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# MATHEMATICAL MODELING IN THE STUDY OF GEODYNAMIC PROCESSES

## МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ В ИССЛЕДОВАНИИ ГЕОДИНАМИЧЕСКИХ ПРОЦЕССОВ

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***Abstract.*** *The article substantiates the most important role of mathematical modeling in the study of geodynamic processes. On examples the possibilities of developed effective management methods are shown by these processes.*

***Key words:*** *mathematical modeling, model, geodynamics, geodynamic processes.*

**Introduction.** Significant progress in the mathematical description of various geological processes has been achieved in 60-70 years. As a result of this, in the 70s an approach was born to the construction of evolutionary geodynamic models and the development on their basis of methods for the joint analysis of various geophysical and geological data. This direction began to develop under the guidance of academician V.P. Myasnikov led to the formation of a new scientific discipline, which is now commonly called geodynamics. Particular progress has been made in the mathematical description of the formation of regional tectonic structures.

**The purpose of the work** is to establish the place and role of mathematical modeling in the study of geodynamic processes.

**Main part.** Success in the development of geodynamics did not have any effect on applied geophysical studies of the structures of the earth's crust and upper mantle. The interpretation of geophysical fields caused by these objects was carried out (and often is now being carried out) according to the following scheme. On the basis of geological concepts and data on the physical properties of rocks, a qualitative static model of the structure under study is built; regulated in the spatial distribution of the physical characteristics of the environment. Then, within the framework of the chosen static model, these regularities are determined, i.e. the position and geometry of the areas of density or magnetization, seismic wave velocities, etc. are established. At the same time, a significant amount of information remains on the possible mechanisms of formation and evolution history of the studied structures (here we mean both qualitative tectonic schemes and specific data, for example, structural geology data characterizing the time and nature of tectonic deformations, tectonic immersion curves and track data analysis describing the history of immersion or uplift, etc.). This information is, at best, attracted at a qualitative level when formulating interpretation models, but is not used in the interpretation process itself, for example, when choosing the final version from a variety of equivalent solutions.

It is known that most of the inverse problems of geophysics belong to the class of conditionally correct problems according to A.N. Tikhonov. Regularization methods can successfully deal with various effects of instability and equivalence, for example, by introducing some additional restrictions on the properties of the desired solutions. Unfortunately, in practice, the choice of regularizers is made formally, on the basis of general considerations or, as they say, the experience and intuition of the researcher. An important role is played by the computational side of the matter, the desire to obtain a solution in a form convenient for computer implementation.

Let us now consider an approach based on the use of geodynamic models that are built on the basis of hypotheses about the mechanisms of formation and the history of the evolution of geostructures [1, 2]. Turning to these models highlights the problem of solving direct problems of geodynamics, i.e. mathematical description of the processes of formation of those geological structures and those heterogeneities in the distribution of physical properties that are reflected in geophysical fields. In the general case, this task is far from being solved. Indeed, real variations in seismic wave velocities, density, magnetic susceptibility, and thermal conductivity are polygenetic in nature. They can be caused by tectonic movements of various scales and signs, various magmatic and post-magmatic phenomena, physical and chemical transformations of matter, and other factors. The mechanisms of action, and especially the interaction of most of these factors, are currently not fully understood, so the construction of appropriate models in many cases is a very serious problem. At the same time, when building models of regional tectonic structures, it is legitimate to assume that tectonic processes that lead to displacements and deformations of rocks, as well as thermal fields, have a dominant influence on variations in physical properties. This allows us to confine ourselves to solving thermomechanical problems in the framework of continuum mechanics.

Note that in order to implement the considered approach to the interpretation of geophysical data, it was necessary to create a new class of geodynamic models for that time, the so-called evolutionary models that reflect the dynamics of changes in the physical properties of rocks and the change in the geometry of the simulated structures over time. In the mid-70s, such models were extremely few in number, since in most cases the tasks were reduced to analytical or numerical estimates of the distributions of velocity fields or stresses.

