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GeoQuat: Developing a system for the sustainable management, 3D modelling and application of Quaternary deposit data

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Keywords: data model, data management, 3D geological modelling, 3D parametric modelling, Quaternary deposits, shallow subsurface, uncertainty, voxel modelling

1 Introduction

A large part of the shallow subsurface in Switzerland consists of Quaternary deposits. About 90% of the underground uses take place in the mainly unconsolidated rock layers. These sediments accommodate more than half of Switzerland's drinking water resources and they represent significant deposits of raw materials (gravels and sands). Furthermore, they are a source for shallow geothermal energy production and a significant part of housing and transport infrastructure takes place on and inside these geological bodies.

Due to the increased demand on these deposits, use conflicts in the shallow subsurface are unavoidable. To plan and coordinate the different uses in these rock layers, knowledge about their composition and spatial distribution is essential.

In Switzerland, numerous projects and studies have been conducted in the shallow subsurface over the last 100 years by private companies, municipalities, cantons, universities and by the confederation. By this, a huge amount of Quaternary deposit data has been generated. To date, guidelines and procedures for storing and managing geological data are missing for the shallow subsurface. In addition, currently no central data storage is available, that can manage the variety of existing document and data types in a uniform structure. Thus, at present existing data is difficult to compare and its use for efficient spatial data modelling is limited.

These challenges are tackled in the framework of the GeoQuat project conducted by the Federal Office of Topography swisstopo in cooperation with the Federal Office for the Environment FOEN and the Federal Office of Energy SFOE. Several cantons, private companies and universities are supporting GeoQuat by providing access to their Quaternary deposit data and/or by sharing their knowledge. The project lasts three years and should be completed by the end of 2017.

2 Objectives

Data harmonization and pre-processing

The first objective of GeoQuat is to develop a system for structured storage of unconsolidated rock data in Switzerland. The data needs to be harmonized and pre-processed Thereby, the unused potential of existing Quaternary deposit data needs to be made accessible to interested users working in the different fields of applied geology.

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3D geological model as base model and 3D parametric models

The second main objective is related to the process of building and managing geological and 3D parametric models. This objective includes a variety of sub-tasks:

- Develop 3D modelling approaches that are adapted to the modelled parameters and respect the density and quality of source data and the heterogeneity of existing geological conditions.
- Ensure the access to 3D models including their metadata describing the used source data and the modelling parameters.
- Focus on the traceability and the reproducibility of the realized 3D models and visualize the estimated model uncertainty. This helps the users to get information about the model usability and to create mainly automated model updates.

In 2011, the Swiss Geological Survey (SGS) began planning the first comprehensive 3D geological model of the Swiss Molasse basin (Baumberger et al. 2016, this volume). Since then great efforts have been made towards the development of a national geological 3D infrastructure. The project GeoQuat builds upon this currently developed infrastructure and extends it for the shallow subsurface.

Topic	Required Data (Input Data)	Desired Products (Elaborated maps & 3D models)
Hydrogeology	Layer based borehole data	3D geological model as base model
	Analysed/estimated hydraulic conductivity per layer	3D model of hydraulic conductivity
	Anthropogenic influence/infrastructure	Groundwater vulnerability
	Ground resistivity (Electromagnetics)	Groundwater volumes
	Hydrogeological test results (pumping tests)	Coupling with groundwater flow modelling
Geotechnics	Layer based borehole data with lithostratigraphic interpretation	Top Bedrock surface
	Geotechnical test results (USCS-Classification, bulk density, SPT)	3D geological model as base model
	Top bedrock (loose rock/hard rock transition)	
	Particle size analyses	
Geothermics	Response tests, temperature logs	3D geological model as base model
	Water saturation	Top Bedrock surface
	Groundwater table	3D model of thermal conductivity
	Weathered rock zone	3D paths of existing heat probes
Mineral Resources (gravel and sand)	Particle size analyses (USCS-classification)	3D geological model as base model
	Layer based borehole data with lithostratigrafic interpretation	3D model of exploitable sand/gravel volumes
	Water saturation	
	Groundwater table	
	Ground resistivity (Electromagnetics)	
Seismic hazard (Ground Foundation Classification)	Layer based borehole data	3D geological model as base model
	Standard penetration tests (SPT)	Derived map of foundation soil classes

Tab 1: User needs: list of required data and desired products (Results of expert board meetings).

3 User needs

As a first step, the potential user groups of applied geology were contacted in order to evaluate what kind of geological data are of interest and which type of 3D models are important for the users in the different fields of applied geology. Four expert boards were formed to analyze the specific needs. The board members come mainly from the private sector, the administration (federal, cantonal and cities) and from geological associations. Tab. 1 contains the summarized results of the first expert board meetings.

4 Pilot regions

In order to test the practicality of the currently developed GeoQuat infrastructure, four pilot regions (Birrfeld, Lake Lucerne, Upper Aar Valley and Visp) were defined (Fig. 1).

Each area has its main topics. Fig. 2 shows the main topics and the resulting products of each pilot region.

5 Management of Quaternary deposit data

There are many different sources of Quaternary deposit data owned by various instances. The variety of data sources and data owners complicate the development and deployment of a central storage for Quaternary deposit data. Due to their different origin, the data is characterized by a large heterogeneity in their format, type and content leading to a large variation of data quality. To make the data comparable a well-structured Quaternary deposit data model is needed.

