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Evaluating the Impact of the Development of the Chayanda Field on Surface Ground Subsidence

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Abstract—In this paper we present the results of studies of the Botuobin, Talakh, and Khamakin reservoirs of the Vendian period in the Chayanda hydrocarbon field (Eastern Siberia). Based on an analysis of variations in the petrophysical parameters of reservoirs upon an increase in effective pressure from 37 to 57 MPa, i.e., under conditions simulating the development of a field for depletion, changes in the volume and compressibility of the pore space are estimated. In this case, the porosity coefficient decreases by 0.043 abs. %, while the compressibility of the pore space decreases by 0.228 1/GPa. The average volumetric compression strain increases by 0.096%, which means a reduction in the volume of developed reservoirs by almost 0.1% relative to the beginning of development. A deformable formation model developed by Yu.O. Kuzmin based on the geodynamic history of the development of deposits is applied to estimate the magnitude of possible subsidence of the ground surface during development. The maximal values of possible surface subsidence (drawdowns) upon a decrease in reservoir fluid pressure by 5 MPa are estimated to be 0.33 m with allowance for the dynamics of petrophysical parameters and 0.335 m with no allowance for it. The maximal drawdowns are already estimated at 0.60 and 0.65 m upon a decrease in reservoir pressure by 10 MPa and 0.78 and 0.83 m upon a complete depletion of reservoir energy, respectively. The results of the studies show that taking into account the changes in petrophysical characteristics caused by the field development processes alters the estimate of the deformation state of the rock massif and the ground surface above the deposit and, consequently, the estimate of the level of geodynamic risk of oil-and-gas complex objects.

Keywords: reservoir, porosity structure, pore compressibility, reservoir pressure, surface subsidence, field development, geomechanical modeling

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INTRODUCTION

The long-term development of hydrocarbon deposits is accompanied by two forms of geodynamic processes: extensive subsidence of the territory of the entire deposit and local deformation activation of fault zones (*Subsidence*..., 1995; Kuzmin, 1999, 2002; Vasiliev et al., 2017, 2019, 2020). Numerous geodetic measurements carried out both in seismically active and aseismic oil and gas regions, including offshore fields and underground gas storages, showed identical forms of manifestation of anomalous geodynamic activity due to a decrease (increase) or cyclic change in reservoir pressure (Kuzmin, 2021, 2022). The increased level of environmental and industrial hazard of the infrastructure facilities of the developed deposits determines the relevance of conducting research on the current geodynamic state of the subsoil.

It is well known that petrophysical characteristics of the formation such as porosity and compressibility coefficient of the pore space decrease as the formation pressure decreases and the effective stress increases due to the development of oil and gas fields. This is especially true for gas fields that are developed in the depletion mode. As it turned out, the most contrasting intense changes in poroelastic parameters are experienced by reservoir rocks with fractured porosity (Zhukov, 2010; Zhukov and Kuzmin, 2020, 2021, 2022). The poroelastic parameters of reservoirs are one of the main indicators, the monitoring of which is necessary during field development. It is important to evaluate the change in the final calculated amplitude of subsidence of the ground surface upon a decrease in the values of poroelastic parameters during the development period, especially the compressibility coefficient of the pore space.

Using the example of the Chayanda oil and gas condensate field in Eastern Siberia, geomechanical modeling was carried out and a comparative estimate of the amplitudes of subsidence of the ground surface was given when the fluid pressure in the reservoir decreased by 5, 10, and 13 MPa, both with and without allowance for changes in the petrophysical properties of rocks.

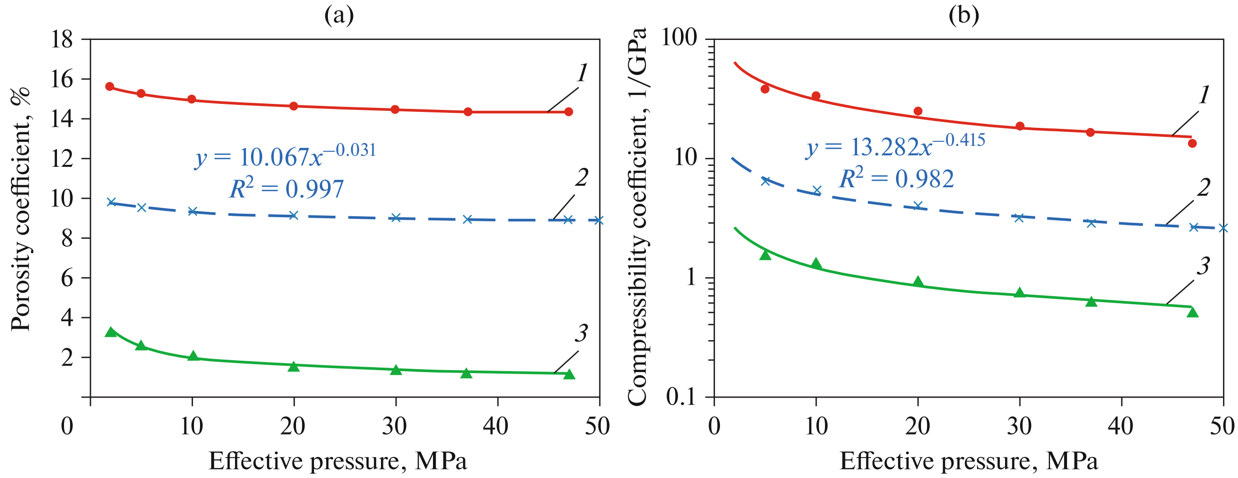

Fig. 1. Changes in (a) the porosity coefficient and (b) the pore volume compressibility coefficient upon an increase in effective pressure in samples with maximal (*1*), average (*2*), and minimal (*3*) parameter values: (a) (*1*) m = 15.6%, (*2*) average, and (*3*) m = 2.6%. (b) (*1*) m = 3.3%, (*2*) average, and (*3*) m = 13.2%.

