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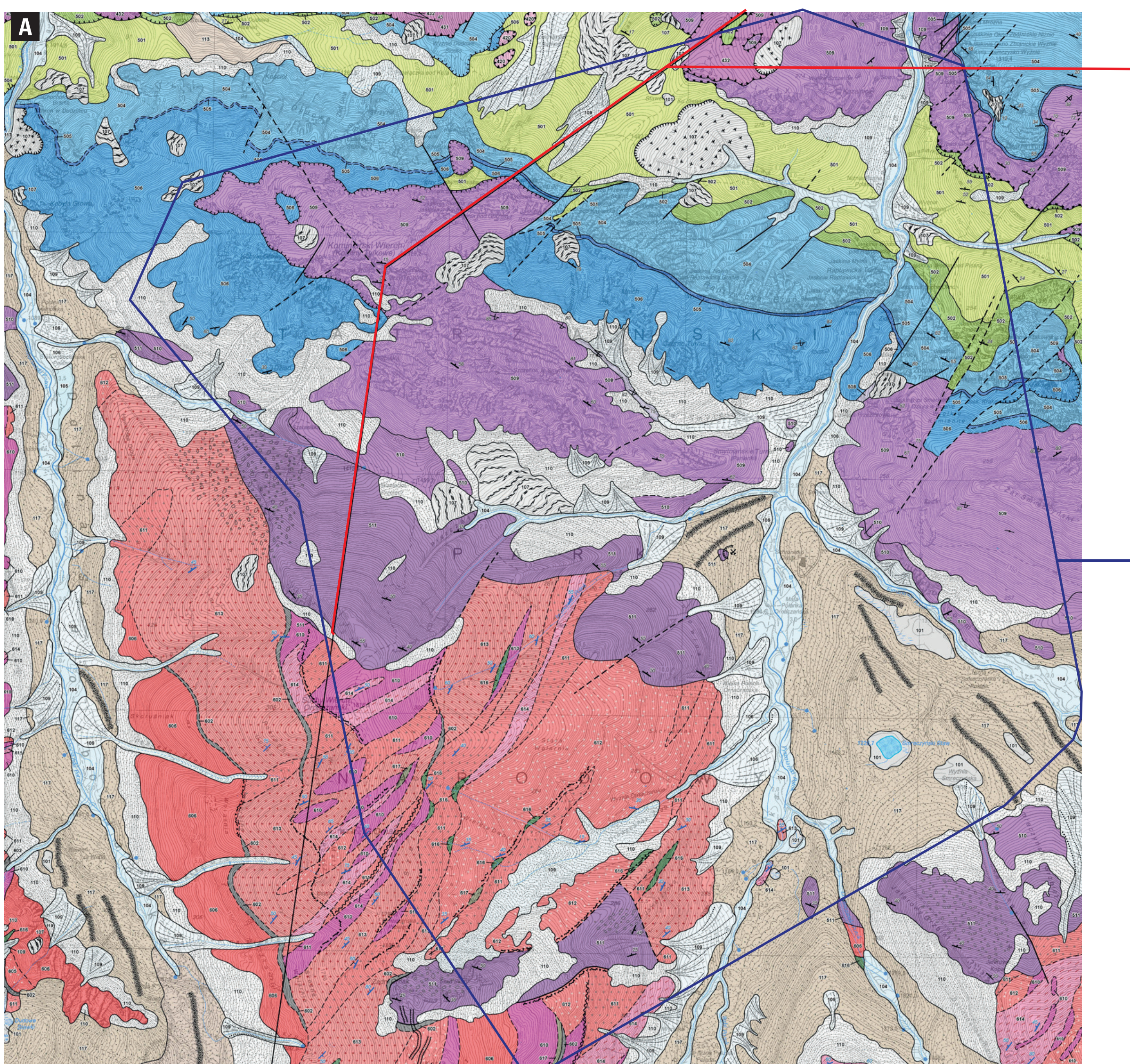
VISUALIZING GEOLOGICAL STRUCTURES

Modern geological maps are 3D, or even 4D models representing the complex structure of the Earth. They interpret a variety of geological information and represent it in graphical form.



