3-Dimensional Geological Mapping. Applications to Urban Geological Environment

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Abstract

3d geographical information system for the city geological environment has two main functionalities: (1) Permanent correction of the geodata base according to the new incoming data or geological concept. (2) User's support: information retrieval system and information services. We define 3-dimensional geological map as the class of 3d models of geological environment that describes the positions of geological bodies in a non-contradictory way. Each class of objects of the model is characterized by the set of it attributes and the geometry type. Relational database structure is used for attribute tables. The geometry type is characterized by its dimension and format. A 3-dimensional geological map is a pure computer model and its visualization as a whole object is impossible. Various 2-dimensional visual images of the model are discussed. The principles of visualization are inherited from the 2-dimensional cartography. Main applications of a 3-dimensional geological map are: (1) 3-dimensional geological map as a self-contained unit. (2) Classical 2-dimensional geological mapping. (3) Compiling new thematic maps. (4) Geological zoning. (5) Information resources for computational modeling. (6) Architecture and mining design. (7) Presentation design.

Keywords

Urban geology • GIS • 3d modeling • Geological maps • Environmental maps

180.1 Introduction

The large-scale geological and environmental maps are used for city development planning, engineering-geological prospecting, and environmental studies and protection in Moscow.

The geoinformatics technologies have been developed in this project especially for the map-making (Mironov 2011). The informational interdependences of maps in the project form the complicated logical structure. Maps with the same parts of content must have coinciding regions or contours. The geohazard and engineering-geology zoning maps use generalized data from geological and hydrogeological maps.

The next step of map's development and using must be the 3d geographical information system for the city geological environment. This system should have 2 main functionalities:

- Geological data maintenance according the new information and conceptions.
- User's support: information retrieval system and information services.

The geological data are essentially 3-dimensional. Geologists think in terms of 3-dimensional geological volumes and use 2-dimensional drawings (maps and cross-sections) only because of lack of the suitable 3-dimensional tools.

3-dimensional geological map is the class of 3d models of geological environment that describes the positions of geological bodies in a non-contradictory way (Mathers et al. 2009; Mironov et al. 2011).

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In the fulfilled Moscow mapping project 3-dimensional modeling was used only at the most complicated sites. In future the 3-dimensional geological mapping must become the principal tool for data maintenance in the information system. Usual 2-dimensional geological maps and cross-sections are only aspects of a 3d model.

A 3-dimensional geological map is a digital model of geological space and may be considered as the original cartographical work. Any geological, geophysical, hydrogeological, etc. information may be integrated into this model and then used in applications.

A 3-dimensional geological map provides source information for calculations of data for new thematic maps, various hydrogeological, geotechnical (Koutepov et al. 2008), direct geophysical and other computational modeling, and civil engineering and mining, e.g. to study the geological condition for the bottom and sidewalls of a pit or a tunnel.

Classical cartography since Cosmas Indicopleustes, Mercator, Gauss and other great scientists has developed a great experience of multi-purpose mapping of the 2-dimensional Earth surface. Some recently developed design methods (e.g. architecture design) place objects into an empty 3-dimensional space to make the view more suitable.

Geology needs the next stage of the informational technology to be developed. All geological objects are essentially 3-dimensional. Geologists imagine the filled 3-dimensional world of their objects but are forced to use 2-dimensional views: geological maps, cross-sections, etc. due to the absence of 3-dimensional tools. Many so-called "3d space models", e.g. block diagrams, perspective views of surfaces consider actually only 2-dimensional surfaces.

Raster models of the 3-dimensional space are widely applied in geophysical, geotechnical, and hydrogeological modeling. One of the principle problems for those tasks is the adequate and correct representation of source geological data.

In this paper, we discuss the principles and approaches to the 3-dimensional geological computer mapping. We consider mapping software as the geological tool, which scientist uses during all the investigation to construct the 3-dimensional model, to provide model based computations and considerations, to improve and to check hypotheses, and to demonstrate results visually.

Properties of the required tool are analogous to those of the vector map editor in GIS. A tool is required to draw the object configuration and to attach the attribute data to the object. Using the cybernetic approach, we define classes of objects in our system and set the operations that can be done with those classes.

One of the great and not yet good perceived achievements of GIS is the technological separation of the geometric design of map objects and the way of their visual representation. It was done intuitively in pre-computer technologies. The cartographers select the visual representation of objects from the early stage of map compiling. The formal topology or geometry properties objects may be violated to make the map more understandable.

The main problem for the editor of 3-dimensional geological map is that all the space must be completely filled up without empty volumes and intersections of geological bodies' interiors. 2-dimensional tools for topologically correct zonal maps provide universal constructions applicable to any division of a plane into polygons. In 3-dimension geometry the universal tool should be too complicate in logical structure, computation algorithms, and user interface. Working tool must be understandable by geologists and work in terms and practices that are habitual to them. Fortunately, geology in many applications does not need universal constructions as it will be demonstrated below.

