Chapter 24: Swiss Geological Survey: Modelling a Small but Complex Country

Roland Baumberger, Robin Allenbach, Stefan Volken, Philip Wehrens, David Jaeggi, and Paul Bossart

Swiss Geological Survey, Seftigenstrasse 264, CH-3084 Wabern

Baumberger, R., Allenbach, R., Volken, S., Wehrens, P., Jaeggi, D., and Bossart, P. 2019. Swiss Geological Survey: modelling a small but complex country; Chapter 24 *in* 2019 Synopsis of Current Three-Dimensional Geological Mapping and Modelling in Geological Survey Organizations, K.E. MacCormack, R.C. Berg, H. Kessler, H.A.J. Russell, and L.H. Thorleifson (ed.), Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Special Report 112, p. 249–265.

Introduction

Over the past years, the society has become increasingly aware that geological data contribute to many aspects of daily life. For example: the security of supply (e.g. energy, water, mineral resources, building material), civil protection, infrastructure, waste disposal, public health, culture, civil engineering as well as design and arts all require geological data to some degree. The Swiss Geological Survey (SGS) has been working on the completion and harmonization of its datasets for several years now in order to provide for the requirements above. The efficient and productive usage of geological data not only necessitates their harmonized description, but also an easy way to provide and access the data. Specialists of all disciplines and the public need to be able to easily access and combine geological data (maps, cross-sections, 3D models and corresponding input data such as wells, seismics, etc.) and information (conditioned data) with information not originating in earth sciences (e.g. engineering, environmental, economics) to generate data compilations specific to their tasks and questions. The SGS aims to enable interdisciplinary collaboration in order to increase the usability of geological data. The introduction of 3D geological models added complexity to the product range and increased the number of datasets available. Their importance has changed dramatically over the years. Today they are one of the core instruments for many purposes and come to use in project planning, permitting, surveillance, etc. For the SGS 3D geological models form the core to achieving the vision outlined above and will play a key role in its future strategic direction.

Organizational Structure and Business Model

The SGS is a division of the Federal Office of Topography, swisstopo, under the auspice of the Ministry of Defense, Civil Protection and Sports. Currently 42 staff members work at the survey (incl. interns and administrative staff). The Swiss government funds 80% of its budget and third parties contribute the remaining 20% by research projects or service contracts.

Geological Mapping and Mineral Resources, Data Management and Geoenergy, Rock Laboratory and Deep Waste Repositories form the three branches of the SGS and a small staff group supports the director of the survey. All three branches have 3D modelling specialists assigned with specific tasks related to the division's core topics (mineral resources, geoenergy, and research, respectively).

Three-dimensional models related to mineral resources and geoenergy are available for our clients, whereas models covering aspects of the research for deep waste repositories stay within SGS. The SGS does not charge for the utilization of its 3D models. Parallel to the current Open Government Data discussion, the SGS is investigating the commercialization of parts of its business towards a "freemium" approach: while basic data remain free of charge, there will be a fee for advanced tools and services.

Overview of 3D Modelling Activities

Modelling activities at the SGS cover the following activities:

Unconsolidated sediments: Modelling of the unconsolidated sediments covers the volume between topography and bedrock. Several block models with different resolutions (Block size xyz, from 10 × 10 × 1 m to 50 × 50 × 2 m) were developed for different areas (5 – 400 km^2), now incorporating parameters such as lithostratigraphy, hydraulic conductivity and resource quality (Figure 1). Various maps (e.g. ground foundation class, groundwater vulnerability or groundwater volume maps) can be derived from those models by including further topic-specific data.

Consolidated sediments: Models of the consolidated sediments start below the rockhead and include the Cenozoic and Mesozoic sediments and in some areas Paleozoic troughs and their infill. Currently three models of the Swiss Midlands (½ of the country) are available. Two are typical layer cake models (high and low-res-

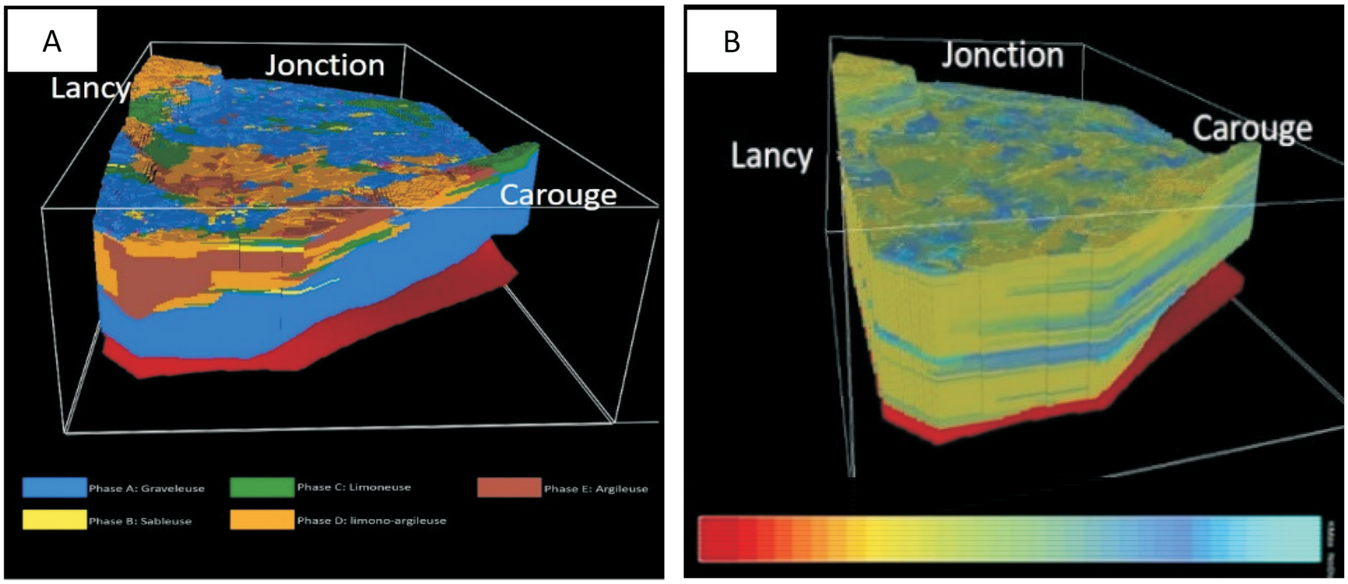

Figure 1. Block models of the greater Geneva area: A) geology, B) hydraulic conductivity [red = low, blue = high].

olution) incl. fault zones (Figure 2); the third, derived from the low-resolution layer cake model, hosts temperature data.

Numerical Hydrodynamic (HM) Modelling: In the framework of the extension of the Mont Terri rock laboratory, the SGS has decided to increase its own knowledge of numerical modelling, especially in the field of hydromechanical-coupled processes. There are four basic objectives:

- modelling of hydraulic and mechanical processes in geological formations such as weakly perme-

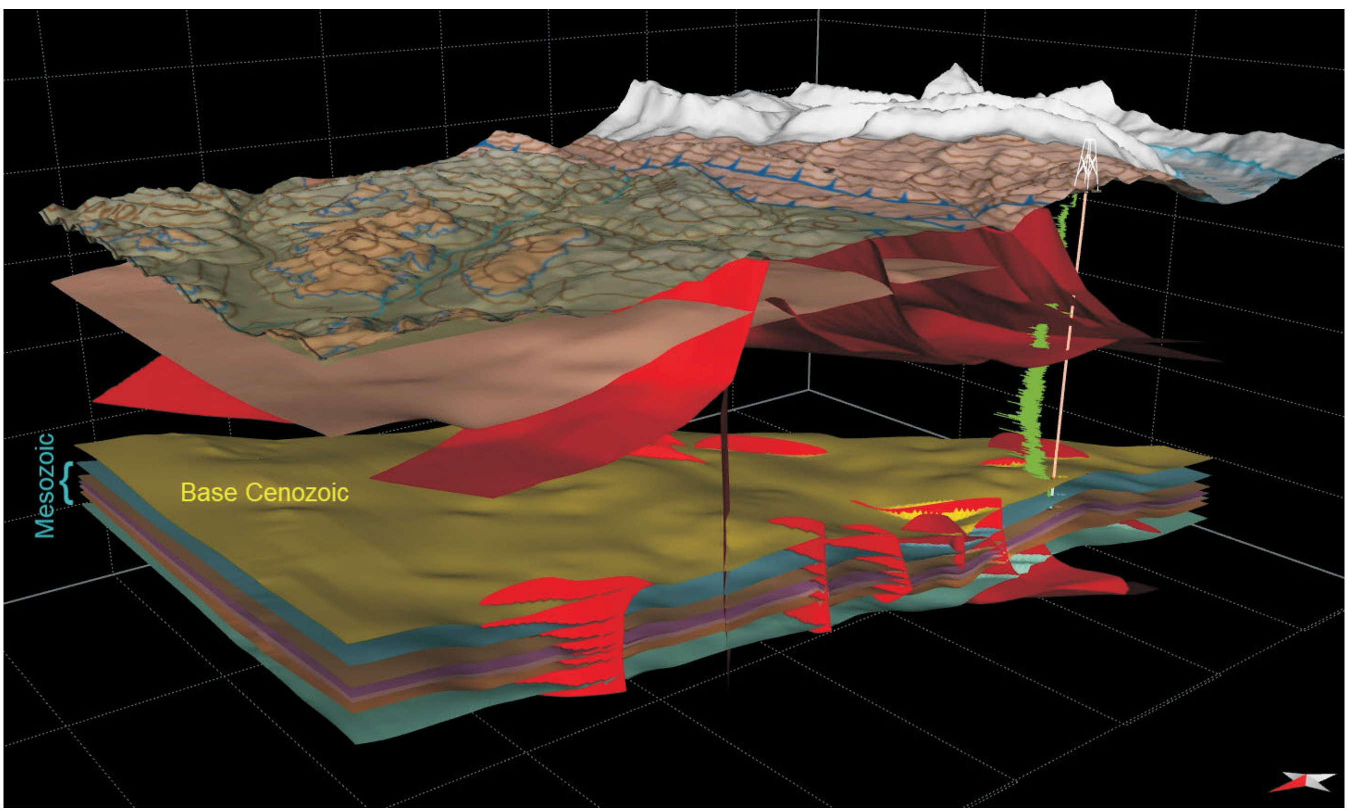

Figure 2. Portion of the GeoMol17 model as seen from the NW (VE 1.5) and the deepest well used in the model: Thun-1 (GR-log in green) with a TD of 4836 mbsl. Surface geology merged with topography forms the top-most layer. The Alps are beyond the model boundary and appear in white.

able argillaceous formations and also highly permeable Quaternary deposits,

- calculation of the design and scope of planned experiments in the rock laboratory,
- prediction of flow and transport processes that are coupled with rock-mechanical processes, and
- parameter estimation on different scales.