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Geology is the science that investigates spatial structures and their interrelationships. The first thing that comes to mind when thinking of geological space is the deep structure of the Earth and its division into crust, mantle, and core. Usually, however, geologists attempt to identify and describe specific geological structures, such as salt domes and oil and gas traps, or sedimentary basins, such as coalfields or groundwater reservoirs. In addition to geological reconstructions of subsurface structures significant for the economy, however, it is equally important to illustrate the forms and processes associated with the shaping and formation of the land surface, including mountain ranges, seas, coasts, landslides, lakes, river valleys and surface forms created in the wake of floods. Studies of this kind are essential to land use and spatial planning.

The best means of representing a surface graphically is a map – a two-dimensional image following certain mathematical rules, drawn in line with strictly defined principles, according to a chosen mapping method, and on a specific scale. Maps are the most common way of representing both the simple and complicated geological structure of the Earth's crust. Such maps can be further supplemented with geological profiles and cross-sections. The first geological map in Poland – of the Holy Cross Mountains – was drawn up in 1919, that is, over 100 years ago, by the

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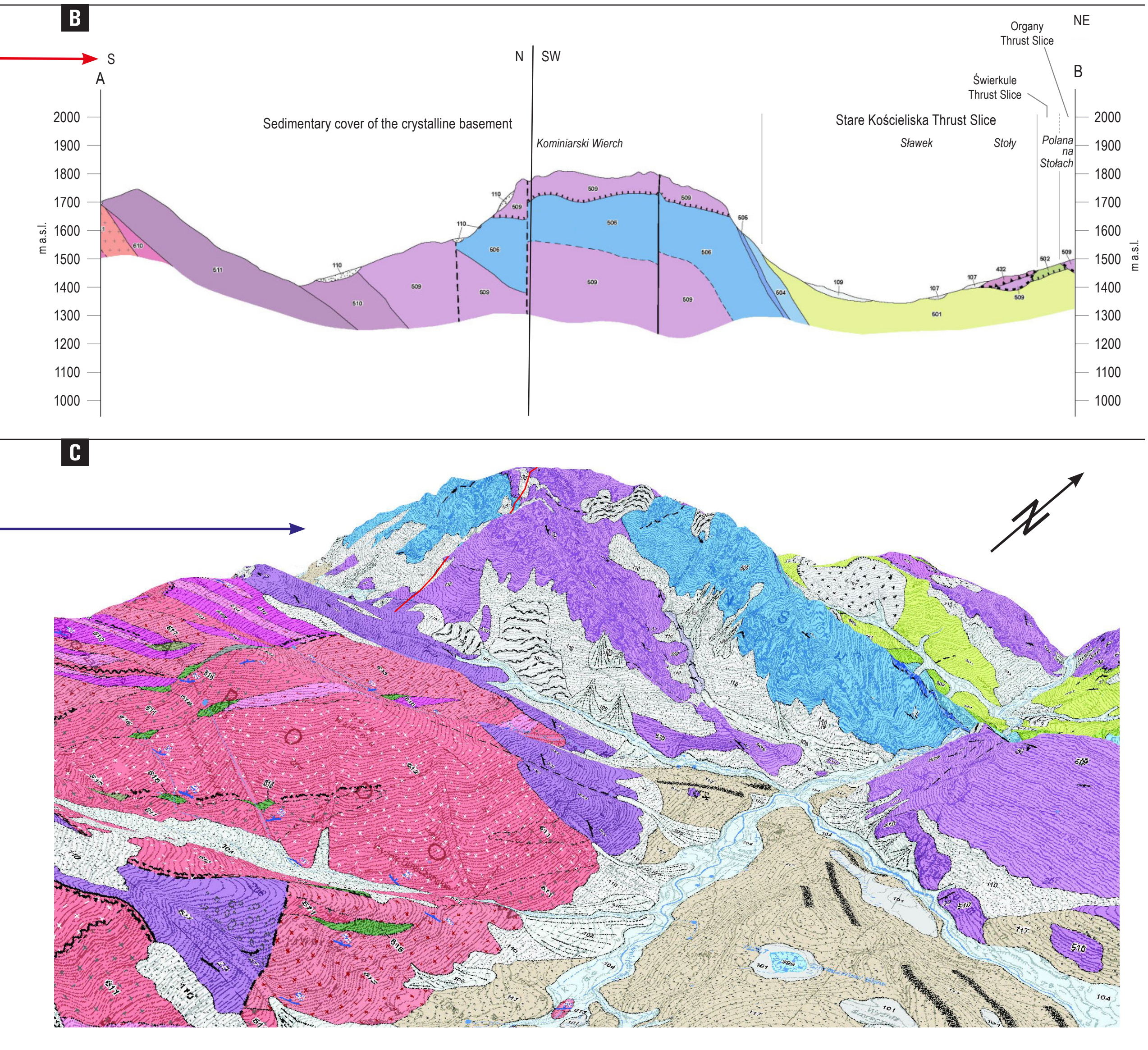


