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THEMATIC ISSUE

From registration to visualization of geological data with MO2GEO: applications of the FieldModule, interpolation methods, and computer visualization

Lars Schimpf · Wolfgang Gossel

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Abstract The registration and screen visualization of geological data are basic steps in modelling of 3D structures and geoscientific processes. Therefore, a standardized coding of geological field observations is reasonable to enable an independent modelling approach. The field module of MO2GEO provides diverse standards for data coding and was tested in the frame of a mapping project. The visualization of profiles and the construction of cross-sections improve the database for a variety of interpolation methods. The subsequently developed 3D models, constructed with diverse modelling tools, can be visualized and serve as the base for diverse applied scientific projects.

Keywords Geological model visualization · Field data recording · Hierarchical geological databases · Geological mapping

Introduction

To generate a geological map, digital tools have to support the geologist in the field by coding and simple data recording, and after a sophisticated modelling procedure the models have to be communicated to other users. These tasks are performed with the proposed tools, MO2GEO and MO2GEO Explorer.

The development and the visualization of geological 3D structures are challenging tasks and supported by numerous software tools. Well-known products in this field are, for example, gOcad (Mallet 2002), Petrel (Schlumberger Ltd 2013), move (Midland Valley Exploration Ltd 2013), Surpac (Dassault Systemes GEOVIA Inc. 2013), Geomodeler (Intrepid Geophysics Ltd 2013), Leapfrog (ARANZ Geo Ltd. 2013), and EVS/MVS (ctech Development Corporation 2013). All these tools have the disadvantage of not supporting national standards for geological data registration. Other software tools like GeODin (Fugro Consult GmbH 2013), the HydroGeoAnalyst (Schlumberger Water Services 2013), GGU Software (GGU 2013), Strater (GoldenSoftware 2013), QuickLog (boring-log.com), PLog (Dataforensics), and gINT (Bentley) register borehole data according to standards and allow for cross-section construction but not for sophisticated 3D geological modelling. In geological field mapping projects, data for not only boreholes but also quarries, cut-offs along streets, excavations of buildings, and even sometimes tunnels have to be collected and registered. None of these information sources are considered in the tools, which work more or less perfectly on pre-structured data sets. The results are more or less complicated structural models that can be visualized in the tools, but the data exchange is seriously limited to a few data formats in each tool. Some of the tools have free viewer or explorer systems but their functionality is very limited, in most cases to 3D zooming and turning. Virtual boreholes and virtual cross-sections, which are very much needed for the examination of the structures and the derivation of information for geothermal energy projects, environmental geology, and so on, are not supported.

MO2GEO starts at the two points of geological data registration and model visualization due to two needs in daily work:

L. Schimpf · W. Gossel (✉)
Department of Hydro- and Environmental Geology, Martin Luther University Halle, Von-Seckendorff-Platz 3, 06120 Halle, Germany
e-mail: wolfgang.gossel@geo.uni-halle.de

L. Schimpf
e-mail: lars.schimpf@geo.uni-halle.de

1. The students at the University have to do mapping courses where there are almost no boreholes but other diverse geological information is available.
2. The models developed in the Department of Hydro- and Environmental Geology should be available to schools, companies drilling for geothermal energy, and so on.

Additionally first steps were made to close the gap between these two modules: Innovative interpolation methods for 2D and 3D were developed and tested in the frame of projects mainly in the federal state of Saxony-Anhalt, and the connection to OpenSource geo-information systems is implemented in diverse steps in the development.

An overview of the existing modules and their objectives is given in Fig. 1.

MO2GEO is developed to be completely OpenSource with OpenSource development tools. This guarantees transparency, opens collaboration options, and causes a wide spreading of the tools, which are advantageous for the University Department.

Methods

General conditions

The development of a set of modular tools to register, process, and visualize geological data is a steady learning process in programming and data processing and management. It also differs in important ways from the skills learned by using GIS or other tools mentioned before. The prerequisites of platform independence as well as the free availability and the complexity of the program led to the decision to use C++ as the programming language. A further deciding factor for this programming language was the opportunity of the integration of different OpenSource libraries (visualization, GUI, parallel processing, etc.). The expected complexity of the recorded or processed data required open, clearly structured, and simple user interfaces. The data need to be entered, processed, queried, and even visualized quickly and efficiently. Another important main emphasis of the development is the storage of the data. A possible method would be to save the data as pure ASCII text files. On one hand, data saved in this way would be accessible and portable, but on the other hand if there were a huge amount of data it would be difficult to manage, since the system would be based on complex folder and file structures. These factors led to the decision to use a suitable database (PostgreSQL). Notwithstanding the wide distribution of multi-core CPUs and the steadily increasing amount of data, most of the existing tools do not provide a multi-threading architecture. But especially in case of interpolation issues, the implementation of parallel programming capabilities provided by the OpenMP library leads to more efficient resource usage and massive time savings. The visualization procedures are realized with OpenGL, which allows for effective platform-independent usage of the hardware components. To enable a RAM independent rendering of the contents, which allows the rendering process to be separated from data manipulation, OpenGL 3.2 was implemented.

FieldModule

The MO2GEO FieldModule application was designed to record, archive, process, and visualize geologic realities of different types in the field. Using a graphical user interface, the application itself controls the data input, output, and visualization, whereas a particular object-relational PostgreSQL database is used for storage and data management. Figure 2 shows the key aspects of the development, which also represent the main features of the program.

