

Three-Dimensional Numerical Geological Mapping: Principles and Computer Programs for Producing New Generation Maps

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INTRODUCTION

Geological mapping is one of the most ancient human activities. People have always wanted to know where they can mine for different stones. The first maps presented places of outcrops for different formations. The mapping principle was simple: people drew distribution fields of different rock types. At the beginning of the nineteenth century, the paleontologic method for determining the formation age was introduced. This method made a revolution in mapping. The main idea of this method is to determine the borders of layers of different ages and to show these borders on maps. The main consequence is the ability to examine the tectonic structure and geological history of the area.

The drilling and geophysical methods of studying the subsurface resources allow study of the behavior of geological bodies at depths. Once people learned about the structure of the upper several hundred meters to several kilometers of the Earth's crust, it became necessary to show the three-dimensional structure of the Earth's interior. The question was how to show, for example, the deep three-dimensional structure of an orogen or a stand-by tank.

For folded areas it was suggested to draw geological maps for different depth sections together with a large number of ordinary geological sections. This method allows "cutting" the upper part of the Earth's core into cubes and drawing the geological structure at the cubes' facets. This kind of work, inspired by Prof. A.A. Bogdanov, was done by geologists at Moscow State University in the vicinity of Lake Balkhash in the years 1970–1976 [2].

It became possible to draw the three-dimensional structure of stand-by tanks with isolines that show roofs and floors of geological bodies at different depths.

Now, with the development of digital GIS technologies, it has become theoretically possible to draw three-dimensional digital geological maps for all types of geological areas. This work was initially done for oil fields, gas fields, and ore deposits, as people have a lot

of information about the three-dimensional geological structure of those areas. This work was mainly commercial and usually based on 3D-seismics.

Our goal is to develop an approach to three-dimensional digital geological mapping for regional mapping that is duly performed by geological services of different countries and different geological institutes. We also aim to implement software necessary for mapping and analyzing the maps.

BASICS OF THREE-DIMENSIONAL DIGITAL GEOLOGICAL MAPPING

What are the basic principles of geological mapping, and what can be found on such maps?

First, we take a regular digital geological map of the surface as the basis of the three-dimensional geological map. The geological bodies that show on the surface should be marked on the map. The goal is to show these bodies as real three-dimensional objects (together with the bodies that remain underground).

Second, we build the probabilistic digital geometry of all the geological bodies considered at their depths. The geometry is derived from the drilling data, seismic profile, and all other types of geophysical data.

Third, using the parameters of the geometry of the folds, breaks, and other geological bodies that are estimated during geological mapping, we design mathematical algorithms to find the most probable three-dimensional form of the bodies.

Fourth, with the three-dimensional digital recording of the geometry of all the geological bodies, we can

construct a section along any vertical or horizontal geometry, or any other surface;

highlight one of the bodies and examine it from any point (rotate, look inside, etc.);

build three-dimensional maps with lithofacies or any other characteristics (e.g., porosity, water encroachment, geochemical characteristics, contours of the geological bodies).

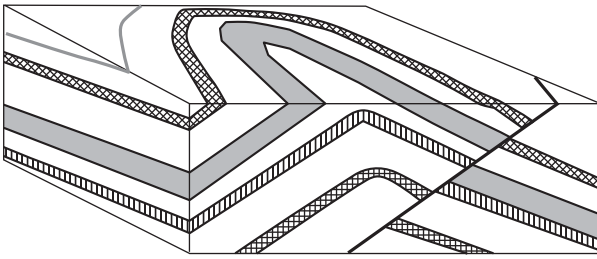


Fig. 1. An example of a three-dimensional geological map of a deformed stand-by tank.

Fifth, with a three-dimensional digital geological map, we can conduct different kinds of research. We can reconstruct the geological history; study mineral reserves; and solve hydrogeological, geotechnical, and ecological problems.

It is clear that three-dimensional digital geological mapping lies at the heart of future geological mapping.

Mapping Stand-by Tanks

The geological structure of stand-by tanks is relatively simple (Fig. 1): flat deposition of the layers and a small number of snaps and intrusions. However, the structure of a stand-by tank can be complicated with saline diapires, reef builds, inversive structures, thrusts, cliniform structure of sedimentary layers, etc.

The geological structure of stand-by tanks is usually extracted from the following data: (1) field geological mapping; (2) drilling data; (3) seismic profiles of different depths; (4) analysis of the anomalies of gravitational and magnetic fields; (5) resistivity prospecting data. The most useful data is, of course, three-dimensional seismic data. If we have such information on some area, it is very simple to create a three-dimensional geological map for this area.