RESULTS

Equipment and Methods of Experimental Research

Experimental studies make it possible to determine directly the volume of the pore fluid squeezed out of the sample at an increase in its all-round compression and, based on the results, calculate both the change in porosity and the volumetric deformation of the sample (Zhukov and Lyugai, 2016). The deformation is calculated with allowance for the well-known fact that the compressibility coefficient of the pore space by several orders of magnitude exceeds the compressibility of the rock skeleton.

The porosity coefficient under conditions simulating reservoir conditions was determined with allowance for the volume of fluid displaced from the pore space of the sample:

$$m = m_{atm} - \Delta V_{por}/V, \tag{1}$$

where m_{atm} is the coefficient of porosity under atmospheric conditions, units of pressure; ΔV_{por} is the volume of pore fluid squeezed out of the sample (change in pore volume), cm^3; and V is the sample volume, cm^3.

The C_{por} compressibility of the pore space was determined by the formula

$$C_{por} = \left(\Delta V_{por}/V_{por}\right)/\Delta P_{eff}, \tag{2}$$

where ΔV_{por} is the change in the volume of the pore space, cm^3 (the volume of the pore fluid squeezed out of the sample); V_{por} is the volume of the pore space of the sample, cm^3; and ΔP_{eff} is the effective pressure changes, MPa or GPa.

In the high-pressure plant, the effective pressure was increased in steps, increasing the over-around pressure and keeping the pore pressure unchanged. At each stage, the volume of the pore fluid squeezed out of the sample was measured and the values of the porosity coefficient and compressibility of the pore space were calculated using formulas (1) and (2).

Changing the Porosity Coefficient

The results of experimental studies showed that the dependence of the average value of porosity coefficient m on effective pressure P_{eff} (Fig. 1a) can be described with a high degree of reliability ($R^2 = 0.99$) by the following power law:

$$m = 10.067 P_{eff}^{-0.031}. \tag{3}$$

When developing a reservoir, a decrease in reservoir pressure by 10 MPa (increase in effective pressure by 10 MPa) will lead to a decrease in porosity in abs. % from 8.976 to 8.933, or by 0.043 abs. %. Taking the value of the porosity coefficient (8.975%) at the beginning of development (at $P_{eff} = 37$ MPa) as 100% and comparing it with the value of the porosity coefficient (8.933%) at $P_{eff} = 47$ MPa, we find that it decreased by 0.48%. By the end of the development, the effective pressure can reach 13 MPa, while the porosity will decrease to 8.916 abs. %, or by 0.061 abs. % relative to the beginning of development.

Change in the Compressibility Coefficient of the Pore Space

The dependence of the average value of the compressibility coefficient on the effective pressure (Fig. 1b) with a high degree of reliability ($R^2 = 0.97$) is described by the power equation:

$$C_{por} = 13.282 P_{eff}^{-0.415}. \tag{4}$$

An increase in effective pressure during reservoir development by 10 MPa will lead to a decrease in the average value of the pore-space compressibility coefficient from 2.844 1/GPa (at $P_{eff} = 37$ MPa) to 2.685 1/GPa (at $P_{eff} = 47$ MPa), or by 0.160 1/GPa, which means a decrease of 5.62% from the value at the beginning of development. At the end of development, the increase in effective pressure may be 13 MPa, while the compressibility coefficient of the pore space will decrease to 2.616 1/GPa, or by 0.228 1/GPa (8.01%) relative to the beginning of development.

Determination of the Structure of Porosity and Its Changes

The source of changes in the structure of the pore space of the reservoir during the transition from atmospheric to reservoir conditions can be determined using the dependence of normalized longitudinal wave velocity $\tilde{V}_P$ on porosity (Turank et al., 1994; Zhukov, 2012; Zhukov and Kuzmin, 2020). In this case, the normalized longitudinal wave velocity is the ratio of the measured longitudinal wave velocity in the sample ($V_{P\ \mathrm{meas}}$) to its velocity in the mineral skeleton ($V_{P\ \mathrm{sc}}$), which characterizes the integral effect of pores and cracks on the rock (Turank et al., 1994):

$$\tilde{V}_P = 100\left(V_{P\,\mathrm{meas}}/V_{P\ \mathrm{sc}}\right). \tag{5}$$

According to expression (5), at a 100% value of the normalized velocity, the rock has neither cracks nor pores. A decrease in the normalized velocity will reflect the presence of intergranular (m_{ig}) and fracture (m_{fr}) porosity in the rock. The effect of intergranular porosity and fracture voidness on the propagation velocity of elastic waves is different. Changes in the porosity of real rocks, for which there is information about both intergranular and fractured porosity, will be located in the area limited by the conditions of the equations

$$\tilde{V}_P = 1.6m_{\mathrm{ig}} + 100, \tag{6}$$

$$\tilde{V}_P = 22.0m_{\mathrm{fr}} + 100. \tag{7}$$

Changes in the structure of the pore space of the reservoir during the transition from atmospheric conditions to reservoir conditions can be represented as a dependence of the normalized velocity of compressional waves on porosity.

Figure 2 shows the results of studies of individual reservoir samples with the highest values of fractured porosity of the reservoir. As can be seen, the slope of the lines of dependence of the normalized velocity on porosity varies from –5.89 to –13.88, which indicates a decrease in both the fracture and intergranular porosity components as the effective pressure increases. If only the intergranular porosity changes, this value would be –1.6 in accordance with Eq. (6), and if only the fracture component is changed, it would be already –22.0 in accordance with Eq. (7). The figure also shows the line and the equation of dependence (7) for the case when only fracture porosity changes.