The first examples of the implementation of the approach under consideration were performed using the model of deformation of the sedimentary cover under the action of vertical movements of the crystalline basement [3]. The sedimentary layer was modeled by a linearly viscous incompressible medium in the boundary layer approximation. A distinctive feature of this model was that in it a transition was made from the evolution of the velocity field to the evolution of the boundaries of the geological section in time. This model was first used for the comprehensive interpretation of seismic and gravity data and drilling data for the Volga-Urals [4]. The task was posed as follows. It was assumed that according to seismic and drilling data, the relief of one structural boundary closest to the surface was known; using gravitational anomalies, it was necessary to determine the relief of the deeper boundaries of the sedimentary cover and the surface of the crystalline basement (it was assumed that there is also one deep well that sets the number of sedimentary layers and their asymptotes). It is known that the inverse gravimetric problem of restoring the shape of several contact surfaces does not have a unique solution.

However, in this case, the relief of all boundaries, from the surface of the foundation to the upper stratigraphic horizon, known from drilling data, were connected by the equations of the geodynamic model, under the assumption that the relief of the boundaries of the sedimentary cover was created as a result of movements of the surface of the crystalline basement. Such a formulation made it possible to significantly reduce the dimension of the problem, so that its solution turned out to be unique and stable. Another example of the use of this approach was the interpretation of seismic and gravitational data for the Puchezh-Katunsky meteorite crater [2] using the model of relaxation of large impact structures in the lithosphere – asthenosphere system.

The first examples of the use of this approach led to the conclusion that the accuracy of solving inverse problems in the framework of geodynamic models is determined mainly by the degree of correspondence of the constructed geodynamic model to the real natural process. The main limiting factor in the application of the model [3] was the absence of sedimentation and denudation processes in the model, which is critically important in modeling and solving inverse problems for regional tectonic structures. A model including these processes was built in [5], which significantly expanded the range of tasks. Evolution models of large platform troughs (for example, the Donets Basin), passive continental margins, and other regional tectonic structures were constructed. It was shown that a number of slow (relaxation) tectonic processes, such as the evolution of passive continental margins in the transition zone from a more powerful continental to a thinner oceanic crust, are determined not only by the dynamics of the movement of matter in the layers of the lithosphere and asthenosphere, but also to a significant extent by the redistribution of the surface load , i.e. sedimentation and denudation processes.

Using new models, it was shown for the first time that isostatic compensation of the surface load can be carried out not only by immersing or raising the lithosphere, but also by changing the thickness of its constituent layers. In particular, an increase in sedimentary load power leads to “squeezing” of the material of the lower layers of the earth's crust from under the sedimentary basin to its periphery. Taking this factor into account for sedimentary basins leads to a decrease in the estimates of the initial extension. It is also important that on the basis of new models it was possible to build a mathematical theory for solving problems of paleotectonic analysis, i.e. problems of reconstruction of tectonic movement velocities based on data on thickness, age and facies composition of sedimentary rocks [6].

New models made it possible to use a large amount of new information when interpreting geophysical data, in particular, data on the lithological-facies composition of sedimentary rocks. Let us consider an example of a joint analysis of seismic, gravitational and magnetic data and data on tectonic sink rates for passive continental margins [4]. The solution scheme was as follows. In the geodynamic model of evolution of the passive continental margin, the structure and evolution of the transition zone from the continental lithosphere to the oceanic is determined by a set of parameters: the characteristic vertical and horizontal scales of the structure under study, the effective viscosities and densities of the sedimentary layer and layers of the earth's crust and upper mantle, the duration of the process (margin age). These parameters were determined from the condition of matching the calculated topography of the upper layers of the sedimentary section with the available seismic data, the correspondence between the estimated surface velocity of the model and the tectonic velocity known from drilling data, and the amplitude and characteristic sizes of the calculated and observed isostatic anomalies. Data were used on the eastern edge of North America. As a result, the modern configuration of all layers was calculated, including the basement and Moho surfaces, which are poorly known from seismic data, due to the large thickness of precipitation and the presence of strong reflecting horizons in them. Data on the surface of the crystalline basement and data on the temperature distribution were then used to set the upper and lower boundaries of the magnetoactive layer, which made it possible to estimate the distribution of magnetization over magnetic anomalies using the method [2]. A comparison of the obtained distribution of the magnetization with the distribution of the zones of expansion and contraction allowed us to conclude that the formation of the Brunswick magnetic anomaly on the eastern outskirts of the United States could be due to the introduction of intrusive material into the tension zone formed during the growth of the sedimentary basin on its inner (facing the continent) board. Note that on the eastern continental margin of South America, which has a similar structure, basalts of two generations with an age of 138–112 and 75–40 million years were discovered, which is consistent with our interpretation.