How should we build the three-dimensional map for the stand-by tanks? First, we take the digital geological map of the surface as the basis. Then, we enter the interpreted data of the drilling and seismic profiles, taking into consideration other geophysical data. The software then draws the three-dimensional digital geological structure.

Mapping of Folded Areas

Orogens of the Ural type have a very complicated geological structure. However, many of the ore districts are well explored and this information allows compilation of their three-dimensional digital maps. In practice, a geologist builds the geological bodies based on the available data, while the software adjusts the geometry of the bodies and draws the optimal geological structure. The most important part is the mathematical prediction of the most probable geometry of the folds, intrusions, breaks, and other geological bodies. This is

usually based on their surface structure analysis. Modern structural geology allows prediction of the three-dimensional structure of the folds using the information about the folds' geometry on open areas. The problem is to construct a numerical algorithm for this analysis and to model the optimal geometry of the geological bodies at depth.

Mapping of Cities and Important Engineering Structures

Cities like St. Petersburg and Moscow, engineering structures (like big storage pools), important underground constructions, etc., should have three-dimensional digital geological maps. Moscow, for example, is a very special hydrological, ecological, and engineering structure. There are a lot of underground structures in Moscow (subway, etc.) and lots of functioning industry. Moscow, as any metropolis, should have a three-dimensional geological map. Such a map should contain (1) boundaries of all natural geological bodies; (2) boundaries of all lithological bodies (as any suite can change consistency bottom-up and facially), e.g., sandstone, clay, and limestone; (3) zones of different porosity, water content, with geochemical anomalies, with different mechanical properties; and (4) underground structures. This map is necessary for different city services. For example, only with such a map one can perform continuous monitoring of the underground water movements in the urban area and drift of geochemical anomalies (mainly for ecological monitoring). It is possible to design construction in the city using this map, as it contains primary engineering and geological characteristics.

During mapping of the areas for engineering structures, it is also possible to introduce any other data that characterizes the mechanical properties of the soil (in addition to the boundaries of geological bodies and standard geological data).

Mapping for Ecological and Hydrogeological Purposes

Currently there are lots of problems concerned with regional ecology, nuclear waste, other hazardous waste disposal, the ecological safety of areas close to oil pipelines, pollution from large industrial centers, etc. It is necessary to build special detailed three-dimensional digital maps for these potentially ecologically hazardous areas. These maps should have special parameters controlling migration of gases and liquids. It will be possible to model the potential underground movement of the ecologically hazardous elements. Three-dimensional digital maps should be the basis for ecological monitoring of potentially dangerous areas, because with them it is possible to model continuously the filtration of the fluids with the data of new geochemical measurements.