While focusing on the application instead of developing modelling codes, the SGS envisages the formation of an expert network consisting of universities and specialized companies (Figure 3).

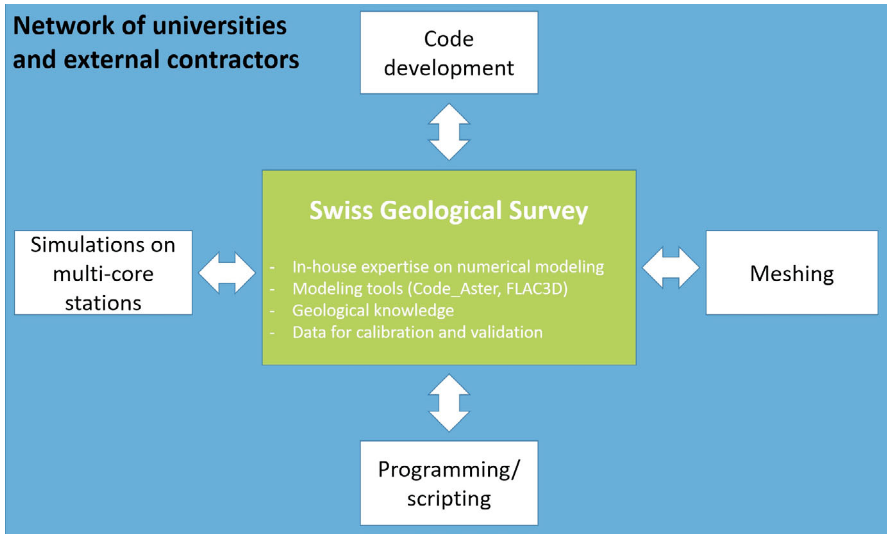

Figure 3. Strategy of numerical modelling at Swiss Geological Survey.

Resources Allocated to 3D Modelling Activities

Total financial resources allocated to 3D geological modelling amount to approximately CHF 1.5 million. This includes 10 staff members directly seconded to 3D modelling activities and their supervisors (6.0 Full-Time-Equivalents) and any service contracts with external contractors.

Overview of Regional Geological Setting

The geological subdivision of Switzerland accounts for macro-scale morphological expressions (Jura Mountains, Molasse Basin, and Alps) as well as for geological-tectonic complexity (Pfiffner, 2008; Figure 4).

Tectonics: The Alps result from the discontinuous collision of the European and the Adriatic plate. Compressional and extensional tectonic phases interchanged in steps lasting several millions of years each. The Alps formed during the Cenozoic by "thin-skinned" tectonics resulting in nappe-stacks related to up doming of the entire tectonic sequences. Many of these nappes consist of Mesozoic-Cenozoic sediments, while crystalline rocks form others. A subdivision into Helvetic, Penninic, Southern and Eastern Alps is based on the formation of the Mesozoic sediments. Within the Alps, other structural types exists, such as "basement-involved thin-skinned" movements in the more internal (Penninic) and the "thick-skinned" styled external massifs (Aar massif, Gotthard massif; Figure 5). In the latter case, the pre-Triassic crystalline basement forms a crustal-scale anti-form with an amplitude of several kilometers (Figure 5). The formation of the Alps subsequently progressed into their Alpine foreland (32-12 my). A "thin-skinned" tectonic style characterizes the Molasse Basin as the sediments were sheared from their basement (pre-Triassic crystalline and permocarboniferous sediments). The basin is subdivided into three regions: 1) The subalpine Molasse (thrust-belt that was thrusted below the Alpine nappes); 2) undeformed Molasse (different tectonics in the western and the eastern part and steeply oriented towards the subalpine Molasse); and 3) the sub-Jurassic Molasse (characterized by several narrow-spaced anticlines). While the western part as well as parts of the central Molasse Basin were thrusted northwards and were deformed on a regional scale, the eastern part shows only weak or even absent deformation. As one of the youngest events (5-10 my), the Jura Mountains formed as a direct consequence of the Alpine orogeny (Figure 5). The sediments in the Plateau Jura are more-or-less horizontal, but dissected by narrow-spaced N-S fault zones. The former are still located on top of their pre-Triassic basement. On the contrary, in the Folded Jura, the sediments are detached from their substrate by a "thin-skinned" style. The detachment horizons were located within the evaporites of the older and middle Triassic. Transport direction was northbound and the transport distance increases from 0 km in the eastern Jura Mts. and reaches 15-20 km in the western Jura Mts. Landmasses are still moving on a measurable scale. However, the horizontal shortening is now restricted to the Po Plain in Northern Italy (Pfiffner, 2008).

Rocks: The pre-Triassic basement consists of polymetamorphic gneisses, amphibolites, migmatites and schists (the so-called *Altkristallin*) intruded by late- to post-Variscan intrusive rocks and young Paleozoic volcanic rocks. Seismic data and deep wells have revealed Paleozoic troughs within the basement below the Molasse Basin and similar Grabens with siliciclastic infill crop out in the Alps. Below the Jura Mountains and the Cenozoic of the Molasse Basin (European continental margin),

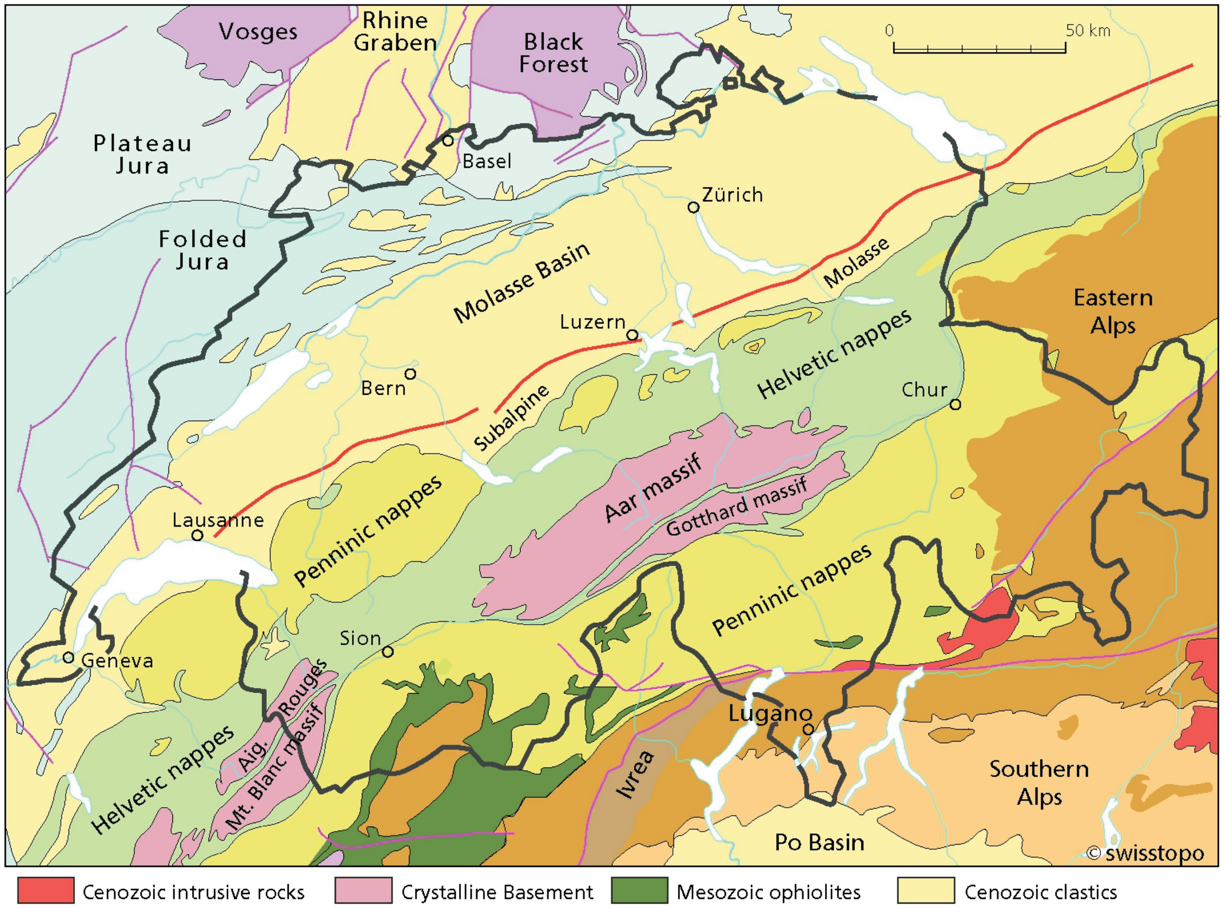

Figure 4. Tectonic overview map of Switzerland.

mainly shallow marine and some coastal deposits ranging from Triassic evaporates to Jurassic platform carbonates and shales dominate the stratigraphic record. In the Helvetic nappes, the complete Mesozoic stack is composed of epicontinental carbonates, gradually grading into shales towards the platform margin.
Siliciclastics deposited in four alternating sequences of marine and freshwater environments in the basin forming north of the alpine orogeny dominate the Cenozoic sedimentary stack. The Penninic nappes (Alpine Tethys) is divided in to three zones:

- Valais Zone (very thick Jurassic and Cretaceous turbidites and upper Cretaceous to lower Eocene schistose, arenitic and conglomeratic deep marine clastics overlying epicontinental Triassic rocks),
- Briançonnais Zone (carbonates of Triassic to early Cretaceous age, Jurassic breccias and upper Cretaceous and Paleogene pelagic and turbiditic sediments),
- Piemont Zone (ophiolithic sequences overlain by pelagic to hemipelagic Jurassic and Cretaceous sediments, e.g. radiolarites, limestones and marls)

In the Southern and Eastern Alps (Adriatic continental margin), Jurassic breccias follow on top of thick series of Triassic carbonates and evaporates. The latter are covered by pelagic to hemipelagic series of Jurassic and lower Cretaceous age. Younger sediments are predominantly abundant in the Southern Alps, where turbiditic sequences of the upper Cretaceous (Flysch) and deep marine clastics of the Oligocene (Pfiffner, 2008).

