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КОРРЕКЦИЯ ГЛУБИННО-СКОРОСТНЫХ МОДЕЛЕЙ МЕТОДОМ ГРАВИМЕТРИЧЕСКОЙ РАЗВЕДКИ ДЛЯ ТРУДНОДОСТУПНЫХ УЧАСТКОВ ШЕЛЬФОВОЙ ЗОНЫ

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Аннотация: В настоящее время большое количество месторождений нефти и газа достаточно разведаны, а потребности в топливных ресурсах с каждым годом растет. Поэтому нефтегазовые компании начинают разрабатывать объекты со сложным геологическим строением или объекты, расположенные в труднодоступных местах, к каким относится Арктическая зона. Из-за климатических особенностей не вся территория Арктического шельфа изучена прямыми методами геологоразведки. Однако перспективность территории толкает нефтегазовые компании на разработку новых алгоритмов с использованием быстрых и доступных методов геофизики. Таким образом, в данной работе описан один из алгоритмов интерпретации данных, который предположительно может быть реализован для участков с минимальной априорной информацией. Основная идея статьи — коррекция структурных построений на основе использования метода гравиразведки в условиях отсутствия на изучаемой территории скважин. По результатам исследований авторы предлагают использовать комплексную интерпретацию гравитационных и сейсмических данных для снижения неоднозначности решения обратных задач.

Ключевые слова: сейсморазведка, гравиразведка, совместная инверсия, моделирование, шельфовая зона.

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Correction of Depth-Velocity Models by Gravity Prospecting for Hard-to-Reach Areas of the Shelf Zone

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Abstract: a large number of oil and gas reserves are now well surveyed, while the demand for fuel resources continues to grow year by year. As a result, oil and gas companies have started to develop sites with complex geological structures or located in virtually inaccessible regions, such as the Arctic zone. Due to climatic conditions, not all of the Arctic shelf has been surveyed via direct exploration methods. However, the untapped potential of the region provides an impetus for oil and gas companies to develop new processes that use quick and accessible geophysical methods. This work outlines one such data interpretation algorithm for potential use in locations about which minimal information is known in advance. The main idea of this article is to correct structural constructions based on the use of gravity prospecting in the absence of wells in the study area. Based on the results of the study, the authors propose to use an integrated interpretation of gravity and seismic data to reduce the ambiguity of solving inverse problems.

Key words: seismic survey, gravity survey, joint inversion, modeling, shelf zone.

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Introduction

The trend the mining industry as a whole and of the oil and gas industry in particular is that the already surveyed inland reserves are gradually becoming depleted [1]. In response, oil industry experts are paying significant attention to shelf areas [2, 3]. The Arctic shelf area in Russia is the largest of its kind in the world, and is considered a high-potential region [4–6]. Several oil and gas fields are being developed in the western part of the Arctic basin. However, the eastern part of the region, which also has high-potential oil and gas sites, is very poorly studied in terms of available geological and geophysical data. This is due to unfavorable climatic conditions in the region, due to which the sea is covered with ice for long periods. The study of hard-to-reach territories with inaccessible geological and geophysical data and underdeveloped infrastructure is a topical issue for the long-term development of the oil and gas industry, including taking into account the environmental component [7]. Numerous authors [8–10] have devoted their attention to the problem of hydrocarbon extraction in difficult geological conditions, and prioritize the development of new approaches [11], designed to significantly improve the process of geological exploration.

It is also worth noting that practically no drilling has been carried out in the eastern part of the Arctic, since the lack of preliminary information about the geological structure of the area when drilling is costly and risky for oil and gas companies [12]. In the early stages of geological exploration for any investigated area, in addition to the results of seismic survey, there are also data on potential fields that may be useful for complex interpretation of the data. Accordingly, the development of new techniques for joint processing and interpretation of geophysical data allows for the creation of an initial geological model of the environment that includes all specific features of the seismic survey and data on potential fields. This will significantly reduce the cost of the work and reduce the time of geological exploration.

1.1 Joint Inversion

Physical-geological modeling is an important stage in understanding the geology of the site in question. The creation of a physical-geological model usually involves the use of a range of geophysical methods that enable the creation of a model that accounts for the specifics of each geophysical method. Different approaches to inversion of geophysical fields have their positive and negative results. In this case, inversion is understood as solving an inverse problem, i.e., determining the parameters of the object of study by measuring the geophysical fields. Inversion can be carried out independently for each method, and the final results can be simply collated by the interpreter. It is also possible to conduct a joint inversion using several geophysical methods as part of the process.