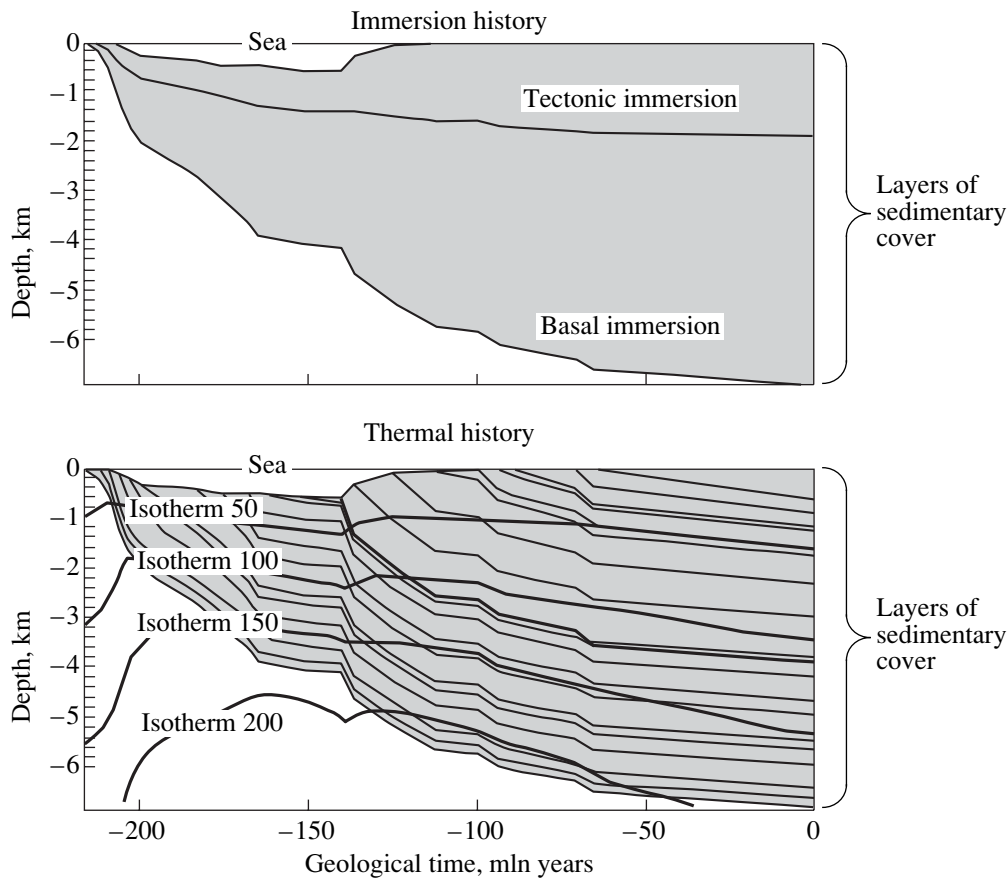


Fig. 2. An example of one-dimensional modeling of the history of the formation of a stand-by tank. The upper part of the picture shows terrain surface curves, basal complex immersions, and tectonic immersion. The modeling approach is described in [3].

Continuity of Three-Dimensional Digital Geological Mapping

The core of three-dimensional digital mapping is that we enter initial geological data into the software that builds the map by itself. Therefore, as soon as we receive new data (for example, after drilling a new cleft or passing a new seismic profile), this data should be entered in the software and the three-dimensional map is updated.

Analysis of Three-Dimensional Digital Geological Maps

Analysis of the maps consists of three tasks: (1) analysis of the modern structure; (2) analysis of the geological history of the region; and (3) analysis of the history of the formation of a mineral deposit or an anomaly.

Analysis of the modern structure is a common type of work with a geological map. However, with a digital record of the geological structure, we can appreciate the volumes of geological bodies, the amounts of mineral deposits, or the volumes of any zones in which we are interested. We can immediately extract any numerical

information that is possible to extract from the initial data.

Analyzing the geological history of the region is a conceptually new task. In principle, we should have the three-dimensional geological structure of the region for every moment of its geological history (which can be reconstructed) and the paleogeographical situation at the region's surface. First, however, it is necessary to reconstruct the geological structure of individual points (e.g., clefts) and along individual quarries.

Numerical reconstruction of the geological history in individual points is now a common job; it is done in many scientific groups. We perform the following calculations (Fig. 2): (1) the subsidence curve; (2) the tectonic setting curve; (3) subsidence and soil erosion velocities; (4) paleotemperatures; and (5) analysis of the history of oil and gas production.

Numerical reconstruction of geological history along the lines of geological quarries for stand-by tanks without complicated tectonic elements started quite recently. The algorithm for this procedure was developed by our group [1, 3, 5] and is also being developed independently by other groups (mainly for oil companies). The basis for this work is a digital picture of the geological section. During numerical modeling we

