylindrical core sample before and after a test to determine ultimate compressive strength

Core from wells 88-R and 120-R (at Challenger Sea field, only within RR-2 formation) was used in the studies. The reservoir characterization by core is poor, and rock material was sampled in only two wells from the upper and middle parts of the reservoir. When selecting samples, the lithological features of the rocks were taken into account. Before selecting the samples, the core was examined, the primary description of a rock was studied, and the thin sections were viewed under a microscope (Fig. 1). A total of 87 samples were examined.

Construction of one-dimensional geomechanical models

A one-dimensional geomechanical model is a set of elastic and strength properties, and principal stresses curves along a well path. These properties are: pore pressure; vertical stress (rock pressure); maximum and minimum horizontal stress; static and dynamic Young's modulus; Poisson's ratio; ultimate compressive strength; ultimate tensile strength; and internal friction angle.

This data set allows for permissible drilling fluid parameters to be determined, in order to prevent problems during drilling, prevent sand ingress during production well operation, and plan hydraulic fracturing in horizontal and inclined wells [17, 18]. An 1D geomechanical model for one of the key wells is shown in Fig. 2.

When creating the geomechanical model, a variety of data, including well logging methods, core studies, drilling reports, and formation testing data was used [19, 20]. The required amount of methods is presented in Table 1.

Geological model and hydrodynamics

Construction of a 3D geomechanical model at the beginning of drilling was made on the basis of a geological model. The change in the stress-strain state of a formation over time is taken into account through using hydrodynamic simulation results.

Geomechanical simulation places stringent requirements on a geologic model. Therefore a new geologic model was built for this project taking into account all of the geologic information as well as the technical characteristics required for successful geomechanical calculations.

The model was built based on a 100×100 m grid, the thickness of cells was 1 m on average, and the total number of cells did not exceed 300 thousand. Such parameters were selected empirically, as geomechanical and hydrodynamic calculations require large computing power. In addition, the RR-2 reservoir overlying seal was superimposed in the geological model to simulate the strength properties of the seal rock in detail. All disjunctive dislocations were included in the model.

3D geomechanical model: at the beginning of drilling

A 3D geomechanical model at the beginning of drilling was constructed by reconstructing a stress-strain state on a relatively large fragment of the Earth's crust. For this purpose, additional cells with rocks were added to the top, bottom, and sides of a geomechanical model, which "pressed" on the cells in the model itself and thus formed stresses [21]. In addition, all cells were filled with elastic and strength properties of rocks and faults in accordance with those permeability and porosity dependences that were obtained at the one-dimensional simulation stage (Fig. 3). In Fig. 3, a rectangle marks the area where the geological model of the reservoir was built.

