Numerical modeling of salt domes formation in Anabar-Khatanga oil and gas area (Siberian sector of the Russian Arctic)

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Abstract. The present work is devoted to modeling the processes of formation and analysis of specific features of the salt domes structure in the Anabar-Khatanga OGA. The performed numerical experiments showed that the specificity of the salt tectogenesis in this region is determined by the features of its geological structure and the history of tectonic development.

1. Introduction

The Anabar-Khatanga saddle, located in the northeast of the Krasnoyarsk Region and the northwestern part of the Sakha Republic (Yakutia), is one of the perspective areas for the Siberian sector of the Russian Arctic.

The analysis of drilling data and seismic cross-sections makes it possible to identify six regionally developed complexes in the sedimentary cover of the Anabar-Khatanga oil and gas area (OGA): Riphean, Vendian, Paleozoic, Permian, Triassic and Cretaceous (figure 1). Riphean limestones lying at the base of the platform deposits are covered with Vendian carbonates from above. Above there are the Cambrian mainly carbonate deposits, which, with a break, are covered by limestone of the Devonian-Carboniferous, or terrigenous Permian deposits. The upper part of the deposits is composed of terrigenous rocks of the Triassic, Jurassic and Cretaceous. A feature of the geological structure of this region is the presence in the Early Middle Devonian salt strata and the associated series of salt domes, which largely determined the structural-tectonic construction of this region. The Nordvik and Kozhevnikov diapirs that were studied on this territory break through the deposits of the Upper Devonian, Carboniferous, Permian and Mesozoic and come out to the surface. The analysis of geological and geophysical materials allows us to assume that the most of local high-amplitude positive structures identified in the Anabar-Khatanga OGA are associated with surface-coming and subsurface salt diapirs which in the time cross-sections are characterized by a staggering out of phase and a reduction in the amplitude-energy characteristics of the wave fields – a chaotic pattern of seismic recording (figure 1).

In this region, the salt-dome anticlinal structures are of the greatest interest in relation to oil and gas potential. Near the known diapirs intersecting the entire of the Upper Devonian, Carboniferous and Permian deposits, structural-tectonic traps associated with the wedging out of terrigenous and carbonate reservoirs onto salt stocks can form; over the subsurface salt domes, in the Permian and Mesozoic deposits classical anticlinal traps can be formed. These circumstances determine the interest in studying the salt tectonics of the Anabar-Khatanga region.
The goal of the present research: using the algorithms and software developed at IPGG SB RAS and taking into account the specific features of the geological structure of the Anabar-Khatanga OGA, to perform numerical experiments on the modeling of salt tectogenesis processes with the aim of establishing the basic regularities of the salt-dome structures formation - the main oil and gas objects of this region.

The mechanism of salt tectogenesis has been thoroughly studied in a century and a half of research. The development of salt tectonics is mainly determined by the fact that salt, unlike terrigenous and biogenic sediments, practically does not compact under the weight of overlying rocks. Therefore, after the burial of salt having a density of 2100-2200 kg/m3 to a depth of more than 1000-1500 m, density inversion occurs and the salt layer begins to float, forming the typical structures of Rayleigh-Taylor instability development. The process dynamics and the shape of the formed structures are determined by the ratio of the densities, thicknesses and (to a lesser extent) the rheological properties of the floating and overlapping layers, as well as the rate of accumulation of the latter and time.

The perturbing factors that distort the symmetry of the resulting structures are external, in relation to the system, movements, edge effects due to the initial form of the salt layer, and the systematic nature of the change in the weight of the overlapping deposits (increase in their thickness or/and density in a certain direction and time).

The highly effective methods and programs of numerical modeling of the described process developed at IPGG SB RAS made it possible to calculate various variants of the development of salt tectogenesis and to reveal the main regularities and specifics of the formation of the salt-dome structures of the Anabar-Khatanga OGA.