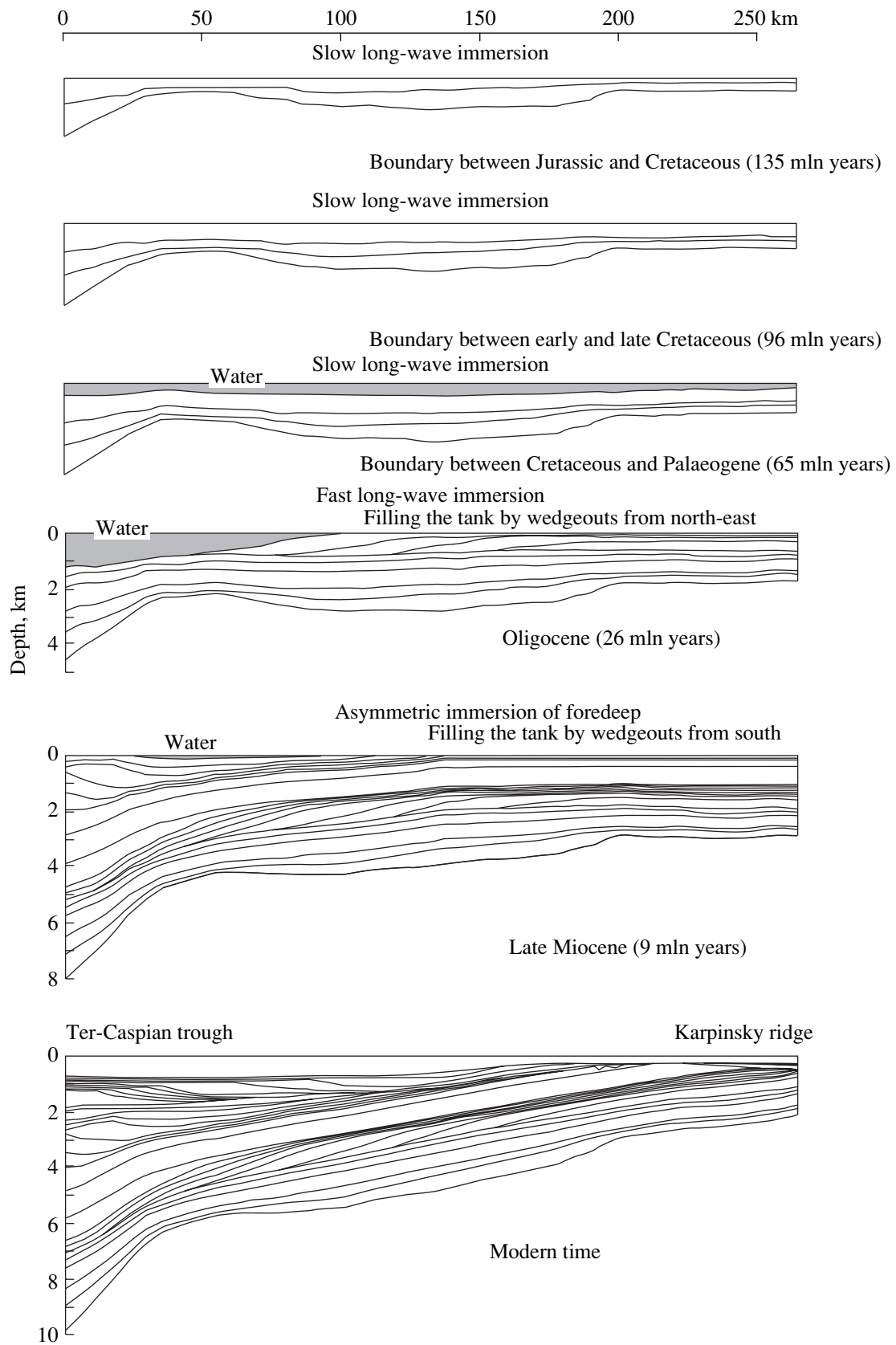


Fig. 3. An example of two-dimensional modeling of the history of formation of a stand-by tank. History of formation of the stand-by tank is shown. The modeling approach is described in [3].

reconstruct the paleogeological section and the paleodepths (or paleoheights) for every chosen moment of the past. To do this, we should supply data about the paleodepths of the formation of each geological body, for erosion, and for the eustatic oscillations of the sea level. Details concerning this approach were described in other papers [1, 3, 5]. An example of such a construction is given in Fig. 3.

For complicated stand-by tanks and geological bodies, reconstruction of the deformation history and of the initial structure plays a very important role. The method of compensated sections compilation was developed for this purpose [3, 6–9]. The idea of the method is to, first, reconstruct the chronology of the forming of folds and snaps and, then, step by step reconstruct the geometry of the initial structure (Fig. 4): the layers are returning to their initial positions along the fault planes, while the folds are straightening. This approach can be correctly applied in a situation where there was no ductile matter flow. In the latter case, the ductile deformations should also be reconstructed and the problem becomes more complicated. During the past few years, balanced section construction has been a necessary part of geological work. They are constructed for all regions (Fig. 5). Balanced sections are also a natural inspector of one's work: if after constructing the geological sections one is not able to reconstruct the sedimentary structure before deformation, it means that there are principal inaccuracies in this section. A "balanced section" is a section through the deformed structure that, when straightened, gives the structure before deformation.

We introduce three basic assumptions in our approach of automatic reconstruction of the balanced snaps [3]: (1) the volume of the rock does not change; (2) the flat deformation assumption, that is, there was no deformation in the direction orthogonal to the section (and hence, the areas of the section layers did not change during the deformation); (3) the layer length did not change during the deformation. The algorithm of the section's reconstruction is based on these assumptions.

Currently there is a problem of software compatibility; we must unite the programs reconstructing the orogen forming history and allowing the creation of balanced sections. If we succeed we will obtain a software package able to create paleotectonic and paleogeographic reconstructions along sections with a complex tectonic structure.

