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APPLIED ASPECTS OF RESEARCHES OF MATHEMATICAL MODELLING OF SALT DIAPIRIZM IN OIL AND GAS BUSINESS

Abstract. The main results received by means of mathematical modeling of formation of salt diapers in crust are discussed. Possible applications of these researches in oil and gas are specified has put. The conclusion is drawn that the numerical technology of formation of salt diapers developed by authors is the effective tool what allows together with other methods to resolve many practical problems at investigation, development of oil and gas fields.
Keywords: salt diaper, sedimentary cover, crust, oil and gas traps, halite.

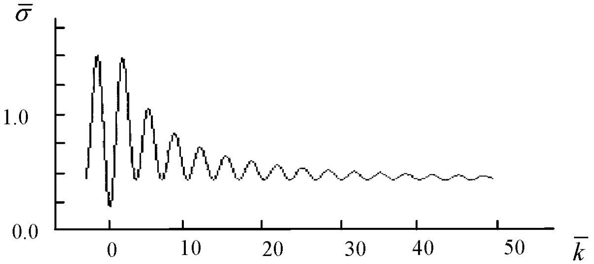
Introduction. More than 70% of world oil and gas fields are located in the fields of salt and dome tectonics. A classical example of the largest fields of salt and dome tectonics are the Gulf of Mexico and Caspian Depression. Two thirds Caspian hollows are the share of the territory of Kazakhstan where there are about 1300 salt domes (diapers) from which more than 1000, aren't reconnoitered yet. Besides, salt domes are used as tanks of storage of oil and gas, and also as burial grounds of radioactive and oil-field waste. Rock salt (halite) is a basis for production of table salt and various chemicals. Let us note that annually the mankind consumes more than seven million tons of table salt. Therefore, geologic-geophysical researches and natural observations, laboratory and numerical modeling, and also analytical researches are devoted to formation of salt and dome structures in crust. The list of these researches is provided, for example, in [1].

In Kazakhstan many tasks of salt and dome tectonics have been set by the academician Zh. S. Erzhanov, 95 anniversary since the birth of whom in 2017 is celebrated by scientific community of Kazakhstan, and solved by his pupils. Several numerical methods allowing to trace correctly evolution of an interface of layers up to formation of salt lenses [2] are developed and proved. Numerical modeling has allowed carrying out the detailed analysis of the mechanism of formation the salt dome of structures, to reveal regularities and features of their development. Results of these researches are summed up in [1, 2].

In the real research the results of mathematical modeling of formation of salt diapers in crust received generally are discussed by geodynamics of school of the academician Zh. S. Erzhanov. Recommendations of possible applications of these researches in oil and gas business are made. The conclusion drawn that the numerical technology of formation of salt diapers developed by authors is the effective tool, which allows together with other methods to resolve many practical problems at investigation, development of oil and gas fields.

Main results. To the middle of the thirtieth years of last century, there were two concepts of formation of salt diapers [1]. According to the first concept, driving force of the salt diapers breaking through thickness of sedimentary breeds in many areas of the globe are horizontal tectonic forces. According to the second concept stated by S. A. Arrennius in 1912 concerning domes in the north of Europe, driving force is buoyancy force, the caused difference of density a halite and a sedimentary cover. In 1934 year, L. Netlton on the models consisting of two layers of viscous liquids with various density has for the first time shown process of formation of salt domes. To them and other authors it is shown [1] that there is a dominant wavelength for which the growth rate of indignations is maximum. It were the first dynamic models of formation of salt domes as a result of action of only one force of emerging in the field of gravity. After this work, the second concept became priority though among geologists even there are also supporters of the first concept now.

Influence of a rheology of the layers, which are under the influence of tectonic forces on development of the initial stage of a diaperizm are a little studied [1]. Works [3-7] where stability of a viscous and plastic current of the powerful- layered environment is considered are devoted to a research in this area. In the figure 1 taken from work [5], the schedule of dependence of disturbance range on wave number for two-layer (flat model) of medium on condition of inversion of density of rocks is shown. The top layer represents plastic material, lower - viscous, i.e. the rheology of layers is diverse. The nature of the first maximum is putting in purely viscous, and the second – in purely plastic properties of material. The rheology of the top layer has essential value here. Follows from the figure 1 that there is a narrow range of wave numbers where loss of stability is not observed ($\overline{\sigma}$ <0). It is area of "return points" of rheological mechanisms of reorganization of loss of stability. The whole range of local maximum in the figure 1 says that formation of diapers with other geometrical parameters and forms is possible.



