Chapter 6: Three-Dimensional Geological Modelling at the Geological Survey of Austria

Sebastian Pfleiderer[1], Gregor Götzl[2], Clemens Porpaczy[2], Magdalena Bottig[2], and Andrea Steinbichler[2]

[1] Department of Mineral Resources, Geological Survey of Austria, Neulinggasse 38, 1030 Vienna, Austria

[2] Department of Hydrogeology and Geothermal Energy, Geological Survey of Austria, Neulinggasse 38, 1030 Vienna, Austria

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Introduction

This paper gives an overview of 3D geological modelling activities at the Geological Survey of Austria (GBA). Activities started as early as 1991, and for the following 16 years continued in the form of small, isolated studies constructing surfaces – so-called "flying carpets" – in GIS. Due to the project-based nature of these studies, irregular funding and high fluctuation of staff, modelling expertise did not increase significantly until 2010, when a modelling team was established and professional 3D modelling software acquired. Regular funding was secured in 2015.

The focus then shifted from modelling for a specific, applied geoscientific purpose to modelling as a geological exercise in its own right. In cooperation with field geologists, large sedimentary basins were modelled at first, as their horizontal, layer cake structure is easy to map and data such as drillings and seismic sections are abundant. In the central Alps, geological modelling started only in recent years and follows a more conceptual approach, as the tectonic setting is complex and subsurface data scarce. Geological models in both sedimentary basins and Alpine tectonic units are now often used for numerical models to study e.g. groundwater flow or geothermal heat distribution.

Today, the modelling team consists of experts from the Applied Geosciences Department but is closely linked to field geologists and data managers. In the Geological Mapping Department, 3D modelling has yet to be established as a regular tool to map and visualize geology in three dimensions. While other Geological Survey Organizations already deliver 3D models in conjunction with 2D maps, the Geological Mapping Department at GBA still restricts itself to publishing maps, accompanied by a vertical cross-section constructed outside any 3D modelling software. 3D data such as strike and dip measurements of structural surfaces, borehole logs, as well as derived products such as cross-sections and structural maps, do not find their way into a common data storage system. Current plans strive for the establishment of an integral workflow and data management system, which would facilitate the modelling.

Organizational Structure and Business Model

The Geological Survey of Austria is a federal institution under the Ministry of Education, Science and Research and is organized in three main departments – Geological Mapping, Applied Geosciences and Central Services. Geological Mapping comprises the Departments of Hard Rock Geology, Sedimentary Geology and Paleontology & Stratigraphy, while Applied Geosciences consists of the Departments of Mineral Resources, Engineering Geology, Hydrogeology & Geothermal Energy, Geochemistry and Geophysics. Central Services include Administration, Geoinformation, IT & GIS, Public Relations and the Library, Archive and Publishing Unit. Approximately 135 persons are employed at GBA, 85 of them as geoscientists.

The geological mapping at GBA forms the basis for the applied geological research on mineral deposits, groundwater, natural hazards and geothermal energy. All activities are grouped into either basic research, applied projects or methodological and experimental development. Data, maps and reports on all aspects of Austrian geology are provided to public administrations, universities, research centers, industry and to the wider public through a geological information service.

The geological modelling team currently consists of five scientists in the Departments of Mineral Resources and Hydrogeology & Geothermal Energy. The team cooperates closely with colleagues performing numerical modelling (groundwater flow, heat flow, geochemical interpolation, geohazard modelling and geophysical inversion) as well as with field geologists and experts on data definition and management.

Overview of 3D Modelling Activities

3D geological modelling at GBA started with individual projects focusing on applied geoscientific topics such as the distribution of coal seams (Lipiarski and Heinrich, 1992), the thickness of groundwater protecting layers (Moser and Reitner 1998), the structure of Vienna's building ground (Pfleiderer and Hofmann 2001) or the geothermal potential of the Eastern Alps (Götzl et al. 2007). The modelling entailed the interpolation of formation tops from drill logs to create structural maps and was performed in GIS (ArcInfo). Later projects, e.g. on the geothermal use of tunnels (Rockenschaub et al. 2009), applied professional software (GeoModeller) to aid the structural modelling.