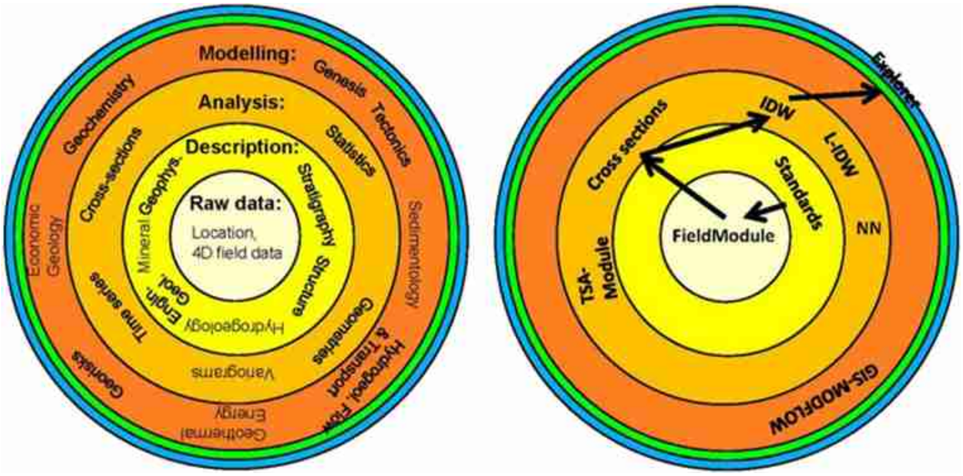


Fig. 1 Existing modules and connecting tools in MO2GEO. *Left* image taken from Gossel (2013a, b)

The most important objective was the support of different geological sites with different kinds of information. In contrast to other existing data acquisition tools, the FieldModule should be capable of managing borehole, outcrop, and fieldstone data (rocks representing the bedrock in areas without outcrops), which all provide different but important geological information. In order to achieve this, a complex set of development-relevant issues had to be considered and processed.

Geological standards and standardized data management

The electronic processing and related digital storage of geological information necessitate the development of appropriate data models, including a standard nomenclature of geological terms and terminology. Usually data are recorded as understandable plain text in the field. However, the individual phrases can lead to difficulties during the digital processing of the data. This well-known problem led to the development of several different national vocabularies, for example Symbolschlüssel Geologie (Preuss 2010) in Germany or the British Geological Survey vocabularies (BGS (British Geological Survey) 2013) in Great Britain. These vocabularies represent collections of terms and definitions to describe geological issues. In the case of the Symbolschlüssel Geologie the vocabulary also includes definitions which are subject to international regulations (e.g. ISO 146881). Anyhow, most of the national vocabularies are not used in other countries and their contents and technical structures differ significantly. But in the scope of increasing international collaboration it becomes necessary to develop international standards to facilitate the data exchange and the professional collaboration. For this reason several working groups have tried to establish international standards (OneGeology-Europe OneGeology 2010, and GeoSciML Commission for the Management and Application of Geoscience Information 2012). The standardization process of the standards used basically comprises a common nomenclature of the terms and terminology and their display (colours and symbols) in geological maps, as well as the exchange and storage of the data. As of date there is no generally accepted international standard. This led to the decision to allow the use of different existing common standards, improvement according to local specifications, and even the setup of self-defined symbols within a database. This ensures a high degree of flexibility and a transnational usability. By default, the standards listed in Table 1 are implemented. The disadvantage of this approach is that data cannot be transferred from one standard to another.

A common nomenclature of geological issues is a very important step towards a standardized acquisition of geological data. Usually the data are manually recorded in the field and later processed by using tools for data acquisition like GeODin or a GIS to create a geological map. The data acquisition itself is then determined by the software used and its corresponding database. Only a few approaches to a standardized data acquisition or management have already been established. One of them, developed by the NLfB (Niedersächsisches Landesamt für Bodenforschung), is SEP 3(*S*chicht*e*nerfassungs*p*rogramm), a tool to facilitate an explicit documentation and

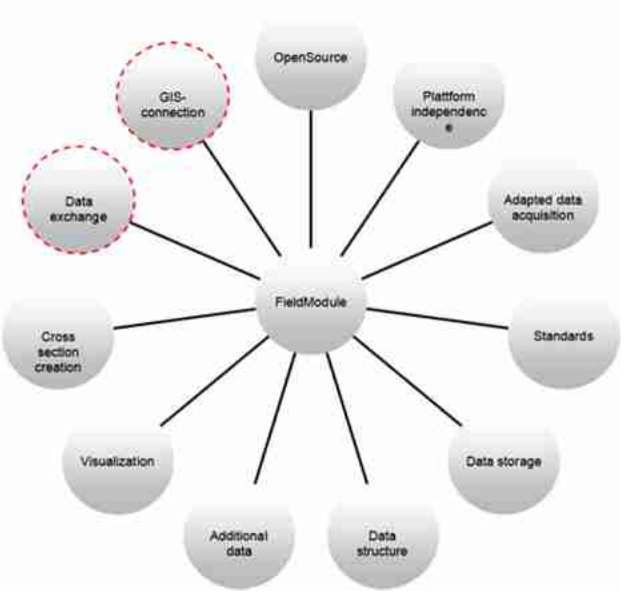


Fig. 2 Key aspects of the FieldModule development. The *dashed red line* indicates aspects that are not realized at the moment

Table 1 Default standards used in the FieldModule

Standard	Application
Symbolschlüssel Geologie (Preuss 2010)	Stratigraphy, different attributes
BoreholeML (Staatliche Geologische Dienste Deutschlands 2012)	Borehole description
Hierarchical classification of rocks (Isaak 2011)	Consolidated and unconsolidated rocks
Guidelines for Soil Description (Food and Agriculture Organization of the United Nations 2006)	Soil description
International Stratigraphic Chart (International Commission on Stratigraphy 2010)	Stratigraphy
BGS vocabularies (BGS 2013)	Structural geology, different attributes
Digital Cartographic Standard for Geologic Map Symbolization US (Geological Survey 2006)	2D/3D drawing, signatures
GeoNames (GeoNames Team 2012)	Geography

easy data exchange (Denino-Thiessen et al. 2002). The basic concept of SEP 3 is to subdivide the determination of geological layers into different data fields (e.g. stratigraphy, genesis, colour). In contrast to other tools, data input implies the usage of standardized abbreviations provided by the Symbolschlüssel Geologie. However, a general consideration of the existing software (GeODin, HydroGeoAnalyst, etc.) demonstrates a dependence of the data management not on existing standards but on the developer of the software.

Database

As described before, MO2GEO FieldModule uses a PostgreSQL database (*M*O2*G*EO *F*ield*M*odule *d*ata*b*ase—m2gfm-DB) to store and manage the collected geological data and the used standards. At the moment the database consists of 69 different tables. These tables build the MO2GEO FieldModule database scheme. This database scheme differs significantly from those used by other applications by being partially hierarchical in some parts. This was done to achieve a project-oriented recording of the field localizations and a reproducible implementation of hierarchical organized standards (e.g. stratigraphy).