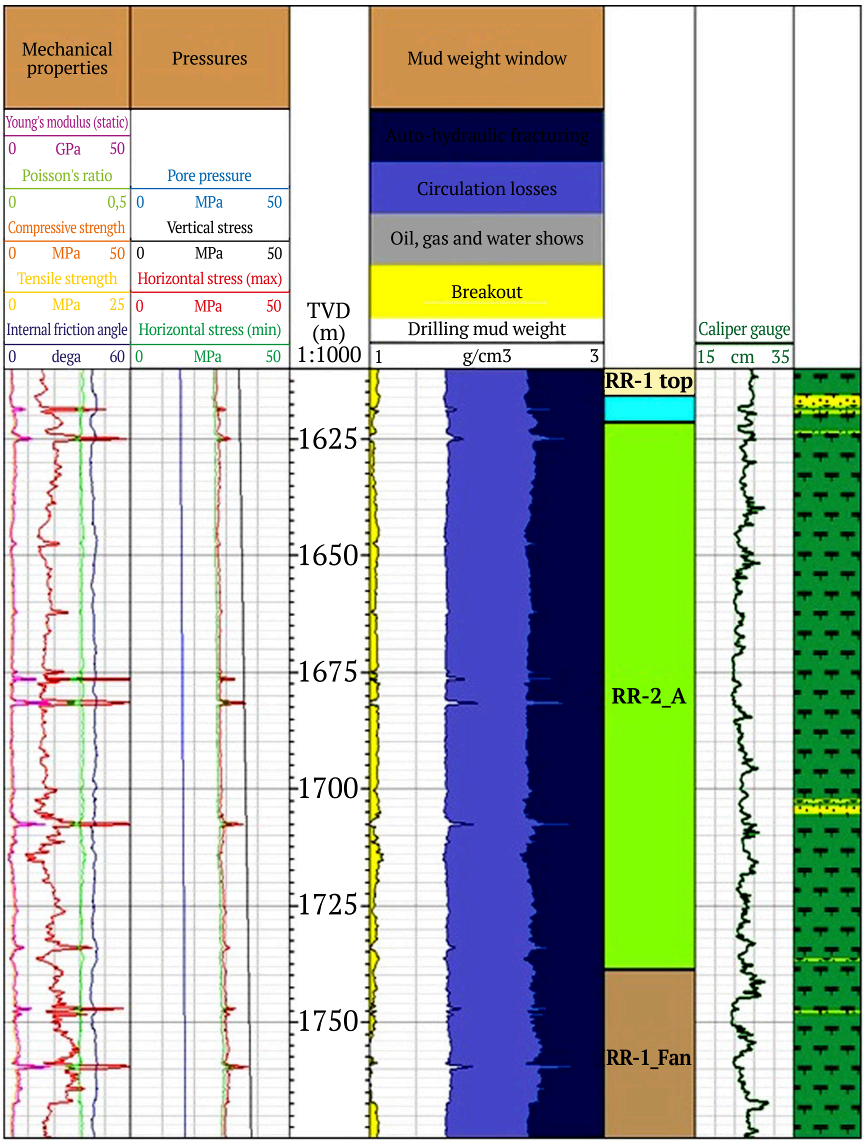

Fig. 2. 1D geomechanical model for 22-R well at the Challenger Sea field (Southeast Dome)

Table 1

Assessment of the completeness of initial data on the studies performed

Data type	Data source	Applications	Degree of confidence
Geomechanical logging			
Acoustic logging	A set of exploration well logging methods	Geomechanical model construction – elastic properties	Low
Density logging	Recorded in the majority of wells in the field	Geomechanical model construction – elastic properties and vertical stress	High
Gamma-ray logging	Recorded in all wells	Calculation of internal friction angle	
Core			
Young's modulus (dynamic)	Laboratory research	Calculation of strength properties	Medium — new laboratory tests; core characterizes only the productive part of the reservoir
Poisson's ratio		Calculation of horizontal stresses	
Young's modulus (static)		Calculation of horizontal stresses	
Ultimate compressive strength		Evaluation of wellbore stability	
Tensile strength			
Other data			
Information about drilling problems	Drilling reports	Geomechanical model calibration	Medium - no drilling problems in the formation interval
Initial reservoir pressure information	Sampling and dynamic well test data	Geomechanical model calibration and pore pressure assessment	High
Stratigraphic picks	Diagram of detailed correlation from the geomechanical model	Applied in the construction of permeability and porosity dependencies, prediction of properties	High
Sequence lithology	Core description, well log interpretation data		High