The majority of sources analyzed by the authors [12–15] feature examples of the advantages of joint inversion. The use of an additional method in interpretation helps to reduce the ambiguity of the solution of the inverse problem [16, 17]. This approach also helps to reduce the number of model variants of the environment studied [18], which significantly improves the reliability of the interpretation work.

There are several joint modeling approaches [19]:

1) sequential, or iterative, inversion by each method in which the results are ultimately interpreted together. Frequently, formulaic dependencies are used to link the parameters of several methods. In international works, this approach is referred to as "cooperative joint inversion".

2) Inversion of multiple methods in one dataset. This modeling approach is called "simultaneous joint inversion".

The term "simultaneous joint inversion" is more precise and includes the aforementioned joint inversion of parameters of each examined geophysical method in one objective function (or matrix). The essence of the method is the selection of the most correct relationship between all the data [20]. As with cooperative inversion, the goal is to reduce the ambiguity of solving inverse problems by utilizing the strengths of each method. In most cases, this approach is automated in nature, and computers are used to significantly simplify the task.

There is no single agreed-upon definition of cooperative inversion, since different researchers interpret it differently in their works [21, 22]. The term is used by a wide range of authors, and mainly in international publications. One group of authors [6, 20] defines "cooperative inversion" as application of measured parameters of different geophysical methods regardless of the process of simultaneous sequential data inversion. An article by a group of researchers led by M. Moorkamp [23] describes the adoption of an iterative approach to conduct the inversion of a certain set of parameters of one method, with the obtained data then being linked by a functional dependency with parameters of another method. The authors of a different article emphasize that in cooperative inversion one method enables the placement of certain restrictions on the other method [24].

1.2 Functional relationships between the physical parameters «velocity-density»

As mentioned above, there is a functional relationship between the velocity and density parameters. This will be discussed in more detail below. The known formulas for recalculating velocity and density are empirical in nature and have been derived based on numerous direct observations of conditions in the field. However, in most cases, real-world geological conditions are complex. It is difficult to link certain dependencies to the parameters of such environments, and sometimes quantitative assessment is not feasible. Birch and Gardner's empirical relations are used to examine simpler geological conditions.

Birch's empirical formula is as follows:

$$\sigma = x \cdot \upsilon_p + y, \tag{1}$$

where *x* and *y* are coefficients of the linear regression equation, σ is density (g/m^3), and υp is the velocity of longitudinal waves (m/s). This relation is used for deep exploration, and in addition to the usual metrics, also accounts for metrics such as temperature and pressure.

Gardner's empirical relation is of great use in oil and gas geophysics, and is better suited for working with sedimentary rocks [25]:

$$\sigma = a \cdot \upsilon_p^b, \qquad (2)$$

where σ represents density (g/cm3), a and b are coefficients determined from well log data, υp is the velocity of longitudinal waves (m/s). The correlation is based on the tendency for the values of velocity and density to increase with depth [25]. As Gardner's formula is empirical, and derived based on a range of experimental data, its use may more accurately represent real-world environmental properties.

The first relation (1) is used to describe regional data, including studies of the mantle. The second formula (2) is mainly used to describe the parameters of the sedimentary cover, which aligns with the objectives of oil and gas geophysics. For this reason, this relation was chosen for further work.

Research results. The idea of seismic density modeling

One of the most significant results of seismic surveys are maps of reference surfaces. to determine the depth of the reflecting horizons, it is necessary to know the average velocity of wave propagation in the overburden [6]. When processing seismic data, the effective velocities are determined from the travel time curves of the reflected waves. The correspondence of average velocities to the effective velocities is reliably determined only for a homogeneous isotropic model of the medium. In practice, with non-homogeneous and anisotropic media, an empirical dependency of the average velocity on the effective velocity is established, which requires processing and interpretation of well data. In the absence of well data, it is possible to estimate the effective depth (heff) using the formula:

$$h_{eff} = \frac{t_0}{2} \cdot \upsilon_{st}, \qquad (3)$$

where t_0 is vertical time (round-trip propagation time), and υst is the stacking velocity.