In 2010, structural modelling started to be recognized as a geological exercise in its own right, preceding applied geoscientific studies, and GOCAD® was introduced as the modelling software of the Geological Survey of Austria. Large sedimentary basins outside the Alps were modelled, such as the Vienna basin (Götzl et al. 2012a), the Styrian basin (Götzl et al. 2012b) and the Molasse basin (Pfleiderer et al. 2016). Recently, work also started to focus on inner-alpine sedimentary basins or valleys (Götzl et al. 2016) and on alpine regions or tectonic units such as the Tauern window (Götzl et al. 2015), the Arzberg region (Götzl et al. 2017), or the Dachstein region (Porpaczy et al. 2017).

In 2017, SKUA® was acquired and is now gradually replacing GOCAD®. Ongoing modelling work centers on two themes. On one hand, bedrock structures *beneath* sedimentary basins are investigated, e.g. in the greater Vienna area and in the border region between Austria and the Czech Republic. On the other hand, a simplified, pan-Austrian framework model is being developed, displaying major tectonic units down to the Mohorovičić discontinuity (Pfleiderer et al. 2018). Altogether, 14 models have been finalized and three are in progress as of 2018.

Resources Allocated to 3D Modelling Activities

3D geological modelling is partly supported by federal funds, which are not tied to any specific project and currently amount to 43,000 Euros per year. These funds cover e.g. the work on the pan-Austrian framework model as well as the development of web-based visualization tools and costs arising from data management or software licenses. Additional funds come from national and international projects that include modelling activities. These projects are financed by European and national funding agencies as well as by government contracts. Summing up the budgets allocated to modelling within these projects, the funds amounted to 36,000 Euros in 2018. In total, the modelling team had a budget of 79,000 Euros available in 2018.

While the federal funds remained constant for the last few years, project money varies from year to year. Nevertheless, the resources are sufficient to cover employment costs for approximately 1.5 persons per year. Hardware costs are paid by in-house budgets and do not impact on either of the two funding sources mentioned above.

Overview of Regional Geological Setting

Schuster et al. (2014) describe the Austrian geology in an easy-to-read, richly illustrated publication, which can also be viewed online (https://www.geologie.ac.at/rocky-austria). Figure 1 gives an overview of the geological / tectonic setting.

The Variscan orogene in the North of the country is composed of granitic and gneissic rocks of the Moldanubian and Moravian superunits, their Mesozoic cover, which is not exposed at ground level, and of Neogene sedimentary rocks of the Autochthonous Molasse.

South of the Alpine frontal thrust, the Alpine orogene is characterized by thrust-and-fold tectonics and includes three superunits. These are (a) the South Alpine and Austro Alpine superunits, which are derived from the Adriatic continent, (b) the Penninic superunit, which represents remnants of the Penninic ocean and continental fragments, and (c) the Sub-Penninic Superunit, which is derived from the European continental margin deformed during the Alpine orogeny. In the East, the Styrian and Vienna basins cover the Alpine orogene with Neogene sediments.

The cross-section in Figure 2 illustrates the tectonic structure along a North-South transect across Austria. Further details on the geology of the Eastern Alps are given by Schmid et al. (2004), Froitzheim et al. (2008) and by Schuster and Fritz (2013).

Data Sources

Data used for 3D geological modelling at the Geological Survey of Austria are listed in Table 1. In Austrian sedimentary basins, most of the data types listed in Table 1 exist with high data densities due to extensive oil and gas exploration. In the central Alps, the only available data are commonly strike and dip measurements as well as outcrop boundaries and fault lines from geological maps. From these, cross-sections are constructed by field geologists using their knowledge gained through mapping together with scarce borehole data.

Borehole data in Austria are currently collected in databases of the federal states and accessible via online web services. Some states offer public, free-of-charge access, others have granted GBA password-protected access. However, the services only provide individual drill logs in image or