The methodology of 3-dimensional geological mapping proceeds in the backward succession than traditional 2-dimensional cartography. At first the conception of the geometrical model for the 3-dimensional geological map is created and the visualization methods follow it.

The 3-dimensional geological mapping should integrate heterogeneous maps and field geological, geophysical, hydrogeological, geotechnical, remote sensing, and other data.

The following consideration is partially based on practices that are already used in our experience in the Moscow project and partially are under development currently.

180.2 The Structure of a Geometrycal Model

All the objects of the 3-dimensional geological map are given by their coordinates in the fixed Cartesian coordinate system (X, Y, Z). We choose the Z-axis to be directed vertically upwards and orthogonal X- and Y- axes in the horizontal plane. In this paper, we do not consider the effects of the Earth curvature.

The model under consideration is applicable to platform areas with horizontal or gently sloping dip rocks, without faults and flexures. The theoretical approach was probated at 3-dimensional geological mapping of Moscow.

The classes of objects should be defined before the modeling according to its aims and degree of a generalization similar to the 2-dimensional mapping. Each class of objects is characterized by the set of it attributes and the geometry type. As in 2-dimensional GIS the attribute table has common relational database structure. The geometry type is characterized by its dimension {no, 0, 1, 2, 3} and the format type {raster, vector}. Basic lines and surfaces are geometry primitives that are embedded into the total space of the model and have their inner coordinate systems (1- or 2-dimensional). Each basic geometry primitive may support several (1- or 2-dimensional) thematic layers.

Basic geometry primitives are used in the model:

- As the placement for the source data,
- As the position for the results representation.

Let us consider the primitives ascending their dimensions.

Non-dimensional classes of objects have only an attribute table and no space attachment.

Dimension 0—a point. The point is given by its coordinates. An example is the sampling point. A point may be attached optionally to the basic line or surface.

Dimension 1—a line. A polyline is given by the sequence of its vertex coordinates. An example is the axis of the borehole; the simplest is the vertical interval.

The (1-dimensional) coordinate of a point along the line is the distance from the start point of the line. A line may be attached to some basic surface. Various 1-dimensional layers may be attached to the line. For example, the borehole axis may be the support for:

- A topologically correct layer of the borehole log (sequence of intervals with homogeneous properties);
- A point layer of aquifer depths;
- A layer of samplings intervals (possibly overlapped);
- Raster geophysical logging data.

Dimension 2—graph surface. The graph surface is given by the function Z = F(X, Y). The function must be computable in our model. It means that the user should have an adjustable tool to define and edit this object, and the system provides various computations, e.g. finding objects intersections. There are 3 most applicable methods to define a function in computational geometry:

1. Exact formula (e.g. Z = const—horizontal plane).
2. Raster grid model (Z-values at points of a regular grid).
3. TIN model—a triangulation of the domain area and Z-values at its vertices (a piecewise-linear interpolation of the surface).

It is possible to use more sophisticated models of graph surfaces.

A graph surface inherits the coordinate system from the (X, Y)-plane. Any objects of 2-dimensional GIS may be attached to the graph surface. It is possible to attach the same objects to various graph surfaces (e.g. 2-dimensional topography or geological map).

Dimension 2—vertical surface. The vertical surface is given by its polyline trace in the (X, Y) plane.

The coordinates in the vertical plane are Z and the horizontal distance along the trace.

Typical 2-dimensional objects that may be attached to a vertical surface are geological cross-sections considered as a vector map or raster geophysical data.

Important remark. In this model arbitrary (pure mathematical) surfaces are not concerned. It is sufficient to use graph and vertical surfaces only according our geological assumptions.

To define 3-dimensional objects following (Mathers et al. 2009), we postulate that each geological body is bounded by two graph surfaces of its roof and bottom. These surfaces must have the same domain. The boundary surfaces must not have faults or flexures. Of course, it is the model restriction proceeding from the above geological assumptions. Nevertheless, such models have a wide field for applications. Over the boundary of the domain the geological body either pinches or have a vertical boundary (e.g. over the total model's boundary).

Dimension 3—basic geological bodies. The basic geological bodies have a fixed vertical order that must be defined in the very beginning according to the aims and scale of model. The main idea is that if the vertical order of geological bodies is fixed it is sufficient to define only the graph surface of the geological body bottom; whereas the surface of its roof is defined as minimal heights of the upper layers' bottoms. This construction provides the automatic correspondence of the geological bodies' boundaries.

Dimension 3—lens bodies. A lens geological body is given with the both graph surfaces of its top and bottom. Lenses are intruded into the model after the main geological bodies have been created. The volume of the lens substitutes the previously filled space in the model. To make the model correctly defined it is necessary to establish the sequence of lenses insertion (a new lens may disturb the previous one).

The difference between main geological bodies and lenses has a methodical and technology background. The idea of main geological bodies is natural for geologists and may be supported with rather understandable program tools. The attempt of building the model based only on lens bodies implies the difficulties of matching the boundaries.

In our practice maps contained a few or no lenses.