All of the tables possess the same basic structure: a set of at least six attributes (Table 2). These attributes ensure the traceability of creation and modification processes within the database. In order to implement the hierarchical structures, two further attributes are needed: the hierarchical level and a reference to the superior element (parent in parent–child relationship). The main differences between a hierarchical and a relational table are shown in Fig. 3.

Table 2 Basic structure of the database tables

Column	Attribute
1	Time of creation process
2	Time of last modification process
3	Dataset identification number—PK
4–n	Attributes for object description (partially FK)
$n+1$	Agent of creation process—FK
$n+2$	Agent of last modification process—FK

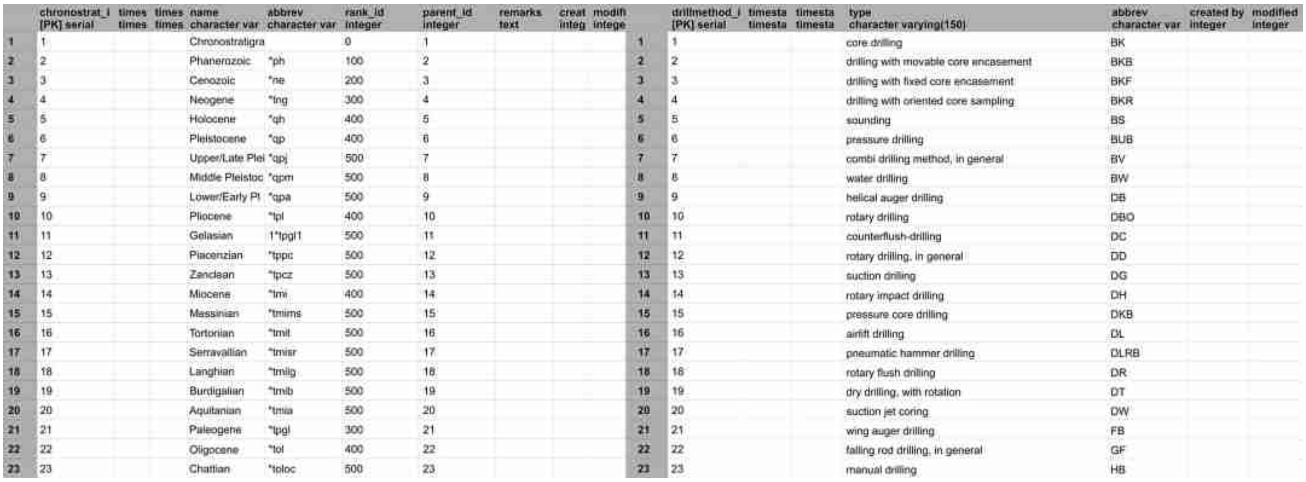
PK primary key, *FK* foreign key

The foreign key refers to the primary key of the database entry which contains the information

FieldModule data management

The MO2GEO FieldModule data management and data acquisition process are mainly influenced by the standards used and the manner or circumstances in which data are collected in the field. The foundation pillar of these processes is the project-related hierarchy of the collected data. This ensures that every created dataset describing a geological feature can be traced back to the dependent project (e.g. geological mapping project). The root of this hierarchy is the project itself, followed by the next hierarchical level, the locality (geological spot). As described before, FieldModule supports different types of geological sites. This also means providing adapted data input forms because of the different information contents (boreholes, outcrops or fieldstones).

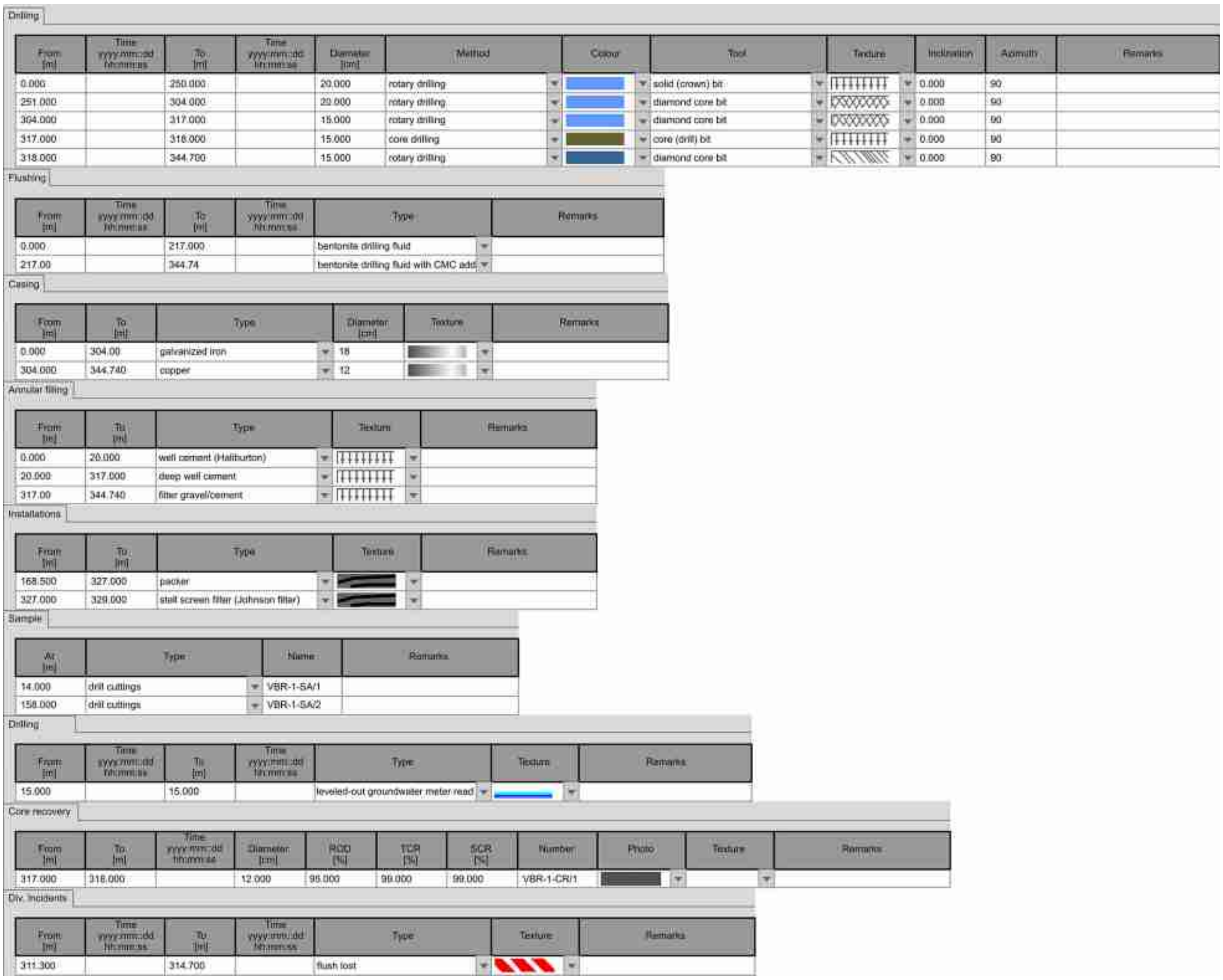
The description of the lithological units is based on the SEP 3 format. But the large disadvantage of this format is the description as a layer (from–to relationship). Therefore, it is not possible to describe a point or linear data (layer boundaries, faults, slickensides, etc.) efficiently. In