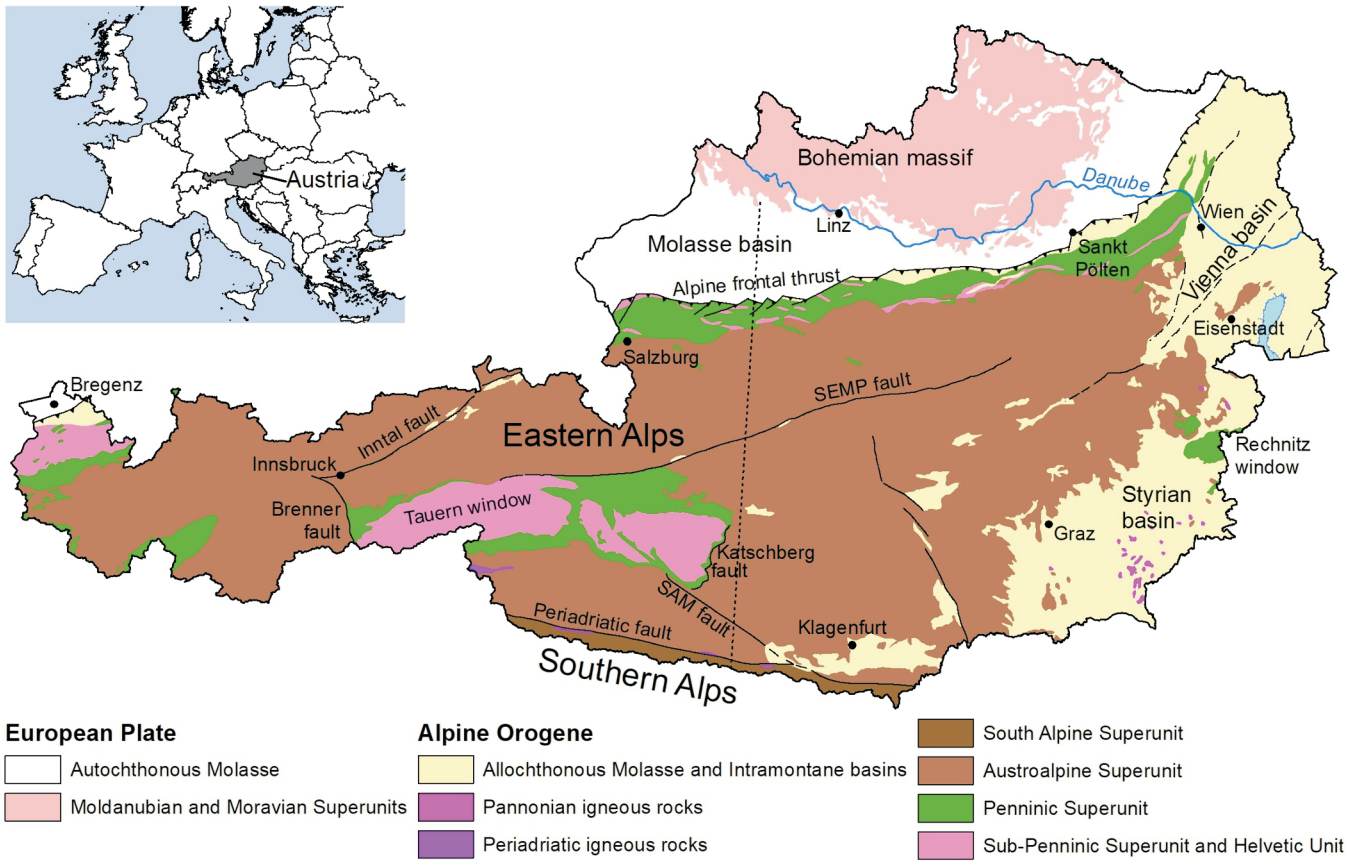

Figure 1: Geological overview based on the Multi-thematic Map of Austria 1:1,000,000 (Krenmayr, 2017; Hintersberger et al., 2018), modified after Froitzheim et al. (2008).