Dimension 3—basic designer's primitives. The architecture and mining design use basic graphic primitives (parallelepipeds, cylinders, etc.) that are not needed in pure geological modeling but may be used in applications of 3-dimensional geology maps. Therefore, we formally include these tools into our technology. The typical problem in the applications is the analysis of engineering-geological, geotechnical or hydrogeological situation near the designed object (e.g. a pit or a tunnel).

3-dimensional map editor is the program tool for the creation and modification of (0-, 1-, 2-, 3-dimensional) objects listed above.

There are two new problems in the 3^d dimension in comparison with the 2-dimensional map editor:

- Matching data at the intersections of 2-dimensional surfaces;
- Defining and editing the graph surfaces.

Two geological cross-sections must be matched up on the vertical line of their intersection, and geological maps of various stratigraphical horizons must be matched up each other and cross-sections. This problem is solved similar to the 2-dimensional map editing. We may set the data at one surface and force using it at another sections. The alternative method is the control of correspondence and fixing errors.

Various interpolation methods may be used to develop the digital elevation model of geological surface. Unfortunately, the mathematically correct methods (interpolation based on the Delaunay triangulation, kriging, etc.) do not provide geologically acceptable results. The reason is the lack of data and the inadequacy of mathematical models to geological conditions.

180.3 Visualisation of 3-Dimensional Geological Map

Visualization of the 3-dimensional geological map is used by geologists to control the consistency of information and geometry model. At the final stage visualization is used for a presentation of the results.

A 3-dimensional geological map is a pure computer model, therefore, its visualization as a whole is impossible. We can only see 2-dimensional images such as:

(1) Axonometric or projective projection of selected objects (possibly with some shifts for better visibility.
(2) Cut parts of objects (block diagrams with cross-sections).
(3) Sectional views of 3-dimensional geological map with the selected surface (e. g. geological cross-sections or horizontal slice).
(4) Animations based on visualization (1–3) (a show of the block diagram from different points of view or a demonstration of changes in the geological section as the section plane moves).

The principles of visualization are inherited from the 2-dimensional cartography. Some new ideas of computer graphics, e. g. transparency of 3-dimensional bodies may be used.

Visualization tools should provide a choice of objects for visualization, a choice of visualization modes, zoom in and out, shifting the image, changing a vertical scale, a spatial rotation of image.

180.4 Applications of 3-Dimensional Geological Map

3-dimensional geological map is a digital model of geological space. Any geological, geophysical, hydrogeological, etc. information may be integrated into this model and then be used in applications. The main directions of applications are:

(1) 3-dimensional geological map as a self-contained unit. From the methodological point of view the compiling of 3-dimensional geological map is the further development of traditional (digital) cartography. The main problem is the integration of heterogeneous information into consistent model. The 3-dimensional cartography promote a better understanding of the geological structure, geological history and geological processes, checking consistence of possible contradictory data from various sources and making the integrated system concept of the situation.
Compiling 3-dimensional geological maps inherits the scaling principle of 2-dimensional mapping: at first the small scale map has to be drawn and after that the large scale maps.
(2) Classical 2-dimensional geological mapping. Drawing of usual geological maps or cross-sections based on 3-dimensional map is purely technical problem. The validity of those results is better than analogous ones in 2-dimensional cartography because of taking into the consideration not only the surface of mapped deposits but also the entire 3-dimension volume. Another problem in the geological mapping is the co-ordination of geological maps of subsequent ages which is satisfied automatically using the 3-dimensional maps.
(3) Compiling new thematic maps. The 3-dimensional model provides information for calculations of data for new thematic maps. The most applicable data are digital elevation models for various geological horizons and thickness of strata. These data may be used for thematic mapping (e.g. isoline maps) or as a source for raster model calculations.
(4) Geological zoning. The 3-dimensional geological map provides data on each stratum thickness at each point of the plan. This information may be used for geological zoning with some established algorithm or mathematical methods of data analysis (factor, regression, cluster analysis, etc.).
(5) Information resources for computational modeling. Hydrogeological, geotechnical, direct geophysical and other computational modeling of geological data needs valid and non-contradictory data on the geological structure of the site. Getting correct source information is one of the main difficulties in computer modeling.
The 3-dimensional geological map provides such information because the geometrical model is built by a geologist, reflects his point of view, and may be corrected according to the results of modeling. The digital

format of the map provides the data conversion into modeling software formats.

We have used the 3-dimension geological map as the source information for groundwater pollution modeling under complicated geological conditions. Another application is the karst hazard estimation in urbanized territories.

(6) Architecture and mining design. Engineering geological 3 dimensional maps are used in civil engineering and mining to study the geological condition for designed construction. After the map is compiled, the designer tries various alternate designs to find the optimal one. Various mapping tools and model computations may be applied at this stage. The typical examples are horizontal and vertical sections along the bottom and sidewalls of a pit or a tunnel. Geotechnical and hydrogeological modeling may be applied too.

(7) Presentation design. Various presentations may be done based on 3-dimensional geological maps ranging from classic maps to animations.

Various visualizations and presentations may be done basing on 3-dimensional geological maps ranging from classic maps to animations.

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