Even now it is possible to reconstruct the three-dimensional geological structure for well-studied regions. There are no crucial obstacles in the way (Fig. 6). It is also important to note that now the three-dimensional geological history includes not only the history of formation and deformations of the geological bodies, but also the history of many other parameters (for example, the temperature at the Earth's surface, in

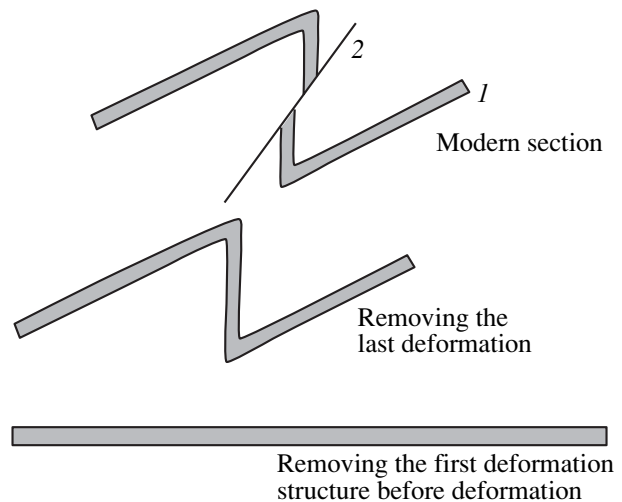


Fig. 4. A simple example of the balanced sections principle. We reconstruct a section by removing deformations step by step: (1) first phase of the deformations, formation of the folds; (2) second phase of the deformations, formation of the crack.

the seas, and at different depths; the width of the lithosphere; pressure; etc.)

With a numerical model of a region's geological history along the sections or in the volume, we can build numerical two-dimensional and three-dimensional models of the forming history or predict the forming of mineral deposits. Nowadays this method is used most widely for hydrocarbons, and we study this question with hydrocarbons as the prime example. If we know the history of the formation of the whole region considered and of individual geological bodies, we can estimate numerically when, how, and from what materials the hydrocarbons were formed, when they started to migrate, what the history of their migration was, and where they are most probably localized now. All this information means that we can study hydrocarbon systems in time (Fig. 7).

CONCEPTUAL REQUIREMENTS FOR COMPUTER PROGRAMS OF THE THREE-DIMENSIONAL GEOLOGICAL MAP

We want the program for the three-dimensional digital geological map to meet the following requirements:

(1) The map should be essentially three-dimensional—all points must have three-dimensional binding, not only geographical (which is usually the case in existing GIS). Efficient spatial search and data analysis should be implemented. Modern GIS (geographical information systems) preserve the main disadvantage of paper maps: GIS are two-dimensional. All information in GIS (including in-depth structure information) is bound to geographical coordinates. The information about the depth is introduced artificially, so any non-trivial three-dimensional analysis turns out to be impos-