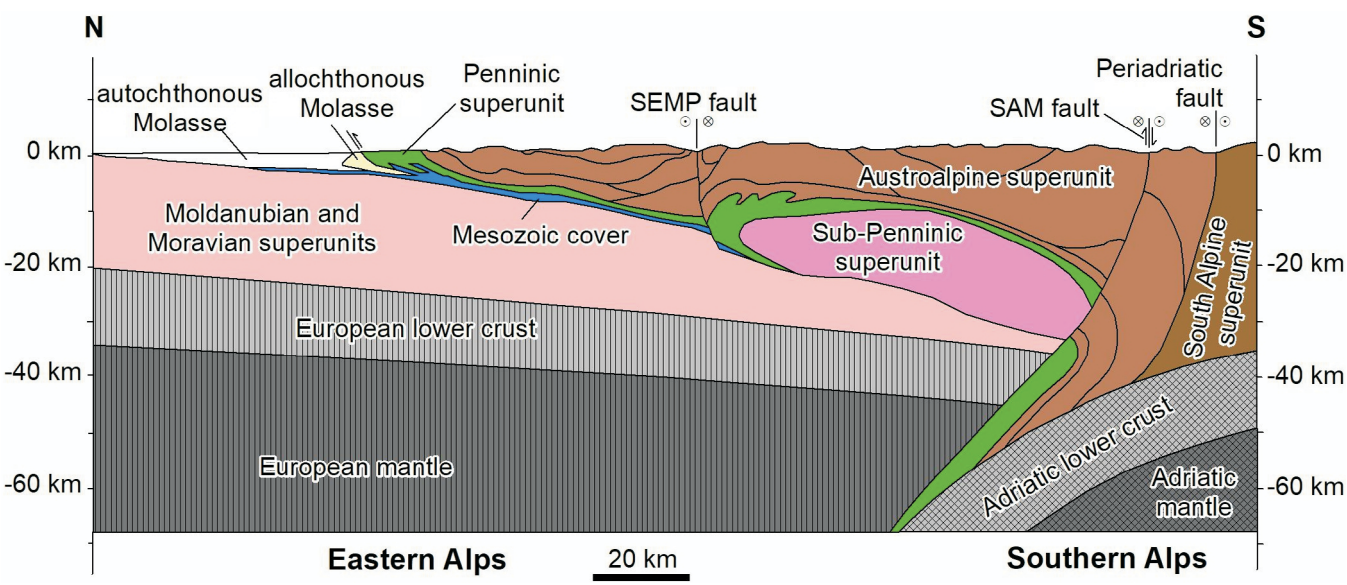

Figure 2: Cross-section through the Eastern Alps after Schuster and Fritz (2013) and Schmid et al. (2004) (for location of cross-section see dotted line in Figure 1).

Table 1: Data types and sources used for 3D geological modelling at the Geological Survey of Austria.

Geometric Type	Data	Source
Point data	Strike and dip	Field measurements
	Formation tops	Drill logs
Line data	Outcrop boundaries	Geological and structural maps
	Fault lines	Geological and structural maps
	Layer boundaries	Cross-sections
	Fault sticks	Seismic sections
2D data	Cross-sections	Literature
	Seismic sections	Oil and gas companies
	Structural maps of surfaces	Literature
	Thickness maps of layers	Literature
	Digital ground elevation models	Open government data

table format, and entire data sets cannot be imported directly for modelling purposes. Only two of the nine federal states share their entire borehole databases with GBA.

Data sharing practices of oil and gas companies in Austria are restrictive with respect to drill logs and seismic sections. Although federal laws prescribe that any exploration data are handed to GBA, the data often remain with the companies. However, agreements exist which allow GBA to obtain data for specific projects. Data can then be used internally but publication of raw data is prohibited without prior consent of the data owners, and derived information can only be published if the exact location of the underlying data is concealed. For the interpretation of seismic sections, GBA relies on subcontracted, external consultants, as no internal expertise exists in-house.

Drill logs and cross-sections published in maps and journals of the GBA, are made accessible to the public through data viewers on the website (https://gisgba.geologie.ac.at/gbaviewer/?url=https://gisgba.geologie.ac.at/ArcGIS/rest/services/AT_GBA_PROFILE/MapServer) and through OpenGIS® web map services. These services show the location of drill holes and cross-sections, provide a preview, list metadata on the title, scale and year of publication, and offer a direct link to the library catalogue.

A countrywide, digital elevation model of the ground surface, constructed from airborne laser scan data with a resolution of 10 × 10 m, is available as open government data (https://www.data.gv.at/katalog/dataset/dgm).

3D Modelling Approach

Currently, the 3D geological modelling team of the Geological Survey of Austria is in a transition phase between explicit and implicit modelling. Some models are still being finalized using GOCAD®, constructing surfaces explicitly through discrete smoothing interpolation between points and subsequent manual editing to achieve plausible results with respect to stratigraphic sequence, layer thickness and fault displacements (Pfleiderer et al., 2016). In 2017, SKUA® was acquired and the implicit modelling approach adopted. Following the structure and stratigraphy workflow, volumes are now constructed by defining litho-stratigraphic sequences, building fault networks, and then modelling horizons.