Gravity surveying can serve as a supplementary method for interpreting seismic reflection methods. Gravity explorations are low-cost and logistically simple, which is why they are often used on the shelf alongside seismic exploration. Gravity data can be used in a comprehensive interpretation to limit possible options for solving the inverse problem when correcting for depth-velocity models.

The following procedure is carried out based on Gardner's formula:

1. Conversion of velocities obtained in velocity analysis into interval velocities (using the Urupov-Dix formula) [26].
2. Conversion of interval velocities to density (using Gardner's formula).
3. Density inversion and obtaining corrected densities for each layer.
4. Correction of interval velocities, taking into account density characteristics (using Gardner's formula).
5. Correction of the depths of reference horizons.

The procedure is presented in visual form in the block diagram in Figure 1.

Testing of seismic density modeling algorithm in the shelf zone of the East Siberian Sea

The site is located on the Arctic shelf in the East Siberian sea. The authors of the article [27] consider the sea shelf as a promising location of hydrocarbons. Geological and geophysical data on the region are limited, as the sea is covered with ice for the most of the year [27, 28]. The nearest wells are located at a

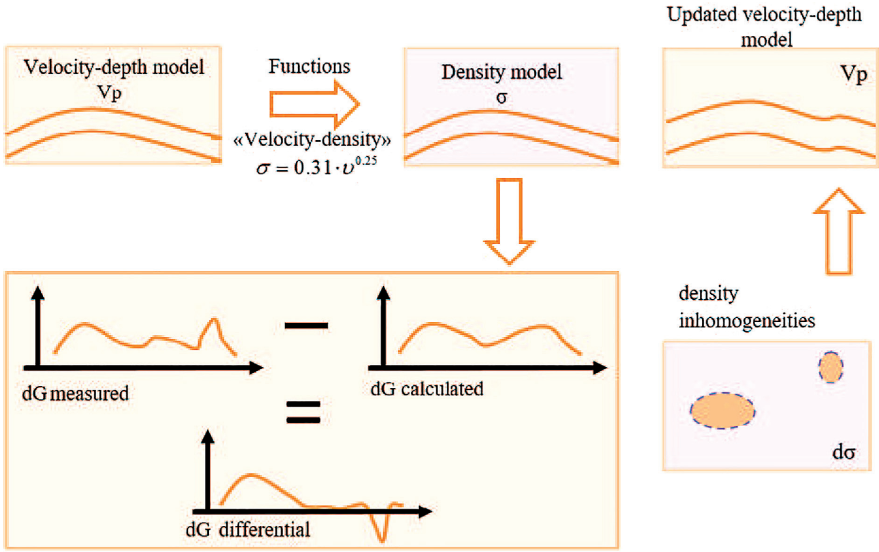


Fig. 1. Block diagram of the implementation of the process

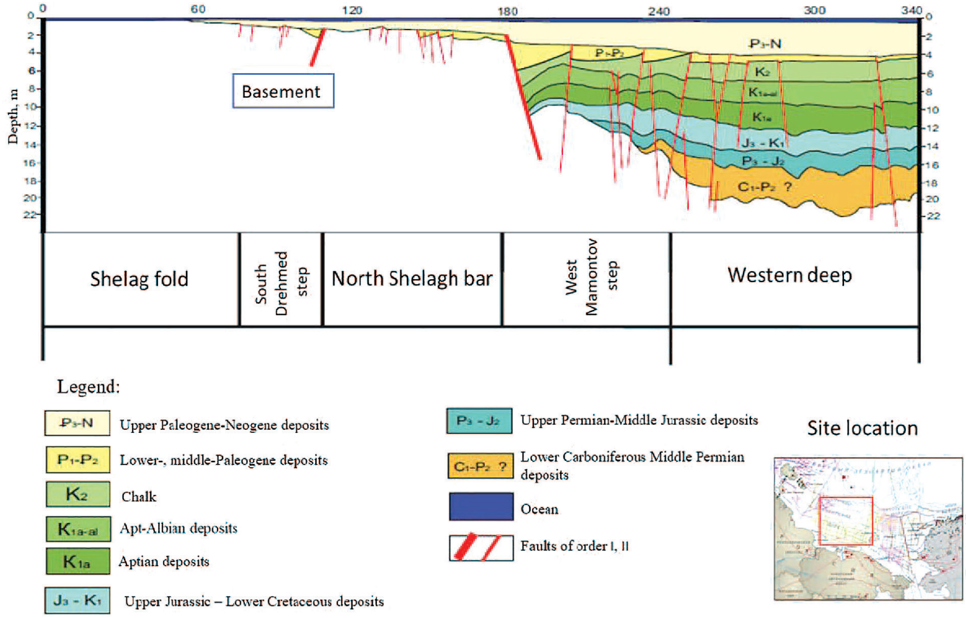
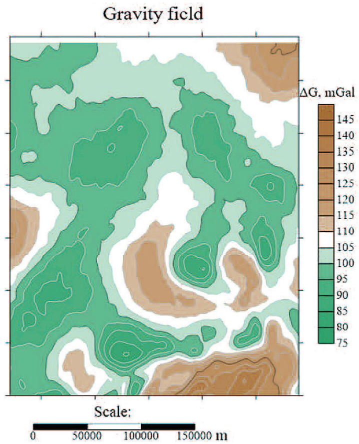