Unconsolidated sediments of the Quaternary cover significant parts of Switzerland. They are the product of various erosion, transport and deposition processes (glaciers, water, and wind) and the composition varies largely in its lateral and vertical extent. The thickness ranges from few to several hundreds of meters and may reach up to a thousand meters in the main Alpine valleys. Areas covered with Quaternary sediments are the preferred settlement, industrial and cultivation zones in Switzerland, due to their predominantly flat to slightly inclined topography. In addition, these areas accommodate a large proportion of existing underground uses and subsequent usage conflicts.

Data Sources

Only a minor portion of the data that flows into 3D geological models has been acquired by the SGS itself and it therefore relies on data provided by third parties. This includes seismics, boreholes and to some extent even

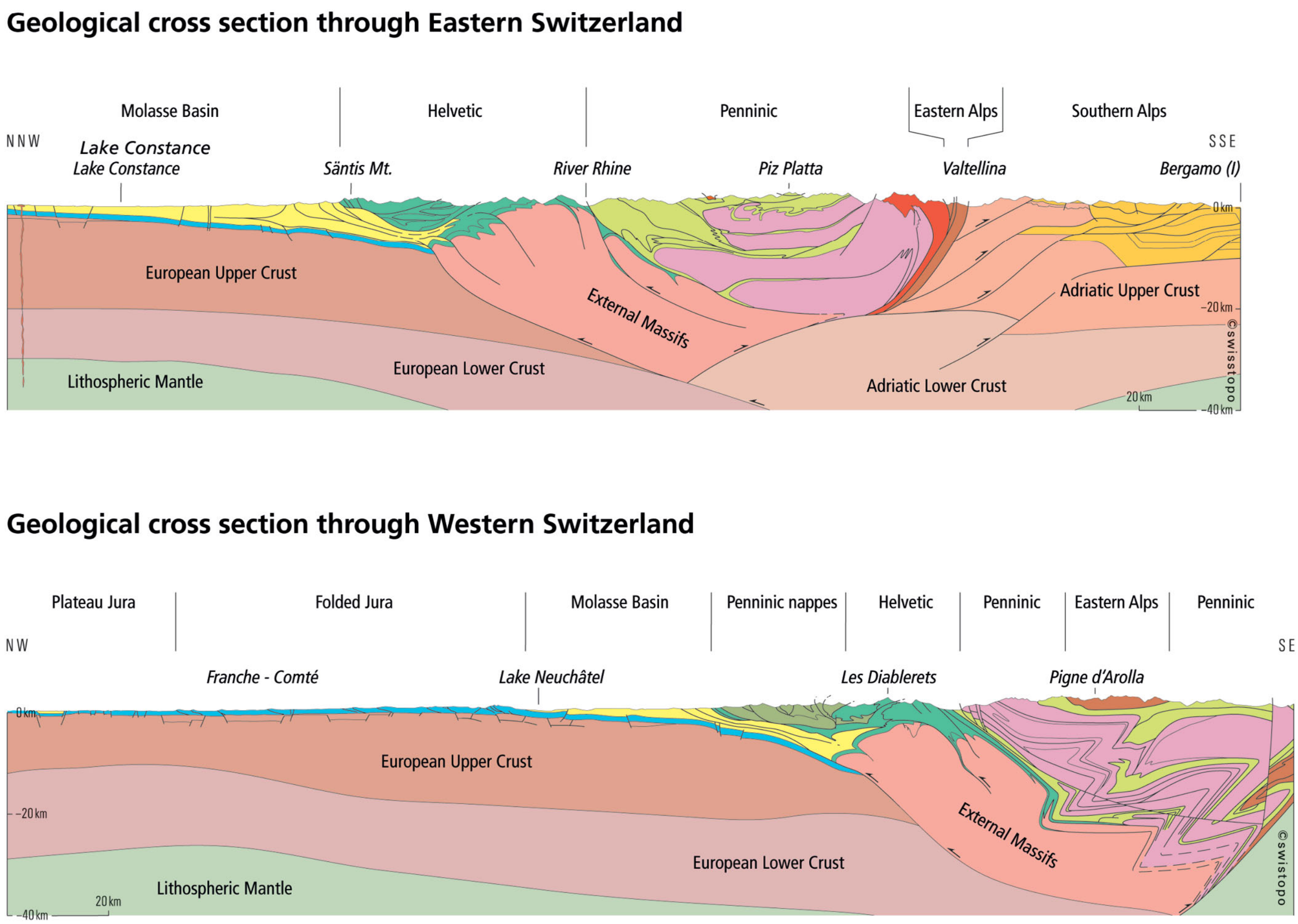

Figure 5. Cross section through Eastern (above) and Western (below) Switzerland, showing the location of the tectonic units and the different tectonic styles mentioned in the text.

cross sections and maps. These datasets are of varying age, quality, and resolution as well as having been acquired for different purposes. The age of the input data often reflects different interpretations and the geological knowledge of a certain time, and the spatial precision of these datasets is often below modern standards. While data is very abundant in the shallow subsurface (annual increase is about 10,000 boreholes/year), the situation is very different in the deep subsurface. There are only around 200 wells deeper than 500 m available, many of them with restricted access privileges. Two private companies own most of the geophysical data and access and usage is partially restricted.

Switzerland is a directional federal republic, consisting of 26 cantons. The subsurface is under jurisdiction by the cantons, resulting in 26 different subsurface legislations and heterogeneous accessibility policies. Consequently, there is no obligation for a homogeneous nationwide data description. A further complication is that intellectual property rights, business or industrial secrets might protect parts of the geological data. Briefly put, there are many issues influencing the accessibility, data quality and publication restrictions due to the absence of a nationwide legislation.

To overcome these issues, the SGS negotiates usage and publication of data with each individual data owner. In addition to this, time consuming preparation, data verification, data QC and data harmonization uses up a significant portion (20-50%) of the staff effort during geological modelling project.

3D Modelling Approach

The SGS uses three modelling approaches: geostatistical, explicit and numerical modelling. For all approaches, data is acquired, quality controlled, transformed (if needed), harmonized, classified and interpreted. Modelling starts only after the input data have passed the conditioning and QC workflows successfully.

Unconsolidated sediments: Models of the unconsolidated sediments are computed with geostatistical methods, based on boreholes, surface maps and cross sections. It is important that the input data used are uniformly classified and harmonized. The choice of geostatistical method, cell size and other model parameters depends on various criteria, such as the parameter to be modelled, the extent of the model, the complexity of the unconsolidated rock geology and the distribution of the input data. For the validation of the realized 3D models different checks are performed: visual checks, variogram analysis and cross validation.

Annually a large amount of new input data is generated in the shallow subsurface, which is why it is of the utmost importance to automate as many steps in the workflow as possible.

Automation ensures the models are up-to-date and their development is traceable. The automated steps of the modelling workflow are colored yellow in Figure 6.

Consolidated sediments: The consolidated deposits of the deeper subsurface are modelled using explicit methods. Typical input data are seismic interpretations, wells, cross sections and geological maps. Human factors like education, knowledge and experience of the modellers may bias the model development. This rises the necessity of standardized data management and procedures, and if possible, easily reproducible automated procedures and workflows (Figure 7).

Data coverage maps (Figure 8) describe the data type (seismic, wells, section and map) available for each horizon in a model. While these maps do not convey the certainty of the model, they do give a very clear indication of which kind of data contributed to each horizon and what the density of data is in a given area of the model. Based on the information retrieved from the data coverage maps, a user can quickly recognize the areas based on algorithms and areas based on measured data, such as wells.

Deriving secondary products is possible from both types of models. In the model-type used for unconsolidated sediments, (semi-)automated workflows result in 2D and 3D products, such as maps showing the soil classification, groundwater volume, groundwater vulnerability or the volumes and quality of mineral resources, respectively (Figure 9). Models derived from the type used for consolidated sediments include the rock-head model (manual borehole correlation) or the all-new temperature model of the Swiss Midlands (Figure 10; developed further by following geostatistical approaches).

Numerical models: Currently swisstopo deploys two codes for numerical hydromechanical modelling at Mont Terri. The commercial code FLAC3D6.0 by Itasca is used for large-scale simulations of the entire rock laboratory, including geological heterogeneity and topography, with all the lab's extension stages over time. These calculations allow us to simulate the large-scale behavior of the rock laboratory by using different built-in constitutive laws, e.g. simple elastic or more complex relations including strain-hardening/softening for improved pre- and post-failure prediction. The second code we deploy is Code_Aster, which was developed by EDF (Éléctricité de France). In the framework of a PhD thesis (at the Federal Institute of Technology Lausanne), a custom-made constitutive law called APD that combines anisotropic plasticity with damage was developed (Parisio 2016, Parisio et al. 2018) for hydro-mechanical (HM) modelling with Opalinus Clay. This modelling procedure was successfully validated on a sequential excavation of a 50 m-long tunnel in the shaly facies. Recently the code was optimized for parallel computing and adapted for the 2D heterogeneous case.