	chronostrat_i [PK] serial	times times	times times	name character var	abbrev character var	rank_id integer	parent_id integer	remarks text	creat integ	modifi intege
1	1			Chronostratigra		0	1			
2	2			Phanerozoic	*ph	100	2			
3	3			Cenozoic	*ne	200	3			
4	4			Neogene	*ng	300	4			
5	5			Holocene	*qh	400	5			
6	6			Pleistocene	*qp	400	6			
7	7			Upper/Late Plei	*qpj	500	7			
8	8			Middle Pleistoc	*qpm	500	8			
9	9			Lower/Early Pl	*qpa	500	9			
10	10			Pliocene	*tpl	400	10			
11	11			Gelasian	1*tpgl1	500	11			
12	12			Piacenzian	*tppc	500	12			
13	13			Zanclean	*tpcz	500	13			
14	14			Miocene	*tmi	400	14			
15	15			Messinian	*tmims	500	15			
16	16			Tortonian	*tmit	500	16			
17	17			Serravallian	*tmisr	500	17			
18	18			Langhian	*tmilg	500	18			
19	19			Burdigalian	*tmib	500	19			
20	20			Aquitanian	*tmia	500	20			
21	21			Paleogene	*tpgl	300	21			
22	22			Oligocene	*tol	400	22			
23	23			Chattian	*toloc	500	23			

	drillmethod_i [PK] serial	timesta timesta	timesta timesta	type character varying(150)	abbrev character var	created by integer	modified integer
1	1			core drilling	BK		
2	2			drilling with movable core encasement	BKB		
3	3			drilling with fixed core encasement	BKF		
4	4			drilling with oriented core sampling	BKR		
5	5			sounding	BS		
6	6			pressure drilling	BUB		
7	7			combi drilling method, in general	BV		
8	8			water drilling	BW		
9	9			helical auger drilling	DB		
10	10			rotary drilling	DBO		
11	11			counterflush-drilling	DC		
12	12			rotary drilling, in general	DD		
13	13			suction drilling	DG		
14	14			rotary impact drilling	DH		
15	15			pressure core drilling	DKB		
16	16			airlift drilling	DL		
17	17			pneumatic hammer drilling	DLRB		
18	18			rotary flush drilling	DR		
19	19			dry drilling, with rotation	DT		
20	20			suction jet coring	DW		
21	21			wing auger drilling	FB		
22	22			falling rod drilling, in general	GF		
23	23			manual drilling	HB		

Fig. 3 *Left* Hierarchical *chronostrat* table (chronostratigraphy). The column *rank_id* describes the hierarchical level and *parent_id* refers to the primary key of the superior object. *Right* Relational *drillinstall* table (borehole installations)



Drilling

From [m]	Time yyyy:mm::dd hh:mm:ss	To [m]	Time yyyy:mm::dd hh:mm:ss	Diameter [cm]	Method	Colour	Tool	Texture	Inclination	Azimuth	Remarks
0.000		250.000		20.000	rotary drilling	🟦	solid (crown) bit	▥	0.000	90	
251.000		304.000		20.000	rotary drilling	🟦	diamond core bit	▩	0.000	90	
304.000		317.000		15.000	rotary drilling	🟦	diamond core bit	▩	0.000	90	
317.000		318.000		15.000	core drilling	🟫	core (drill) bit	▥	0.000	90	
318.000		344.700		15.000	rotary drilling	🟦	diamond core bit	▨	0.000	90	

Flushing

From [m]	Time yyyy:mm::dd hh:mm:ss	To [m]	Time yyyy:mm::dd hh:mm:ss	Type	Remarks
0.000		217.000		bentonite drilling fluid	
217.00		344.74		bentonite drilling fluid with CMC add	

Casing

From [m]	To [m]	Type	Diameter [cm]	Texture	Remarks
0.000	304.00	galvanized iron	18	▤	
304.000	344.740	copper	12	▤	

Annular filling

From [m]	To [m]	Type	Texture	Remarks
0.000	20.000	well cement (Haliburton)	▥	
20.000	317.000	deep well cement	▥	
317.00	344.740	filter gravel/cement	▥	

Installations

From [m]	To [m]	Type	Texture	Remarks
168.500	327.000	packer	■	
327.000	329.000	steil screen filter (Johnson filter)	■	

Sample

At [m]	Type	Name	Remarks
14.000	drill cuttings	VBR-1-SA/1	
158.000	drill cuttings	VBR-1-SA/2	

Drilling

From [m]	Time yyyy:mm::dd hh:mm:ss	To [m]	Time yyyy:mm::dd hh:mm:ss	Type	Texture	Remarks
15.000		15.000		leveled-out groundwater meter read	▬	

Core recovery

From [m]	To [m]	Time yyyy:mm::dd hh:mm:ss	Diameter [cm]	RQD [%]	TCR [%]	SCR [%]	Number	Photo	Texture	Remarks
317.000	318.000		12.000	95.000	99.000	99.000	VBR-1-CR/1	■		

Div. Incidents

From [m]	Time yyyy:mm::dd hh:mm:ss	To [m]	Time yyyy:mm::dd hh:mm:ss	Type	Texture	Remarks
311.300		314.700		flush lost	🟥	

Fig. 4 Complete listing (collage) of all input subforms of technical data from a borehole. The datasets are independent and can be created depending on the special needs

addition, describing a whole lithological unit on a large scale requires more or less static conditions. But in nature different parameters (e.g. water content, weathering, boundaries, sedimentary structures, and discontinuities) can vary or even be absent at different localities. This led to the development of the principle of the acquisition of layer-bound point information: To record the data, a vertical profile line is projected onto the investigated area. Now each point of interest on this line is described separately. This allows multiple conditions of the parameters to be set up within one lithological unit. By default the description of lithological units and their parameters are based on the standards taken from Preuss (2010), Gillespie et al. (2011), and Isaak (2011). On the contrary acquiring technical data used for borehole description (equipment, materials, methods, etc.) does not need point information at all, except a few parameters (e.g. sampling). For this reason these data are recorded in the SEP 3 from–to format and partially as point information.