A. A geological map of the Tatra mountains in the region of the Ornak mountain shelter, at the scale 1:10,000 (Piotrowska et al. 2011)

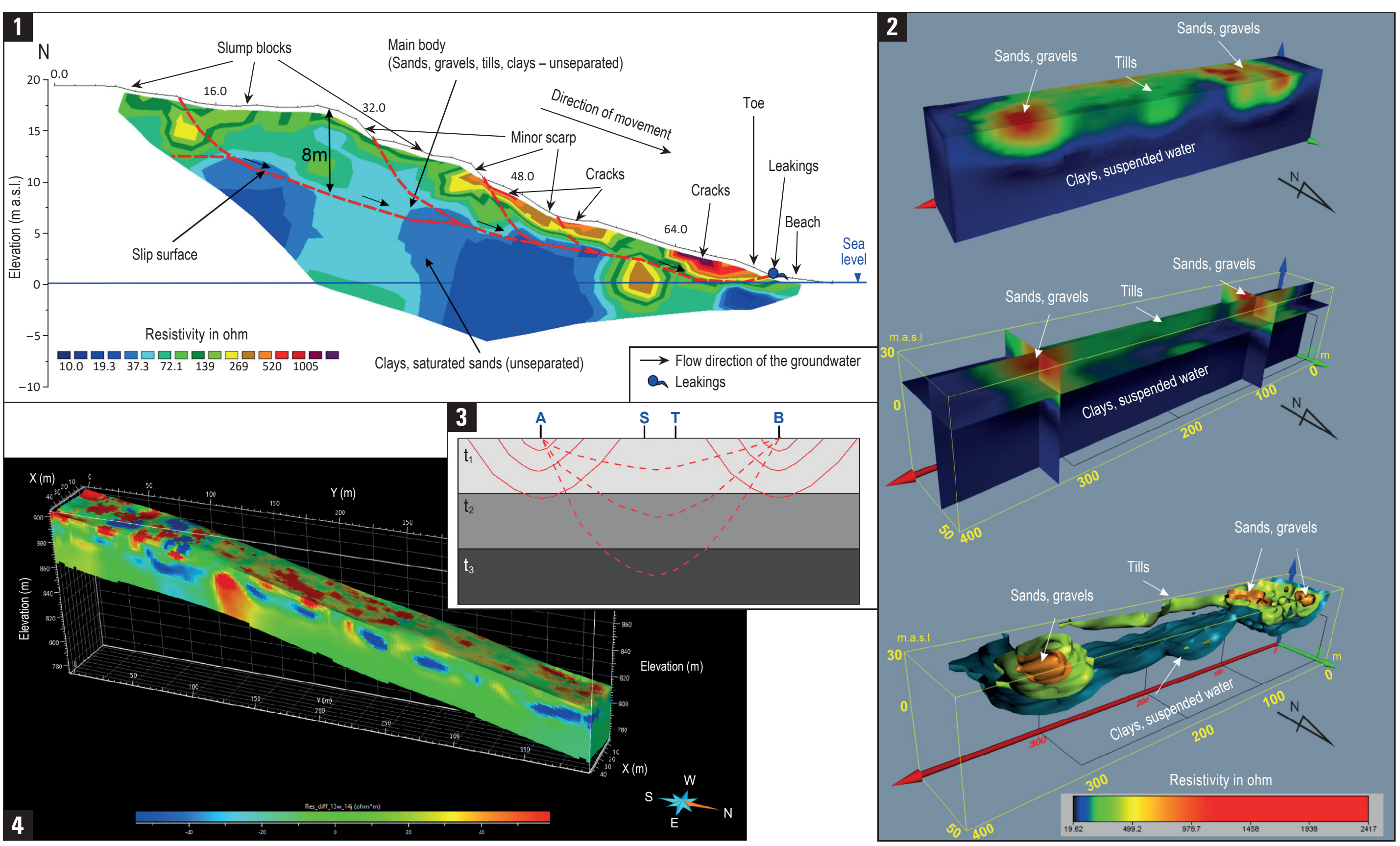
B. Geological cross-section (after Piotrowska & Cymerman 2011)