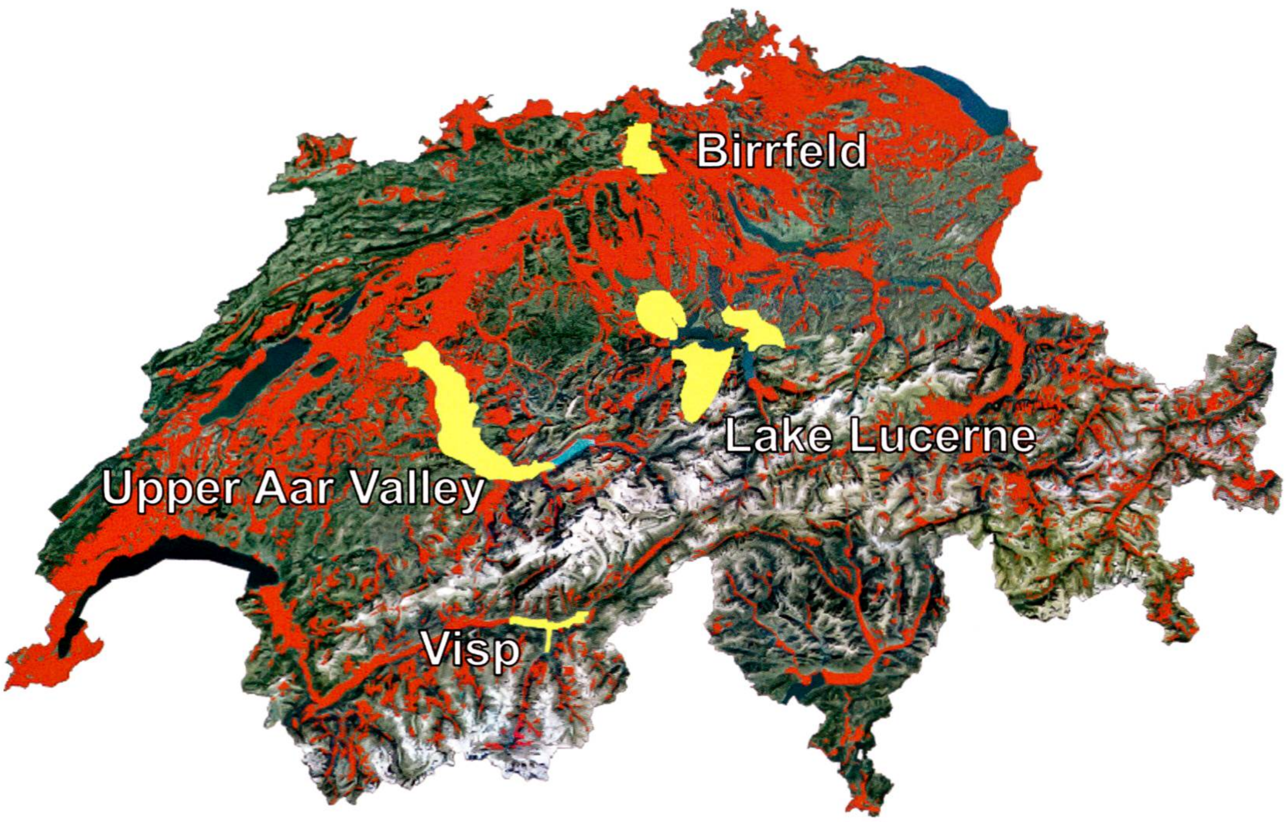


Fig. 1: Yellow colored areas: The four pilot regions of GeoQuat (Birrfeld, Lake Lucerne, Upper Aar Valley and Visp). Red colored areas: Quaternary deposits as shown on the Geological Map of Switzerland 1:500'000.

5.1 The QLG data model

As part of the GeoQuat project, the QLG data model aims i) to specify a harmonized structure for geological data and ii) to describe all relevant Quaternary geological object types and properties (attributes). A rough overview of the QLG data model is displayed in Fig. 3.
The QLG data model is currently implemented at the SGS in conjunction with the setup of the national borehole database that is based on the Borehole data model (Brodhag & Oesterling 2014).
The QLG data model consists of the following components:

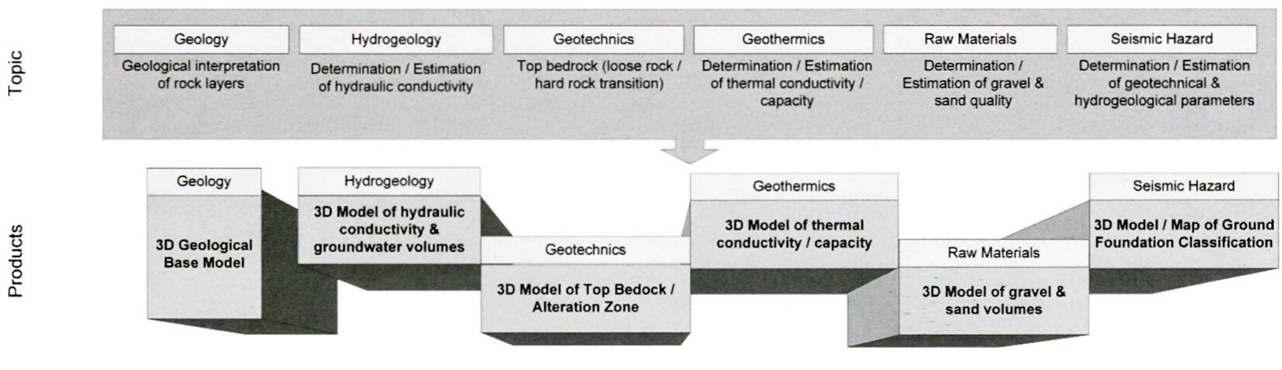
«Data Source»
In the uppermost part, the «Data Source» group contains all data concerning origin, type, holder, age of publication, etc. This source file can have different formats (reports, well logs, excel, pdf, etc.).

«Wells», «Geological Cross-Sections» and «Geophysics»
Wells, geological cross-sections and geophysical data are the main components of the QLG database, and are linked to the «Data Source» table. Geophysical data include seismic, geoelectric, electromagnetic, gravimetric as well as ground penetration radar (GPR) measurements.
The «Wells» group includes all types of boreholes, penetrometer surveys and excavations. All of them contain detailed data on the excavated/drilled Quaternary geological layers.

The «Data Source» group and the «Wells» group correspond to the «Inner and Outer Core» of the Borehole Data Model (Brodhag & Oesterling 2014). The other components of the QLG data model correspond to the «Modules» in the Borehole Data Model.

«Layers» and «Layer Classifications/ Interpretations»
The original lithological description in the «Layer» table followed by the «Layer Classifications/Interpretations» which integrates material properties (e.g. plasticity, compaction, water content based on Swiss and European standards: VSS, SIA, EN, ISO) and classifications.