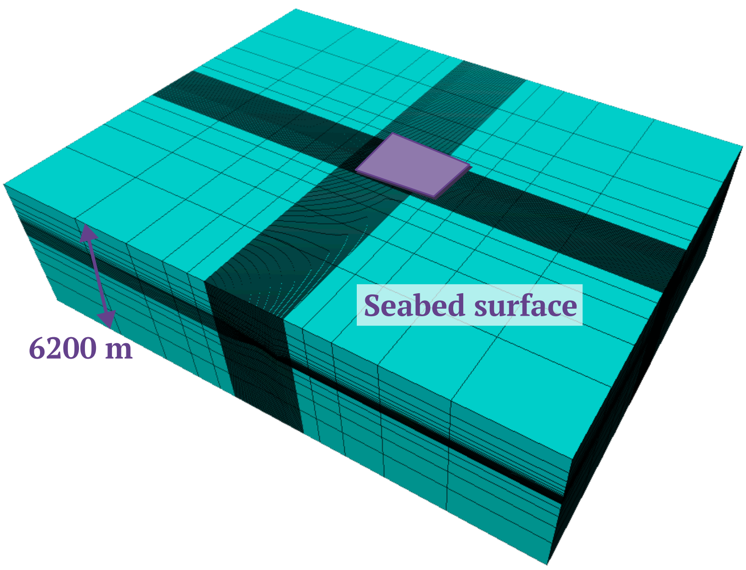

Fig. 3. General view of geomechanical grid

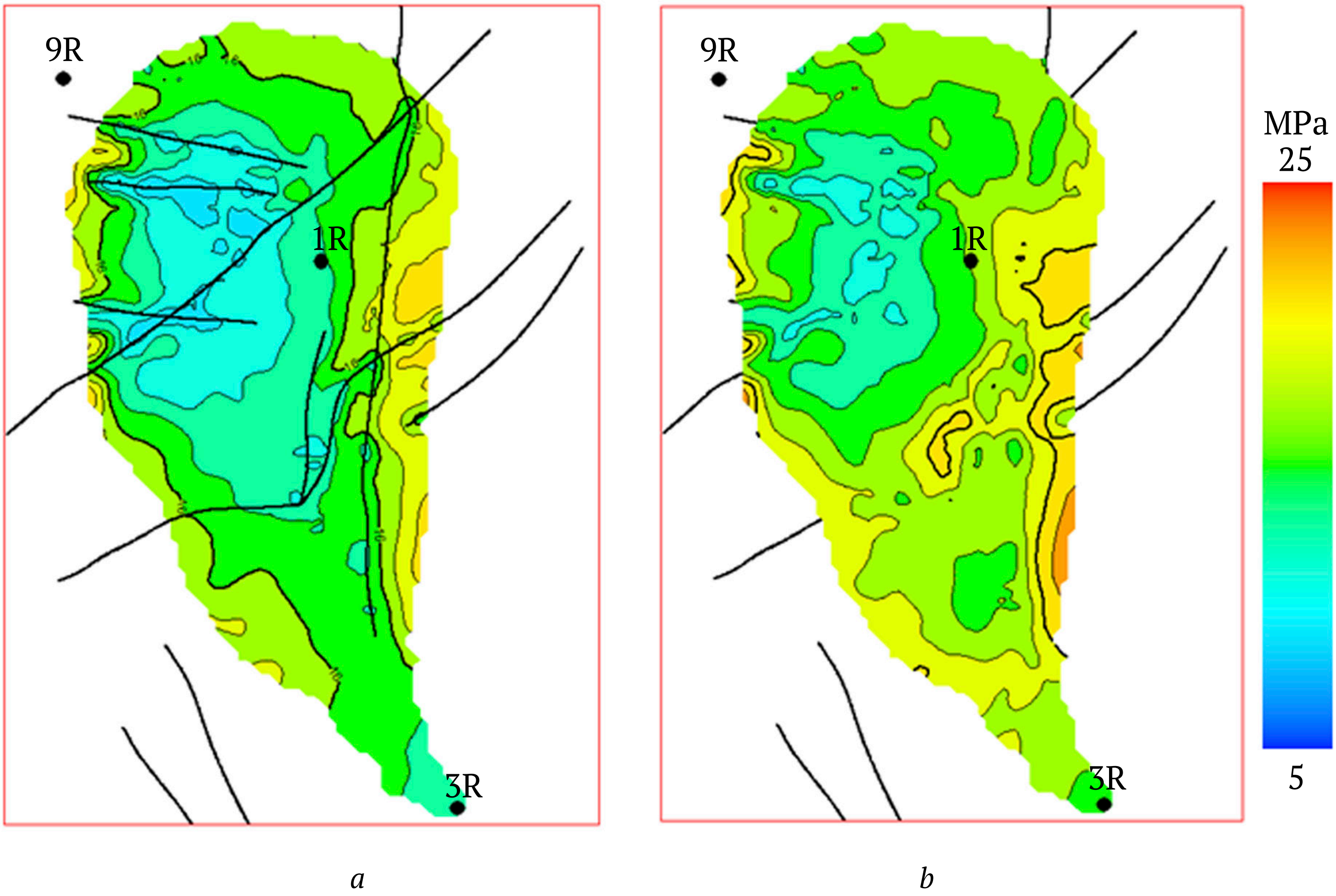

Fig. 4. Comparison of effective stress maps as of 01.01.2015 (*a*) and 01.01.2022 (*b*)