The data acquisition and management process also affects the usability of the tool, of course. As in all software development projects there is the question about user-friendliness and this is always a compromise. MO2GEO FieldModule has a clear and functional graphical user interface. Basically there is a single input form for every single attribute or parameter. These stored attributes then can be selected from tree-views or choice boxes or by database queries. In the case of lithological or technical data, the input form has a tabular layout divided into several views regarding their major content (see Fig. 4).

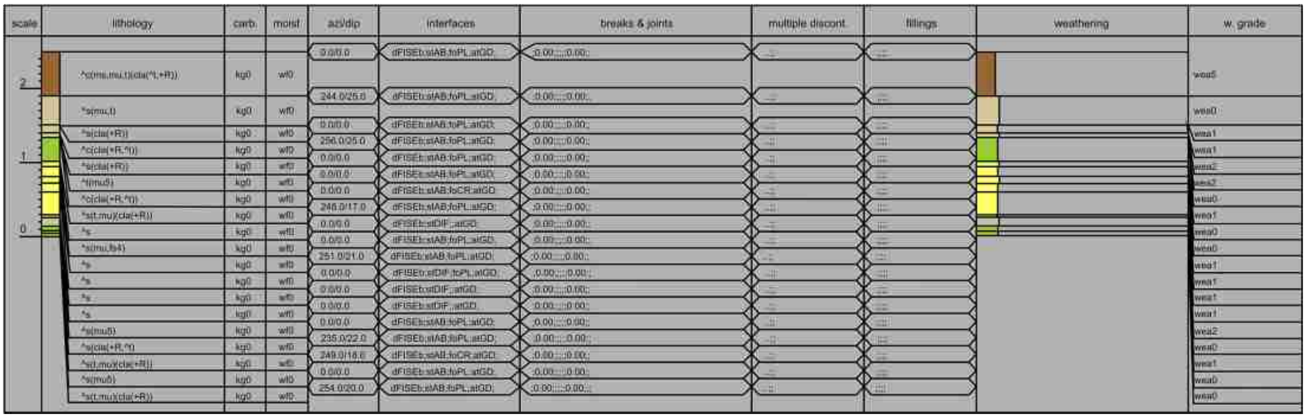


Fig. 5 Tabular 2D-visualization of an outcrop profile taken from a mapping project

Visualization and cross-section creation

A very important aspect of the geological work is the visualization of the collected or created 2D and 3D data. This is already helpful for the field work. Visualizations are a fundamental tool to support the reasoning process and to understand and analyse scientific issues (Rink et al. 2014). The geological or technical data can be visualized in up to four different viewports like in common CAD- or 3D-software. Each of the viewports can display the same or varying information. This offers the advantage and possibility of practical data comparison and control. Recording information along a vertical profile line, as described before, facilitates the visualization process. These structures allow an easy conversion from the input into OpenGL-compliant data. The standard visualization of outcrop and borehole data is organized in a tabular frame to visualize the recorded data in a compact, informative, and user-friendly way (see Fig. 5).

Every frame consists of display areas (columns) for each individual attribute, where a graphical and/or a textural (standardized ciphering, abbreviation) representation of a dataset (row) is displayed. The visualization of the lithologies and other geological features is implemented as a classical outcrop profile showing the lithological units as a graphical implementation. Figure 5 shows the separation of the datasets by a separating line, which also represents the discontinuities inside a lithological unit. A single dataset corresponds to a data row of the corresponding input form. The visualization of technical data is based on the same principles as those of the lithological profiles, but differs in a few points. This is exemplified in Fig. 6. In contrast to a common lithological profile, the visualization is calculated with regard to the diameters and annular spacing. The advantages of a column-based visualization of the information in conjunction with geological or hydrogeological modelling are pointed out by Velasco et al. (2013).

The graphical implementations use OpenGL textures which are created by the user during the data input (geological and technical data) and consist of a background colour and an optional overlaying transparent signature based on the FGDC Digital Cartographic Standard for Geologic Map Symbolization (US Geological Survey 2006). It is also possible to use drilling core images as a texture without editing the picture outside FieldModule. This is realized by the implementation of a small UV-mapper to create the necessary texture coordinates.

Creating geological cross-sections is always one of the most common procedures in geological work. Depending on usage, cross-sections represent the geological conditions either underground or at the surface. Besides the pure depiction, they are also used in 3D underground modelling as a database for the interpolation of strata surfaces. The possibility of creating cross-sections is a very important step towards the development of a stand-alone modelling tool. Cross-sections can be created in different ways: One of the typical possibilities is to use a topographical map and a geological map as well as strike and dip values. However this method is limited in reflecting the exact geological conditions at depth since only information about the geology of the surface is available. Creating cross-sections from drilling information compensates for this disadvantage at the corresponding depth. Here the distribution of strata boundaries between the drillings is correlated. The data associated with the drillings as well as the geological expertise of the editor form the basis for the correlation. MO2GEO FieldModule uses this technique to create cross-sections. Nevertheless the process of the construction is not restricted exclusively to the use of drilling data; outcrop and fieldstone information can also be inserted.