Several standardized classifications have been used to codify the geological layers:
- the *USCS-Classification* (Casagrande 1948) which divides soils in: i) coarse-grained, ii) fine-grained, iii) organic and iv) peat. The classification is done from the lithological



Pilot Region	Geology	Hydrogeology	Geotechnics	Geothermics	Raw Materials	Seismic Hazard
Birrfeld	x	x	x	x	x	
Upper Aar Valley	x	x			x	
Visp	x	x				x
Lake Lucerne	x				x	

Fig. 2: Main topics and the resulting products of each pilot region.

description of the layer following the Swiss standards SN 670 004 (2004) and SN 670 005a (1997): i) Coarse-grained deposits (grain diameter Ø > 0.06 mm) are firstly coded by «G» or «S», according to their relative amount of gravel and sand, respectively. The presence of fine-grained material, i.e. silt (M) or clay (C) as a second phase (< 15%), is subsequently coded, e. g.: GC, SC or GM, SM. The grain-size distribution of the main phase is also evaluated by means of an additional «W» (well-graded, variable sizes) or a «P» (poorly-graded, uniform size), ii) Main phases for fine-grained materials (Ø < 0.06 mm) are clay (CL) and silt (ML). Distinction is made according to their grain-size characteristics and their plasticity (Casagrande 1948), iii) Organic soils are considered as fine-grained materials because of the significant amount of clay or silt (OL, OH), iv) Peat (PT) are highly organic soils, mainly composed of carbon in various stage of decomposition.

- The *KiRoSt* classification (Vitins & Kündig 2016) codifies raw material resources, i. e. gravels and sands, commonly extracted for industrial purposes (e.g. concrete). This classification is developed based on Swiss standards (SN 670 005a, 1997; SN 670

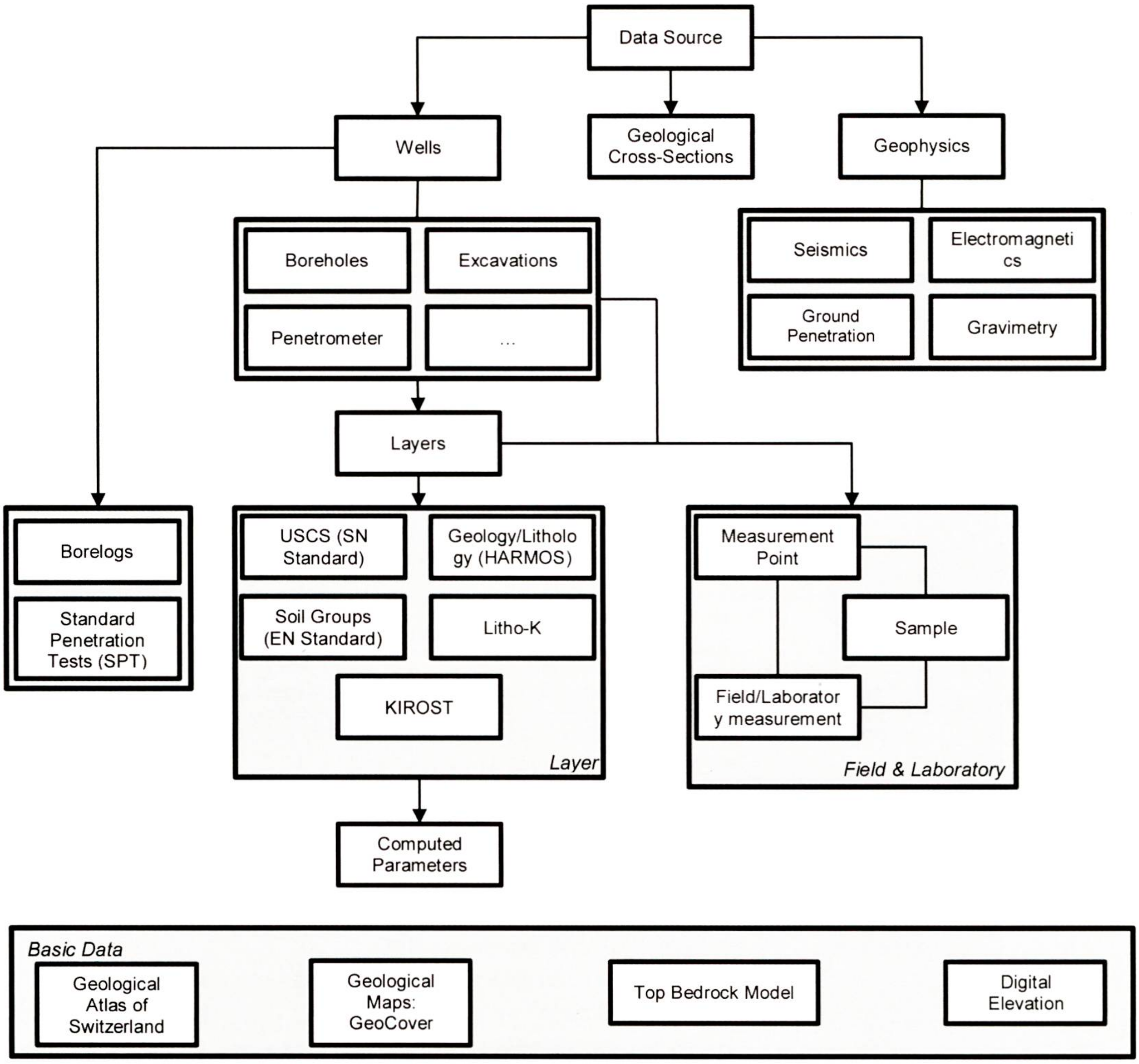


Fig. 3: Generalized overview of the QLG data model.

008a, 1997) and targets an estimation of the quality, as well as of the volumes of a given raw material resource.
- The *Soil Groups* classification (ISO 14688-2, 2004) sorts soil materials into groups of same composition and geotechnical parameters. Particle size distribution (grading), plasticity, organic content and genesis are used by this classification.
- The *HARMOS* classification from the SGS aims to harmonize and standardize legends of the Geological Atlas of Switzerland 1:25'000. (Strasky et al. 2014). The GeoQuat project targets to be in line with the HARMOS classification.

«Computed Parameters»
The table «Computed Parameters» integrates computed values from the «Layer Classifications/Interpretations», such as hydraulic conductivity or angle of internal friction. Computation is based on Swiss standards (e. g. SN 670 010, 2011).

«Field and Laboratory Measurement»
Another group of relevant data is the «Field and Laboratory Measurement» group. Two specific cases are considered:
- In situ measurements: groundwater level, hydrodynamic parameters from pumping tests and strength data from standard penetration tests;
- Laboratory analyses: distribution curves and other geotechnical tests.

The outcomes of these measurement data and analysis comprise a good basis for Quaternary deposits characterisations and for elaborations of 3D models.