C. The use of a numerical model as a background for a geological map: beige – Quaternary; green – Cretaceous; blue – Jurassic; purple – Triassic; red – crystalline basement preeminent geologist Stefan Czarnocki. The application of Digital Elevation Models (DEM), which began at the turn of the twentieth and twenty-first centuries, has transformed the use of geological maps, making them more adaptable; furthermore, the development of laser scanning (LIDAR) has lent them a spatial dimension. In turn, the growth of "qualified" tourism (requiring physical fitness and the ability to use specialist sports-tourism equipment – e.g. yachting, cycle or kayak touring), in tandem with the universal availability of navigational systems, has stimulated increased interest in geotourism maps, which are excellent tools for promoting greater public awareness of geology.

Going three-dimensional

Thanks to the use of geographic information systems (GIS) in geology and the introduction of advanced IT tools, it has become possible to more easily reconstruct and visualize the geological structure of a selected area at any depth in the form of virtual three-dimensional (3D) models. This is the spatial interpretation of geological information previously archived in the form of databases or cartographic materials (including analogue cartographic materials). The advantage of three-dimensional models is that they can be continuously improved and updated, including by increasing their resolution and adding new information as data becomes available.

The basic form of a geological spatial model is a structural model, that is, a solid bounded by certain surfaces. Examples include the ceiling and floor surfaces of geological units and discontinuities such as fault planes. The structure of three-dimensional models is recorded numerically in the form of a grid mesh – meaning the spatial area is divided into points with specific coordinates. If, in addition to coordinates, each point also contains information regarding other parameters, such as permeability, porosity, or resistivity, a parametric model is created. A model of this kind can form the basis of a variety of geophysical,



Geophysical modeling:
1. Two-dimensional Electrical Resistivity Tomography (2D ERT) model – cross-section through a landslide at Jastrzębia Góra
2. 3D ERT model – resistivity distribution with interpretation of the geological structure of the cliff in Jastrzębia Góra
3. Diagram illustrating the general measurement mechanism used by electrical resistivity methods. One-dimensional model – vertical electrical sounding
4. 4D ERT differential model – changes in resistivity distribution that occurred between 2014 and 2017 in a part of the Bachledzki Wierch landslide (Podhale).
The 3D model shows the distribution of resistivity with a geological interpretation of the cliff located in Jastrzębia Góra, whereas the 4D model presents a fragment of a landslide at Bachledzki Wierch, illustrating the change in resistivity distribution that occurred between 2014 and 2017.

hydrogeological, or reservoir simulations. Three-dimensional models are versatile instruments that can be used both as research tools and to popularize the discipline.