To create a cross-section the user has to select the lithological units which should be connected. The number of profiles used depends on the purpose but must be at least two. As described before, cross-sections can also use

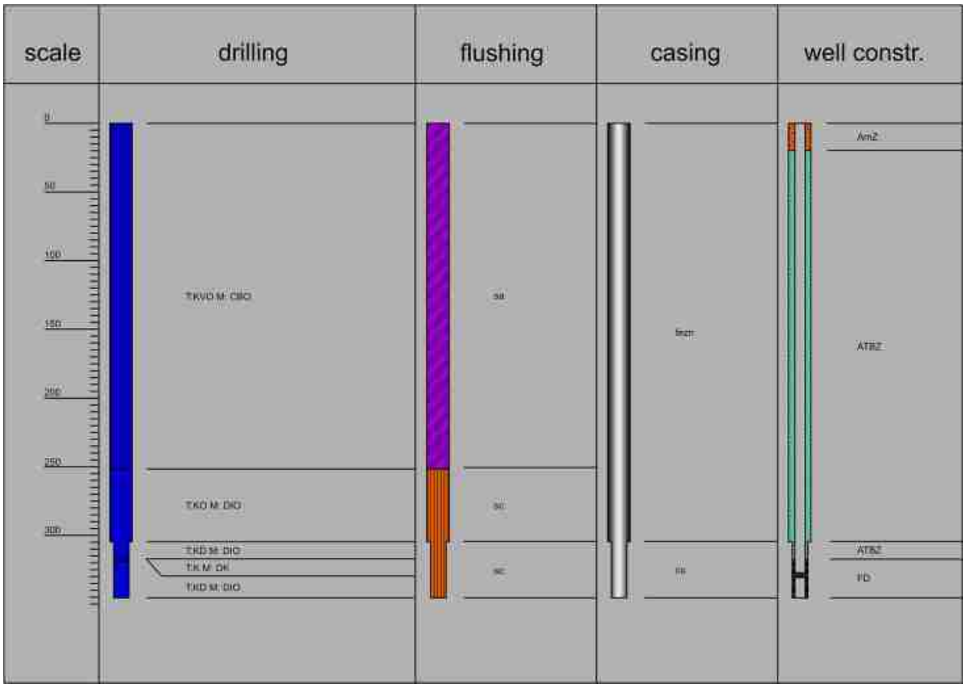


Fig. 6 Excerpt from a borehole visualization showing only four data fields

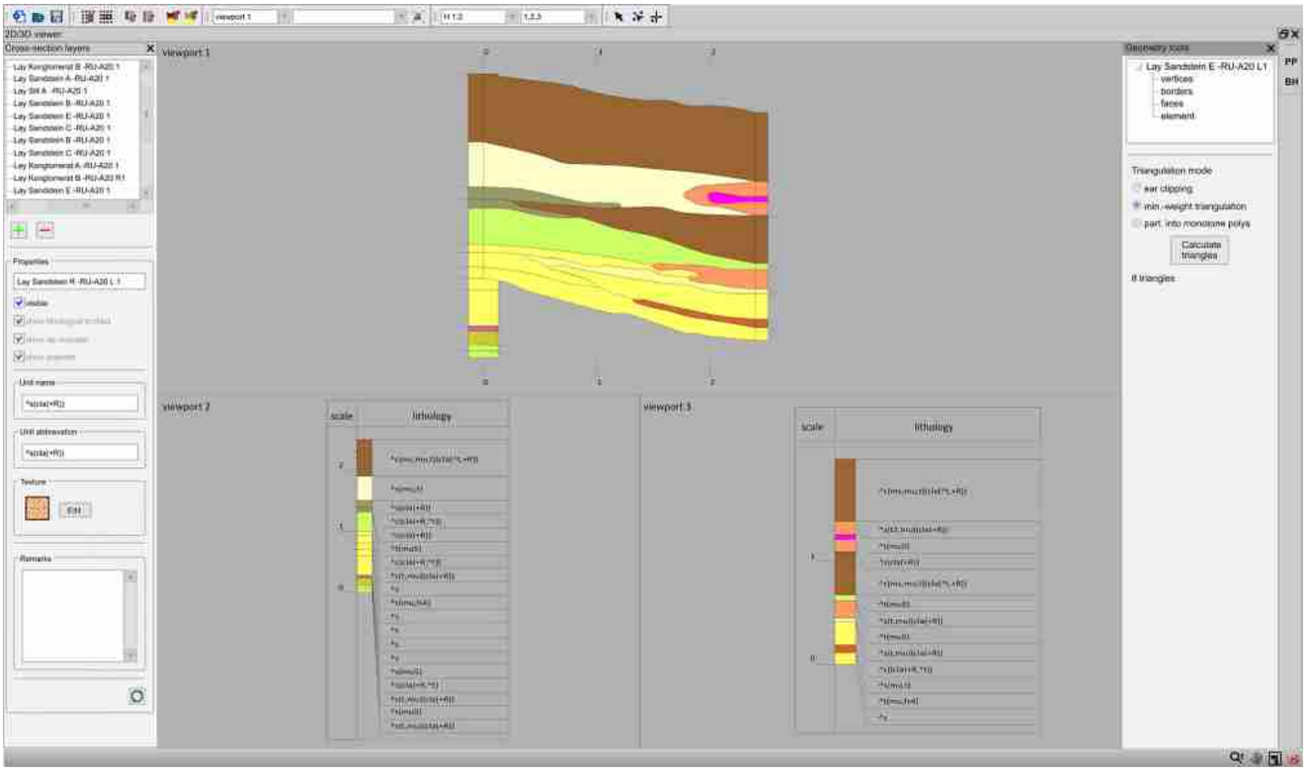


Fig. 7 Cross-section created from two lithological units consisting of 19 layers. The *thin blue lines* within the lithological profile indicate the calculated apparent dip

outcrop information, so it is possible to connect single lithological profiles from boreholes or outcrops as well as multiple profiles from a single outcrop. The selected lithological profiles are then projected onto a line and the apparent dip is calculated. The next step is to choose the strata which should be connected to a layer or, if the layer fades out, only one stratum. Now the upper and lower boundaries can be created by drawing vertices by hand.

These vertices build the margin of the resulting polygon and are used for triangulation. The polygon can be both convex and concave, which offers the possibility of also creating folding geometries. To triangulate the surface, three triangulation methods were implemented: ear clipping (Eberly 2008), minimum weight triangulation (Mehnen 2001) and partitioning into monotone polygons (de Berg et al. 2008). Figure 7 shows the resulting cross-section in the upper viewport and the two lithological profiles in the lower viewports.