5.2 Quality Codes and Uncertainty Evaluation

As mentioned before, the available Quaternary data are of various origin and quality. Thus, a quality code (QC) assessing the reliability of the geological information has been assigned to each geological layer. The QC is composed of three criteria. Tab. 2 shows the first criterion estimating the quality of the *geological description* of a given layer. Significant uncertainty is also present in the XYZ location of wells, as a large number of wells do not have appropriate coordinates. Therefore, the second and third criterion assess the quality of available information on XY *location* and Z *elevation*, respectively. The quality of the information on XY location depends on the precision of XY coordinates. «Very bad» data have position

Code No.	Code Text	Code Description
1	very bad	- No description - Anthropogenic material
2	bad	- only simple indication of lithological phases (gravel, sand)
3	middle	- At least one layer description **WITH** quantity indication **OR** - One layer parameter **OR** - Precision on grain size
4	good	- At least one layer description **WITH** quantity indication **AND** - At least one layer parameter **OR** - Grainsize indication
5	excellent	- At least three layer parameters **AND** - Description of lithological phases with quantity indication **OR** - Grainsize indication - Available Laboratory Measurements

Tab. 2: Quality Code (QC) for evaluating the quality of available lithological description.

accuracy in the hectometre scale (> 100 m), while «excellent data» have position accuracy in the decametre scale (< 1 m). The Z location is strongly linked to the precision of XY coordinates. By means of available XY coordinates, the Z value of a borehole (surface level) is compared to the digital elevation model (DEM) SwissALTI3D. The quality of the information on Z elevation is subsequently evaluated depending on the match or mismatch with data from the SwissALTI3D DEM.

5.3 Input Data

In addition to the QLG database with its structured Quaternary deposit data, there are other sources of input data, mostly independent spatial data sets. Some of them are listed in the lowest part of Fig. 3 and in the upper-right case of Fig. 5a. These are i) the digital elevation model (swissALTI3D), ii) the GeoCover vector data sets representing the surface geology nationwide, as well as iii) the Top Bedrock Model reproducing the modelled Bedrock surface (Baumberger & Allenbach 2016, this volume). It is planned that the Top Bedrock Model will also be continiously refined by the layer information of the QLG data model. Thus, the Top Bedrock Model represents the boundary between the shallow and the deep subsurface.
Another important data source are the results of geophysical studies. Some of these results are already independent 3D models that can be directly integrated in the geological modelling framework. A good example of this are air-based electromagnetic campaigns. In summer 2015, a helicopter-based electromagnetic survey was conducted in the pilot region of Birrfeld (Ibs-von Seht et al. 2016). Indeed, for 3D geological base models, obtained resistivity data can be used to constrain the geometry of a given formation, while for 3D parametric models, resistivity data can be linked to material properties. More information about this study can be found in the text box.

5.4 Data capture

The available Quaternary deposit data were captured for all pilot regions according to the QLG data model. Fig. 4 contains statistics on the entered well data for the three pilot regions Upper Aar Valley, Birrfeld and Visp. These structured data are the main data source for the implementation of 3D geological models. They are stored in a relational database and can be queried, processed and analysed to match as input data for the development of 3D geological models.

6 Creating 3D models of the shallow subsurface

6.1 3D model types

Two principal groups of 3D models can be distinguished (Fig. 5a, middle case): i) *3D geological base models* aim to reproduce the geometry of geological formations, and ii) *3D parametric models* aim to simulate the heterogeneity of material properties, e.g. hydraulic conductivity. The basic difference is shown in Fig. 5b schematizing a borehole log. Input data for a *geological base model* require first an interpretation and the grouping into identical geological formations, while input data for a *parametric model* might be directly estimated from the lithological description of each soil/deposit layer.

The project GeoQuat targets both types of the aforementioned models at a regional scale. 3D parametric models reproducing the heterogeneity of hydraulic conductivity are of particular interest for hydrogeological, geotechnical and geothermic applications. 3D geological models are of particular interest for understanding the geologic history and the intrinsic characteristics of each formations, e. g. overconsolidated clays.

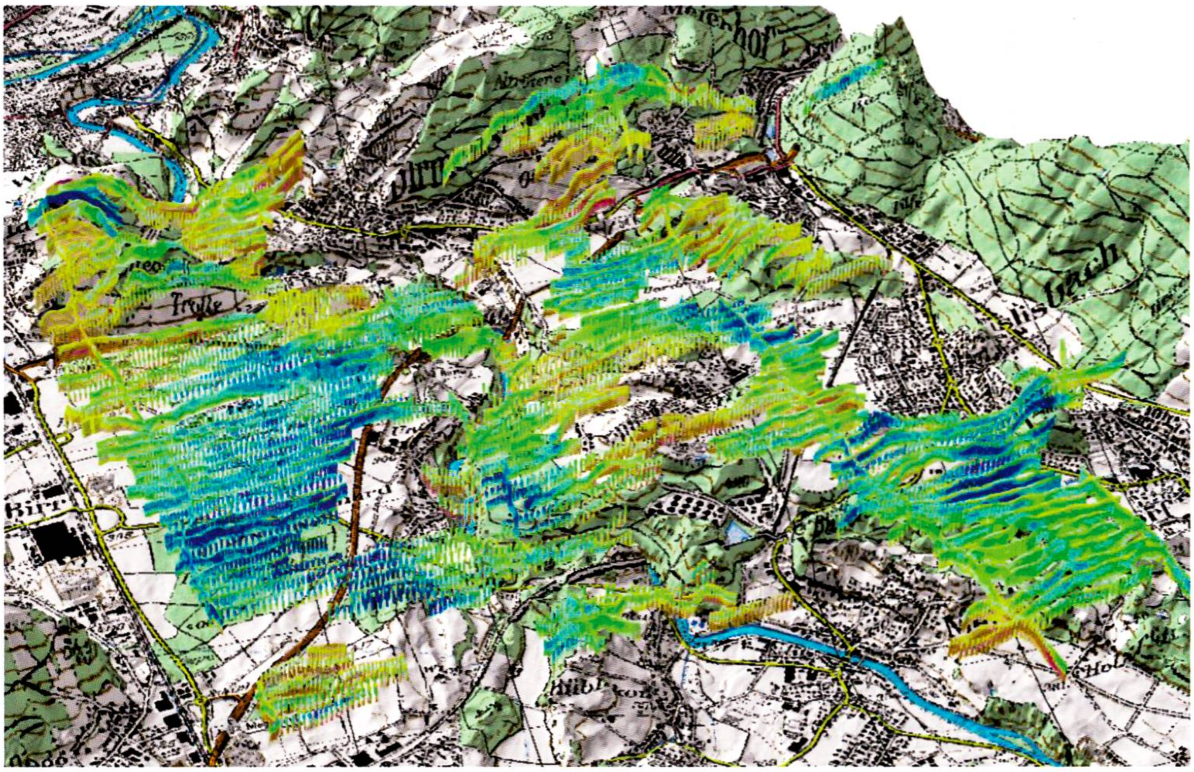
Aero electromagnetic survey (AEM) in the Birrfeld region

In July 2015 swisstopo and Nagra commissioned the Federal Institute for Geosciences and Natural Resources (BGR) in Hannover to conduct an aero-electromagnetic survey in the pilot region Birrfeld. The size of the investigated area was 33 km^2 and the total length of the profile lines was 340 km.