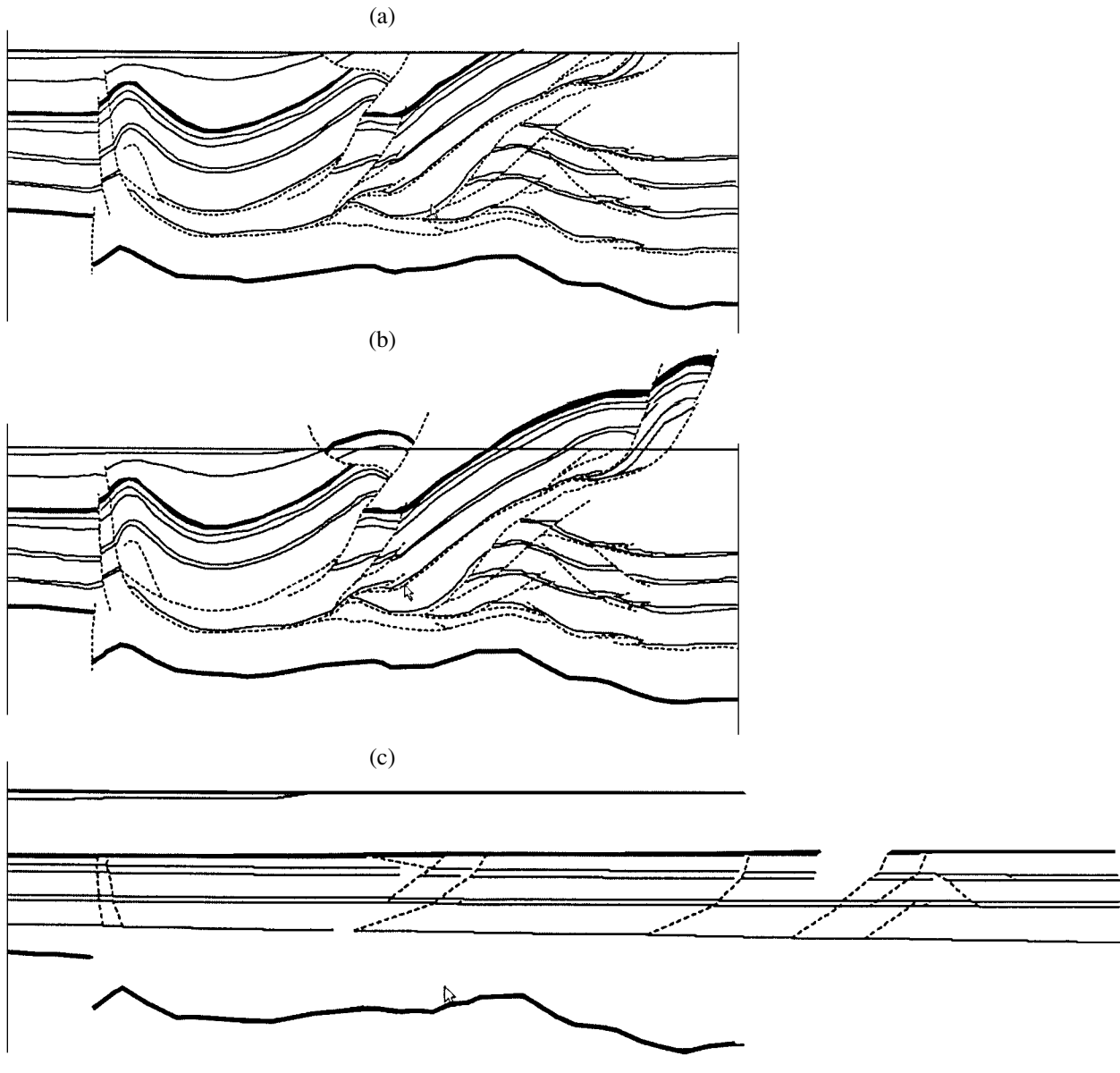


Fig. 5. An example of a balanced crack. (a) Simplified geological section along the profile crossing the Chernyshev ridge (Polar Ural), prepared for the balance check. (b) Geological section (a) with geometrically reconstructed eroded regions. (c) Reconstruction of a section with “gaps” done by the length preserving method. “Gaps” are introduced in order to bring the lengths of borders, geometry, and vergence of the cracks in the initial section and in the reconstruction into compliance. Thus, “gaps” mark places on the initial section where we have to modify our interpretation of seismic recordings.

sible. Thus, existing GIS give sufficient information about the surface section of a three-dimensional geological structure and very little information about its in-depth structure. Geologists would like to have an information system that is more geological than geographical, binding the information to three axes (x , y , z) instead of two (x , y), which is the case in existing GIS.

(2) The mathematical algorithms for building the three-dimensional geological structure should allow for human-computer interaction and not be completely automatic. This requirement means that a geologist

working with the software should have almost full control over the three-dimensional structure. This possibility will allow him to realize his perception of the geological structure of the mapped area. On the other hand, the three-dimensional models constructed by different people can be quite different. For this reason the program should support several “designer” versions of the three-dimensional model for the same area. Let us illustrate this feature with the example of one simple fold. Here is the list of parameters that control the three-dimensional geometry of the fold: (1) type of the fold

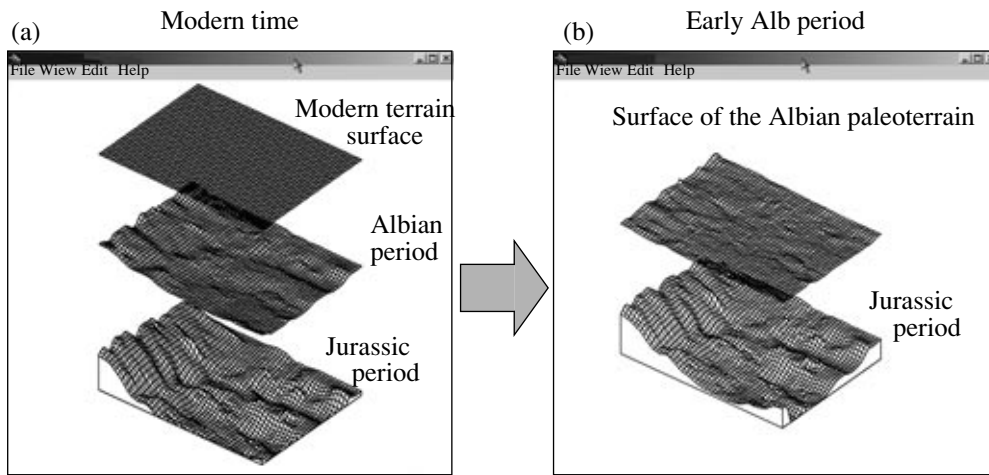


Fig. 6. An example of the digital three-dimensional geological map for a region in Western Siberia (a) at the present moment (footwalls of the Albian and Jurassic stages are shown) and (b) with reconstruction for the early Albian stage with a picture of paleoterrain.