2. The numerical modeling methods, the basic geological model of the object

Figure 1. Seismogeological cross-section showing the West-Nordvik salt dome. Legend: 1 – reflector, 2 - seismic complex.
In accordance with the theory of simple fluids with fading memory [1], the first approximation of the rheological equation of state, to describe the irreversible deformation of almost any material, is the equation of the Newtonian fluid. In this case, the Newtonian viscosity is interpreted as the "natural viscosity" of a given material, defined as the upper asymptote of its viscometric viscosities. This approximation is adequate for deformation rates less than a certain critical value for this material. In the case of rocks, the critical deformation rate can be estimated to be of the order of $10^{-14}$ s$^{-1}$ [2]. Available data [3] show:

- the rate of deformation in the processes of salt domes growth does not exceed this limit;
- in spite of a very large variation in the estimates of the effective viscosity of sedimentary rocks, especially salts, depending on the estimation method and deformation rate, the upper asymptotic for all is close to 10$^{20}$ Pa s;
- the typical mushroom shape of mature salt diapirs certainly indicates the proximity of viscosities of salt and host rocks in this process.

Proceeding from it, for the considered class of tasks, it is completely correct to represent the medium as a homogeneous viscous Newtonian fluid. The known smallness of the Reynolds number (of the order of $10^{-22}$) determines the investigated flow as a "creeping", the evolution of which can be represented by a sequence of quasistationary states connected together.

Thus, the modeling of salt tectogenesis in this paper is reduced to the calculation of the gravity driven creeping flow of a Newtonian fluid with an inhomogeneous density, bounded from above by a free surface. In the rectangular Cartesian coordinates $X_1, X_2, X_3$ we consider the half-space $F (x, t) = x_3 - h (x_1, x_2, t) = 0$, $x_3 \leq h (x_1, x_2, t)$; $\{x\} = \{x_1, x_2, x_3\}$, $t$ is the time, $n$ is the vector of the unit normal to this surface. The half-space is composed by a set of immiscible layers (or closed bodies) $D_k$, separated by boundaries $S_k(x,t)$, whose configuration is varied by the calculated flow. The flow is driven by normal gravity force $g$ applied to the density perturbation, which is related to the configuration of the boundaries $S_k(x,t)$. The initial conditions are determined by any given configuration of the boundaries $S_k(x,t)$. The density, stresses, and pressure are represented by the sums

$$
\rho(x,t) = \rho^0(x_3,t) + \rho^0(x_3,t), \quad \sigma(x,t) = \sigma^0(x_3,t) + \sigma^0(x_3,t), \quad P(x,t) = P^0(x_3,t) + P(x,t),
$$

where $\rho^0(x_3,t), \sigma^0(x_3,t), P^0(x_3,t)$ are the characteristics of the hydrostatic state $\tau_0 = -\delta_{ij} \rho_0 = -\delta_{ij} \rho_0 \int_{x_3}^0 p_0(x_3) dx_3$, $\delta_{ij}$ is the Kronecker delta, and $\sigma(x,t), \tau(x,t), P(x,t)$ are their small perturbations. Flow $\nu$ is associated with the perturbations.

The problem of calculating the creeping flow is divided into a quasistationary and evolutionary. In the case of a quasistationary problem $S_k(x,t_n)$ given at some time $t_n$, and the corresponding density perturbation $\rho(x,t_n)$, it is required to find the flow field $\nu(x,t_n)$ and the shape of the free boundary $F(x,t_n)$. The smallness of the perturbation of the free boundary $h$ (with respect to the horizontal dimensions) and the derivatives $\partial h / \partial x_1, \partial h / \partial x_2$, allows to linearize the boundary conditions of the quasistationary problem and write it with respect to perturbations in the form:

$$
\nu(x,t_n) = \rho(x,t_n) - \rho^0(x_3,t_n), \quad \rho(x,t_n) = \rho_k = \text{const} \quad \forall x \in W_k,
$$

$$
\mu \nu^2 \nu - \nu p = -\sigma g, \quad \mu - \text{viscosity},
$$

$$
\nu \cdot \nu = 0,
$$

$$
(v_3 = \tau_{31} = \tau_{32} = 0)_{x_3 = 0},
$$

with the additional condition for determining the perturbation of the free surface $(\tau_{33})_{x_3 = 0} = -\rho^0 |g|h$, ($\nu$ and $p$ are continuous everywhere in the half-space).

The evolutionary problem consists in finding the motion of the boundaries $S_k(x,t)$ from equations:

$$
\frac{\partial S_k}{\partial t} + \nu \cdot \nabla S_k = 0,
$$

with certain initial conditions $S_k(x,t_0) = \nu(x,t_0) = 0$. 