The aim of the study was to find the answer to the following questions:

- Can groundwater bearing layers be determined by AEM?
- Is a distinction between soft rocks (e. g. gravels, clays) using the AEM data possible, e. g. for volume determination of mineral resources?
- Will the AEM data provide indication about the Top Bedrock surface?

Multiple antennas covering 6 different frequencies were used in order to measure the resistivity of the subsurface at various depths. As a result, the resistivity for each of the 62 profile lines could be captured and visualized in 3D. The figure below shows all profile lines with the different resistivity values represented by different colors.



By comparing the AEM results with the existing borehole data the following conclusions about the applicability of AEM data can be drawn:

- The groundwater table could be distinguished in several parts of the investigated area.
- Unsaturated gravels in the lower subsurface could be identified easily because of their high resistivity values. This information is very useful for the prospection of gravel resources.
- In several areas fine-grained sediments could be distinguished.
- The Top Bedrock surface couldn't be detected as the depth of the AEM data was limited to about 60 meters depth due to interferences caused by power lines and other anthropogenic infrastructure.

Conclusion

If reference boreholes are available, AEM is a cost effective method to get useful 3D information of the lower subsurface.

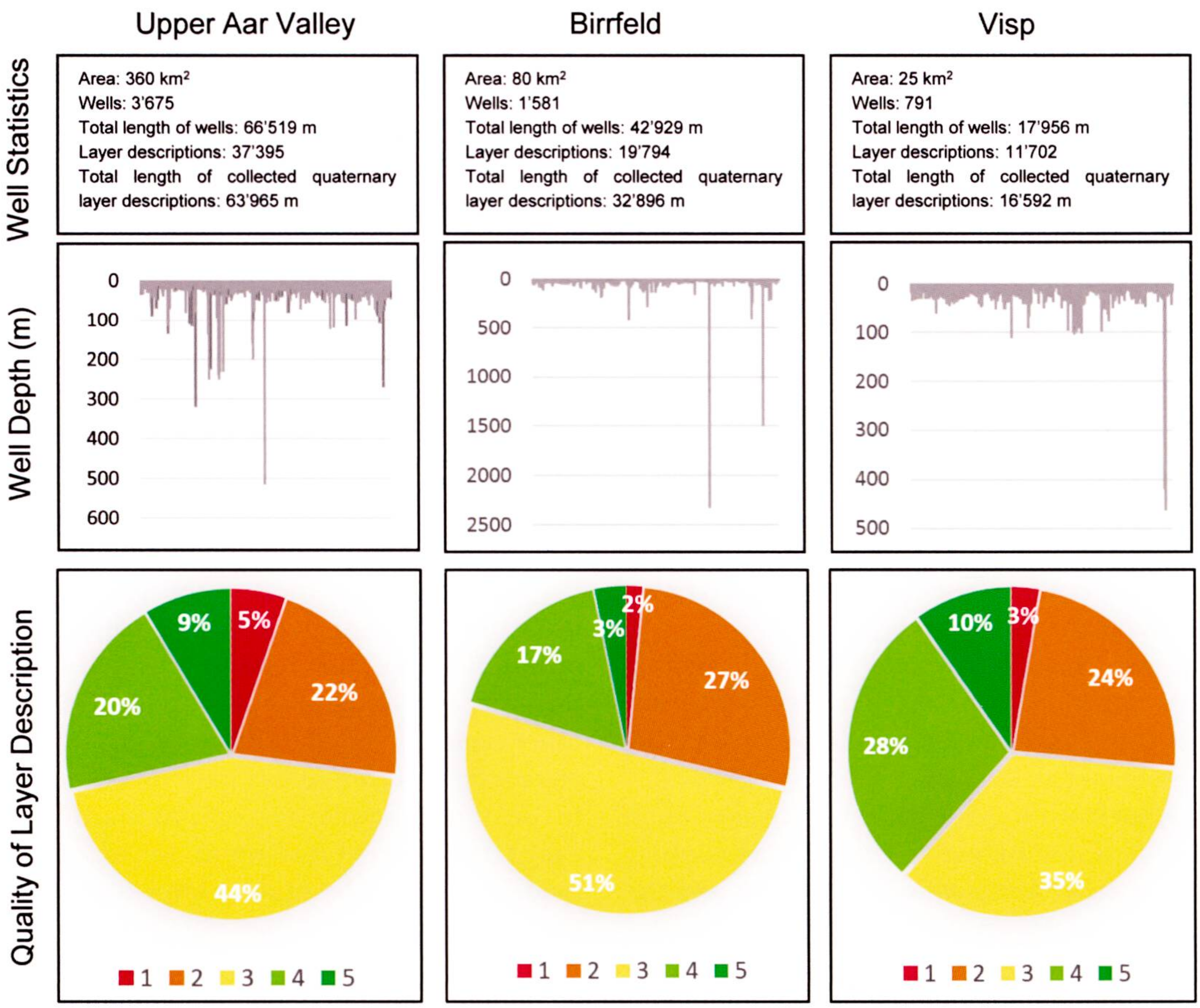


Fig. 4: Well statistics of three pilot regions: Upper Aar Valley, Birrfeld and Visp.