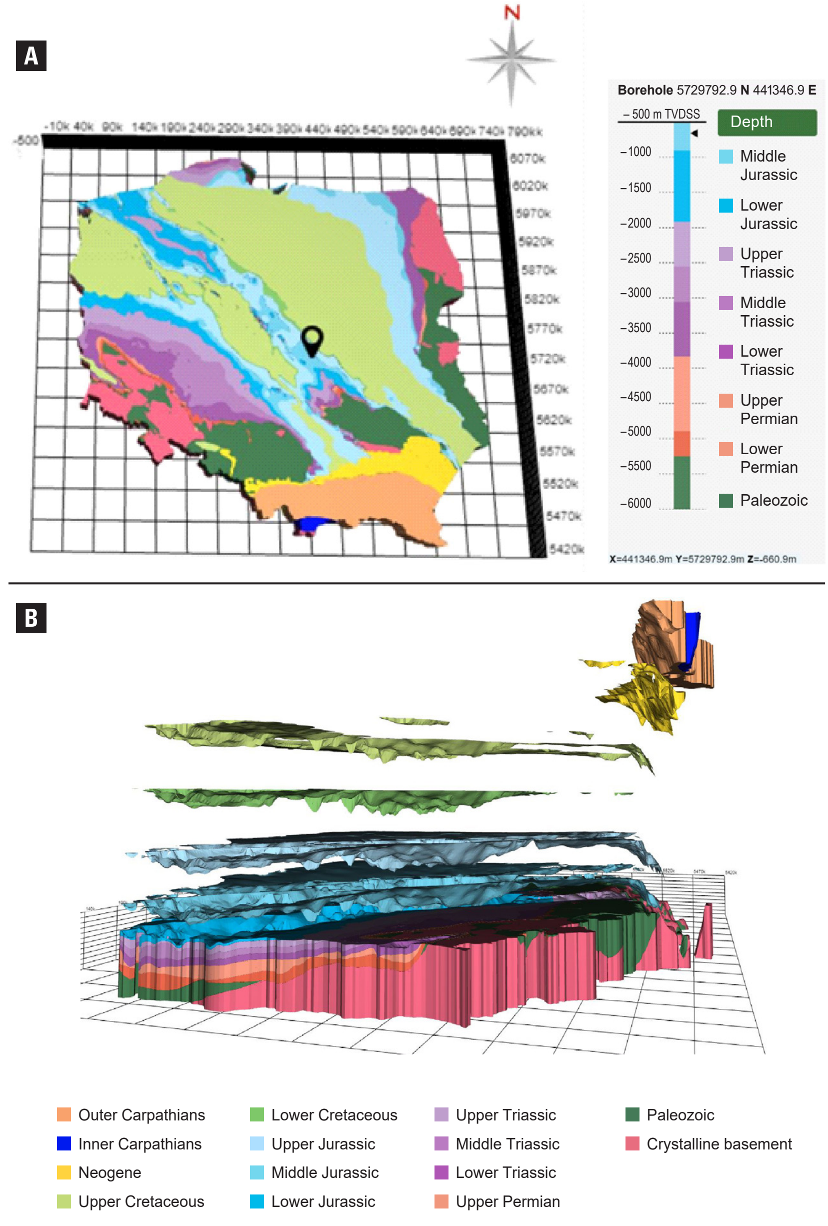
One example of such a structural model is the "3DGP" spatial model of the subsurface structure of Poland, developed at our Institute, which displays the geological structure of the whole country from a depth of 500 m to a depth of 6 km. Using the Geo3D Viewer, it is possible to "drill" a virtual borehole in any part of the map (top view of the model) and obtain a profile containing information such as geographic coordinates, the surface ordinate, the boring depth, and the floor depth and thickness of each unit in the model. The "lift layers" function can also be employed to separately visualize the solids of subsequent stratigraphic units – from the most recent down to older ones.

Visualizations of sedimentary basins and geological structures are perhaps the most stimulating and useful from the research perspective. They offer the opportunity to examine the geological structure and spatial relationships of geological units in detail and in such a way that they can be used or exploited most effectively. Such model of the Lublin Coal Basin makes it possible to identify the evolution of the basin for exploration purposes (thus increasing the efficiency of exploration and resource management), to plan and effectively manage various forms of economic activity in the post-mining underground space, and to predict the effects of this activity on the environment. This model can be applied in searching for energy raw materials, underground reservoirs, and storage places in geological structures, such as for CO_2 sequestration and liquid fuel storage, as well as in developing geothermal energy.