$$\eta_1 = 10^3 Pa \cdot s,\ \eta_2 = 10^{18} Pa \cdot s,\ \tau_{1S} = 5 \cdot 10^7 Pa,\ \tau_{2S} = 5 \cdot 10^3 Pa$$

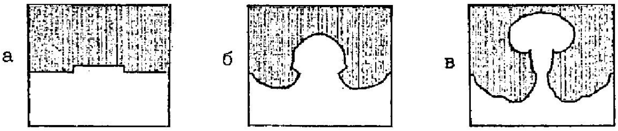
Figure 1 – Dependence $\overline{\sigma} = \overline{\sigma}(\overline{k})$

Axisymmetric loss of stability of the two-layer environment leads to formation of a single salt dome (as a rule, a giant dome), or a single salt dome and a circular salt shaft of the correct form [6]. Similar giant domes are characteristic of Caspian Depression of Kazakhstan. In a three-dimensional case the complicated rheological environment behaves as Veyssenberg's [7] liquid and has effect of a prodomost that leads to formation of salt columns in crust which meet in the nature.

Thus, the rheology of layers for indignations has anisotropy that leads to non-uniform distribution of diapers on space and to different scale of their sizes. It is necessary to notice that have significant effect on formation of salt diapers distribution of deformation fronts in crust which nature is putting in formation and distribution of lonely tectonic waves on border of the elastic lithosphere linked to a viscous asthenosphere [8]. These lonely tectonic waves (solutions) extend with a speed about 1 km. in a year. They are described by the equations like Kartevega Friza-Byurgersa, and also the with use of regulyarizator for equation of Kartevega and Frieze with cubic nonlinearity. By the nature, they are close to gravitational and capillary waves on the surface of liquid and cause poorly damped oscillations of the land surface during tens of thousands of years [8].

The first works on numerical modeling of formation of salt domes are devoted to flat tasks and had rather approximate character [9, 10]. The model of non-uniform liquid has allowed to exclude from consideration difficult boundary conditions on border of layers and it is "natural" to trace their evolution. Correct computing technologies have been developed for calculation flat [1, 2, 11-19], axisymmetric [13, 18], and with development of computer facilities, and spatial currents [1, 2, 20-25]. The review and the analysis of these works is provided in [1].

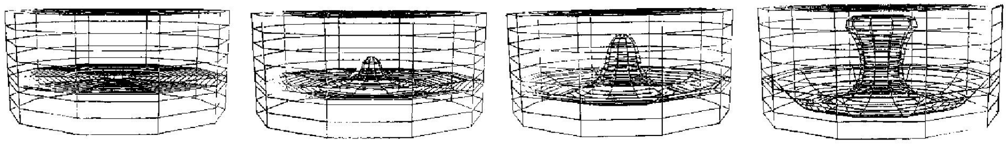
In the figure 2 formation flat salt and in the drawing 3-axisymmetric salt diapers for various moments of dimensionless time is shown [14, 18]. Here the 1 index has designated respectively density, dynamic viscosity, power of a sedimentary cover (ρ_1, μ_1, h_1), and the 2 index - (ρ_2, μ_2, h_2) the same sizes for a halite.



$\bar{t} = 0.$ $\bar{t} = 0.6$ $\bar{t} = 1.0$

$$\rho_1 = 2600\,kg/m^3, \rho_2 = 2200\,kg/m^3, \mu_1 = 2.6\cdot10^{17}\,Pa\cdot s, \mu_2 = 1.0\cdot10^{17}\,Pa\cdot s, h_1 = 4.8km, h_1 = 3.2km$$

Figure 2 – Formation of a salt diaper (flat model)



a b c d

$$\rho_1 = 2600\,kg/m^3, \rho_2 = 2200\,kg/m^3, \mu_1 = 2.6\cdot10^{17}\,Pa\cdot s, \mu_2 = 10^{17}\,Pa\cdot s, h_1 = 6km, h_1 = 3km,\ R = 18km$$

$$а - \bar{t} = 0,\ б - \bar{t} = 0.5,\ в - \bar{t} = 0.7,\ г - \bar{t} = 1.0$$

Figure 3 – Formation of an Axisymmetric Salt Dome

In the listed above works on formation of salt diapers some regularities and features of development of a nonlinear stage of gravitational instability have been investigated. Phases of development of gravitational instability are allocated, the cellular structure of a current is shown, are estimated influence at walls of effects. So in works [2, 11-19], at assessment of parameters of emerging of a dome, the following consistent patterns are determined:

1. If to increase the parameter M characterizing the relation of dynamic viscosities of layers (dynamic viscosity of the top layer to dynamic viscosity of the lower layer), then development of gravitational instability is slowed down.