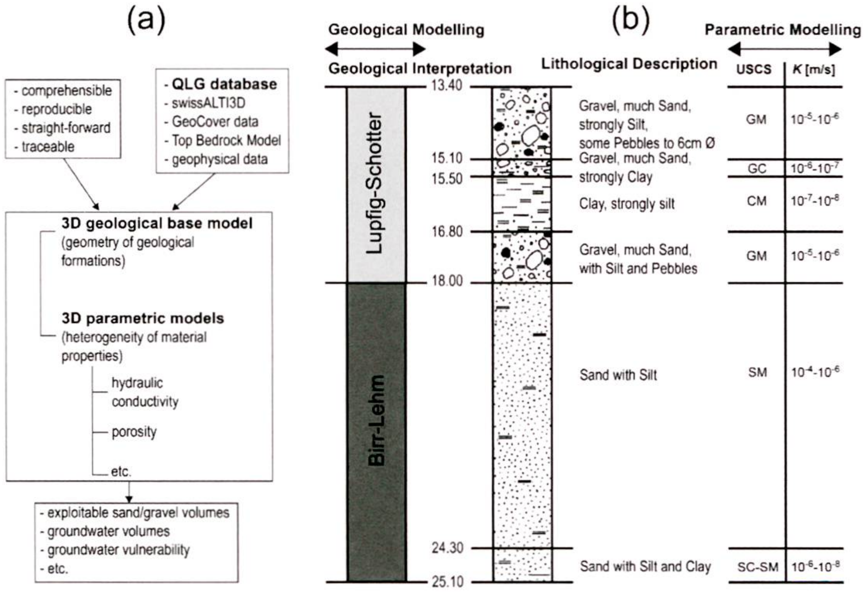


Fig. 5: Schematics of a] the geological modelling framework targeted by the GeoQuat project and b] a borehole with lithological description of layers; (right) input data for parametric modelling are directly estimated from the lithological description, while (left) input data for geological modelling require first an interpretation.

6.2 Modelling approaches

The focus is given on approaches for building 3D geological base models. The scope is to discuss the different approaches and illustrate one methodology able to match the requirements searched in the GeoQuat project (Fig 5a). These include a modelling approach that is *reproducible, straight-forward* and *easy to implement* for realizing a *dynamic* modelling approach where the 3D model is rapidly corrected or updated with the insertion of new data. The pilot region Birrfeld is used for the illustrative example. Finally, a 3D parametric model (hydraulic conductivity) of Birrfeld is also presented without discussing in detail the methodology.

3D geological base models are achieved via *vectorization* (layer-based models) or *geostatistical* (voxel-based models) processing (Stafleu et al. 2011).

Vectorization process: In a *vectorization* process, the objective is to realize contour maps representative of the bottom and the top layer of a given formation. The process becomes highly time-consuming when modelling several geological formations, because each body is treated separately; as well as it is hard to reproduce complex Quaternary structures such as clay lenses. Another constraint is the difficulty to obtain good surfaces from a direct interpolation of available data, even in the presence of a large number of boreholes. It is thus necessary to manually draw the contour lines for modelling layers. Although, this manual step gives importance to the geological knowledge, it is not reproducible.

Geostatistical process: In a geostatistical process, the goal is to interpolate a numerical value, matching a geological formation, to a cell (voxel) of a 3D voxel model. Geostatistical algorithms are divided into two families: i) *estimations* and ii) *simulations* (Goovaerts 1997, de Marsily et al. 2005).

Estimations include interpolation methods such as kriging, inverse distance weighting or nearest-neighbour interpolation and may be considered as «deterministic», because given a parametrization they lead to a unique solution. The main assumption behind a «deterministic» approach is that two identical formations observed in two different boreholes may be interpolated in 3D. Contrary, «stochastic» approaches are based on the idea that the subsurface heterogeneity is unpredictable.

Simulations use thus «stochastic» algorithms where a given parametrization leads to multiple solutions. Typical *simulations* algorithms include the Monte Carlo method, the Sequential Indicator Simulation (SIS) or multiple-point geostatistics.

On one hand, considering the previously indicated requests, *simulations* are not an option because they lead to multiple solutions necessitating post-processing. On the other hand, a modelling approach based on geostatistical *estimations* has the potential to be reproducible, straight-forward and easy to implement leading to 3D geological models that can be rapidly improved with the insertion of new data.

A critical characteristic of an interpolation method for modelling geology is the capacity to conserve the initial geological codification during the computation. In other words, the interpolation algorithm must not calculate new values. In the case of *estimations* this reduces the algorithms to a nearest-neighbor interpolation or a Voronoi tessellation (Kitanidis 1997). Anisotropy of the searching ellipsoid (Fig. 6) may be integrated to favour the interpolation in a given direction. This is important for integrating a certain degree of geological knowledge, e. g. direction of the paleo-glacial flow. The available pre-existing geological data, i.e. boreholes, maps and cross sections, must be the core of the modelling framework. Furthermore, virtual boreholes, that are fictive boreholes where the geology is fully interpreted, might be added to real data in order to i) favour the 3D interpolation and ii) integrate the geological knowledge of a site.

7 Illustrative Examples – 3D Geological Base Model

7.1 3D Geological Base Model

The pilot region Birrfeld is used to illustrate the approach. The location of Birrfeld is strategic for understanding and investigating the Quaternary history (glacial advances and retreats) of the northern foreland of the Swiss Alps. Refer to Graf (2009) and Preusser et al. (2011) for detailed information about the geology and the geological history of Birrfeld. Only major characteristics are treated herein. The South area of the pilot region is characterized by an overdeepened glacial basin and corresponding Quaternary deposits, i.e. glaciolacustrine, till and glaciofluvial deposits, with a thickness reaching maximum depth of about 150–200 m. The overdeepening is absent in the North part with Quaternary formations mainly composed by glaciofluvial deposits filling the alluvial valleys and reaching maximum depth of about 50 m. Deposits older than the last glacial maximum, i. e. older than the late Pleistocene, are seen to form hills bordering the glacial basin and alluvial valleys.

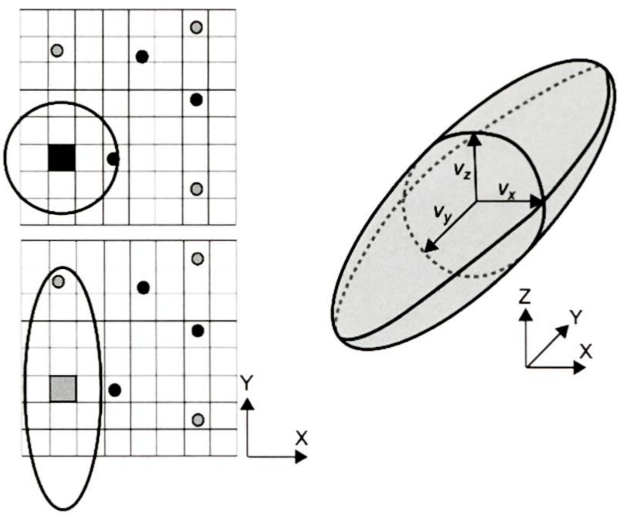


Fig. 6: Schematic illustrating the role of a searching ellipsoid during spatial interpolation: (left) above, isotropic and below, anisotropic searching ellipsoids. (Right) Searching ellipsoid in 3D: anisotropy is used to favor interpolation in a given direction.