in terms of proportion between thicknesses of the limb and the joint (concentric, congruent, synclinal, anti-synclinal); if the thickness changes, the thickness change coefficient should be specified; (2) the type of joint (ancone, smooth curve, box); (3) the fold's axial line at the map and the inclination of the axial surface at several points; (4) the hinge of some geological bound of the fold and the vertical coordinate of the hinge; (5) the proportion between the relative size of the limb and the joint. The software should provide the possibility for the geologist to enter these parameters manually, and then it should be able to make the corresponding calculations. This attribute means that the software should give an instrument to a geologist, but not impose predefined solutions on him.

(3) The program should not demand too much initial data. Usually, the only information a geologist has about an orogen is the geological map; the terrain map; and, perhaps, maps of several clefts. For the stand-by tanks, the number of clefts is larger and there is also seismic data, but here the geological map of the region gives less information. Adding initial data should increase accuracy. Therefore, the software should incorporate the possibility of constant changes in the three-dimensional model.

(4) The map should contain more information than the usual paper map. It should include information about the three-dimensional morphology of isochronic geological borders, facial borders, layers, faultings, geological (lithological) bodies, intrusions, and zones of secondary alterations, as well as about the spatial distribution of different material parameters (petrophysical and others, such as porosity, penetrability, etc.) bound with geological bodies.

In particular, information about geological layers should include data about geometry, lithology, the absolute age, and the petrophysical properties of the

layers; information about the faultings should include data concerning the geometry and age(s) of the shoves and the fillings; information about the intrusions should be filled with data on geometry, composition, the absolute age, and the petrophysical properties; information about zones of secondary alterations should contain data on their geometry, type, and age. All initial geological information used for the spatial model construction must have three-dimensional binding.

(5) The primary technical requirement is that the new software should not begin its work from scratch; it

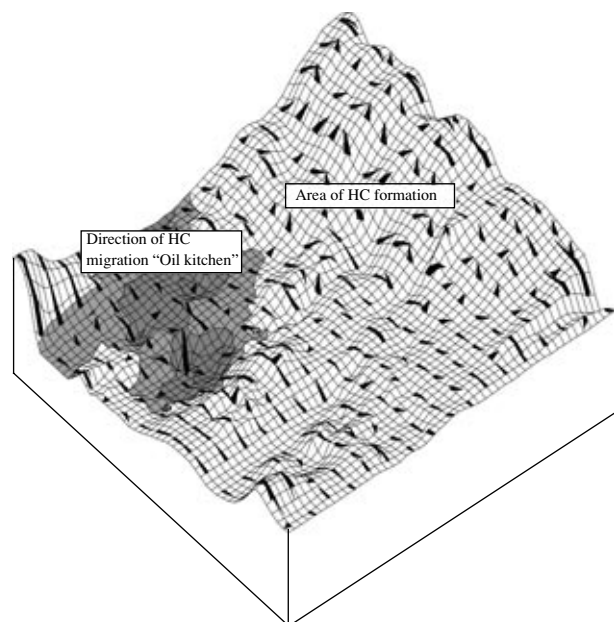


Fig. 7. An example of three-dimensional oil system. We show the region of hydrocarbon (HC) formation and the directions of their migrations.

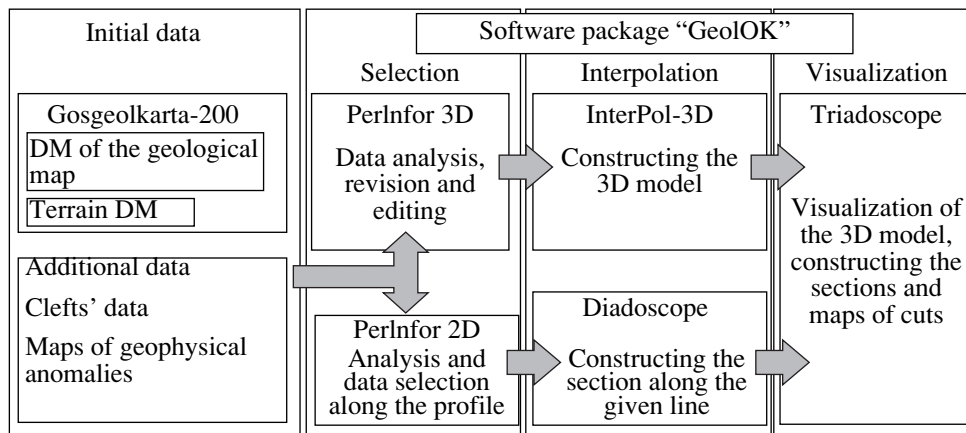


Fig. 8. Units of the software package "GeolOK."