Large-scale numerical modelling (rock lab scale): The kilometer-scale heterogeneous model of the Mont Terri rock laboratory includes the 100 m thick Opalinus Clay, dipping with 45 degrees to the southeast, in a depth of 300 m below surface. On top of the Opalinus Clay lies the Passwang Formation consisting of limestones and marls, and below lies the Staffelegg Formation consisting of marls (Figure 11a). We carried out the excava-

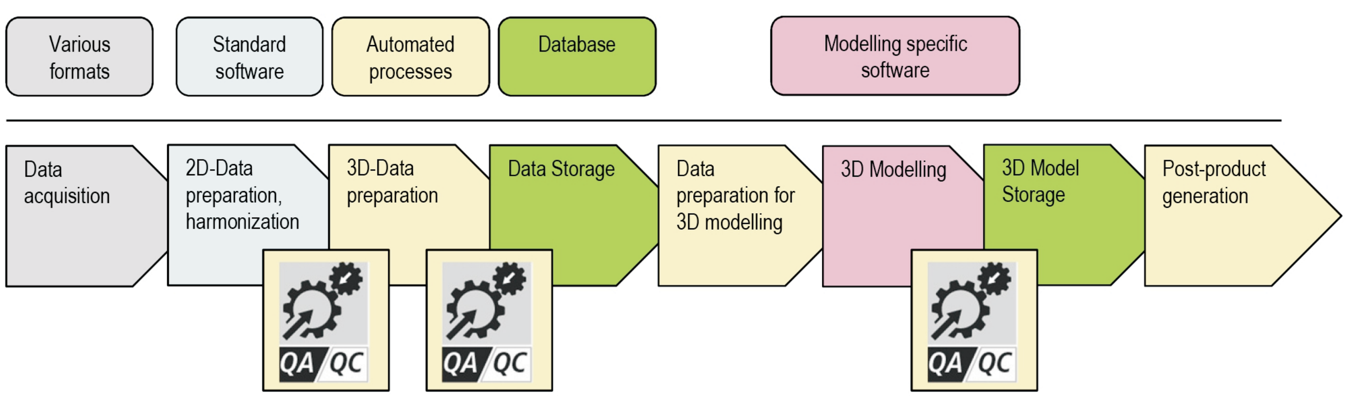

Figure 6. Modelling workflow: from raw data to block models and post-products.

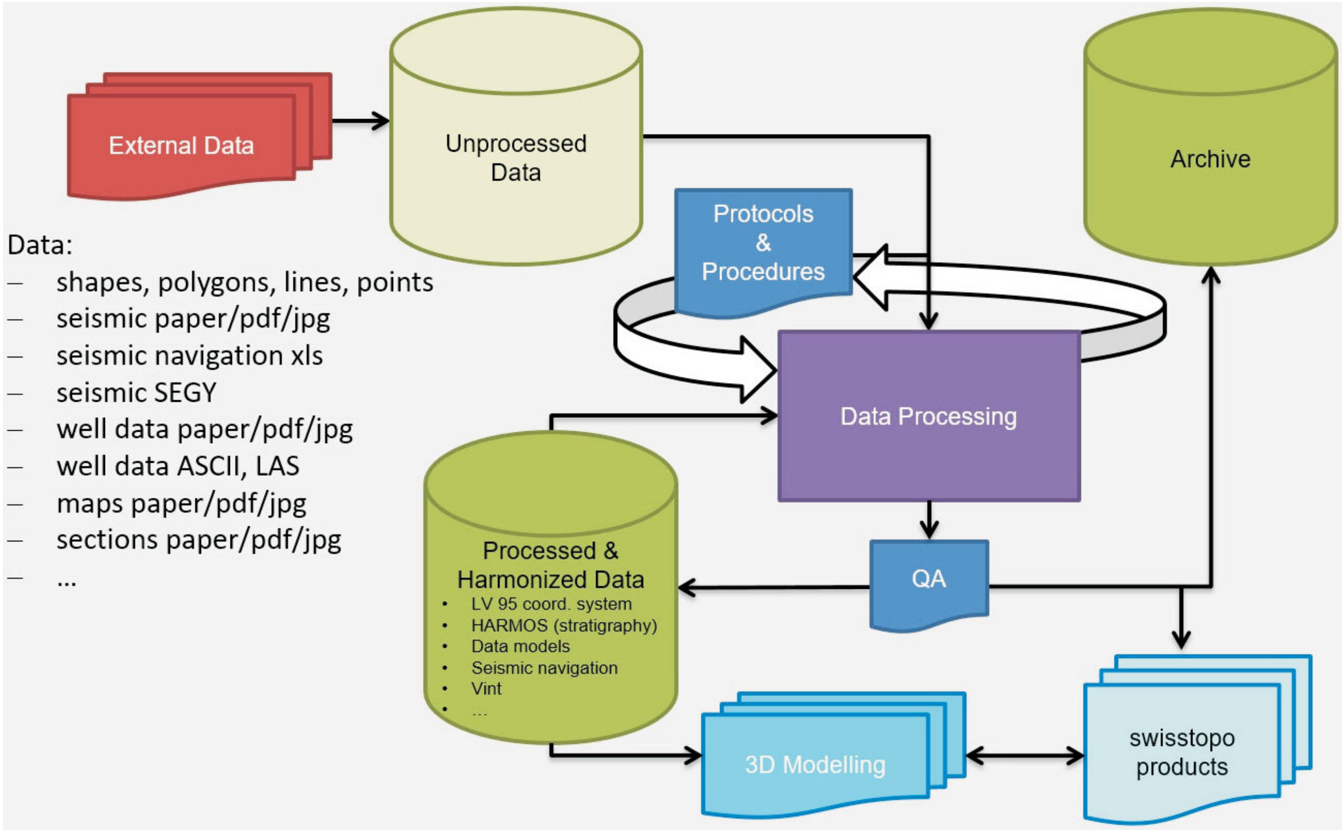

Figure 7. The basic workflow developed for the 3D geological models of the deep subsurface. Much of the data used to complete the models (deep wells, seismic, gravimetry) did not come to use at the SGS prior to 3D modelling. This step forward in digital geology required the development of new protocols, procedures and QA steps.

tion in the model sequentially with four main excavation stages (1988, 1998, 2008, and 2018), leading to a better understanding of large-scale deformation and pore-pressure changes. It also helped to evaluate the influence of topography on the in-situ stress state at rock laboratory level.

Modelling results are shown in Figure 11b, indicating a significant porewater pressure decrease (blue areas around galleries in Figure 11b). Because of the different rock mass deformability, displacement magnitudes are highest within the shaly facies of the Opalinus Clay, intermediate within the sandy facies, and lowest within the overlying and underlying limestone formations. Due to changes in topography, slightly lower vertical stresses are obtained in the southern part of the rock laboratory.

Predictive modelling of the MB-A mine-by test in sandy facies (niche scale): A 10 to 100 m-scale model was elaborated to predict the hydromechanical behavior of the rock mass during a mine-by experiment. The highly instrumented target section is shown in Figure 12. The modelling sequence includes the pre-excavation of the two niches dedicated to instrumentation at the end of the 30 m-long mine-by section, the excavation of 20 m gallery before the mine-by section, a 15-day sequential excavation of a 30 m mine-by section (planned to be carried out in May 2019). We applied two approaches, both using Code_Aster.

First, we used a simple 3D-elastic approach that included anisotropy and heterogeneity of the rock mass. The input parameter set is based on data from Jaeggi and Bossart (2014). Our focus was the highly instrumented target section in the middle of the MB-A tunnel. The results of our model predict overpressures along bedding immediately at the initiation of excavation and a pressure decrease vertical to bedding that results in a long-term pressure decrease parallel to bedding (Figure 13). Modelled pressures at instrumented boreholes rise from 2.0 MPa to 2.8 MPa just before excavation and drop to 1.2 MPa after excavation. Deformation within the rock mass at distances >3 m from the tunnel are in the mm-range, which seems to be reasonable for sandy facies. Modelled tunnel convergences are in the range of 10 mm and are comparable to existing monitoring data.

Second, we applied a two-dimensional approach taking into account Anisotropy, Plasticity and Damage (APD). Results from these 2D APD runs show a reduced plasticity, volumetric dilation-induced pore pressure

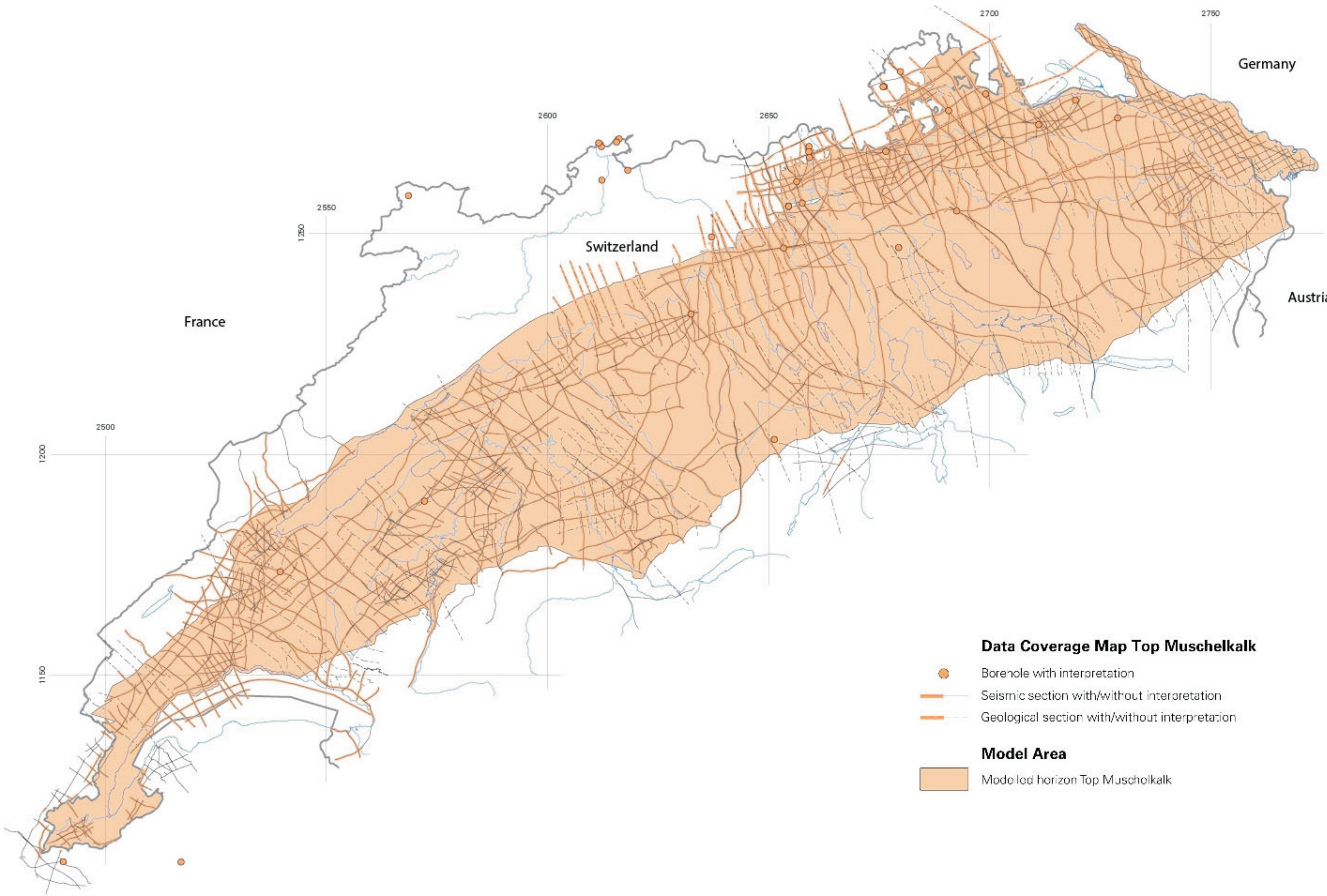

Figure 8. Detail of the Data Coverage Map of GeoMol17's Top Muschelkalk. High densities of seismic lines and deep wells in the NE of the model already indicate that these areas are of a higher certainty than areas lacking comparable input.