The proposed geological modelling approach includes three steps: i) *data pre-processing:* geological interpretation and codification of boreholes data, implementation of virtual boreholes, cross sections and maps; ii) construction of the *3D voxel model* and iii) *3D interpolation* with a nearest-neighbor method having an anisotropic searching ellipsoid. For this illustrative example, 300 boreholes from the QLG-database were geologically-interpreted by Graf (2016), who identified 46 formations. No virtual boreholes, cross sections and maps data are implemented in the *pre-processing* of this example. The *3D voxel model* is composed of voxels with size dX = 25 m × dY = 25 m × dZ = 2 m (dX is N-S, dY is E-W and dZ is vertical) for a total of 6,050,254 voxels. The *3D interpolation* with an anisotropic searching ellipsoid of size dX = 8,000 m × dY = 4,000 m × dZ = 100 m is realized with the geostatical software «Isatis» (Geovariances 2016).

Fig. 7a shows the 300 boreholes color-coded by the type of geological formation and used to constrain the 3D interpolation, in general: blue to green colors state for flood sediments and glacio-lacustrine deposits, green to yellow colors state for tills and glaciofluvial gravels and yellow to red colors stand for glaciofluvial sands and gravels. In light brown is the Top Bedrock Model. In the center of the model data are homogeneously distributed, while in the South part the distribution is heterogeneous. Fig. 7b shows the geographic location of pilot region Birrfeld with the points of view for the different figures. Figs. 7c and 7d illustrate the obtained *3D geological base model*: entire modeled volume and sliced volume, respectively (grey voxels show sectors where the geology has not been interpolated).

Not surprisingly, this test presents obvious errors due to the lack of data, the heterogeneity of data distribution, as well as limitations of the interpolation method when dealing with an insufficient number of data. The South part of the model is a good example of this (Fig. 7c). Yet, in the model center

(Fig. 7d) where the data are abundant and homogeneous, results are promising and show the potential of the proposed method. The geological interpretation of all available boreholes, the digitalization of cross sections and the insertion of virtual boreholes is currently in progress. The geological model will be updated accordingly, as well as with the advents of new borehole data.

7.2 3D Parametric Model (hydraulic conductivity)

In the QLG-database each lithological layer encountered in boreholes is classified according to the USCS (SN 670 004, 2004; SN 670 005a, 1997). The USCS code of each layer is subsequently linked to the hydraulic conductivity by means of a norm (SN 670 010, 2011) or a methodology based on grain size characteristics (Cornaton & Perrochet 2006, Preisig et al. 2014) as shown in Fig. 5b. The logarithmic of hydraulic conductivity is used for interpolating data in 3D via a deterministic or a stochastic approach.

Fig. 8 illustrates cross sections in the computed 3D models: (center) *3D geological base model* (section 7.1) and (below) modeled heterogeneity of hydraulic conductivity. Warm colors denote high values (aquifers), cold colors indicate low values (aquitards). Above is the geological cross section R3 of Graf (2009) for comparison (color-codes are the same as in section 7.1). Cross sections are oriented W–E between Swiss coordinates (LV95): 2'659'000 / 1'255'000 and 2'663'000 /