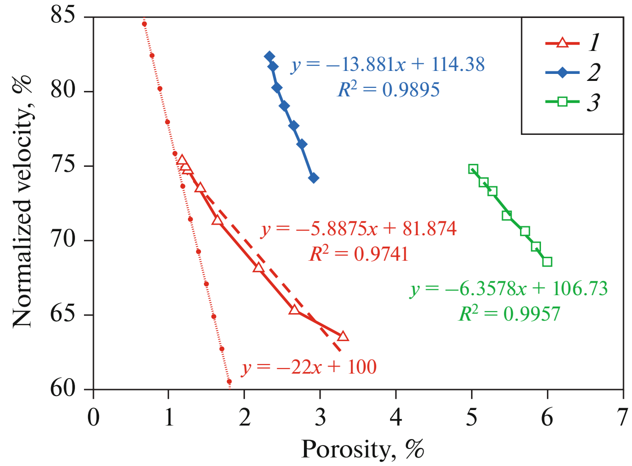

Fig. 2. Dependences of the change in the normalized velocity of longitudinal waves on porosity for reservoir samples with the highest values of fractured porosity under conditions simulating the transition from atmospheric conditions at the initial stage of field development to reservoir conditions (effective pressure varies from 37 to 47 MPa). m_{fr} = (*1*) 1.134, (*2*) 0.889, and (*3*) 0.875%. Here and below in Figs. 3–5, the dotted line is the smoothed initial time series.

For each of the three studied samples, graphs of changes in both the total porosity and its two components were obtained with an increase in effective pressure up to 47 MPa (Fig. 3). In the first approximation, the change in porosity at an increase in effective pressure from 37 to 47 MPa can be considered as a model for changing the structure of the pore space upon a decrease in pore pressure by 10 MPa for areas of the field with increased reservoir fracturing.

In connection with the complex and heterogeneous structure of the reservoir, we also consider the change in the structure of the pore space of the reservoir during the transition from atmospheric conditions to reservoir conditions for individual reservoir samples with the highest values of intergranular fractured porosity of the reservoir.

As can be seen from the data in Fig. 4, the slope of the line of dependence of the normalized velocity on the porosity of the samples varies from –12.26 to –8.22, which indicates a decrease in both the fracture and intergranular components of porosity with increasing effective pressure. The graph and equation of dependence (6) are also given for the case when only intergranular porosity changes.

For each of the three studied samples, Fig. 5 shows graphs of changes in both the total porosity and its two components upon an increase in effective pressure up to 47 MPa. In the first approximation, these changes (in the range of effective pressures of 37–47 MPa) can be considered as a model for changing the structure of the pore space upon a decrease in pore pressure by 10 MPa for areas of the field with the least reservoir fracturing.

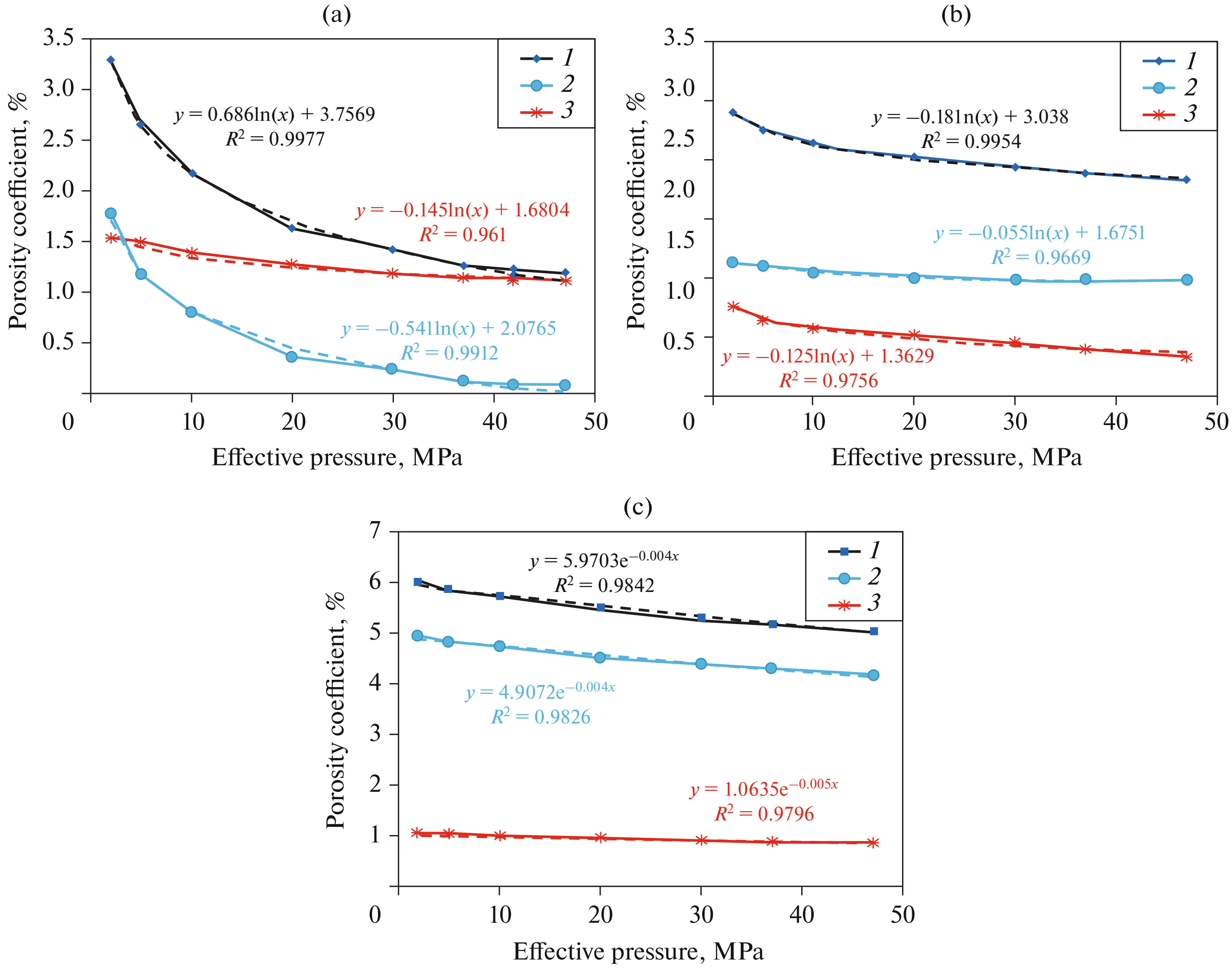

Fig. 3. Change in total porosity (*1*) and its intergranular (*2*) and fracture (*3*) components with an increase in effective pressure from 2 MPa (atmospheric conditions) to 47 MPa (reservoir conditions during field development) with a decrease in reservoir pressure by 10 MPa for three reservoir samples with the highest values of fracture porosity m_{fr} = (a) 1.134, (b) 0.889, and (c) 0.875%.