For further numerical modelling, results from both modelling approaches are exported in the form of surfaces. The computation of geologic grids, the assignment of petro-physical properties to cells and the simulation of e.g. groundwater or heat flow are performed by other software applications such as FEFLOW or COMSOL Multiphysics®.

Clients

The Geological Survey of Austria does not operate commercially. Geological modelling is carried out within research projects and performed for stakeholders of these projects rather than for clients. Stakeholders include water and mining authorities, engineering departments, spatial planning institutions and geothermal energy providers. As these stakeholders represent end-users of the models and usually have little geological expertise, there is no collaboration between them and GBA as such when creating the models. The modelling team therefore rather seeks collaboration with field geologists who can provide expert knowledge in the area under investigation.

Modelling areas are most often defined by the respective funding bodies, e.g. cross-border model areas by European Regional Programs or

model areas of inner-alpine valleys by provincial governments. For European research projects, stakeholders' interests are commonly collected at the start of the project and regular stakeholder meetings organized to inform about the projects' progress. For projects commissioned by provincial governments, a much closer interaction exists. Before modelling, base data are often provided by these governments, and regions (and layers) of interest are defined in cooperation. During modelling, feedback is given regularly and any problems encountered are discussed together to ensure satisfactory results.

After project completion, and without remaining funds, there is no continuing support of end-users. Once the model has been delivered, they are responsible for storage, maintenance and ongoing use. When new data become available or new interests of users are expressed, updating or refining of existing models is performed within new projects. These cases however have so far rarely occurred.

Apart from the use by stakeholders, finalized models are stored on a GBA server and made accessible to in-house staff. For public use, a web-based viewer was developed which accesses the models stored internally and provides an interface for visualizing 3D models, querying them with virtual drill holes and slicing through them in any browser, without the need for downloading any data or software. This viewer went online in 2016 and quickly became one of the most visited pages of GBA's website (https://gisgba.geologie.ac.at/3dviewer/). Currently, it shows only one model, Vienna's underground geology (see Figure 3), but plans are well advanced for a front page allowing the selection of one of the 17 models, before viewing (Figure 4).

To present 3D geological models to the wider public, two types of physical representations were realized, a glass block and a 3D print (Figure 5). The former was produced by a laser engraving technique, etching 80 million points into a glass block to make surfaces, fault planes and drill holes visible in three dimensions (Schimpf and Wycisk, 2016). The latter was made by sending four simplified, closed surfaces to a 3D printer, which produced four plastic shapes which can be stacked upon each other.

Recent Jurisdictional-Scale Case Study Showcasing Application of 3D Models

Information on this topic is currently not available.

Current Challenges

Approximately half of the funds for 3D geological modelling constitute project money. These projects typically last one to three years. To secure continuous funding, and to keep the staff and their experience, new projects have to be acquired constantly. As project money varies from year to year, this can pose a financial challenge. In addition, the modelling team depends to some degree on in-house data managers and programmers whose contribution, time and costs have to be planned well in advance. This sometimes adds an organizational challenge.

Concerning the acquisition of base data, the modelling team often faces significant challenges as ownership of seismic sections and most borehole data lies outside GBA. Only if projects are commissioned by institutions which hold and provide the necessary data, or if data owners are part of the project team, these problems are solved easily.

On the data management side, GBA is still lacking an integral workflow and data management system for 3D modelling. Base data are currently stored in dispersed data bases and modelling products are filed individually. This makes maintenance and update of data and models difficult. When new base data are collected and previous modelling results are refined in the course of new projects, it becomes a challenge to know which version was based on what subset of data and which layers represent the latest result. Current plans at GBA strive for the establishment of a central data archiving system. Keeping a detailed log file of modelling activities and results in a central system would increase transparency and facilitate modelling, especially for new staff joining the team.

3D data collected by field geologists, such as strike and dip measurements of structural surfaces, do not find their way into a common data storage system. Considerable time is spent to gather and prepare base data before modelling. The Geological Mapping Department has yet to recognize and embrace 3D modelling as regular tool to map and visualize geology. This department's main objective still is to publish 2D maps, accompanied by vertical cross-sections constructed outside any 3D modelling software. The conceptual and organizational challenge here is to promote closer cooperation and to make field geologists and modellers "grow together".