The usefulness of modelling geological structures is best illustrated by visualizations of salt domes. Fifteen or more salt structures have been identified in the belt of the central Polish anticline. They are made of evaporites, that is, chloride and sulphate compositions created by the evaporation of water from pools occupying large areas of the Polish lowlands that formed, inter alia, in the Zechstein. Due to the malleable properties of salt, these have developed into salt domes and pillows. Their internal structure is exceptionally complicated. Some of the salt domes protrude completely through the younger Mesozoic rocks. Models of the structure of Quaternary sediments overlying selected salt domes and in their immediate vicinity were made to determine the mobility of salt in the Polish salt dome belt.

Harnessing data

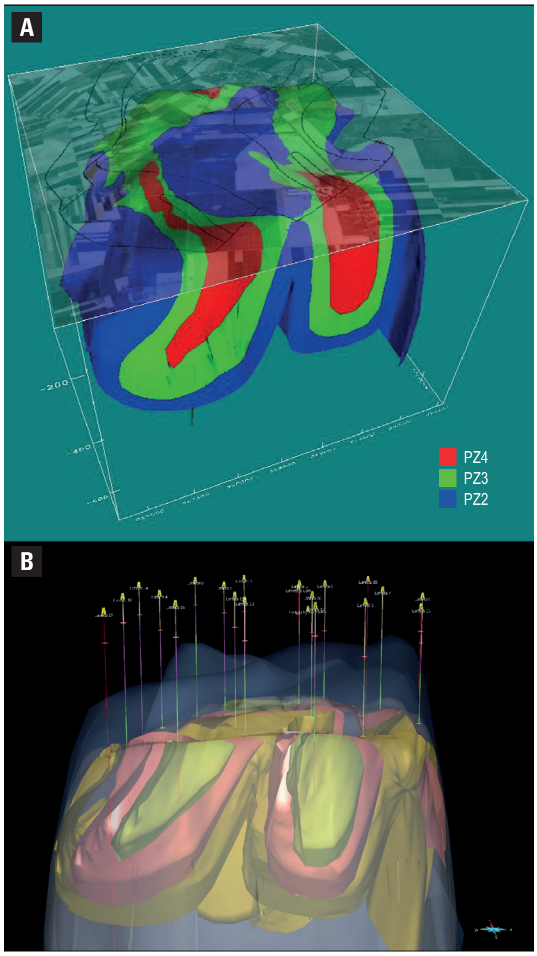
By presenting complex structures in an accessible and comprehensible way, 3D models can speak strongly to viewers' imagination. Such models are created on the basis of point data (from boreholes) and also surface and linear information (such as geological maps at various scales, geological cross-sections and geophysical data, including seismic interpretations, seismic profiling and borehole geophysics). The software used to create such models primarily verifies the correctness and sequencing of the data entered. The surface boundaries of the modelled structures are anchored at specific locations – as determined from boreholes, intersection lines on maps, cross-sections or geophysical profiling – and are then interpolated and extended to project surfaces in places not covered by data and those that combine data (different geological information) in a given range or domain (in this case depth). A properly constructed model is free of intersection errors and preserves correct



Spatial model of the subsurface structure of Poland (3DGP):

A. Drilling a "virtual borehole" at a selected location,

B. Use of the "lift layers" function. Based on the example of the three-dimensional model of the subsurface structure of Poland (https://geo3d.pgi.gov.pl/pl/model_Polski_2005)



A. Model of the Łanięta salt dome in the desktop Geo3D viewer.
B. View of a structural model of the Łanięta salt dome in the SKUA/GOCAD program.

The Łanięta diapir is a medium-sized salt dome that resembles an ellipsoid in horizontal cross section. The salt dome shown here consists of the deformed rocks of individual cyclothems (PZ2, PZ3, and PZ4), above which is an anhydrite-clay-gypsum cap formed from the residue produced by the dissolution of the chloride sediments. The external boundaries of the salt dome are almost vertical.