2. If to increase viscosity of layers, leaving M invariable, then development of gravitational instability is slowed down.

3. Increase in power of the top layer promotes introduction of light liquid in heavy narrower "languages", and heavy in easy – the wide front. If to increase salt power, leaving at the same time power the over salt breeds invariable, then the cross sizes of salt domes increase, and distances between domes decrease. If to increase power the over salt breeds, leaving at the same time the power of salt invariable, then the cross sizes of domes decrease, distances between domes increase. The salt dome grows quicker in that environment where there are big capacities of salt and the over salt breeds.

4.At an equal thickness of layers and their identical viscosity the decision has "auto model character". It means that for two different options irrespective of the size of an order of viscosity of layers, it is possible to pick up such time points that pictures of a current will be identical.

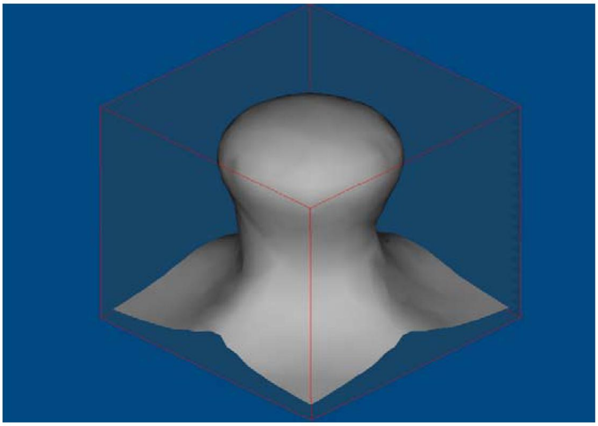
5.With increase in a dome gain spherical shape, and with reduction M - similar to a column.

Thus, on process of formation of salt diapers in crust both physical, and geometrical parameters of the environment have significant effect.

For the purpose of clarification of influence of a subsalt bed on growth of salt domes, a series of calculations for the three-layer environment in which rock salt is located between two more dense breeds [2, 14] has been carried out. It has been established that the nature of movement of salt in the three-layer environment differs from two-layer as the sole of rock salt linked to the deformed basis in the course of instability is involved in the movement up the same channels, as salt though density of rock salt is less than density of a subsalt layer. This results from the fact that the salt dome, moving up, forces out heavy over salt a layer down owing to what under a dome the area of the lowered pressure where a part of a subsalt layer flows is created. It should be noted that when viscosity of a subsalt layer is much more viscosity a halite ($\mu_3/\mu_2 \geq 500$), development of instability will be occurs as and in two-layer model, i.e. the subsalt layer is not deformed.

In works [14] influence of an inclination of layer of rock salt on formation of salt domes is estimated. It is shown that there is an additional moment of forces promoting turn of the emerging rock salt towards reduction of thickness of the salt massif. Similar feature is characteristic of salt and dome tectonics of Caspian Depression.

In the figure 4, the created three-dimensional single salt dome is represented [1, 2]. For further studying of the main regularities of development of Taylor instability a series of calculations which has allowed to establish that regularities fair for flat currents take place and in a three-dimensional case, but there are also differences [2] has been carried out. The comparative analysis of development of flat gravitational instability with spatial at identical physics and geometrical parameters shows: characteristics of growth of a salt dome (growth rate, a dome form) in axisymmetric and spatial models differ from characteristics of growth of a salt dome in flat model. In an axisymmetric case a dome up to achievement of the top wall wide takes the similar to a column form, at the same time the cross size of his trunk and it is, approximately, equal to the initial power of salt.



$$\mu_1 = 5\cdot10^{17}\,Pa\cdot s,\ \rho_1 = 2600kg/m^3,\ h_1 = 6km,\ \mu_2 = 10^{17}\,Pa\cdot s,\ \rho_2 = 2200kg/m^3,\ h_2 = 3km$$

Figure 4 – The Created Salt Dome in time point of t=0.5 (Spatial model)

In a flat case in the same time points the dome arch, without reaching the top wall, spreads in the horizontal parties, and the trunk is strongly wrung out by heavy liquid, i.e. the dome gets a similar to a mushroom form.