The role of sedimentation was also investigated by the example of the Gakkel ridge [7] and by analyzing the history of subsidence of the lithosphere of the Great Valley (California) in the delta of the river. Sacramento [8]. In the latter case, the thermal regime and the history of the subsidence of the pre-arc basin located above the oceanic lithosphere of about 150 million years old were modeled. In this case, it was necessary to simulate not only the cooling of the oceanic lithosphere covered by a thick (up to 14-16 km.) Sediment layer, but also the thermal regime of the subduction zone, taking into account the change in the subduction rate over time and the age of the submerged plate. The constructed thermal model is in good agreement with the data on the current heat flow, the history of tectonic immersion, and the data on the thermal transformations of organic matter contained in sedimentary rocks. The obtained modern unsteady temperature distribution in the lithosphere was used to calculate the ultimate strength profile. Strength profile predicts the presence of a brittle layer in the upper part of the crust, which can extend to a depth of 20 km or more. This explains the presence in the delta region of the river. Sacramento anomalously deep (up to 20 km) earthquake cluster. In neighboring regions, differing in the structure of the crust, sedimentary cover thickness and heat flow, the earthquake depth does not exceed 12 km. This work, based on a joint analysis of seismic data, drilling, heat flow and plate tectonic reconstructions, is an interesting example of the use of geodynamic modeling and basin analysis techniques to assess seismic hazard.

New possibilities in modeling geodynamic processes and the interpretation of regional geophysical data appeared after the creation of a thermo-mechanical model of the evolution of the rheologically stratified surface shell of the Earth [7]. The model includes the lithosphere (consisting of a sedimentary layer, the earth's crust and the subcrustal mantle), the asthenosphere and part of the upper mantle below the asthenosphere. To obtain boundary conditions at the base of the model (in the subasthenospheric mantle), the model is asymptotically consistent with the model of the Earth’s global evolution [7]. The layers of the model differ in density and effective viscosity, sedimentation and denudation processes are included in the equation of the evolution of the day surface, it is assumed that the roof of the asthenosphere is a rheological boundary and coincides with some isotherm (usually 1300 degrees C).

This model made it possible for the first time to study the features of the development of small-scale convection in the regions of tension and compression formed under the action of intraplate or mantle influences. Numerical calculations [6] and analytical estimates [7] showed that such imbalances lead to the formation of circular flows in the asthenosphere, which persist for a long time after the end of the active stage, i.e. period of external tectonic forces. The evolution of tectonic structures in the absence of external tectonic influences (relaxation stage) is determined by a number of factors, including the distribution of density and temperature in the surface shell, the width of the extension or compression region, and the intensity of sedimentation and denudation processes. It is important that if the density in the asthenosphere does not decrease with depth, then small-scale flows support the same character of deformations that was at the active stage: slight stretching and sinking continue in the regions of extension, and compression and rise in the regions of uplift [7]. These effects are important for constructing scenarios of the formation and evolution of sedimentary basins and mountain structures.