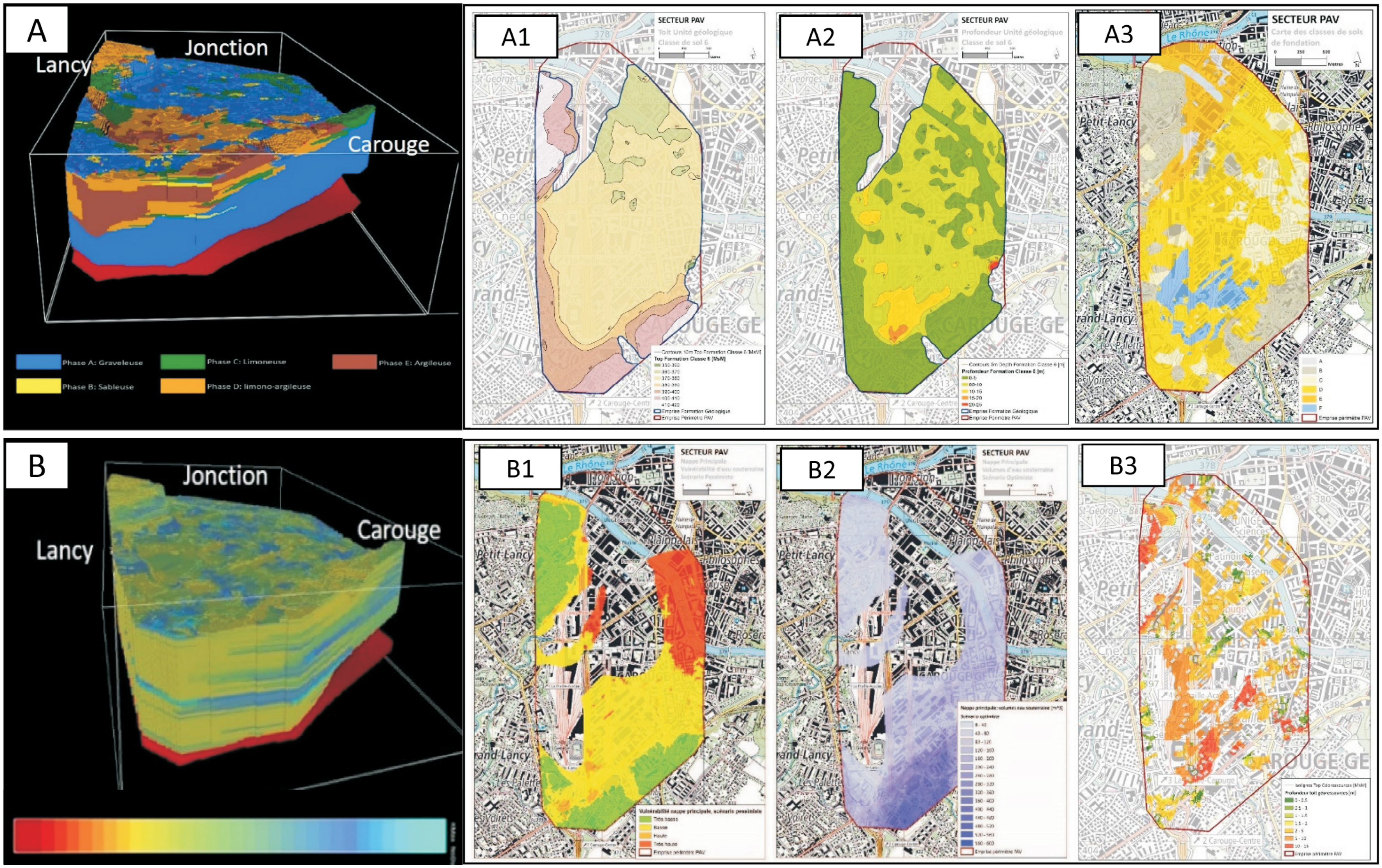

Figure 9. A) Geological model and post-products: A1) formation top map, A2) formation depth map, A3) ground foundation class map B) hydraulic conductivity model and post-products: B1) groundwater vulnerability map, B2) groundwater volume map, B3) mineral resources volume map).

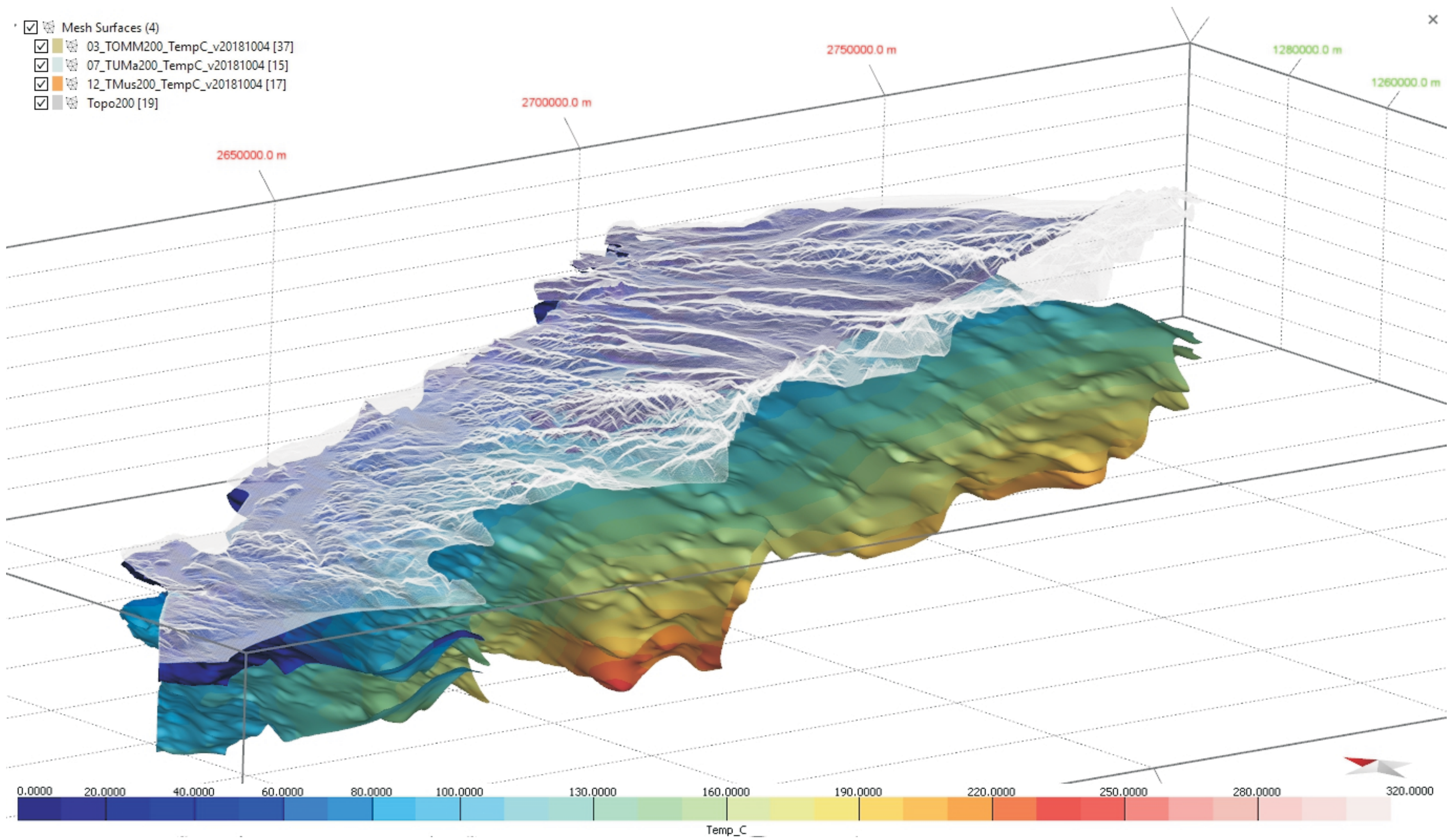

Figure 10. Temperature gradients plotted onto three horizons of GeoMol15. The temperature values are from an earlier temperature model and now merged with the improved GeoMol15 structural model. The top-most translucent layer is the topography, two are Cenozoic and one is Triassic.