Comparison of numerical calculations to results of laboratory modeling, geological data of formation of salt structures has allowed to establish that numerical models describe formation of salt domes, their development to adequately natural situation.

Development of gravitational instability (depending on physics and geometrical parameters of the environment and initial indignation) proceeds quicker (or more slowly on separate phases) in flat model, than in spatial.

Recently are obtained by scientists of the Siberian Branch of the Russian Academy of Science essentially new educated about a possibility of heavy hydrocarbons at big depths that confirms D. I. Mendeleyev's hypothesis of an inorganic origin of oil and points out the prospect of her search and production at big depths. Information on formation of salt diapers at big depths is for this purpose necessary that is connected taking into account thermal effects and complication of a rheology.

Such thermal model of formation of salt diapers in crust (is given the new term the deep diaperizm) is developed and proved by pupils of school of Erzhanov Zh. S. It is based on Rayleigh – Taylor instability in approach of Bussinesk's with exponential dependence of dynamic viscosity on temperature [1, 26-32].

In system of coordinates about (axis O is directed vertically up) process of formation of a deep salt diaperizm (without radiogenic sources of heat) it is described by the following system of the hydrodynamic equations [26, 30]:

$$0=-\frac{\partial p}{\partial x_i}+\frac{\partial \sigma_{ik}}{\partial x_k}-\rho g\delta_{3i},(i=1,2,3);\quad \sigma_{ij}=\mu(\frac{\partial V_i}{\partial x_j}+\frac{\partial V_j}{\partial x_i}),(i,j=1,2,3);\quad \frac{\partial V_\beta}{\partial x_\beta}=0; \qquad (1)$$

$$\frac{\partial \rho_*}{\partial t}+\frac{\partial}{\partial x_\beta}\left(\rho_* V_\beta\right)=0;\quad \frac{\partial \mu_*}{\partial t}+\frac{\partial}{\partial x_\beta}(\mu_* V_\beta)=0; \qquad (2)$$

$$\rho C_p\left(\frac{\partial T}{\partial t}+V_\beta\frac{\partial T}{\partial x_\beta}\right)=\frac{\partial}{\partial x_\beta}\left(k\frac{\partial T}{\partial x_\beta}\right)+\sigma_{\gamma\beta}\dot{\varepsilon}_{\gamma\beta};\ \left(\gamma,\beta=1,2,3\right), \qquad (3)$$

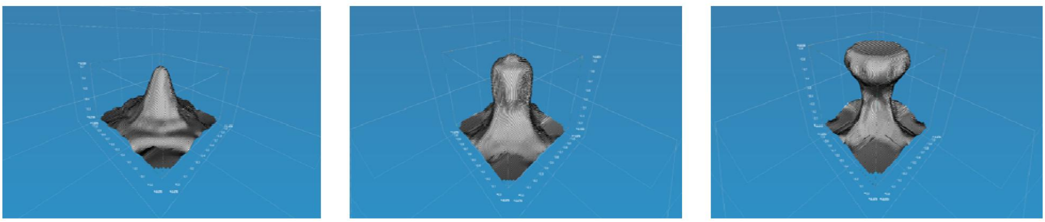
$$\rho=\rho^*(1-\alpha(T-T_*));\quad \mu(t,x)=\mu_*(t,x)\exp\left\{\frac{E}{R}(\frac{1}{T}-\frac{1}{T_*})\right\};\ x=(x_1,x_2,x_3)\in\Omega \qquad (4)$$

Here p - pressure, V_1,V_2,V_3 - speed components, σ_{ij} - a tensor of viscous tension, g - acceleration of gravity, ρ - density, μ - dynamic viscosity, C_p - specific heat with a constant pressure, k – heat conductivity coefficient, T - absolute temperature, α - coefficient of thermal volume expansion, R - a universal gas constant, E – energy of activation, ρ_*,μ_* - not indignant density and not indignant dynamic viscosity depending on the chemical composition of material (or density and dynamic viscosity at an absolute temperature T_*), δ_{3i} - Kronecker's tensor. On the repeating Greek indexes, summation is supposed.

The coordinated entry and boundary conditions [26, 30] are added to system of the equations (1) - (4) which are carried out in the area Ω. In initial time point, distribution of not indignant density, not indignant dynamic viscosity and temperature is set. Boundary conditions can be various. On a part of border of area sticking conditions, on other her part – sliding conditions are satisfied. On one part of border of area temperature, on other her part a thermal stream is set. Besides, conditions of frequency and symmetry of a current are possible [26, 30].