Interpolation

Interpolation methods are an essential link between the cross-section results and the 3D model that is already visualized in MO2GEO. This link is missing in the recent version because the topological methods are not adequately elaborated. For folded and faulted structures the layer surfaces (or bottoms) may have two or even more z values for one x–y location.

Standard interpolation methods (IDW and Nearest Neighbour methods) are implemented in MO2GEO with slight improvements. The only new method, L-IDW, reported in Gossel et al. (2012), is only useful in special cases.

The smoothing method for the common Nearest Neighbour method averages the values of neighbouring grid points. Only the grid points nearest to the measurement points are fixed. This allows the user to decide how far the averaging should go and when to stop.

> The 3D interpolation method of InVis is described on the download page (Gossel 2009).
> The implemented IDW method works with all points of the dataset and is parallelized.
> Other interpolation methods will follow such as geostatistical methods.

Visualization

The MO2GEO Explorer module for the visualization of 3D models is still under development by the working group to spread geological 3D models to the public. To allow the visualization of models created with different tools (gOCad, move, etc.) the following input formats were implemented: Esri grid, Surfer grid, gOCad ASCII, and DXF. There are several orthographic and perspective projections to ensure a good examination quality as well as the possibility of changing various lighting settings. Besides the capability of visualizing the data, the creation of virtual boreholes and cross-sections is a very important feature of Explorer (Fig. 8). The cross-section lines and borehole locations can be set by either mouse-clicking or using real world coordinates. Calculating the relevant geometric information is done by ray-tracing and ray-triangle intersection algorithms. The generated cross-sections as well as the boreholes are also a fast and easy possibility to check and validate the geological model. These benefits of a visual inspection are also described in Rink et al. (2012) as described for Field-Module, to allow RAM independent rendering and fast calculation of the geometries of high poly models, OpenGL 3.2 and OpenMP routines were implemented. The 3D visualization and the creation of virtual cross-sections and boreholes from the model can be used for educational purposes as well as for professional questions and their solutions.

Applications

Mapping project in the town of Halle

In the scope of the development of FieldModule, a mapping project in the town of Halle was performed. The aim of this project was to determine the distribution of Carbonian and Permian magmatic and sedimentary rocks. But as described before, the field mapping was also necessary to develop and test the data acquisition methods of FieldModule.

Quaternary base, Lower Saxony

For the district of Celle in Lower Saxony (area of about 3,500 km^2) the Quaternary base was interpolated. The striking feature is that here the database consisted of not only borehole information but also expert knowledge about the outline of subsurface glacial channels presented on an isoline map (Kuster 2005). This kind of database is rarely used in geological modelling, but it points to the capability of the modular modelling system.

Bitterfeld

In the Bitterfeld area a wide variety of data are available in 3D, for example hydraulic conductivities derived from lithologs, hydrochemical analyses, and groundwater pressure. Nevertheless the dataset is quite sparse, especially in vertical dimensions, in this area of about 100 km^2. The horizontal resolution with 450 observation wells in the upper aquifer and 400 observation wells in the lower aquifer is quite good.

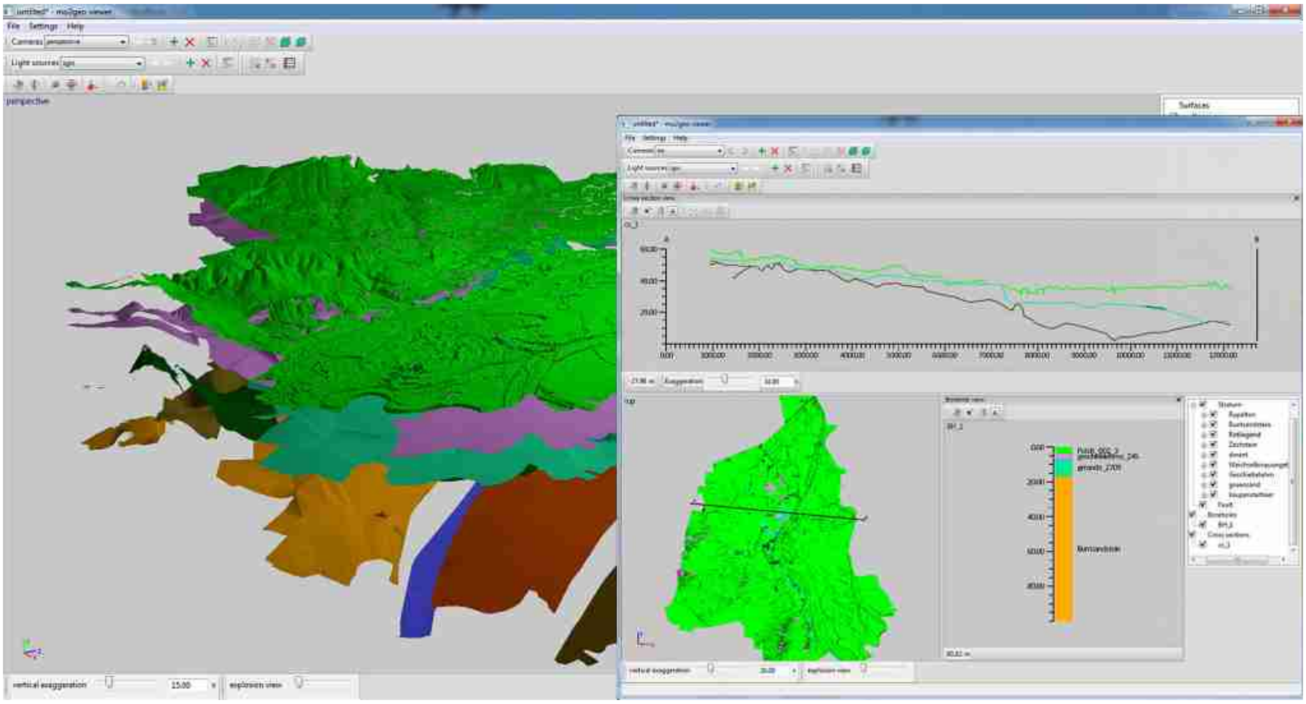


Fig. 8 Overview of the different features of MO2GEO explorer

Magdeburg

Together with the geological survey of Saxony-Anhalt a 3D geological model of the district of Magdeburg (Saxony-Anhalt) was built that comprised information of boreholes, baselines for diverse horizons, and outcrops of layers at the Quaternary base and at the surface. For geological modelling process the tool move (Midland Valley Exploration Ltd. 2013) was used. The main task in this project is to make the model results publically available.