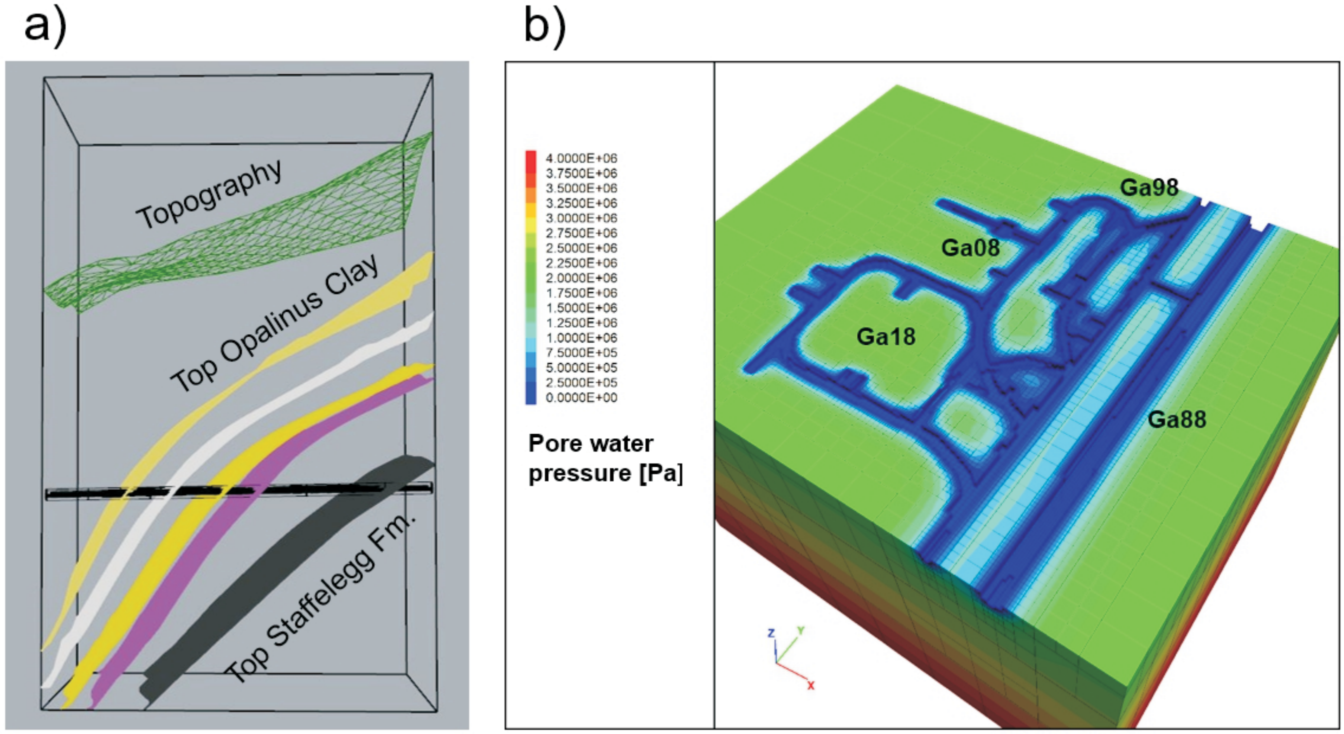

Figure 11. Large-scale modeling of the Mont Terri rock laboratory, a) model geometry including the most important bounding surfaces and the rock laboratory (horizontal black bar), b) pore-pressure distribution at rock lab level 10 years after excavation of Ga18.

with an enhanced hydromechanical effect along bedding (Figure 14). Vertical and lateral displacements are about 20 mm at time step 67.5 days after excavation, which leads to total convergences in the order of 40 mm. At the same time, stress-induced damage extends about 2 m into the rock mass along bedding.

Finally, both model approaches will be calibrated with the effectively measured mechanical and hydraulic measurements, and serve then for more reliable predictions of the rock mass behavior.

Clients

While regulators (permitting, monitoring) and project planners (energy, water, mineral resources, civil engineering) are the primary users of our models, research, commerce and industry also use them models for their purposes. As explained earlier, the SGS is reliant on the cooperation with its clients, as most of them are also data providers at the same time.

Model development mentioned below in the “Jurisdictional-Scale Case Study” section was possible only, due to a very close collaboration between several administrative bodies, research institutes and industry.

The SGS uses the Geosciences in Space and Time (GST) software framework for the publication of the layer cake and block models over the internet. It allows a browser-independent visualization of 3D models without the need of a browser plug-in. GST is based on a three-dimensional data storage, relies on OGC standards and supports several relational database management systems (e.g. Gabriel et al., 2011; Le et al., 2013) and Refer to GeoMol Team (2015) and Landesgeologie (2017) for technical and functional basics.

All the models published are available in a 3D viewer at https://viewer.geomol.ch. There is no direct support by SGS staff for the usage of the models. The website provides multi-lingual access and the data visualization is directly fed by the 3D database. The user can also extract cross-sections, depth slices and virtual boreholes from any location within the layer cake and block models.

Available models can be ordered free of charge in the most common 3D formats (ASCII, DXF, Move and GoCAD) as well as in ESRI (Grid, SHP). Continuing and use of regular updates regarding content (e.g. new parameters), geographical extension or corrections should encourage the continuing usage of the model.

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

The Swiss Plateau (or North Alpine foreland basin in geological terms) is a place of work and residence for more than half the population of Switzerland, thus subjecting the region to intensive land use. On the one

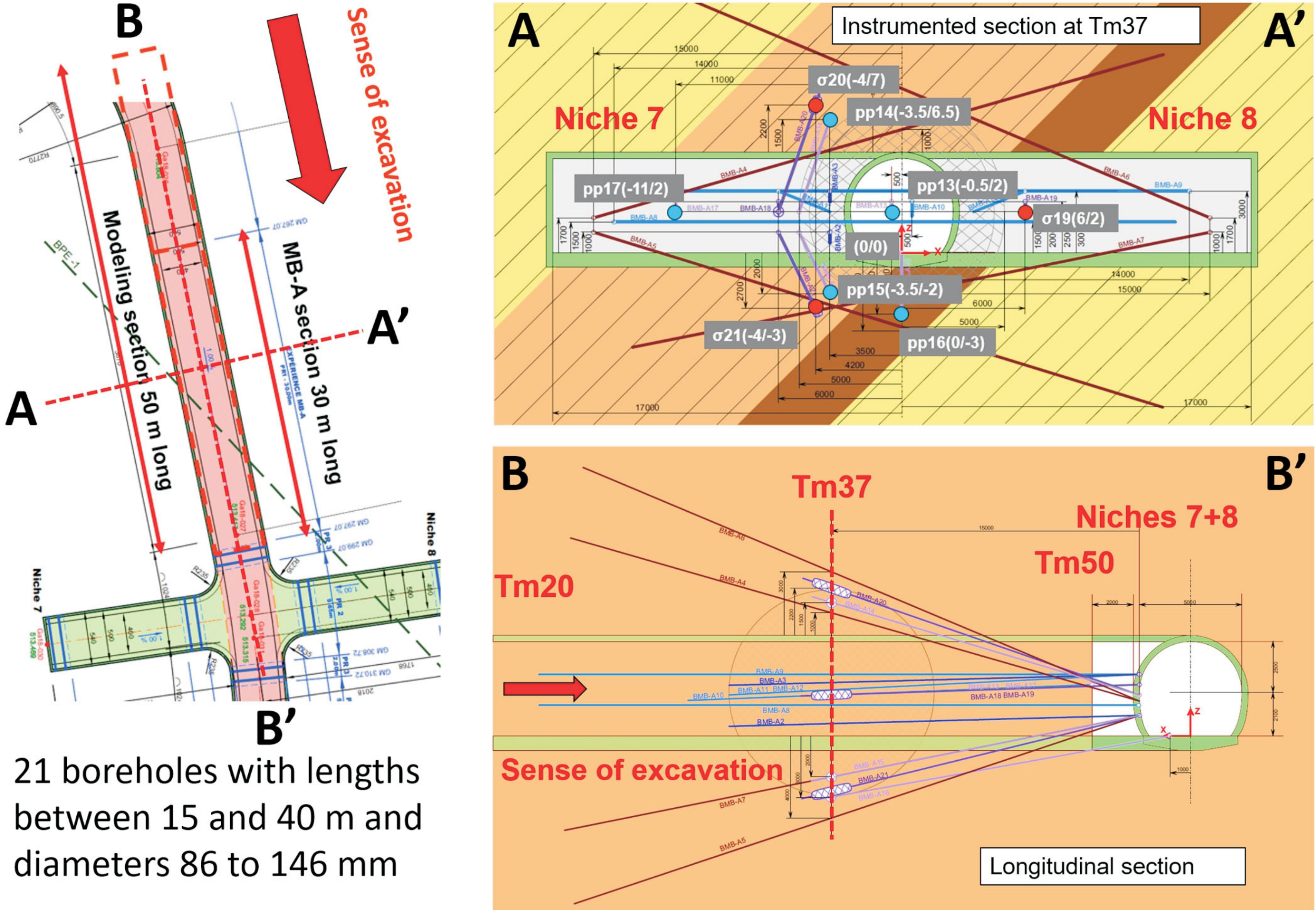

Figure 12. Layout of the MB-A mine-by experiment at Mont Terri rock laboratory. Colors in A-A' section are yellow for shaly facies, reddish for sandy facies, and brown for carbonate-rich sandy facies.