GLOSSARY

Ceiling surface
– the uppermost surface bounding a layer of sediments/rocks.

Floor surface
– the lowermost surface bounding a layer of sediments/rocks.

Intersection
– image formed as a result of geological surfaces intersecting with the ground surface.

Geological unit
– a unit distinguished by a set of common features – e.g. several layers of sediments that formed at the same time or place.

Facies
– a type of rock defined by a particular set of distinctive characteristics – e.g. relating to its genesis, formation environment, or petrographic composition.

Further reading:

Szynkaruk E., et al. 3D geological modelling at the Polish Geological Institute; in *Synopsis of Current Three-Dimensional Geological Mapping and Modelling in Geological Survey Organizations*, K.E. MacCormack, et al. (eds.), 2019: 229–238.

Kamiński M., Zientara P., Krawczyk M., Electrical resistivity tomography and digital aerial photogrammetry in the research of the "Bachledzki Hill" an active landslide – in Podhale (Poland). *Engineering Geology* 285 (2021) 106004.

stratigraphic ordering (the sequence of occurrence of individual geological types, rock porosity, or rock resistivity.

The physical properties of rocks, particularly their electrical resistance, are measured when conducting some types of geophysical surveys, such as using the electrical resistivity method. The methodology applied in research of this kind was refined and developed by the Schlumberger brothers in the early twentieth century. Today, it allows us to create electrical resistivity models of rocks in one-, two-, three- and four-dimensional space. Advances in technology led to an evolution from simple, one-dimensional, layered 1D SE geophysical models (vertical electrical sounding) to 2D ERT geophysical models (two-dimensional electrical resistivity tomography). 3D ERT has developed rapidly since the beginning of the twenty-first century, thus paving the way for the introduction of 4D ERT modelling in recent years. The latter displays changes in rock resistivity over time and space. Geoelectrical methods owe their popularity to the ease of data gathering they permit and to the low cost of performing fieldwork. Measuring resistivity using these methods requires a constant source of electrical current. The electricity is conducted into the ground via two metal electrodes (A and B). The difference in potentials is then measured at two further electrodes (S and T).

In ERT (electrical resistivity tomography) research, electrodes are positioned along a straight line and connected using multiwire cables to a selector – a switching unit used to automatically select the appropriate four electrodes. Though there are many other electrode arrangements, those most commonly used are the Wenner and Wenner-Schlumberger measurement systems and, more recently, a new system known as the multiple gradient arrangement, which was developed for multi-channel measuring instruments. A multi-channel system makes it possible to take several simultaneous measurements between potential electrodes in different locations with the position of the current electrodes remaining fixed. This greatly accelerates surveys without reducing the number of measurement points. Once the correctness of the connections has been checked, the computer program automatically selects the appropriate electrodes and, once each measurement has been taken, records the result. It repeats this procedure until all the points on the section are completed. The result is a measurement of what is known as the "apparent resistivity" of the rocks. To obtain true values for the resistivity of rocks, the values for apparent resistivity are subjected to a process of two-dimensional or three-dimensional inversion.

The electrical resistivity method is particularly useful in monitoring terrain that is at threat of large-scale shifts or movements – such as in the mountains or along the Baltic coastline. The method is illustrated by studies of active landslides in the coastal area of Jastrzębia Góra and on Bachledzki Wierch in the mountains of Zakopane – both shown in the accompanying figures.

Making it visual

Various kinds of geological maps and reference information on documents compiled in Poland, including geophysical profiling and boreholes, can be found in the Central Geological Database (CBDG).

Structural models are created using data integration tools such as Petrel (Schlumberger) or GOCAD (Aspen Technology, Inc.), which have been used successfully in geology. These are complicated, specialist software packages available under license. Special viewers such as Geo3D, which make it possible to produce slice maps and cross-sections along any cutting plane, are used to bring the results of three-dimensional modelling using this licensed software to the widest possible audience. The Res2DINV and Res3DINV software is employed to model and process electrical resistivity data. For the visualization of electrical resistivity models, however, GOCAD and Voxeler software is used. ■