Thus, the results of the studies showed the complex nature of the change in the structure of the pore space during field development and the contribution of each type of porosity (intergranular and fractured) to this change.

RESERVOIR MODELS OF THE CHAYADINA FIELD AND RESERVOIR PRESSURE DYNAMICS

Hydrocarbon deposits at the Chayadina field are confined to productive terrigenous, slightly inclined Vendian horizons occurring at depths of 1420–2020 m (Kreknin et al., 2016). The deposits were modeled as prismatic bodies of a certain length, width, and thickness separately for each productive horizon (Botuobin, Khamakin, and Talakh) and together as a single deposit (Fig. 6).

The development period of productive layers of the field is conditionally taken equal to 100 years. It was assumed that the development will be carried out in the gas mode, i.e., for exhaustion. In the first approximation, the combined geological model of gas deposits for the productive horizons of the field can be taken as a reservoir with a length of 90 km, a width of 36 km, and an average thickness of 31.5 m that occurs at a depth of 1450 m.

Productive formations were modeled by rectangular prisms with geometric characteristics: width is $2a$, length is $2b$, depth of the upper boundary of the effective gas-saturated part of the reservoir is d, depth of its lower boundary is D, and average depth of the reservoir is H (see inset in Fig. 6). In the calculation, the following parameters of productive gas-saturated reservoirs were used for modeling the geological and structural characteristics of the Chayandinskoye field: Botuobin Reservoir (V_{bt}): $2a$ = 40 km, $2b$ = 80 km, $D - d$ = 7.1 m, H = 1.30 km; Khamakin Reservoir (V_{hm}): $2a$ = 60 km, $2b$ = 115 km, $D - d$ = 12.2 m, H =

1.23 km; and Talakh Reservoir (V_{tl}): $2a = 60$ km, $2b = 85$ km, $D - d = 23.4$ m, $H = 1.34$ km.

For a reliable prediction of reservoir pressure during field development, it is necessary to set gas production volumes and well flow rates with allowance for a large number of factors. In a first approximation, it can be conditionally assumed that the formation pressure during the development of the Chayadina field will decrease from 13.1 to 8.1 MPa by 2040; to 3.1 MPa by 2060; and, by 2120, it will drop to a minimal value of 0.1 MPa, at which there will be already difficult to obtain gas without the use of special methods.

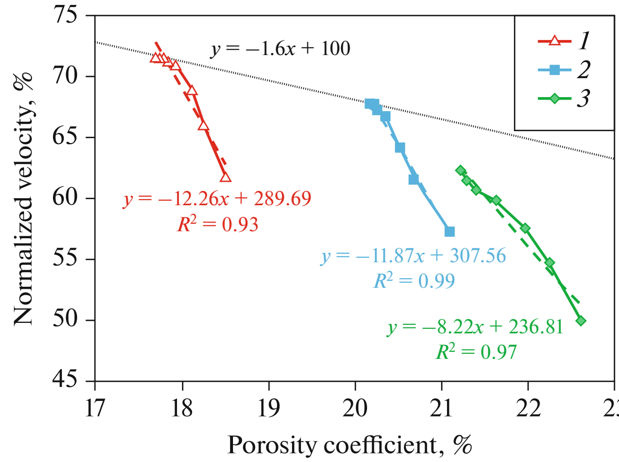

Fig. 4. Dependences of the change in the normalized velocity of compressional waves on porosity for reservoir samples with the highest values of intergranular porosity under conditions simulating the transition from atmospheric conditions to reservoir conditions (effective pressure varies from 2 to 47 MPa). m_{ig} = (*1*) 17.74, (*2*) 20.21, and (*3*) 21.08%.

MODELING OF SUBSIDENCE OF THE GROUND SURFACE DURING THE DEVELOPMENT OF PRODUCTIVE LAYERS

To date, there are a number of models for the formation of subsidence of the ground surface, which can be conditionally divided into three groups.

The *first group* includes semianalytical (engineering) models. This approach was first used by J. Geertsma in (Geertsma, 1973). The model uses an empirical compaction coefficient obtained from experimental data by repeated tests of the core material under uniaxial compression conditions. The value of the empirical coefficient is chosen depending on the porosity and mineralogical composition of the rocks. The model assumes that subsidence of the ground surface is entirely due to the compressibility of the formation itself. Similar concepts were used later in (Fokker and Ordic, 2006; Sroka and Hejmanowski, 2006; Addis, 2018). However, in reality, besides the developed reservoir, the surrounding rock mass, including the overlying stratum, is also deformed. This point was not taken into account in this group of models.

The *second group* is analytical models that estimate the deformations of the entire rock mass, including the vicinity of the reservoir. Back in (Geertsma, 1973), for this purpose, the well-known mathematical formalism of “deformation kernels” based on the Green’s functions (Mindlin and Cheng, 1950) was used and formulas for the distribution of vertical and horizontal displacements of the ground surface over a disk-shaped formation were obtained.