Discussion: the author's point of view and direct research

In this paper, we calculated the state change over time (4D geomechanical model). After building a geomechanical model of the reservoir at the beginning of drilling, a hydrodynamic calculation was performed. This established the reservoir pressures and saturations at certain points in time. These were the input parameters for calculating a stress-strain state at these points in time. As a result of the calculation, the following was obtained: the directions of principal stresses; the values of effective and principal stresses (Fig. 4); as well as the values of elastic strains. In addition, Mohr's circles can be used to estimate how close the rock is to fracture under reservoir conditions. In Figure 4, the fracture line is shown in dark green, and the ratios of normal and tangential stresses in a single cell are shown in the form of a classic Mohr circle. When a stress circle touches the fracture line, this leads to rock continuity failure and a fault or fracture is formed. In the case of the RR-2 reservoir, the rocks are in a stable state at this point in time and during the development period for which the model was built.

A one-dimensional post-drilling geomechanical model allows multi-stage hydraulic fracturing to be planned. This includes the number of stages, positioning multi-stage hydraulic fracturing ports and packers.

The economic efficiency of the two options is presented in Table 2.

Table 2

Performance (efficiency) indicators

Indicator	Values	
	Option 1	Option 2
Internal rate of return (IRR), %	15	22
Accumulated production, kt	165	212
Net present value (NPV), million rubles	327	612
Payback period, year	7.5	5

In order to assess the process efficiency of MGF, production forecasts were made using a hydrodynamic model for an exploration well with conventional completion (perforated liner) and with five-stage MGF. In the first case, the accumulated production was 165 kt over 15 years, and in the second case, 212 kt over 17 years. The difference in the cumulative production is due to the different initial well flow rates, as well as the rate of oil withdrawal during the first few years of development. Thereafter, the production and daily flow rate curves showed similar behavior. An economic analysis of the efficiency was performed, in order to select the most effective option.

A positive economic effect is the most important indicator of the success of the methods used and a prerequisite for their implementation. As part of the research, the economic effect of drilling of a new extended-reach exploration well with conventional completion and that of drilling the same well with MHF were evaluated and compared. Such economic indicators as costs, revenue, depreciation and residual value of a well, net profit (cash flow) were calculated, including with discounting (E = 10 %). This also took into account: income tax, export duty, mineral extraction tax, and property tax. The cost-effectiveness was assessed by three indicators: NPV, IRR, and payback period.

Conclusion

When assessing the parameters of multistage hydraulic fracturing using 4D simulation, the following tasks were addressed:

1. The advantages and disadvantages of the parameters of the MHF technique on a shelf were analyzed.
2. A preliminary 4D geomechanical model of RR-2 reservoir of the Challenger Sea field (Southeast Dome) was built.
3. 1D and 3D geomechanical models were developed and additional core studies were conducted at Odoptu Sea, taking into account RR-2 reservoir features to refine the geomechanical model.
4. Production forecasts were assessed with the use of fundamentally different well completion schemes.
5. The optimal parameters of multistage hydraulic fracturing were determined.
6. Based on the hydrodynamic model, the predicted production from a design well with conventional completion (perforated liner in a horizontal wellbore) and with multistage hydraulic fracturing (5 stages) were calculated.
7. The economic efficiency of the development options without and with MHF was evaluated. The base case (option) is economically viable, IRR is 15 %, NPV is 327 mln rubles. The second option is economically viable at discount rate of 22 %; NPV is 612 mln rubles.
8. Applying MHF (5 stages) will almost double NPV and increase the cumulative production by 30 %.

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