Lessons Learned

The adoption of an implicit modelling approach with SKUA® proved a promising step to facilitate modelling and to introduce a transparent and verifiable workflow. Although introduction of the method and software requires training (and time), the approach will soon fully replace explicit modelling at GBA.

To build bridges between the modelling team and mapping geologists, the software tool Subsurface Analyst (part of the ArcHydro Groundwater suite by Aquaveo) was acquired to prepare and visualize 3D data (cross-sections, logs) in GIS as well as to derive cross-sections from finalized 3D models in GIS. This has led to a

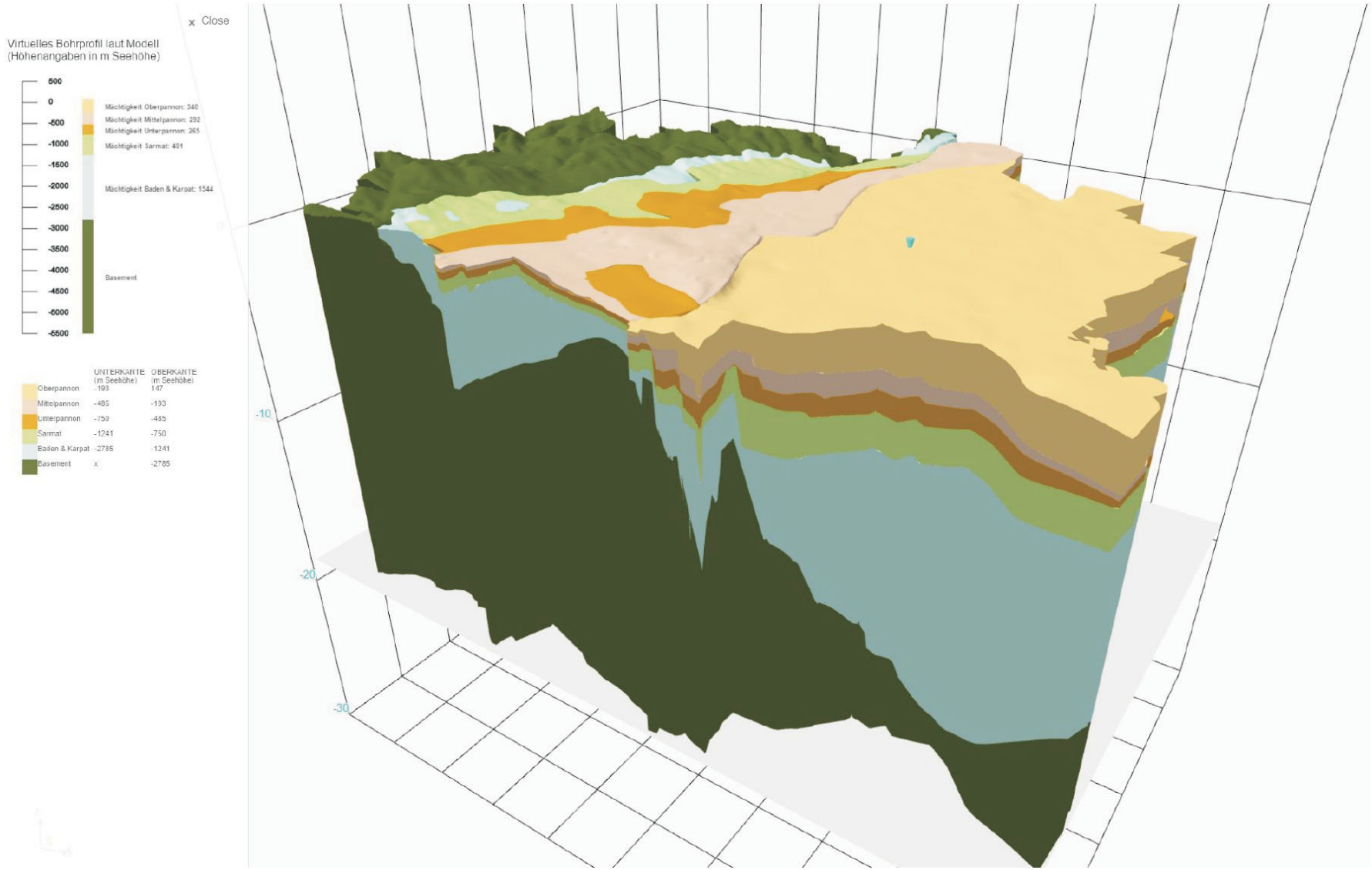

Figure 3: Screenshot of the 3D viewer on the homepage of the Geological Survey of Austria.