Later, using the concepts of fluid diffusion in the framework of the Rice–Clery poroelastic theory, Segall constructed closed analytical solutions that relate production parameters to changes in the stress–strain state of rocks in the vicinity of the reservoir for the conditions of a plane problem (Segall, 1985, 1992). Further development of these concepts (Walsh, 2002; Rudnicki, 2007; Muños and Roehl, 2017; Dyskin et al., 2020) was carried out based on the clarification of development modes and rheological parameters of the medium.

Note that all the mentioned models are analogues of the developed reservoirs, were axisymmetric (sphere, disk, and ellipsoid of revolution), and were placed in an elastic weightless half-space.

In Russia, the Kuzmin–Chernykh analytical model of the deformable prismatic reservoir (Kuzmin, 1999; Chernykh, 2001) is the most widespread. In this model, formulas are obtained for vertical and horizontal displacements of the surface of an elastic half-space, inside which an object of regular geometric shape (rectangular parallelepiped) is placed.

The difference of the approach implemented in (Kuzmin, 1999) is that it takes into account the weight of the medium and the genesis of the reservoir formation. Estimates showed that additional subsidence due to the influence of the weight of the formation reaches 15–20%. As a rule, deposits are structures of the anticline type, and the genetic correction makes it possible to take into account the force that formed the deposit itself.

The final subsidence value is determined by the combined action of three factors: a drop in reservoir pressure, which reduces the reservoir volume and leads to surface subsidence; the weight of the thickness lying above the reservoir; and the genetic factor, which refers to the upward forces that form the anticlinal uplift and reduce subsidence. The competition of these three forces leads to the formation of the final amplitude of subsidence of the ground surface during the development of the field.

It is important to note here that the presence of analytical models makes it possible to create hybrid (numerical–analytical) models, when reservoir conditions with a complex geological structure can be simulated using the principle of superposition of solutions from prismatic elements of various sizes.

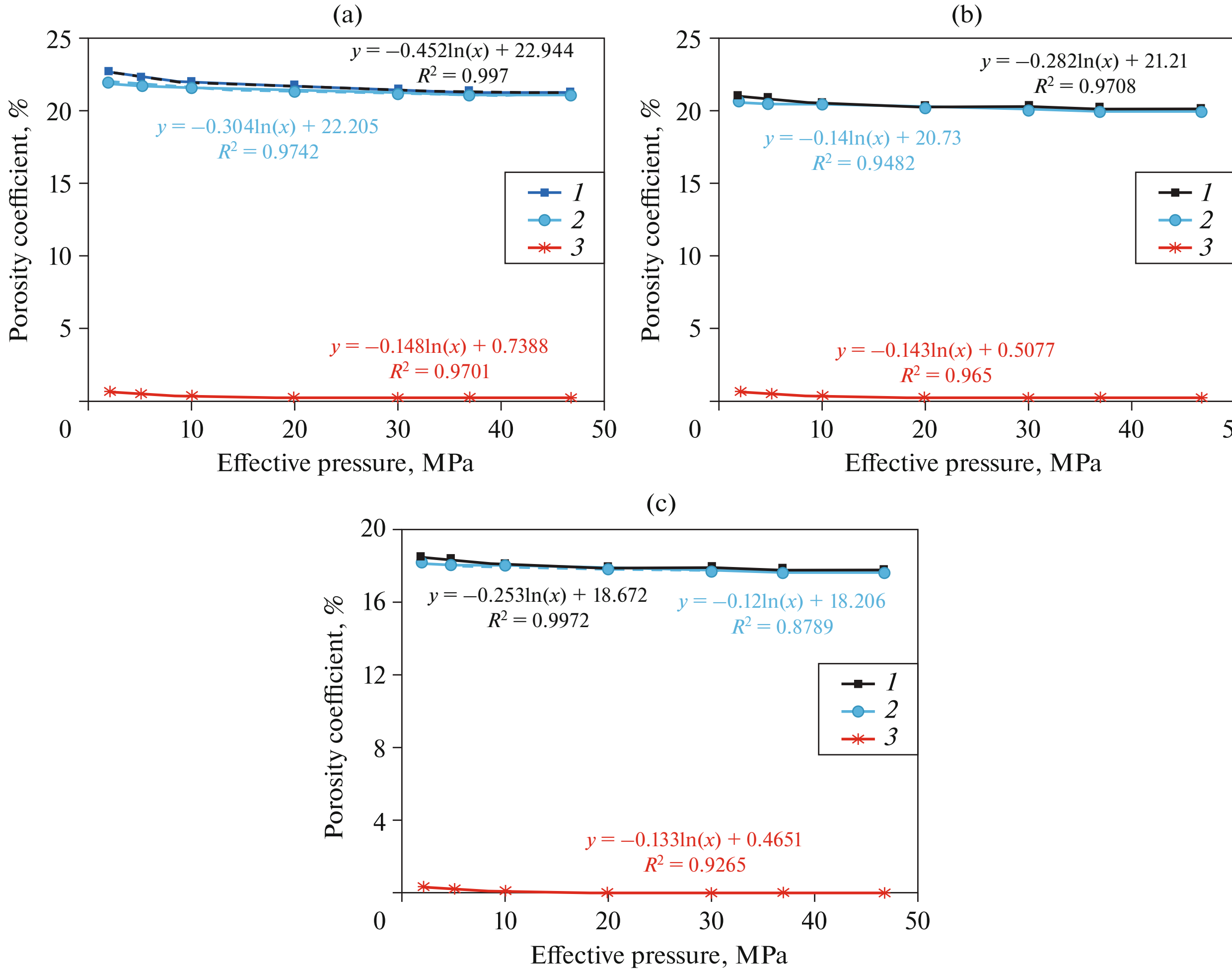

Fig. 5. Change in the total porosity (*1*) and its intergranular (*2*) and fracture (*3*) components with an increase in effective pressure from 2 MPa (atmospheric conditions) to 47 MPa (reservoir conditions of the field upon a decrease in reservoir pressure by 10 MPa) for samples of reservoir at the highest intergranular porosity. m_{ig} = (a) 21.06, (b) 20.21, and (c) 17.74%.