The corresponding divergent numerical method, with use of the scheme of splitting on physical processes and monotonous differential schemes [26-30] was developed and reasonable.

In figures 5a) - 5c) three-dimensional formation of a salt diaper in deeply lying sedimentary complexes at various moments of dimensionless time is shown. In initial time point layers were horizontal. Power of a sedimentary complex (cover) h_1 and power of rock salt (halite) h_2 have been chosen on 7,5 km. Density relied equal $\rho_1^*=2600kg/m^3$, $\rho_2^*=2200kg/m^3$, and dynamic viscosities $\mu_1^*=5\cdot10^{20}Pa\cdot s$, $\mu_2^*=5\cdot10^{19}Pa\cdot s$. Sizes k,C_p,α,E have been chose as constants in all area and equal to their average values $k=4W/m\cdot K^0$, $C_p=1,2kJ/kg\cdot K^0$, $\alpha=2\cdot10^{-5}/K^0$, $E=20kJ/mol$. On the lower bound temperature was set equal $250C^0$, and in her central part - is $50C^0$ higher (models heterogeneity of a thermal stream from the lower layers of Earth). In initial time point, distribution of temperature in area has been defined by linear interpolation.



a) $t=0.30$ b) $t=0.65$ c) $t=1.10$

Figure 5 – Spatial profiles of a deep salt diaperizm at various moments of dimensionless time

Calculations have shown that the main regularities and features of process same, as well as in case of constant kinematic viscosity of layers, but slightly differ in a quantitative sense [26-33]. Under certain conditions, thermal gradients significantly influence both volume profiles and the speed of formation of salt diapers of a deep bedding [33]. Therefore, existence, rather nearby temperature indignations of a thermal stream from the lower horizons of crust leads to formation of salt columns.

Earlier formation of similar structures by authors of this work has been explained at the expense of the complicated rheology (viscous and plastic model) which has prodomost properties of liquid of Veyssenberg's [7]. The accounting of dependence of dynamic viscosity on absolute temperature leads to formation in the developed phase "similar to a leaf of a tree" of salt and dome structures [33].

In works [27-31] were estimated possible a collector of oil and gas (oil and gas traps) which technique of definition is based on the following reasons. The sedimentary cover and a subsalt bed on small intervals of time are fragile rocks which mechanism of destruction are fragile cracking (destruction) which is followed by a dilatansiya. Exactly thanks to the fact that rocks possess fragile destruction in zones of the increased concentration of tension there is a destruction to formation of pore space, excess stress are removed. Local zones of the lowered tension (oil and gas traps) where the hydrocarbons which are in layers of rocks migrate are as a result formed. Zones of destruction of a sedimentary cover and subsalt bed were determined by criterion of rock strength (strength excess by a deviator of tangent tension). For salt domes oil and gas traps are formed in areas of their wings (over a wing and under a wing spaces), and also in the field of sub dome space of a subsalt bed. It was revealed deep drilling of salt diapers and is confirmed with results of the carried-out numerical calculations [27-31].

At the developed gravitational instability of an isotherm also diomorfna to a profile of a salt diaper are strongly bent. They fill the area adjacent to wings of a salt dome where temperature is increased on 30–90°C rather neighboring areas of a sedimentary cover [27-31]. It is well known, that the size of a geothermal gradient is one of the main parameters and signs of generation of minerals [34]. Temperature increase on 10°C, increases the speed of chemical reaction twice in the environments favorable for allocation of hydro carbonic connections, including oil. In work [34] by means of space, monitoring cards of distributions of a geothermal gradient of the top part of crust and a thermal stream of Kazakhstan are constructed. The analysis of these cards has shown that fields of the Western Kazakhstan and the water area of the Aral Sea are located in zones with the increased level of a geothermal gradient. Calculations have shown that distribution of isotherms and distribution of zones of the raised deviator of tangent tension quantitatively confirm that hydro carbonic stocks are tied to areas with the raised temperature gradients.