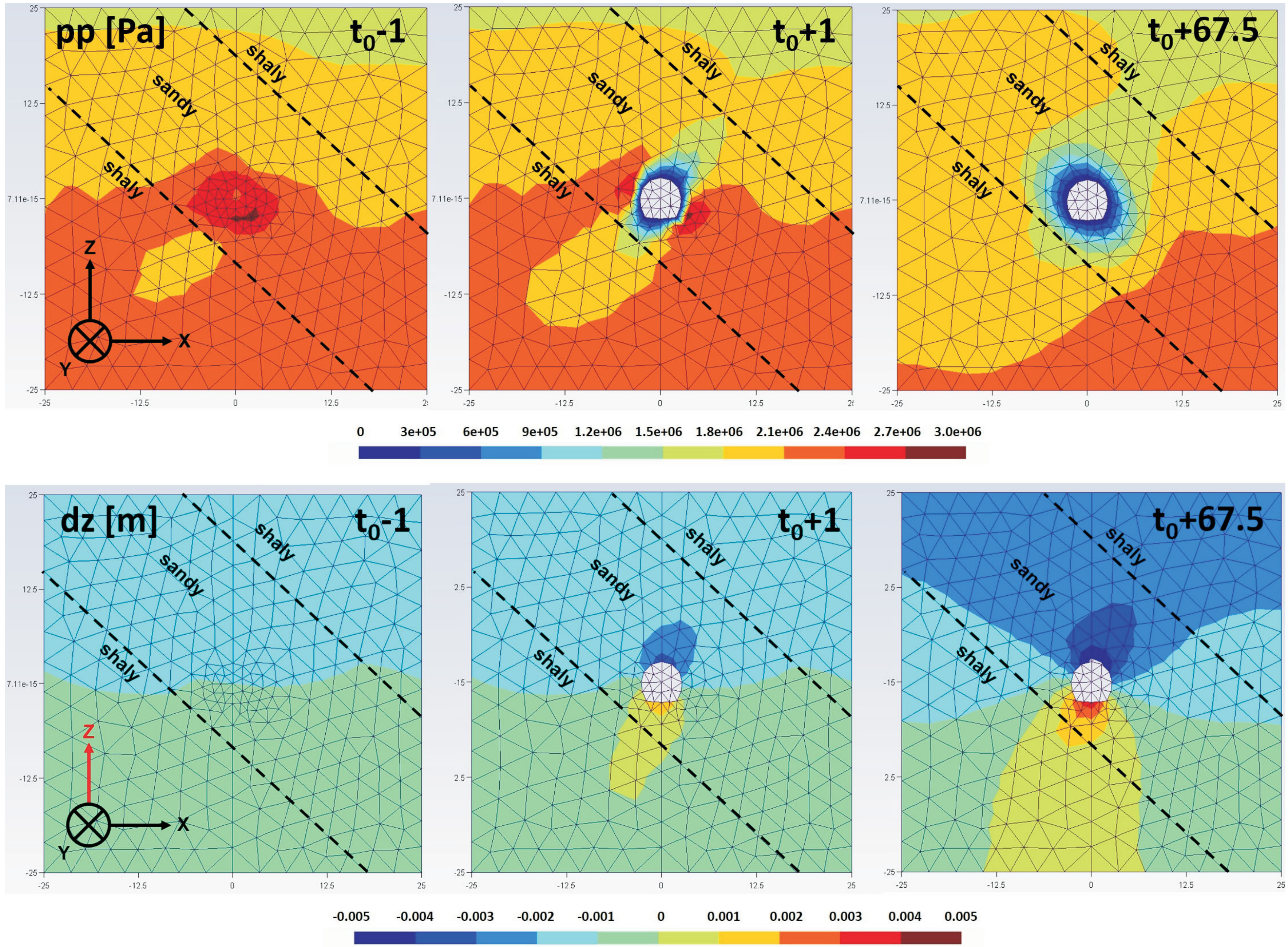

Figure 13. 3D elastic – pore pressure distribution (pp) and vertical displacement (dz) at TM37, just before excavation (t0 - 1), just after excavation (t0 + 1) and 67.5 days after excavation (t0 + 67.5).

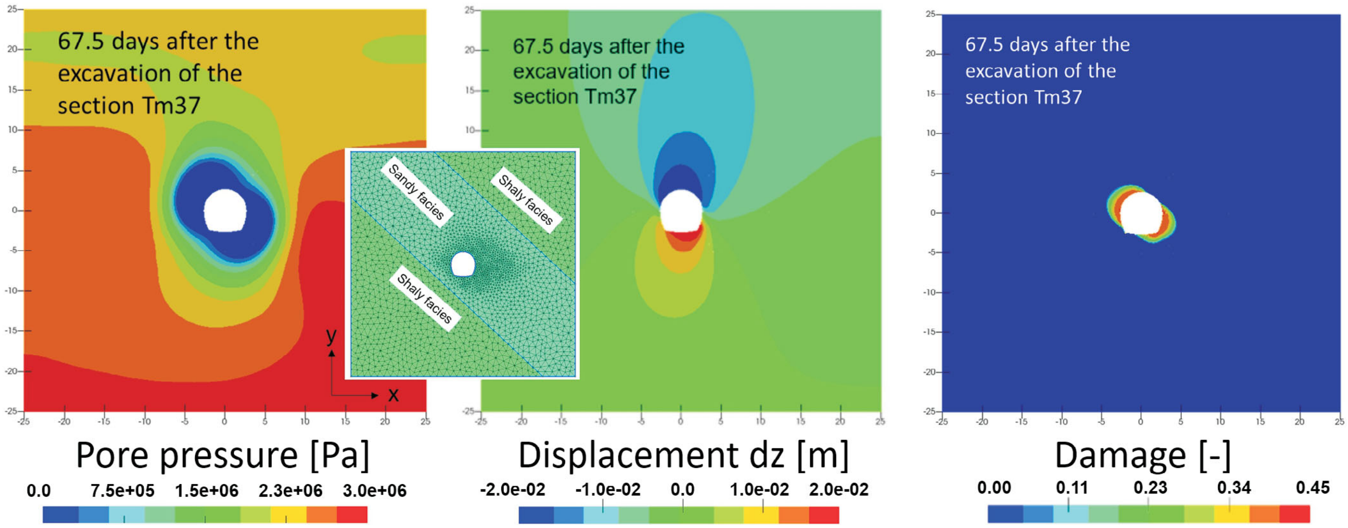

Figure 14. 2D APD (anisotropic plasticity coupled with damage) – pore pressure distribution, displacement and damage at TM37, 67.5 days after excavation.

hand, there is a high demand for resources such as rocks and soils as well as groundwater and geothermal energy. On the other hand, those responsible for private and public infrastructure (public transport, roads, geoenergy) are increasingly involved in planning in the same areas. The development of these geopotentials and the sustainable management of the finite resource of subsurface space has social, political, economic and geoscientific relevance.

A low-resolution 3D geological model of the Swiss Molasse Basin (GeoMol 15) was produced as part of the project "GeoMol – Assessing subsurface potentials of the Alpine Foreland Basins for sustainable planning and use of natural resources" (2012 – 2015), within the framework of the EU's "INTERREG IV B Alpine Space" program (GeoMol Team, 2015. Recently the SGS produced a more detailed 3D geological model (GeoMol 17) of the same region in a separate sub-project (Landesgeologie, 2017). The results of GeoMol denote the first steps in systematically describing and visualizing Switzerland's subsurface. For the first time ever in Switzerland, the SGS published a jurisdictional-scale 3D geological model that is available at no costs and accessible to the wider public. The GeoMol project thus makes an active contribution to the sustainable management of the subsurface.

Current Challenges

Several years ago, the SGS recognized the necessity of developing 3D modelling expertise as well as fundamentals in managing geological data in the digital age. This eventually led to the formation of a small modelling group made up of earth scientists with various backgrounds. Over the last five years, this group has evolved into a highly specialized team, which produced several 3D geological models. Following these successes, we will address challenges related to technological, work force, financial, and conceptual issues.

- Organization: The form of government (federal administration plus 26 cantons), the absence of a nationwide legislation regarding the subsurface, the necessity to generally coordinate activities between all these independent, but however interdependent institutions, the partly unwillingness to share (meta-)data (even to a minimum extent) of the right owners and the (partly) not up-to-date understanding of current and future challenges regarding the subsurface impede jurisdiction wide, coordinated and effective modelling activities.
- Bureaucracy: A constantly increasing number of regulatory requirements in legal, financial, technological and organizational terms at the federal level hinder and endanger the forward-looking and real-time development of adequate frameworks for future activities.
- Technology: Technology continuously advances and directly challenges the way 3D geological models are developed, stored and published.
- Work force: According to political requirements, federal staff (incl. SGS) is limited, with new staff only available exceptionally or if funded by third parties. Therefore, the SGS contracts out parts of its modelling activities and collaborates with partners from the administration, industry and academia to push forward the Swiss 3D geological mapping program.
- Finances: Service-related finances have not been the limiting factor over the past few years. However, budget cuts may strike at any time. As any other governmental organization unit, the SGS follows the annual budgetary cycles, which

- hinders on reliable and much requested forward planning.
- Concepts: New data and modelling approaches require an adaptation of methodologies, workflows and, consequently, of modelling concepts. As this topic is complex as well as time consuming, it probably does not receive the attention it deserves.

Building Information Modelling (BIM): Additional challenges and opportunities will arise with the advance of BIM into applied earth sciences. In Switzerland, efforts to combine BIM with subsurface models began in 2016 and have continued since. In a joint research project between the SGS, the Swiss Cadastral Survey and the University of Applied Sciences of Geneva, the partners investigated the mutual dependencies of both approaches in a detailed 3D subsurface model of the city of Geneva (Figure 15). It became evident that the integration of geological data and models into the BIM process requires a high degree of standardization.

Model updates: Further challenges arise when attempting to combine 3D geological models of different resolutions. An excellent case study is the regional scale GeoMol 17 model, which is being updated by integrating a local-scale 3D geological model originating from a 3D seismic survey (Figure 16). Different resolutions and concepts converge in this type of update and have to be adjusted in order to fit together. The SGS will be confronted with this type of update as the Swiss Confederation is subsidizing subsurface exploration in order to realize the requirements set for renewable energies. Data gained from these exploration campaigns will be made available to the federation and allow the SGS to continue updating the GeoMol models with modern data.

Lessons Learned

To date, Private-Public-Partnerships (PPP) between regulators, industry and academia form the foundation for all the models produced by the SGS.