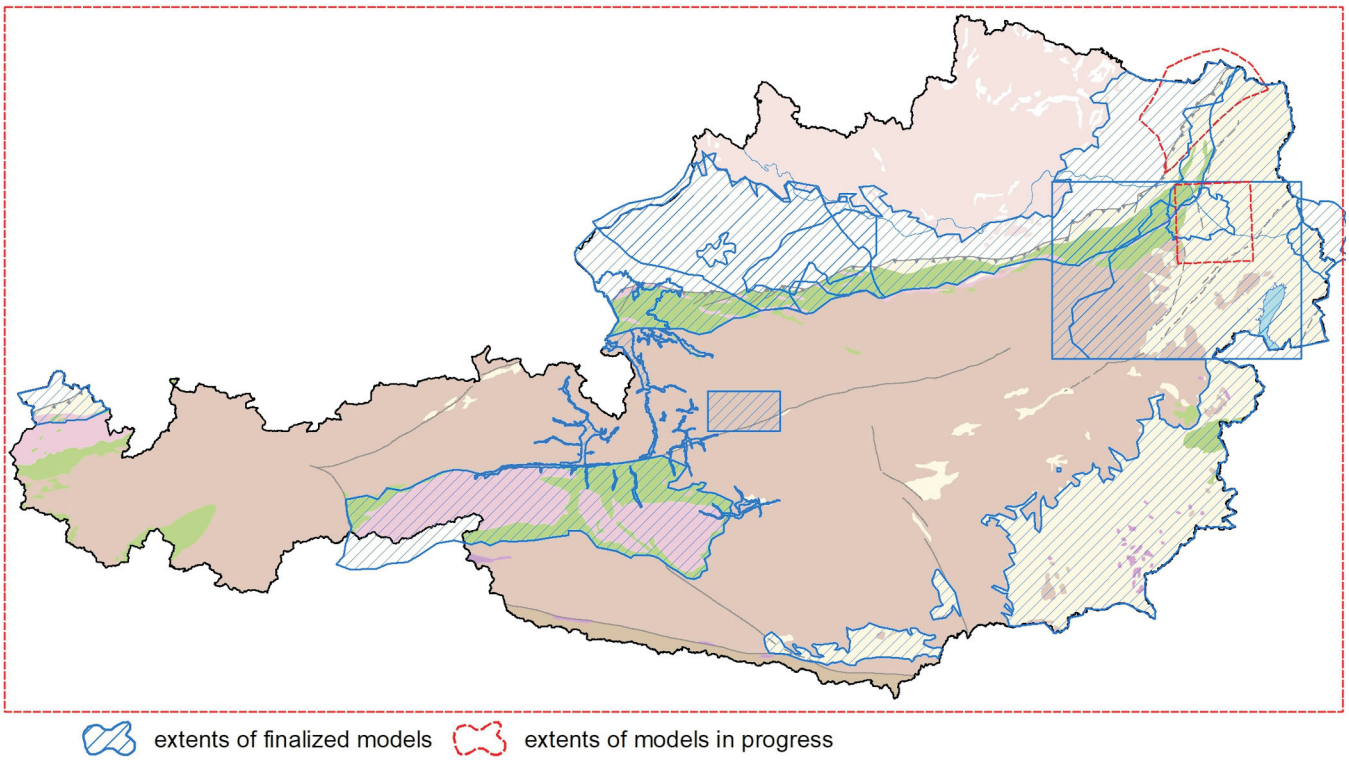

Figure 4: Extents of 3D geological models constructed at the Geological Survey of Austria.

situation profitable to both sides, as geologists can make cross-sections drawn on paper available to modellers, and modellers can make their models useful to colleagues who work in 2D GIS.

The 3D viewer developed by in-house programmers became a success story not only by showing 3D geological models to the outside world and boosting the popularity of GBA's homepage but also by sharing the source code on GitHub (https://github.com/geolba/3dViewer). The Hungarian Geological Survey for example used the code and, with the help of GBA's IT & GIS Department, further developed it to present their geological models.