The *third group* includes numerical and laboratory models, in which, unlike analytical models, the use of finite or boundary element methods makes it possible to take into account the complex geometry of the reservoir to a greater extent, dividing it into separate elements (Kashnikov and Ashikhmin, 2007; Marketos et al., 2015; Ma and Zoback, 2017).

It should be noted that, due to a lack of initial geological and field information when dividing the productive stratum and the enclosing rock mass into a large number of "cubes," it is necessary to use some average value of the coefficients of porosity, compressibility, etc., as their filling. This fact significantly limits the use of numerical models for the analysis of vertical and horizontal surface displacements and their attenuation with distance. The issue of a lack of data on the determination of the compressibility coefficient of the pore space is particularly acute. This indicator is determined based on the data of the petrophysical analysis of rock cores taken in wells. There are several of these wells in the field, as a rule, even for large oil and gas facilities.

The compressibility of the porous (intergranular and fractured) space is one of the key parameters for estimating the subsidence of the ground surface. Despite the detailing of the reservoir geometry, a researcher using finite element methods still comes to a geomechanical model of the field that is heterogeneous in structure, but homogeneous in terms of deformation properties of the reservoir (layers). It is important to note that, for example, displacement gradients in this model have to be calculated in each specific finite element and then summarized over the entire reservoir, which is also not a completely correct procedure.

Therefore, when it is necessary to analyze the patterns of formation of the process of subsidence of the ground surface and, especially, the distribution of displacement gradients, it is advisable to use a genetic model of a deformable layer. This model has been repeatedly tested at a number of fields (including offshore ones) and underground gas storage facilities, where the calculated displacements were directly com-

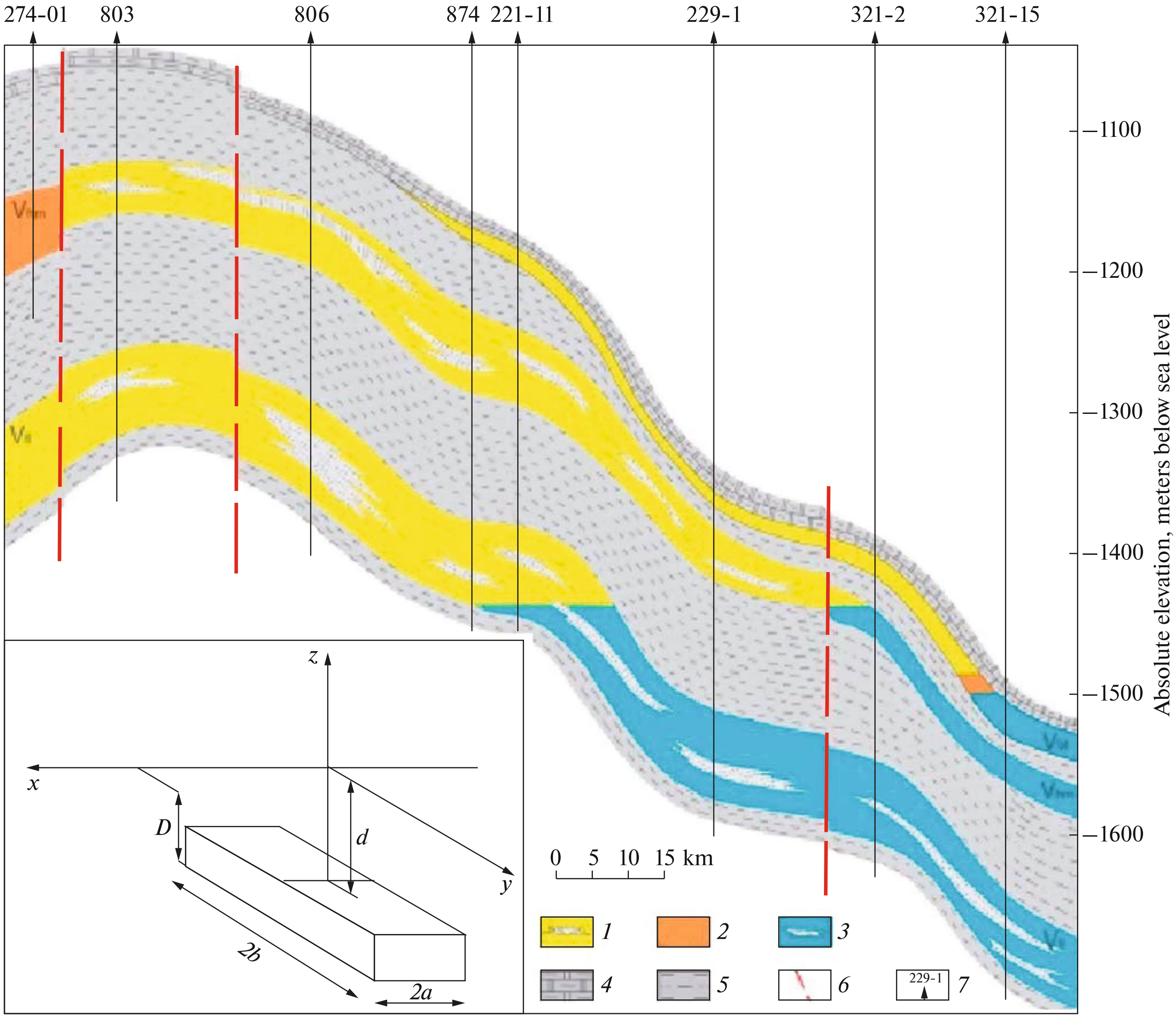

Fig. 6. Schematic profile section of the productive horizons of the Chayandina oil and gas condensate field (according to (Kreknin et al., 2016) as amended). The inset shows a diagram of the prismatic model of each of the productive layers: (*1*) gas-saturated sandstones, (*2*) oil-saturated sandstones, (*3*) water-saturated sandstones, (*4*) mudstones, (*5*) clayey dolomites, (*6*) tectonic faults, and (*7*) location and numbers of wells.

pared with the results of surveyor–geodesic monitoring (Kuzmin and Nikonov, 2002; Kuzmin, 2008, 2014, 2018, 2020; Izyumov and Kuzmin, 2014; Kuzmin et al., 2018, 2019; Kuzmin D.K., 2021; Gatiyatullin et al., 2021).