Fig. 2. Geological cross section of the area located on the shelf of the East Siberian Sea

considerable distance. The possibility of drilling parametric wells on the shelf of the East Siberian Sea is still difficult. This is due to difficult weather conditions and, as a result, rather expensive logistics and the cost of geological works. To choose a profitable drilling site, oil and gas companies try to carry out geological exploration using geophysical survey tools in advance because of the cheapness of the methods used. The



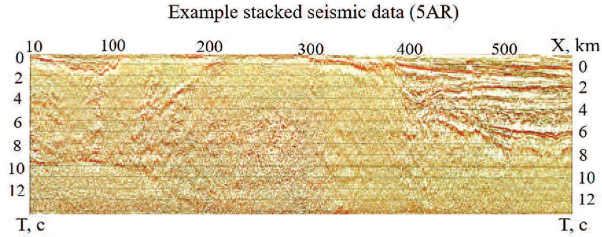


Fig. 3. Initial materials: gravity map (left) and seismic profiles (example on the right)

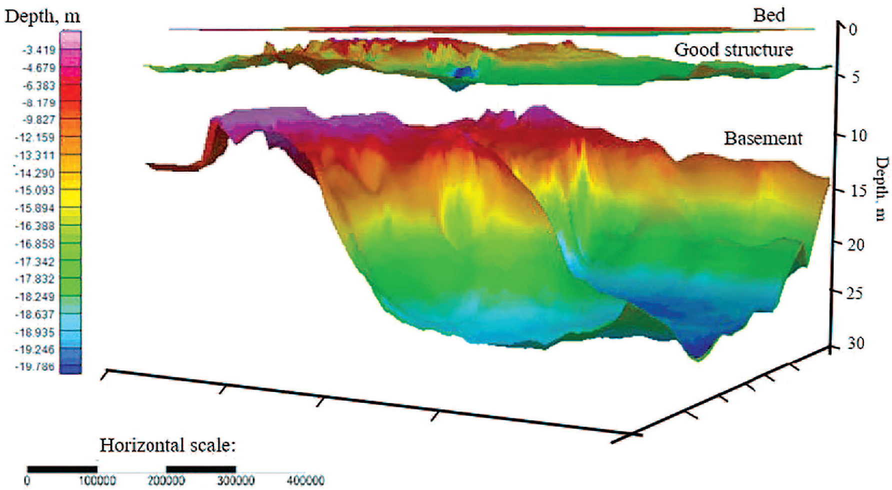


Fig. 4. 3D model of the examined site

geological environment may have a rather complex structure, which may not be reflected in the seismic data. Accordingly, the need to use additional geophysical methods to refine the geological structure of the territory increases significantly. Figure 2 shows an approximate geological cross section of the territory.

The initial data provides a map of the gravity field, velocity cross sections and structural maps for the bottom, potential structure and bedrock (Fig. 3 and 4).

Structural maps formed the basis of 3D models (Figure 11). Depths were established as a result of velocity analysis and were not confirmed by drilling data.