It has been also established [27-31] that thermal gradients have significant effect on formation of a subsalt bed, strongly deforming sub dome space. In a subsalt bed, extensive areas in which also rather big on an absolute value deviator of tangent tension was raised are observed. In the lower central part of a dome at the expense of the dynamic pressure and the increased temperature, the considerable suction of a subsalt bed is carried out. Therefore, if at a subsalt bed there are large reserves of hydrocarbons, then they, owing to a dilatansiya, will migrate in the central part under of sub dome space. Quantitative assessment of these volumes, taking into account porosity and filtration characteristics of the environment, allows defining probable reserves of hydrocarbons. Let us note that obtaining information on characteristics of sub dome space gravitational, magnetic and seismic investigations are almost impossible.

Recommendations. The results of mathematical modeling of salt domes given above allow making some recommendations in oil and gas business.

The analysis of flat, axisymmetric and spatial mechanisms of gravitational instability can explain formation of domes of the giants, ring massifs, linear ridges and salt columns characteristic of salt dome tectonics of Caspian Depression [3]. The initial and boundary-value problem dynamic task describing formation of salt domes is correct at the return a current of time. That is, it is possible to restore a prehistory of formation of salt domes. It will give additional geological and morphological information, which can be used in a geological exploration [35]. It is possible to carry out conducting of operational wells with an inclined curvilinear trajectory by passing poorly strong salt dome, preventing a holding strap-boring column [36].

At the known profile of the top cap of a dome and power of a subsalt bed, and also distribution of a thermal stream, computer modeling allows is detailed "to beat off" under a wing space of domes and sub dome space. At the known petrography of a sedimentary cover, a halite and a subsalt bed the developed technique allows to reconnoiter and estimate possible a collector of oil and gas that by other methods difficult.

Against the background of reservoir pressure deviator of tangent tension play a fundamental role when forming oil and gas traps. Change of position of extreme values of deviator of tangent tension can specify the direction of migration of oil, which is shown that in a sub eaves part of salt domes oil disappears in the course of her production.

Rational use of information on distribution of the field of tangent tension will allow to conduct optimum both investigation, and extraction of hydrocarbons with essential decrease in material inputs. Here problems of optimum placement of delivery wells, carrying out hydraulic fracturing, and increase in oil recovery of layers belong.

Problems of a filtration and replacement can be formulated; measures for reduction a bearing strain of upsetting columns are developed, using information on the intense deformed condition of a sedimentary cover and a subsalt bed.

It is possible to develop ecologically safe technology of construction deep and super deep in salt and dome structures [37].

It is not the full list of those applications of computer modeling of formation of salt diapers, which eventually will lead to effective increase in oil recovery of layers.

Conclusion. The developed numerical technology of formation of salt diapers is the effective tool in oil and gas business. She allows together with other methods to resolve practical problems at investigation, development of oil and gas fields.

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ПРИКЛАДНЫЕ АСПЕКТЫ ИССЛЕДОВАНИЙ МАТЕМАТИЧЕСКОГО МОДЕЛИРОВАНИЯ СОЛЯНОГО ДИАПИРИЗМА В НЕФТЕГАЗОВОМ ДЕЛЕ

Аннотация. Обсуждаются основные результаты, полученные с помощью математического моделирования формирования соляных диапиров в земной коре. Указываются возможные приложения этих исследований в нефтегазовом деле. Сделан вывод о том, что разработанная авторами численная технология формирования соляных диапиров является эффективным инструментом, которая позволяет вместе с другими методами разрешить многие практические проблемы при разведке, разработке нефтегазовых месторождений.

Ключевые слова: соляной диапир, осадочный чехол, земная кора, нефтегазовые ловушки, галит.

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МҰНАЙГАЗ САЛАСЫНДА ТҰЗДЫҚ ДИАПИРИЗМДІ МАТЕМАТИКАЛЫҚ СҮЛБЕЛЕУДІ ЗЕРТТЕУДІҢ ҚОЛДАНБАЛЫ МӘСЕЛЕЛЕРІ

Аннотация. Жер қыртысындатұздық диапирлерді қалыптастыруды математикалық сүлбелеу арқылы алынған негізгі нәтижелер талқыланады. Мұнайгаздық салада осы зерттеулердәң мүмкін қолданыстары көрсетіледі. Авторлар жасаған тұздық диапирлерді қалыптастырудың сандық технологиясы, басқа әдістер-мен бірге көптеген іс-тәжірибелік проблемаларды барлау жүргізгенде, мұнайгаздық кенорындауын әзірлеуде шешім табуды мүмкін ететін, оңтайлы құрал болып табылатыны туралы қорытынды жасалды.

Түйін сөздер: тұздық диапир, жауын-шашындық қапшық, жер қыртысы, мұнайгаздық тұзақтар, галит.

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