EFFECT OF CHANGES IN PETROPHYSICAL PARAMETERS ON THE FINAL ESTIMATE OF THE DEFORMATIONS OF THE GROUND SURFACE

When carrying out model estimates, a situation arises when detailed calculations are based on a limited array of experimental data on the mechanical parameters of the simulated medium: Young's modulus, Poisson's ratio, rock compressibility coefficients, and pore volume. Often, researchers do not take into account the fact that, during the development of the field and as the fluid pressure in the reservoir decreases over time, the mechanical parameters of the reservoir rocks can also change (Zimmerman, 1991; Mavko et al., 1998; Yang and Shenglai, 2016; Zhukov, 2020), significantly affecting the calculated (predicted) amount of subsidence. In order to make a more accurate prediction when calculating subsidence, we took into account changes in the porosity coefficient (see Fig. 1a) and the pore space compressibility coefficient (see Fig. 1b) accompanying the

Table 1. Initial parameters for estimating the possible magnitude arising during the development of Chayandina field subsidence of the ground surface and calculation results*

Duration of development, years	Reservoir pressure P_{por}, MPa	Formation pressure reduction ΔP_{por}, MPa	Effective reservoir pressure P_{eff}, MPa	Porosity coefficient in reservoir conditions m, %	Pore space compressibility factor C_{por}, 1/GPa	Subsidence with no allowance for changes in porosity and compressibility of pores, cm	Subsidence with allowance for changes in porosity and compressibility of pores, cm	Effect of taking into account changes in porosity and compressibility of pores, cm
0	13.1	0.0	37.1	8.976	2.844	0.0	0.0	0.0
20	8.1	5.0	42.1	8.964	2.813	33.0	32.5	0.5
40	3.1	10.0	47.1	8.933	2.685	63.8	60.0	3.8
100	0.1	13.0	50.1	8.916	2.616	83.0	78.0	5.0

* Explanations in the text.

increase in effective pressure during field development. For this, the results of laboratory studies of the petrophysical parameters of rock samples occurring at different depths were analyzed.

To calculate subsidence, a genetic model of a deformable formation was used (Kuzmin, 1999). The formula for calculating the vertical displacements of the ground surface (U_{gs}) consists of the product of two factors:

$$U_{gs} = PhG, \tag{8}$$

where physical factor Ph includes parameters such as porosity m, compressibility C_{por} of the pore space, and the ΔP_{por} change in reservoir pressure.

Geometric factor G in formula (8) takes into account the extent of reservoir ($2a$), its width ($2b$), the depth of the upper (d) and lower (D) edges, and the thickness of the reservoir ($D - d$) (see Fig. 6), as well as the average depth of the formation (H). These reservoir geometries were taken from geological profiles laid down along and across the extent of the deposit.

The subsidence of the ground surface, which can be expected during the long-term development of productive layers, was modeled for three conditional time intervals: after 10, 40, and 100 years from the beginning of development (Table 1, Fig. 7). Taking into account the close values of the average porosity for all three productive formations, we used the average values of porosity and compressibility of the pore space at a reservoir pressure of 13.1 MPa at the beginning of field development as the initial (initial) values: $m = 8.976\%$ and $C_{por} = 2.844$ 1/GPa. The values of porosity and compressibility factor of the pore space at the current values of reservoir pressure are given in Table 1.

The vertical displacements of the ground surface were calculated with allowance for changes in the porosity and compressibility of the pore space during field development at $P_{por} = 8.1$, 3.1, and 0.1 MPa. Figure 7 also shows the displacement curves, which were obtained with no allowance for changes in the porosity and compressibility of productive rocks.

DISCUSSION

The following results were obtained based on the magnitudes of possible subsidence of the ground surface during the development of the Chayadina hydrocarbon field that were calculated using a genetic model of a deformable reservoir (Kuzmin, 1999).

For the case of a decrease in reservoir pressure from 13.1 (at the beginning of development) to 8.1 MPa (approximately 10–20 years from the beginning of development of the field), the maximal amplitudes of vertical displacements can be 330 and 325 mm (see Fig. 7b). At a final reservoir pressure of 3.1 MPa (after 40–50 years from the beginning of development), the vertical displacements of the ground surface are estimated to be 638 and 600 mm (see Fig. 7c). At a reservoir pressure of 0.1 MPa at the end of development (i.e., after 100 years), the maximal subsidence can reach 830 and 780 mm (see Fig. 7d).

Thus, it is shown that taking into account changes in the porosity coefficient and the pore compressibility coefficient significantly reduces the estimate of the displacement amplitude and has an accumulative character in time. If in 10–20 years from the beginning of the development of the field, the decrease in the estimate of the magnitude of vertical displacements will be only 5 mm, then after 40–50 years of development, the discrepancy will be 35 mm, and by the time the development is completed, it will reach 50 mm (see Figs. 7d, 7e).

This means that, when calculating vertical displacements (subsidence) of the surface in deposits, it is important to take into account changes in the porosity coefficient and, especially, the compressibility coefficient of the pore space over time. Otherwise, when estimating the industrial safety of facilities, significantly overestimated expectations of geodynamic risks will be predicted. The geodynamic hazard is known to be estimated base on displacement gradients (Kuzmin, 1999). That is why when modeling subsidence of the ground surface, in order to obtain a more accurate final result, it is necessary to take into account all the changing factors during field development.