Let us consider an example of using the model of the evolution of the surface shell in modeling the history of immersion and the gravitational field in the orogen – piedmont deflection system [8] using the example of the Ciscaucasia deflections. Calculations showed that the violation of mechanical and thermal equilibrium in the compression regions of the continental lithosphere by intraplate forces leads to the formation of small-scale flows in the asthenosphere under the outer edges of the compression regions. These flows create additional compression in the orogen and extension at its periphery, which contributes to the formation of foothill deflections. This mechanism does not deny the role of the elastic bending of the lithosphere under the influence of the weight of a mountain structure. The problem is that the weight of the topography in many cases is not enough to create the observed deflection, so for many mountain structures it is assumed that there is a so-called latent load - an additional positive density anomaly inside the crust. For the Greater Caucasus, this is a particular problem, since deep foothill troughs are developed in its eastern and western parts, where the height of the mountain structure is relatively small. In the central part in front of the highest mountains, the Stavropol arch is located, and the foothill trough is absent. We will return to the question of the formation of foothill deflections under the action of the load formed during the compression of the lithosphere. In this case, it is important for us that small-scale convection introduces an additional component of immersion, forming deep deflections in front of relatively low mountain structures.

The constructed model of the formation of piedmont troughs made it possible to give a new interpretation to the tectonic dip curves for the Northern Ciscaucasia [8]. An analysis of the data of more than 100 boreholes located in different parts of the trough allowed us to compare the main events in the history of the subsidence of these areas with regional tectonic events and phases of volcanism in the Caucasus region. It is important that in the model of the elastic bending of the lithosphere, the phase of external tectonic compression is accompanied by the thrust of the orogen onto the deflection region, and, as a consequence, by the subsidence of the deflection. A comparison of the history of immersion in foothill troughs with the phases of tectonic compression for a number of mountain structures, including the Caucasus, showed the presence of an inverse correlation: the phases of uplift in the orogen correspond to the phases of uplift in the foothill trough, and the phases of dormancy correspond to periods of immersion. It is this relationship that follows from the model of evolution of the surface shell. Comparison of the simulation results with data on the history of the subsidence of the Pre-Caucasus troughs allowed us to conclude that the Greater Caucasus was formed as a result of at least four compression phases. The first phase occurred 39.5 million years ago, which coincides with the closure of the ocean basin and the beginning of the continental collision in the Caucasus. Three subsequent stages occurred during periods 16.6 - 15.8; 14.3 - 13.7 and 7.0 - 5.2 million years ago. The presence in Maykop time of the rise on the site of the modern Greater Caucasus was confirmed by Italian scientists who conducted research in this area as part of the INTAS joint project with the IPF [8]. The model of small-scale convection also better agrees with the data on the gravitational field of the Pre-Caucasus troughs [7].

The absence of a piedmont deflection in front of the central, most elevated part of the Greater Caucasus can be explained by the model of extension — compression of the lithosphere by intraplate forces [7, 8]. In these works, a model of tension – compression of an effectively elastic shell that is inhomogeneous vertically and horizontally is constructed, and an analytical solution is obtained for small strains. It is shown that, with sufficient accuracy, the deformation of such a shell in the absence of gravity can be described by the following equation, first used to describe the stretching of the lithosphere in [9]: $W(x,z) = -(z - z_n)\partial U/\partial x$, where *(x,z)* - cartesian coordinate system with axis *z* upward *W(x,z)*- the vertical component of the displacement vector, *U(x)* - the horizontal component, which in the case of small deformations of a thin plate, depends only on the horizontal coordinate, $z_n$ - - zero level, called in the problems of modeling sedimentary basins, the level of extension. In this model, it is assumed that the process of structure formation under the influence of tensile or compression forces can be divided into two stages: deformation by external forces in the absence of gravity and the subsequent establishment of isostatic equilibrium.

It was shown in [10, 11, 12] that the position of the zero level is determined by the distribution of mechanical properties in the lithosphere with depth and a formula is obtained for calculating the depth to this level.

**Conclusions.** Modeling of geodynamic processes is largely studied by physical, chemical, geological changes occurring on the surface and inside the Earth. Their dynamics allows us to develop effective methods for managing these processes.

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***Аннотация.*** *В статье обоснована важнейшая роль математического моделирования в исследовании геодинамических процессов. На примерах показаны возможности разработанных эффективных методов управления этими процессами.*

***Ключевые слова:*** *математическое моделирование, модель, геодинамика, геодинамические процессы.*

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