Oil-and-gas-bearing territories in the Arctic: new models for finding and clarifying boundaries

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Abstract. A fundamentally new digital model of the Earth’s lithosphere, which has no analogs in the practice of geophysical research, is described. It is a computer database (DB) of geophysical characteristics of the lithosphere processes, including geodeformation indicators. To study these characteristics, a specialized program was developed that allowed, using DB, to implement at a detailed and qualitative level models for analyzing, assessing and predicting the geophysical characteristics of the lithosphere, geodynamic risk, as well as justifying geodynamic indicators of the location of hydrocarbon deposits. The assessment of geodynamic risk is based on the use of a mathematical indicator, which is the spatial distribution of the values of the rotor of the full displacement vector in the geological environment. The proposed mathematical models, numerical methods, and algorithms open up new prospects for conducting scientific research both in the field of managing complex distributed territorial systems and in solving practical problems of analyzing, assessing, and predicting geodynamic risks and searching for hydrocarbon deposits.

1. Introduction
Numerous studies [1], [2], [3], [4], [5] established that the changes occurring in the lithosphere of the Earth are the consequences of various geodeformation processes in it. Such processes, genetically associated with dangerous geodynamic phenomena, are usually subdivided into the “fast” component - seismic processes (earthquakes) and the “slow” component - the modern movements of individual layers and blocks of the earth’s crust. A quantitative assessment of geodynamic risks is an urgent problem for mankind since it directly determines the level of protection of modern civilization and the infrastructures it has created against manifestations of earthly catastrophes.

Developments in the field of geodynamic risk assessment have brought the authors to such an important applied aspect of research as identifying a stable relationship between certain geodynamic risk indicators and the locations of hydrocarbon deposits (oil-and-gas).

In this paper, we consider mathematical models, methods, algorithms, and software [6], [7], [8], which made it possible to assess the geodynamic risks and study the relationship of their parameters with the geodynamic indicators of oil-and-gas-bearing territories in the Arctic zone.

2. Formal apparatus for assessing geodynamic risks
Models for assessing geodynamic risks are divided into deterministic, probabilistic, and fuzzy.
Two types of deterministic models were used: two-dimensional and three-dimensional. Three-dimensional models [7], based on boundary conditions that take into account four conditions, are most effective in assessing geodynamic risks:

- on the presence of significant horizontal shear stresses at the upper boundary of the model (near the Earth’s soil surface);
- on the effect of disturbances from the distributed load at the lower boundary of the model (Moho discontinuity);
- on the absence of vertical shear stresses at the upper boundary of the model space;
- on the absence of vertical shear stresses at the lower boundary of the model space.

The distributed load was approximated by data on the anomalous gravitational field, presented in the form of Fourier series.

Deterministic models are focused on the assessment of geodynamic risks for sufficiently extended territories of a regional scale. However, they did not always “work” correctly in smaller areas due to the absence or sparse data on the fields of various geodynamic anomalies.

Probability models for assessing geodynamic risk are devoid of such shortcomings. It was assumed that the sequence of geodynamic states of the geological environment of a certain territory is a simple stream of homogeneous events satisfying the conditions of independence, homogeneity, andordinariness.

In [9], based on the Kolmogorov differential equations, the dynamics of the probabilities of three states of the geological medium are described — equilibrium stable, nonequilibrium unstable, quasi-equilibrium.

In determining the states, it was assumed that at some point in time, the geologic environment possesses some energy parameter that quantitatively characterizes the energy of dangerous geological processes (DGP) occurring in it.

Concerning territories that are significantly heterogeneous in the tectonic sense, the use of both deterministic and probabilistic models was also not always justified due to the uncertainty of the data. Therefore, models based on the mathematical apparatus of fuzzy sets were applied.

When forming the base of the rules of the fuzzy inference system, the characteristics of anthropogenic impact, the technical condition applicable to buildings and structures, the geoelectric and acoustic fields, the characteristics of the hydrogeological network, and climatic indicators were used as input variables. These data were obtained based on the analysis of macroseismic characteristics of earthquakes, as well as information on stresses and displacements calculated using deterministic and probabilistic mathematical models.

The clustering of territories was carried out based on fuzzy block risk classification methods using the fuzzy c-means algorithm (FCM algorithm) [9].