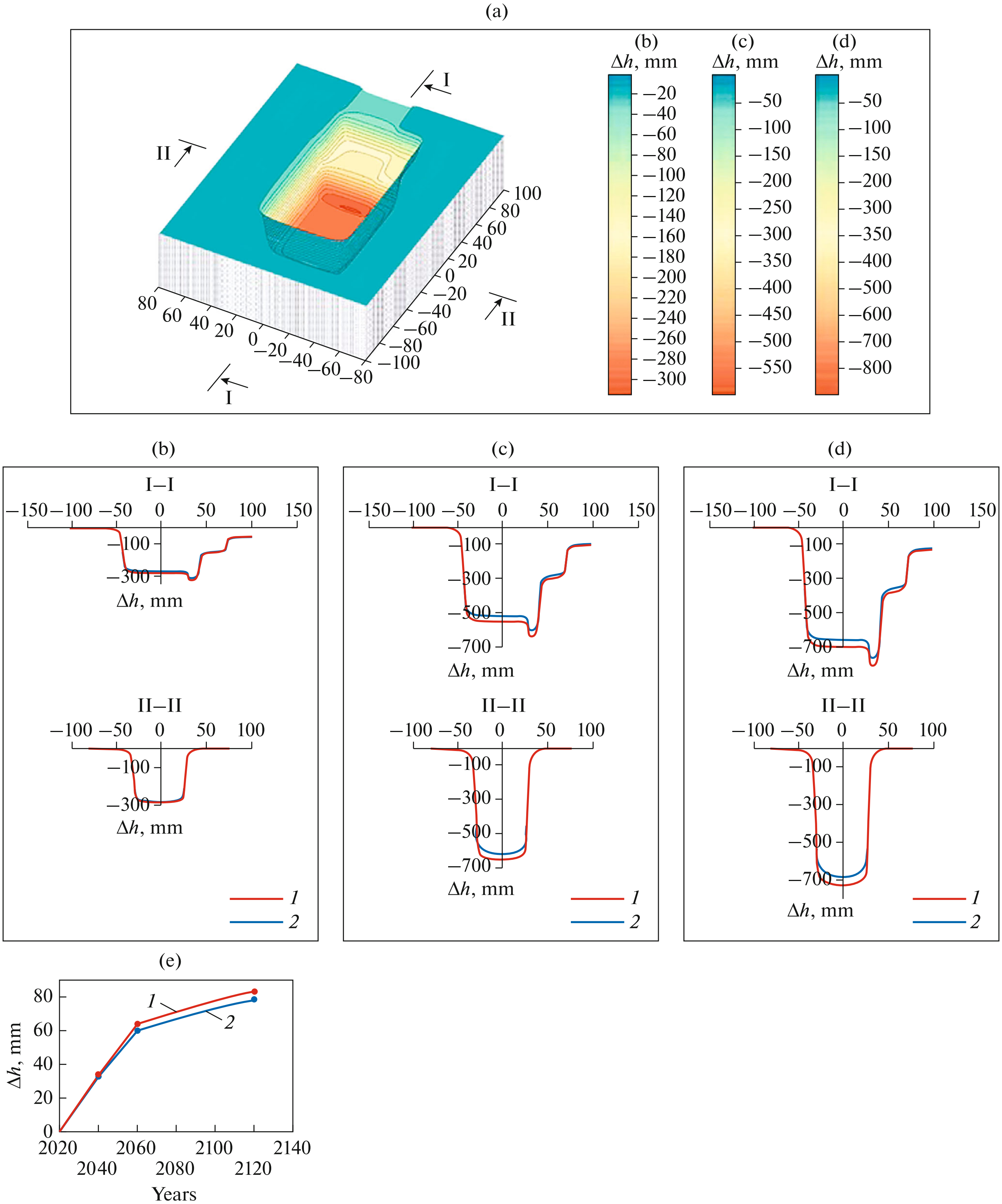

Fig. 7. Volumetric model of vertical displacements of the ground surface (subsidence) during the development of (a) the Chayandina oil and gas condensate field and their distribution along the profiles along (I–I) and across (II–II) the field (b) at P_{por} = 8.1 MPa after 10–20 years of development, (c) at P_{por} = 3.1 MPa after 40–50 years of development, (d) at P_{por} = 0.1 MPa after 100 years of development, and (e) summary graph of maximal subsidence: (*1*) at constant values of porosity (m = 8.964%) and pore compressibility coefficient (C_{por} = 2.844 1/GPa) and (*2*) taking into account their changes over time during field development.

CONCLUSIONS

The results of physical modeling of the development of the Chayandina field for depletion at a decrease in fluid pressure in the reservoir by 10 MPa showed that the decrease in the porosity coefficient of the three productive horizons of the Vendian deposits will be 0.060 abs. % and the compressibility coefficient of the pore space will decrease by 0.228 1/GPa. The change in the structure of the pore space of rocks in the process of changing the effective reservoir pressure depends on the predominant type of porosity (intergranular or fractured). In the first approximation, changes in the structure of the pore space at a decrease in pore pressure can be taken as models of changes in porosity for areas of the field with various values of reservoir fracturing.

The estimates of the maximal value of possible surface subsidence at the initial stage of field development are 33 cm upon a decrease in reservoir pressure by 5 MPa with allowance for the dynamics of petrophysical parameters and 33.5 cm without it. Upon a further decrease in reservoir pressure by 10 MPa, the maximal subsidence is already estimated at 60 cm with allowance for the dynamics of petrophysical parameters and 65 cm without it. According to calculations, the maximal subsidence at the end of the development of the Chayandina field can be 78 and 83 cm, respectively.

Obviously, taking into account the dynamics of petrophysical characteristics during the long-term development of oil and gas fields significantly changes the estimate of the amplitude of deformations of the rock mass and the ground surface above the deposit, which makes it possible to determine more accurately the level of geodynamic risk of the field being developed.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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