The essential lessons learned are:

- The regular discussion and exchange with an independent review board is highly recommended. First, the modelling team retrieves external advice on its

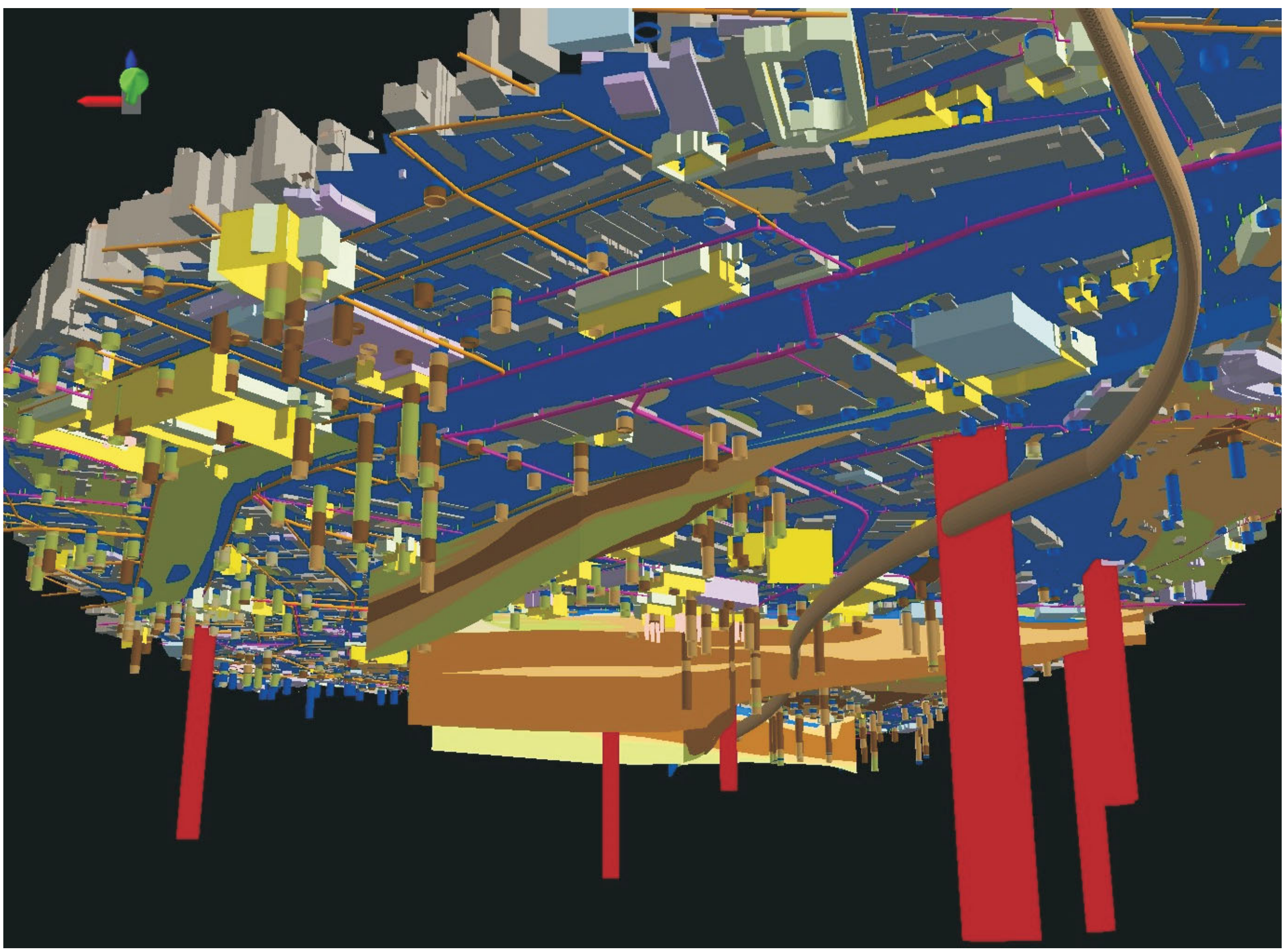

Figure 15. 3D view of building information and geological data within the Geneva model perimeter.

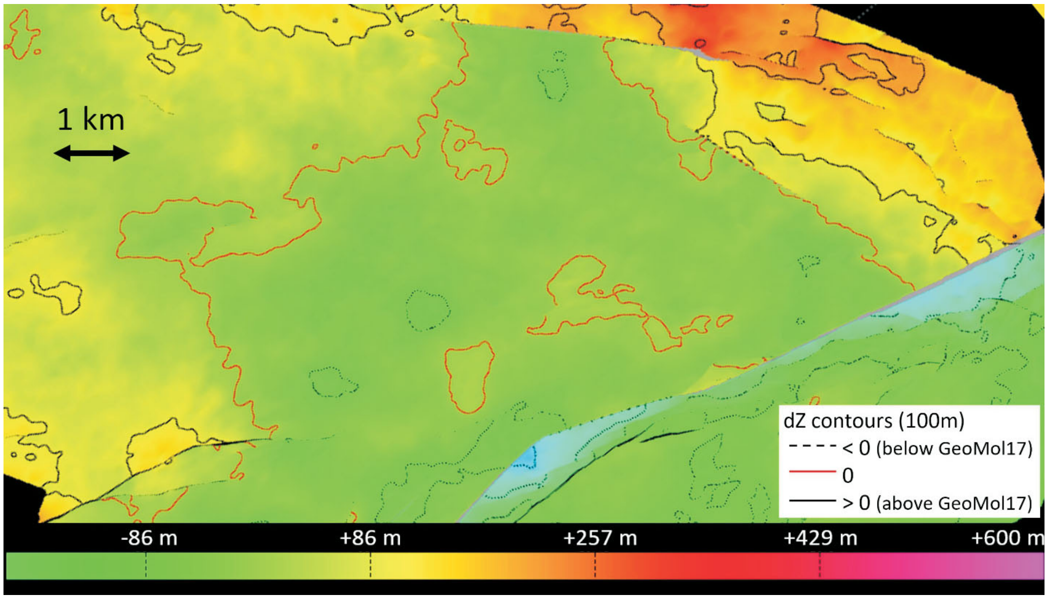

Figure 16. Grid depicting the difference in depth between a Triassic horizon from GeoMol17 model and its equivalent from a high-resolution model based on a 3D seismic survey. Towards the top-right, the seismic signal deteriorates within the 3D survey, probably contributing to the difference between the grids. Other discrepancy sources are, of course, the velocity models and poor data areas between faults (blue area).

modelling work and products. Second, it required to formulate and present its knowledge, progress and technical approach on a regular basis. Third, the team can establish a network and personal contacts with the experts.

- Data management must be a mandatory part of the project organization. Data acquisition, harmonization and storage is very time consuming and must be either part of the project work in close collaboration with the data management team or be done by the data management team itself. A retroactive pushback of project data is usually out of scope of the data-management-team capabilities and out of interest of the project team.

Regarding a PPP, the SGS emphasizes the following lessons learned:

- The collaboration between different project partners is an opportunity (e.g. exchange of knowledge and methodologies) and a challenge (e.g. the coordination of different approaches regarding time and methods) at the same time.
- The usage of different software packages may result in difficulties when it comes to data exchange. Overcoming these difficulties is possible by using the same data formats and attributes.
- The choice of methodology may cause problems when it comes to merging parts of the models.
- Contracts need to be unambiguous in terms of ownership, intellectual property, timelines, milestones, form and formats of the deliverables and input data required.
- The work of the project partners needs to be coordinated in terms of timelines, stratigraphy and methodologies.

Next Steps

Models of the unconsolidated and consolidated sediments: The next big step is devoted to the validation of the geostatistical and explicit models of the SGS. The goal is not only to establish milestones for quality control along the modelling workflow, but also to define minimum and advanced requirements and parameters for quality assessment.

Regarding numerical modelling, the SGS began with simple hydro-mechanical models and applied these with different codes. One of the codes (ASTER) was further developed to treat APD cases to consider Anisotropy, Plasticity, and Damage. Together with our specialist network, our combined knowledge is on such a level that we can extend our skills to cover further processes, and even to enter new modelling fields such as:

- incorporating reactive transport into the flow and transport processes,
- modelling heat transport in the framework of the Swiss Energy Strategy 2050, and
- modelling CO_2 hydro-mechanical processes in relation of caprock integrity (claystones).

Scale is important for all these subjects. We will start at a course scale (GeoMol) and refine the heterogeneity and processes down to the small scale. Private companies can then also use these models.

The work on BIM will continue. A joint collaboration between the SGS, the professional association of Swiss geologist CHGeol and the University of Applied Sciences of North-Western Switzerland FHNW aims at implementing BIM and geology in a applied research project starting in 2020.

In early 2018, the SGS started a national 3D geological mapping program, called the "National Geological Model" (NGM). For the next eight years, the SGS envisages a comprehensive coverage of entire Switzerland with integrated, harmonized and multi-dimensional geological data in different resolutions. To achieve that goal, all production activities from maps to models will be synchronized with respect to methodologies and data description based on data models. Besides that, the SGS complements the existing modelling activities mentioned above (mainly in the Swiss Midlands) with 3D models also covering the Jura Mountains and the Swiss Alps. These models will be data driven, i.e. only existing data will be used for their development (e.g. maps, sections, boreholes, seismics).

After having achieved a high level of performance and knowledge in 3D geological modelling during the past few years, the NGM also serves to shift the focus from data production to integrated data dissemination and utilization. Therefore, and in parallel to data production, an internet-based 3D viewer available to the public will be established that allows the visualization, analysis and processing of geological data of different sources. Online geological 3D modelling is under consideration and remains reserved. For our organization, three-dimensional models will be the enablers and drivers of the digital transformation. Maps and models will still be our main activities. However, in the near future, data-driven or IT services requested by our partners based on both these products will catch up with them in terms of importance for SGS. Therefore, the SGS actively advances the transition from "maps to models to services".

References

Gabriel, P., J. Gietzel, H.H. Le and H. Schaeben. 2011. A network based datastore for geoscience data and its implementation. – Proc. 31st Gocad Meet., Nancy.

GeoMol Team (2015): GeoMol – Assessing subsurface potentials of the Alpine Foreland Basins for sustainable planning and use of natural resources. – Proj. Rep., Bayer. Landesamt f. Umwelt.

Landesgeologie (2017): GeoMol: Geologisches 3D-Modell des Schweizer Molassebeckens – Schlussbericht. – Berichte der Landesgeologie 10, 128 p.

Le, H. H., P. Gabriel, J. Gietzel and H. Schaeben. 2013. An objectrelational spatio-temporal geoscience data model. – Computer & Geosci. 57, 104 –117.

Parisio F., V. Vilarrasa and L. Laloui. 2018. Hydro-mechanical Modeling of Tunnel Excavation in Anisotropic Shale with Coupled Damage-Plasticity and Micro-dilatant Regularization: Rock Mechanics and Rock Engineering, Special Issue, 12/2018: Selected Contributions from the 51st US Rock Mechanics/Geomechanics Symposium Held in San Francisco, California from 25 to 28 June, 2017.

Pfiffner, O.A. 2008. Kleine Geologie der Schweiz. – Nagra Arbeitsbericht NAB 07-33 – 50p., Nationale Genossenschaft für die Lagerung radioaktiver Abfälle, Wettingen (CH).