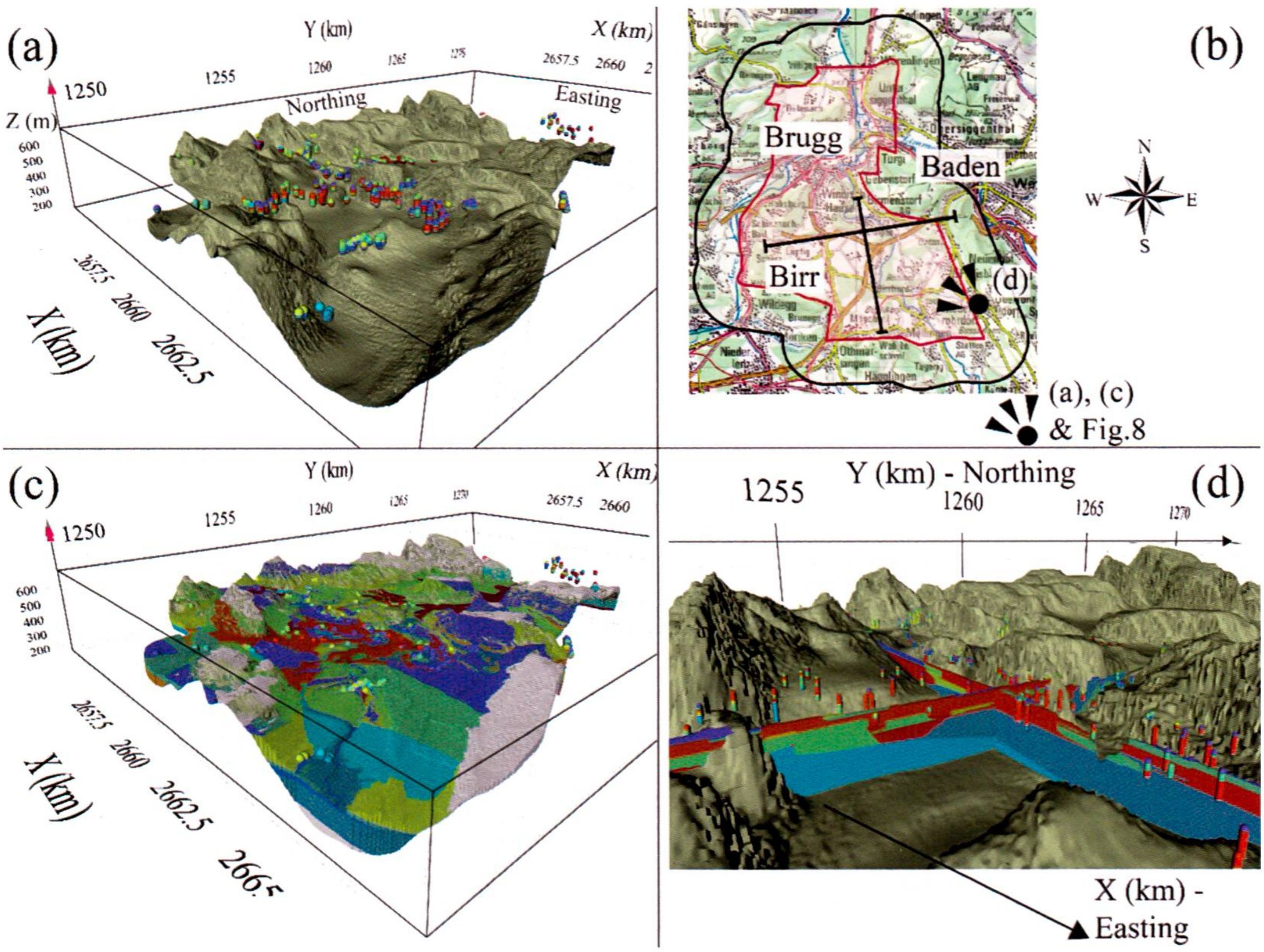


Fig. 7: a] 3D view of the model domain with borehole data color-coded by the geology and the Top Bedrock Model (in light brown), b] geographic location of pilot region Birrfeld with the points of view for the different figures, c] modeled Quaternary geology with d] an enlargement to the model center (two orthogonal slices). Vertical exaggeration 5 ×.

1'256'000 (lateral extent of about 4.5 km, see also Fig. 7b for location). Input data for the presented parametric model include 1,585 boreholes interpolated on the previously described 3D voxel model. An ordinary kriging with a searching ellipsoid of anisotropy dX = 4,000 m × dY = 2,000 m × dZ = 100 m is used to model the data.

8 Summary and Outlook

The above-described 3D modelling examples show the large potential of 3D modelling in the field of applied geology. By the spatial comparison of input data, the process of 3D modelling can assist in solving various geological problems.

Nevertheless, one must be aware that the creation of 3D models is highly dependent on the availability and quality of QLG data. If uniformly structured QLG data are missing, the reliability and use of 3D models is very limited. Therefore, the focus of GeoQuat is on enhancing the awareness of the QLG data model to show its importance. Ideally, in

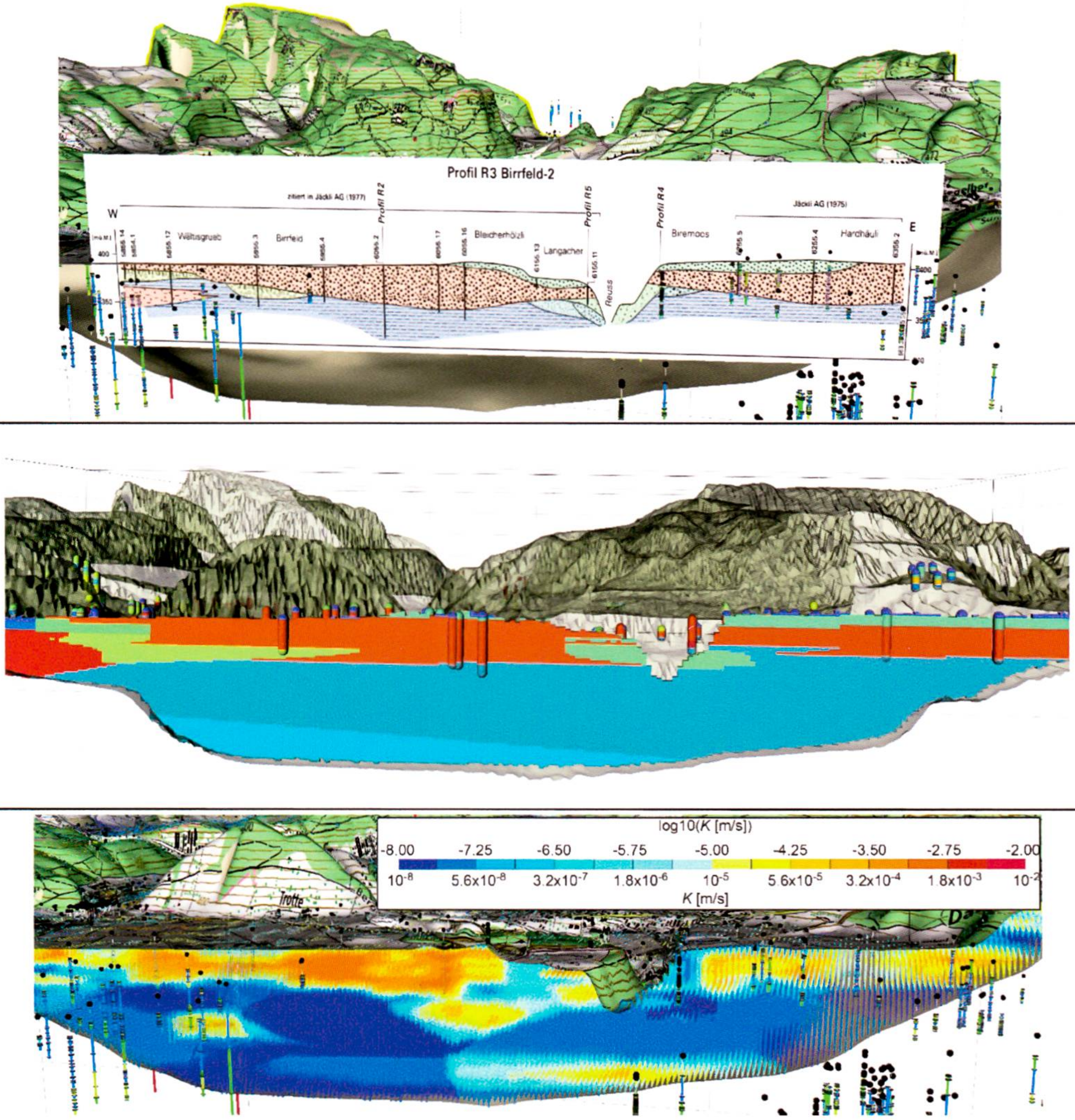


Fig. 8: 3D view of the model with (above) geological cross section R3 from Graf (2009), (center) modeled geology and (below) modeled hydraulic conductivity. Lateral extent of about 4.5 km, vertical exaggeration 5 ×.

future more and more data suppliers manage their data according to the QLG data structure.

A further focus of GeoQuat will be laid on the management of 3D model uncertainty. The users of a 3D model must be able to know the model uncertainty. But the uncertainty varies inside a 3D model because of changing density and quality of the input data and the geological complexity. A possible solution would be to create a 3D uncertainty model besides the 3D geological or parametric model.

In addition, it is planned to extend the pilot regions and to add new regions in collaboration with other partners and extend the focus also to the interaction between anthropogenic activities and urban geology.

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