At the first point, the velocities obtained from the hodographs were converted into interval velocities (υi) for each layer according the Urupov-Dix formula [26]:

$$\upsilon_i = \sqrt{\frac{\left(\upsilon_2^2 \cdot T_2\right) - \left(\upsilon_1^2 \cdot T_1\right)}{(T_2 - T_1)}}, \qquad (4)$$

where υ_1 and υ_2 are the effective velocities for the top and bottom respectively; T1 and T2 are the vertical time for the top and bottom, respectively.

The next step was to recalculate the interval velocities in density using Gardner's empirical relation [25]:

$$\sigma = 0.31 \cdot \upsilon_i^{0.25}, \quad (5)$$

where σ is density (g/cm^3), and υ_i is interval velocity in the layer (m/s).

Each layer of the depth-velocity model received its own density distribution, which was limited to approximately the density range in accordance with the little available information from the drilling data for the nearest surveyed region [27, 30]. The table below shows the density data for each layer before and after the density inversion. The results of the density inversion for the practical model are shown in Table 1.

The density inversion was conducted from the lower to upper layers. The marginal error value was set in the input parameters. Since the goal was to reduce the discrepancy between the calculated gravity fields from each structure and the observed gravity field, the values of the marginal error in the inversion were taken from 1 to 0.1 mGal, decreasing from horizon to horizon. The solution of the inverse problem was based on 'lateral' density inversion. This approach is based on E Packer's algorithm [31], in which density in the layer changes laterally, and vertically is constant. In the density inversion, the gravitaty effect was calculated for each layer and then subtracted from the observed field [32]. Residual local anomalies formed a new distribution over the layer, refining the location of density inhomogeneities. While conducting inversion from layer to layer, the magnitude of the discrepancy between the observed and calculated gravity fields decreased. As a result of the inversion, the densities in each layer were corrected for the existing gravity field (table 1,

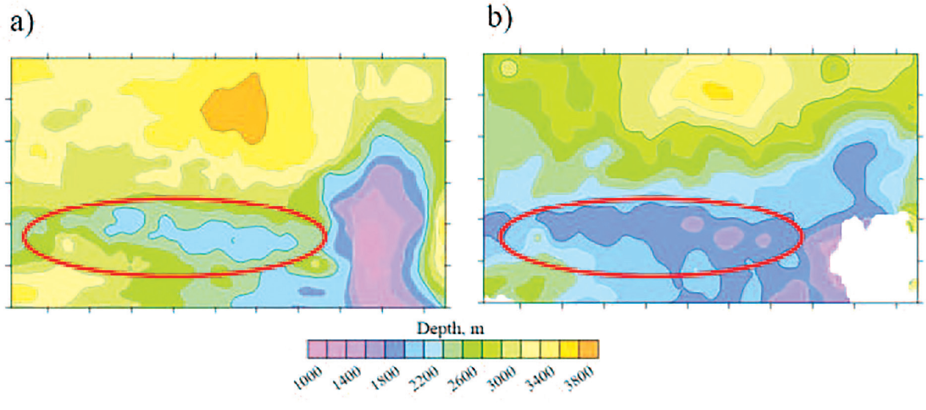


Fig. 5. Fragments of structural maps for the prospective horizon obtained before (a) and after (b) velocity refinement (red line indicates the area of refinement of structural constructions)

Table 1
Results of the density inversion for the examined environmental model

Structure name	Densities before inversion, g/cm^3	Densities after inversion, g/cm^3
Bottom of the sea	1.95	1.95
Perspective structure	2.008 – 2.278	2.001 – 2.282
Foundation	2.007 – 2.762	2.079 – 2.814

column 2). The corrected velocities were then calculated using Gardner's formula and used as the basis for the updated depths in the modeled cross section.

The end result was a corrected depth-velocity model. A structure presumably containing potential areas of oil and gas was used as an example. After seismic density modeling, it was possible to refine the geometry and position of several structures on the map (Fig. 5) so that the resulting model complies with seismic and gravimetric data.

Conclusion

The results of seismic density modeling demonstrate the applicability of the seismic density modeling algorithm for correcting velocity constructions and refining individual structural constructions. the results of the application of the algorithm to real data also made it possible to refine the depths of reference horizons. The algorithm can be used to assess the region's oil and gas potential.

The use of relatively simple gravimetric modeling results allows the method to be widely applied in the future to correct depth-velocity models on land and water areas with limited preliminary information and exploration.

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