In the framework of studies on the analysis, assessment and prediction of geodynamic risks in the Arctic zone, a global model for their assessment was built, based on which the stress and displacement fields were restored in the entire lithosphere of the Earth, taking into account the spatial variation of elastic modulus. Thus, a digital model of the Earth’s lithosphere was constructed, reflecting its physical characteristics on a global scale. This made it possible to identify many geodynamic features of the lithosphere using a global model implemented in the corresponding software package.

In particular, it was shown that the epicenters of seismic events on the Earth are concentrated in the regions of the greatest values of the rotor modulus of the full displacement vector in the geological environment. Thus, the specified differential operator is conveniently used as a mathematical indicator of geodynamic risk.

The probabilistic geodynamic risk was calculated on a global scale at all depths of the Earth’s lithosphere. The calculation results are in good agreement with the distribution of earthquake epicenters over the past 100 years, which indicates the adequacy of the proposed approach to the quantitative assessment of geodynamic risk.

Another important applied aspect of model research related to the topic of this paper was the search for geodynamic indicators of hydrocarbon deposits. Using the digital model of the lithosphere of the
Earth, the authors found such an indicator [10], [11]. It has been successfully tested concerning many well-known oil-and-gas bearing basins in the world (Fig. 1), including the Arctic zone. Thus, when assessing the geodynamic risk in various regions of the Earth, it was found that oil-and-gas bearing basins are territorially located at the boundaries of the left-rotating vortex structure associated with the rates of horizontal shear strain. That’s why this characteristic is most suitable for the search for oil-and-gas bearing fields.

![Figure 1. Distribution of oil-and-gas bearing fields and horizontal shear strain rate vectors (in arbitrary units). Depth - 3 km. Ellipses indicate the areas of left-rotating circulation of the velocity vectors of horizontal shear strain. Rectangles indicate the West Siberian oil-and-gas bearing basins.](image)

As follows from a number of scientific sources, analysis of materials from engineering surveys activities and exploration drilling in the area of well-known oil-and-gas bearing fields, along with oil-and-gas deposits of a structural or tectonic type, which are a single deposit with a common oil-water interface contour, significant accumulations of oil-and-gas are recorded in local zones, the location of which, as a rule, is confined to the boundaries of the basement blocks and regional faults.

So, within such zones, the physical and mechanical properties of rock formation change under the influence of excess pressure, and due to secondary porosity and fracturing, areas with increased filtration and capacitive properties arise, forming distinctive “traps” of the geodynamic type for hydrocarbon fluids, which migrate along cracks and faults and form an oil-and-gas deposit at a certain quantitative concentration. As shown by the experience digital model of the Earth’s lithosphere created by the authors and a set of mathematical models, methods, algorithms and software tools for analyzing geodynamic processes makes it possible to search for oil-and-gas bearing basins and, if there is the necessary research data, to evaluate the boundaries of the deposits at any scale level.

3. Results
1. A set of mathematical models, algorithms, computational procedures and software tools for assessing the geodynamic risk in territories of various sizes and geological structure has been developed and practically implemented.
2. The complex of mathematical models for assessing geodynamic stresses, displacements, and deformations in the lithosphere differs from the existing ones by significantly detailed input data on the lithosphere of the Earth.

3. The assessment of geodynamic risk is based on the use of a mathematical indicator, which is the spatial distribution of the values of the rotor of the complete displacement vector in the geological environment.

4. The method of formalized presentation of geodynamic risks, based on fuzzy relationships, allows one to accurately rank natural, man-made and anthropogenic processes by the degree of their impact on objects, as well as assess the integral risks for territories.

5. The proposed approach to the study of geodynamic risks based on new mathematical models, numerical methods and algorithms open up new prospects for improving the management of complex distributed territorial systems in the Arctic, as well as in solving practical problems of assessing geodynamic risks and search for hydrocarbon deposits in the Arctic zone.

4. Conclusion
A fundamentally new digital model of the Earth’s lithosphere, which has no analogs in the practice of geophysical research, is created, which is a computer database (DB) of its physical characteristics and lithosphere geodeformation processes.

To study the indicated characteristics of the lithosphere processes, the specialized DMGRLE - Digital Model Geodynamic Risk Lithosphere of the Earth program has been developed, which allows not only generating the most diverse queries to DB but also at a more detailed and qualitative level, implementing various models for assessing the physical characteristics of the lithosphere, as well as geodynamic risk, justify the geodynamic indicators of the search for locations of hydrocarbon deposits.

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