3
The evolution of the flow is calculated by solving the problem (1) with specified by (2) \( S_k(x) \) and the corresponding density perturbation \( \sigma(x) \) and the subsequent integration of (2) (with the obtained \( \mathbf{v}(x) \)), with respect to small time increments \( \Delta t \). Equations (2) can be easily solved numerically. The main computational difficulties in the calculation of creeping flows of the studied type are related to the quasistationary problem (1). Its solution was obtained analytically in the form of a Green function [4], so that the calculation of the creeping flow at each instant of time reduces to calculating the convolution integrals:

\[
\begin{align*}
    v_i(x) &= g \iint \sigma(\xi) V_i(x,\xi) \, d\xi_1 \, d\xi_2 \, d\xi_3, \\
    p(x) &= g \iint \sigma(\xi) P(x,\xi) \, d\xi_1 \, d\xi_2 \, d\xi_3,
\end{align*}
\]

where \( V_i(x,\xi), P(x,\xi) \) – corresponding Green functions.

The use of the convolution integral gives greater computational advantages than the solution of the system of linear algebraic equations arising in the realization of difference methods [5]. Exact solution of the boundary value problem in the form of a Green function makes it possible to apply the convolution theorem with the help of the fast Fourier transform procedure [6]. It was realized in the CoreModuleFFT program developed in the laboratory of mathematical modeling of natural oil and gas systems of IPGG SB RAS, used in the paper.

The above method allows us to calculate the flow caused by the action of the Archimedean forces, creating structures of salt tectonics, in general. To model their formation under the specific geological conditions, it is necessary to take into account the regional vertical movements forming the sedimentary basin and the processes of accumulation, compaction and erosion of sediments for each moment of evolution.

The regional model that determines the specificity of the demonstration of salt tectogenesis are based on the following data on the development of the basin, derived from the results of the geological and geophysical study of the territory [7, 8, 9].

- 407-384 million years (Eifelian age) – the formation of salt evaporitic sediments. At the same time, according to most researchers, the salt basin was of limited dimensions and occupied the submerged part of the depression extended in the northeast direction.
  Therefore, the starting position of the salt pack was set in the form of a strip about 20 km wide (the length of the calculated model was 40 km). The thickness of the pack was set from 0 m at the edges to a maximum of 700 m in the three most powerful "depocenters" in the axial part of the depression, spaced about 10 km apart. Considering that in the cores of the diapirs emerging on the surface, the salt formation is represented by practically pure rock salt - up to 99.7% NaCl, the density of these deposits was set at 2100 kg/m3. The density of the underlying rocks, mainly represented by limestones and dolomites with anhydrite lenses, is assumed to be 2800 kg/m3.
- 385-303 million years – the formation of mainly carbonate sediments of the Upper Devonian-Carboniferous with a thickness of 1500-1600 m.
- 303-286 million years – the depositional break, erosion of 500 m of sediments.
- 286-225 million years (Permian, Triassic) - the formation of terrigenous deposits with a thickness of 5200-5500 m.
- 225-208 million years (Triassic) – the raising of the territory, erosion of the 100 m of sediments.
- 208-97 million years (Jurassic-Lower Cretaceous) – the formation of terrigenous deposits with a thickness of 1500 m.
- 97-94 million years (Cretaceous) – the raising of the territory, erosion of the 300 m of sediments.
- < 94 million years (Upper Cretaceous, Cenozoic) – the formation of terrigenous deposits with a thickness of 300 m.
Based on these data, a piecewise constant rate of immersion and upwelling of the basin with accumulation or erosion of sediments is given for the territory. It was believed that the accumulated deposits were compacted as the immersion, so that the density of overlapping carbonate deposits of the Devonian and Carboniferous reaches 2700 kg/m$^3$, the density of the most submerged terrigenous rocks of the Permian age reaches 2,500 kg/m$^3$, and for the Upper Cretaceous 2300 kg/m$^3$ (with intermediate values in the Triassic and Lower Cretaceous).

3. Modeling results

In figure 2 the results of modeling are presented in the form of a series of sequence stages of system development. As shown by numerical experiments, the development of salt tectogenesis in the Anabar-Khatanga OGA is characterized by the following features.

The insignificant width of the basin, in which the accumulation of salt occurred, did not allow the development of parallel swells and ridges of domes growing from them, with a distance between swells (ridges) of the order of the main characteristic wavelength $\lambda \sim 2d$, where $d$ is the thickness of the convection layer (in this case – the thickness of the layer from the bottom of the salt pack to the surface). As a result, only one range of diapirs was formed from an unstable pack.