Results

The results will be shown according to the applications. The results for the projects with FieldModule and the visualization tool are described in more detail than the projects with a focus on interpolation techniques because they are reported elsewhere.

Investigations of the scope of the mapping project in the urban areas of the city of Halle (Saale) prove that there are no suitable existing standards for geological data acquisition in the field. The methods developed for collecting information on locations of different types (boreholes, outcrops, and fieldstones) were deduced from well-known and typical geological field-working methods. As already mentioned, none of the commercial tools support locations of different types. Therefore, these tools are absolutely not suitable for this task. The usage of a predefined standardized nomenclature ensures an effective and clean description of geological attributes without the risks of construing plain text phrases. This data input guarantees an easy comparison of different sites and helps to avoid the neglect of important information. Initially, using FieldModule seemed to slow down the data acquisition process in comparison to the manual method. But with the increasing amount of data and the ability to use existing attributes (e.g. already created lithological units) this trend was reversed. Also the hierarchical database structure turned out to be helpful determination key in some cases. Another important aspect is the absence of post-editing, since the data are organized, managed, and stored in a database from the beginning. In an urban region most of the geology is covered due to anthropogenic fillings or construction work. In this case the creation and visualization of a virtual cross-section connecting two or more outcrops and boreholes support the fieldwork by giving some clear and consistent information on what can be expected in the covered areas. They also help to find and identify areas of unexpected changes in the geological features. Additionally the detailed visualization of the collected data can improve the comparison of different outcrops more than a normal camera picture does in the field.

The application of diverse interpolation methods for the Quaternary base of the district of Celle showed the result that the newly developed L-IDW method led to a more reasonable picture than the other interpolation techniques.

In addition to the investigations of Gossel et al. (2012), the methods of Nearest Neighbour, an IDW with all points, and a simple smoothing algorithm were used, but they had the same disadvantages as the already tested tools and methods, as there are interpolation problems in the glacial channels and on the tops of the Quaternary base.

The 3D interpolation of the contamination in the Bitterfeld area with the tool InVis revealed isosurfaces that are reasonable and comparable to numerical modelling results. For this kind of interpolation the horizontal resolution of the two aquifers had to be high as it is rarely given for projects of this size.

Offering a tool to visualize modelling results and use them interactively was one of the main tasks of the Magdeburg project. Because the 3D model was created with move 3D, it was important to ensure the support of different data formats. However the application of MO2GEO Explorer showed that the raw output data of the modelling software are not suitable for visualization purposes. The common problems were missing normals, mixed triangle winding orientation (clockwise and counterclockwise), and unused vertices, as well as zero surface triangles. This necessitates a lot of data processing. Another problem was the size of the output data itself. File sizes of several hundred megabytes made it impossible to use existing mesh-processing tools. The implementation of OpenMP routines reduced the time effort of loading and processing the data to a minimum. Setting the focus on a good rendering offers a much better visualization quality than the modelling tools are able to. This facilitates an appeal to a broad, and also non-scientific, audience. Moving freely in the 3D space is a very useful feature because the standard zooming mode of other tools is based on field-of-view manipulation, which usually leads to deformation of the model. The application of MO2GEO Explorer also showed that the fast and easy creation of virtual cross-sections and boreholes increased the usability of the created 3D models.

Discussion

The discussion focuses on the methods implemented for the new tools. Also here the methods of FieldModule and the visualization tool are discussed in more detail than the interpolation methods.

MO2GEO FieldModule includes features provided by different commercial solutions. Furthermore it offers the ability to customize standards and visualize the collected data. Using standardized geological terms required an analysis of national and international standards. It became quite obvious that these standards are very different from each other and conform only in the rarest cases. The differences are justified by the diverging areas of application as well as the historical development of geology as a science and the national research emphasis. This led to the decision to use user-defined standards, as long as there is no generally accepted international standard. Additionally, in Germany the principle of encoding geological data plays a more important role than in other nations. A comparable or better principle could not be found but the advantages of the use of encoded terms become apparent in the visualization. Considering this, the interoperability of the standards in FieldModule must be regarded as partially limited. However, offering the ability to use standardized data is a very important step towards the interoperability of geological databases and data exchange. Another limiting factor is the incomplete data exchange and GIS connection. Beside this, the possibility of collecting and using geological surface data of different types, which is not realized by any other tool, is a very important step in improving the geological modelling process.

For the interpolation tools the necessity of a further geostatistical interpolation tool is obvious and greatly discussed. The proposed method is only suitable for datasets with high resolution and therefore not suitable for most projects. Without having any information about the fit between the resolution of input data and the heterogeneity of the geological structures, the whole interpolation remains suspicious. In these cases only a numerical modelling approach can lead to more reliable results.

The development and results of MO2GEO Explorer showed that using a tool which supports data from different modelling programs is a great advantage. Notwithstanding, this shows the need for a generally accepted data export format with the capability to store a huge amount of data in a fast and easy processable structure. Another perception was the necessity of data processing to achieve a good visualization result which also helps to clean the data from unwanted information and to reduce the size of the model itself. This is a very important feature, because none of the modelling tools provides mesh cleaning capabilities at all. Altogether, Explorer was able to handle all of the different data formats without any difference in time consumption, except when loading and processing the data for visualization.

Conclusions and perspectives

The conclusion evaluates the workflow of the modular tool compared to integrated tools. Whereas the integrated tools are easy to handle, the loose connection of modules in MO2GEO may be difficult for a user. Although all modules come along with graphical user interfaces, they have to be connected manually.

The connection to numerical modelling tools as already started in Gossel (2013a, b) is planned.

The development and application of FieldModule shows that there is a great demand for an international standardized geological nomenclature and data acquisition processes, as well as the embedding of surface structures into the modelling process. The complexity of these questions demands that further development focusses on less diverse problems. This includes the enhancement of existing features and their interoperability as well as geological modelling techniques. Here the focus will be on the implementation of geometrical and geostatistical methods and interpolation techniques. Since the visualization of geological data is realized with Explorer and cross-sections can be created using FieldModule, these interpolation methods are needed to close the gap between the cross-section-based constructive modelling approach and the 3D visualization.

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