Next Steps

With respect to model creation, current work will produce three new models. Two models focus on the bedrock structures beneath sedimentary basins to aid the use of thermal groundwater and geothermal energy, while a third model will shed light on Austria's deep tectonic structures on a pan-Austrian framework scale.

Concerning methodology, the explicit approach will be phased out and fully replaced by implicit modelling. In addition, planning and implementation of a central data storage and management system for 3D data and models will be carried out as a future step.

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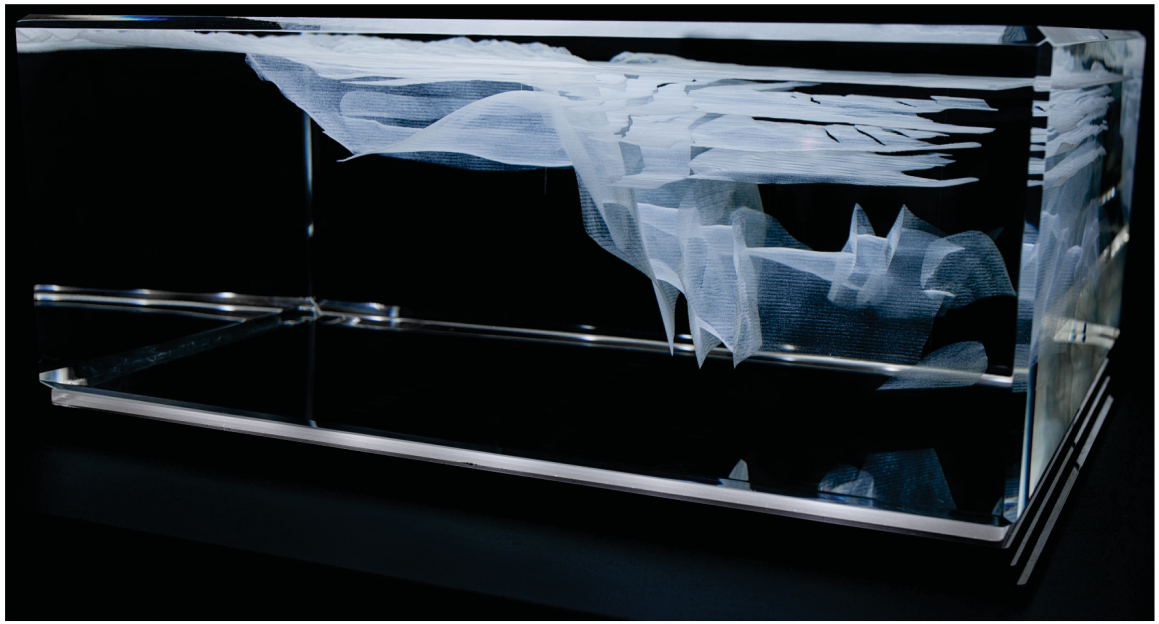

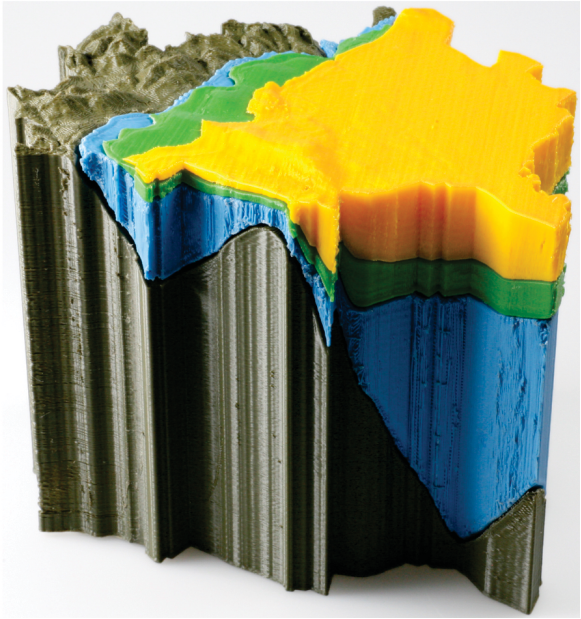

Figure 5: Physical representations of a 3D geological model of Vienna's subsurface: left, glass block (30 x 27 x 12 cm); right, 3D print (15 x 11 x 12 cm).

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