A large deficit in the density of the salt pack, in relation to all overlapping rocks, including terrigenous deposits of the Upper Paleozoic and Mesozoic, has led to the fact that the most developed salt diapirs rise all the thickness of the deposits, coming in some cases to a surface.

The considerable thickness of the deposits overlapping the unstable pack, combined with the high density of the underlying dolomites and anhydrite, led to the growth of diapirs in the form of pillars - streams, crowned with a mushroom-shaped bulb, expanding as it approached the free surface. (When the density of rocks underlying the unstable pack is close to the density of the overlapping rocks, the compression of the diapirc base does not occur, and salt domes grows as the anticline smoothly narrowed to the top [10]). The high density of carbonate rocks, initially lying on the salt pack, promotes an additional compression of the growing domes base. As a result, an essential feature of mature diapirs is their pipelike structure, with a core made by a substrate that rises, in a number of cases, to the entire height of the diapir (which suggests the possibility of finding the substrate rocks in the cap-rock of the domes that have come out to the surface and eroded). This effect, along with the pronounced 3- dimensional character of the structures, is strongly promoted by the extremely low density of the salt-pack rocks. An important (including, in practical terms) feature of the salt tectogenesis revealed by modeling for the study area is the formation of a significant number of small, buried, deep-lying diapirs located relatively close to each other - at a distance of about 3-4 km (although the most large and mature, the diapirs that have reached the surface are 10-15 km apart). This phenomenon is largely due to the fact that the salt pack is covered by high-density carbonates thicker than 1 km (and initially, up to erosion - more than 1.5 km), above which lie significantly less dense terrigenous rocks. As a result, there is a local instability that forms the growth of an additional perturbation mode with a wavelength $\lambda_m \sim 2d_m$, where $d_m$ is the thickness of the layer from the bottom of the salt to the top of the carbonate formation, where a density contrast occurs.

According to the calculations, noticeable growth of the domes began in early Permian and by the beginning of the Triassic, their amplitude reached 1000 m. The main growth of these diapirs occurs in the Mesozoic. By the end of the Triassic, the most intensively growing domes passed the "pillow" and "finger" stages, and during the Jurassic the amplitudes were significantly increased and classic mushroom-shaped diapirs were formed. In the Cretaceous and Cenozoic the process of growth of the main domes continued and at the same time their transformation into funnel-shaped bodies took place. In the upper parts of the domes, typical overhangs continued to form, and in the axial parts of the diapirs hats depressions were formed. This is due to the fact that against the backdrop of the continuous process of floating and spreading salt under a free (day) surface, saturated with low-density salt the diapirs edge continued to float, while the inner parts of diapirs enriched with heavy substrate began to plunge (figure 2, the final stages).
The main growth of the buried domes of the shorter-wave mode - cryptodiapires, forming in the sedimentary cover anticlinal traps perspective for oil and gas potential, occurred most intensively in the Late Cretaceous and Cenozoic.

**Figure 2.** The calculated stages of the salt-dome structures evolution of the Anabar-Khatanga saddle. Above the section for each stage is the time of evolution of the model and the corresponding geological age (in brackets). Red color shows the bottom and top of the salt pack.
4. Conclusion
The present work is devoted to modeling the processes of formation and analysis of specific features of the structure of salt domes in the Anabar-Khatanga OGA. The performed numerical experiments showed that the specificity of the salt tectogenesis in this region is determined by the features of its geological structure and the history of tectonic development:

1. The accumulation of the Devonian salt pack is not universal, but in a separate, relatively narrow depression.
2. Significant depth of burial of salt deposits.
3. Extremely low density of salt deposits, composed of practically pure rock salt, with respect to all deposits, primarily to high-density carbonates underlying and directly overlapping rocks.

The results of numerical experiments, which are in good agreement with the available data of the geological structure of the Anabar-Khatanga saddle, have shown that in the region as a result of the salt tectogenesis processes, the diapirs emerging to the surface and buried, with which most of the oil-and-gas-perspective objects are associated, were formed. With known salt domes, structural-tectonic traps can be associated, closed cryptodiapirs in the structural plans of the Permian and Mesozoic stratigraphic levels have developed classical anticlinal structures.

The performed works had mainly regional character, at the same time the methods, algorithms and programs developed in the course of the conducted researches can be used at creation of detailed models of the perspective oil and gas objects connected with salt domes that cannot be deciphered in wave seismic fields.

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