should be included in the existing partially automated process of geological data processing. In particular, this requirement means that there should be a way to import digital cartographical data of the Rosgeolkarta-200 sheets. There is no need to duplicate the functions of input and storage of the cartographical information of the existing GIS used now in the geological organizations. This program pack should be oriented toward solving its own problems. In addition, scalability is also a primary concern: on better hardware our software should work better.

"GEOLOK"—A SOFTWARE PACKAGE FOR THREE-DIMENSIONAL DIGITAL GEOLOGICAL MAPPING

The principles mentioned above were implemented in the software package "GeolOK." We developed this package for constructing three-dimensional geological maps in the years 1995–2006. Let us describe the structure of our software.

The program pack for three-dimensional geological mapping consists of the following elements (Fig. 8): the input module and the database; the module for the calculations, interpolation, and three-dimensional structure analysis with the initial data; the database of the three-dimensional geological structure; output and representation units; and three-dimensional analysis and three-dimensional selection units.

There are also additional units that provide reconstruction of the history of immersion and structure deformation in time and modeling of different processes which took place during this evolution, such as heat transmission, fluid filtration, and oil and gas formation.

Today, this software package is being tested in three regions of Russia with different geological structures.

PRACTICAL RESULTS

We tried to construct the three-dimensional geological map of the Astrakhan arching of the Caspian Sea region and for some others regions with stand-by tanks with our software. Now, we are able to show on the screen of a computer all geological surfaces (facets of geological bodies), construct sections along any surface, rotate the map and examine it under any angle, and reconstruct the geological structure and the paleogeographical surface for different moments of time. The software allows us to study the development of hydrocarbon systems and shows possible places of oil and gas localization at the present moment. In general, the program is able to solve the main problems we described above.

THREE-DIMENSIONAL GEOLOGICAL MAPPING—WHAT NEXT?

Suppose that we already have a working version of the three-dimensional geological map for stand-by tanks. What are the future possibilities for geological mapping? First, these maps can be constantly updated if new information becomes available. Then, we can proceed to four-dimensional mapping, that is, add time to the picture. We should be able to move back in time and examine how a geological structure appeared 5, 10, 100, 500 million years ago. We can even make animations showing the three-dimensional history of the region together with the paleogeographical history of the surface. Such maps can prove to be very useful, for example, for finding hydrocarbon agglomerations, which have, over the ages and with new deformation phases, migrated in depth. Reconstruction of the three-dimensional history of the geological structure will help to find different mineral deposits that could have migrated or have been compressed during faultings.

Currently, it is technically possible to have three-dimensional geological digital maps for the whole territory of Russia and the Earth. The level of detail of the

maps will depend on how well a given region has been studied.

CONCLUSION

Three-dimensional digital geological mapping is a necessary part of modern regional geological exploring, especially for regions with stand-by tanks, ore fields, big cities, and large engineering facilities.

For stand-by tanks, it is necessary to develop a software package that allows construction of the three-dimensional digital picture of a stand-by tank and analyze its geological history. This package should contain the following programs (we are developing this package at the moment, and most of its units are already working): (1) numerical analysis of the geological history at a given point (e.g., in the cleft, or the section constructed using the information from fieldworks); (2) numerical analysis of the geological history along a section with reconstruction of the paleostructure and the paleogeography for all the stages of its development; (3) constructing the three-dimensional digital geological map and comprehensive analysis of the modern structure (we can examine the structures and their assemblies from any point, measure any volumes, and so on); (4) specific software for hydrogeological, geotechnical, and ecological purposes; (5) specific software for finding hydrocarbon and other mineral deposits.

Currently, it is technically possible to have three-dimensional geological digital maps for the whole territory of Russia and the Earth. The level of detail of the maps will depend on how well a given region has been studied.

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We believe that the foremost specialist of the twentieth century in geological mapping and one of our teachers, A.A. Bogdanov, would have been very interested in our research.

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