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Characterization of Subsurface Heat-Transport Processes in the Canton of Aargau Using an Integrative Workflow

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ABSTRACT

In a referendum in May 2017, Switzerland decided to phase out nuclear power in favor of further developing renewable energy sources. One of these energy sources is geothermal energy, which, as a base-load technology, fills a niche complementary to solar and wind energy. A known surface-heat-flow anomaly exists in the Canton of Aargau in Northern Switzerland. With measured specific heat-flow values of up to 140 mW m^{-2}, it is an area of interest for deep geothermal energy exploration. In a pilot study, which started in late 2018, we want to characterize the heat-flow distribution in the vicinity of the anomaly in more detail to facilitate future assessment of the geothermal potential of this region. To achieve a complete characterization of the heat-flow values as well as their spatial uncertainty, we develop a workflow comprising: (i) assimilation and homogenization of different types of geologic data, (ii) development of a geological model with focus on heat transport, and (iii) numerical simulations of the dominant heat-transport processes. Due to its nature as a pilot study, the developed workflow needs to be integrative and adaptable. This means that data generated during the course of the project can easily be integrated in the modeling and simulation process, and that the generated workflow should easily be adaptable to other regions for potential future studies. One further goal of this project is that the generated models and simulations provide insights into the nature of the heat-flow anomaly in Northern Switzerland and to test the hypothesis that upward migration of deep geothermal fluids along structural pathways is the origin of this particular heat-flow anomaly.

1. INTRODUCTION

Part of the Swiss Energy Strategy 2050 (Swiss Federal Office of Energy, 2019) is that around 4'400 GWh per year of electricity should be provided by deep geothermal installations (Weber, 2018). In Northern Switzerland, surface heat fluxes can reach up to 140 mW m^{-2}, significantly higher than the Swiss average (Medici and Rybach, 1995).

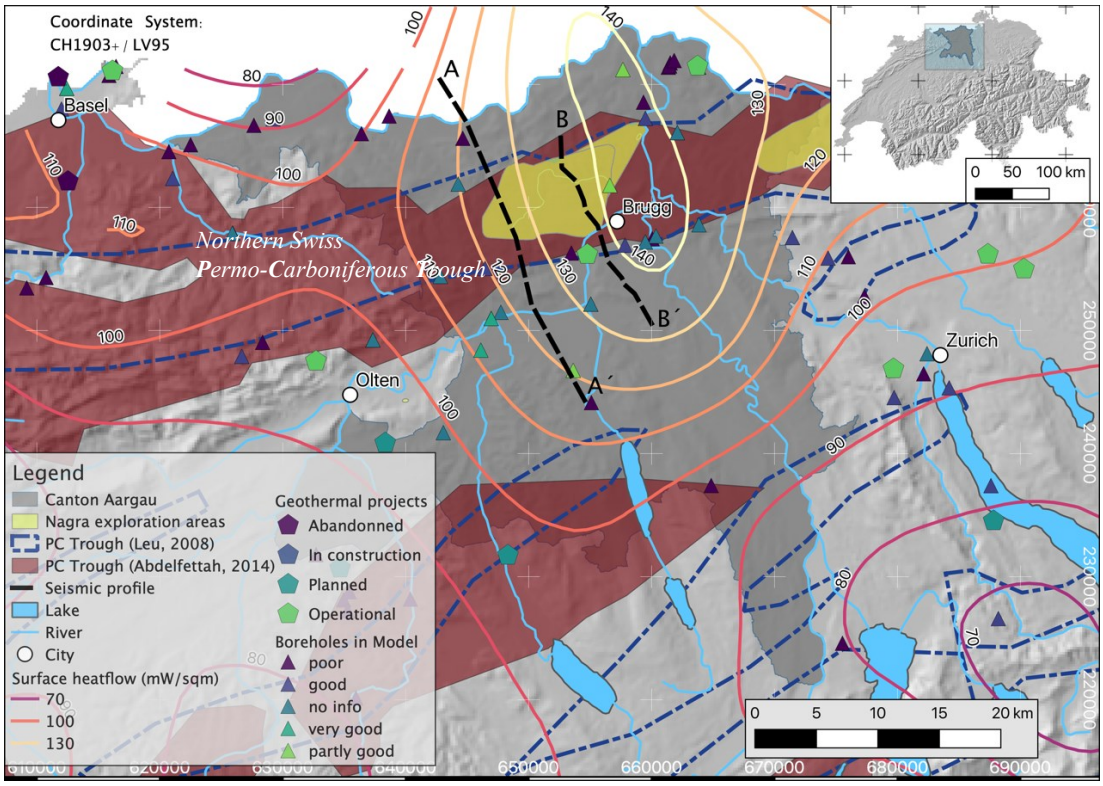

Figure 1: Our map of the project area in the Canton Aargau. Relevant boreholes in the area are colored by their data quality, based on the classification of Schärli and Kohl (2002). Permo-Carboniferous troughs are outlined in blue, based on Leu (2008), and shaded in red based on Abdelfettah (2014). The heat-flow contours are based on Medici and Rybach (1995).

Geothermal gradients in Northern Switzerland varied during its geological evolution since the Carboniferous. Mazurek et al. (2006) reconstructed the thermal history of the sedimentary basin systems in Northern Switzerland, based on apatite fission-track and vitrinite reflectance data. They found that, with high geothermal gradients (80 K km^{-1} to 100 K km^{-1}) in the Permo-Carboniferous strike-slip basin, geothermal gradients generally decreased to less than 20 K km^{-1} in the Paleocene. Further, recent geothermal gradients are elevated in the top 2500 m (32 K km^{-1} to 47 K km^{-1}), due to a Quaternary increase of heat flow. They conclude that this increase in heat flow, which is also shown in earlier surface heat flow data (Medici and Rybach, 1995) may be caused by advective heat transport along Paleozoic faults in the crystalline basement. These are most likely normal faults bounding the so-called Permo-Carboniferous trough(s) of which all besides the major, northernmost one (see Fig. 1), are merely presumed to exist (Leu, 2008; Naef and Madritsch, 2014). Based on gravity forward modelling, Abdelfettah et al. (2014) presented an updated geometry of the Permo-Carboniferous Trough (see Fig. 1, red polygons). In the area of the Canton of Aargau, their trough geometry generally agrees with a previous interpretation by Leu (2008) (dashed, blue line in Fig. 1). More to the west, however, the interpretation by Abdelfettah et al. (2014) differs significantly, as here the main trough splits into two trough systems. It should be noted, that the trough geometries presented in Figure 1 are described as “deep basin, 1 – 3 km thickness” in Abdelfettah et al. (2014).

For assessing origin of the heat flow anomaly in northern Switzerland, Rybach et al. (1987) tested multiple hypotheses, such as a cooling magma body, local uplift, strong petrophysical contrasts, or ascending deep waters. They conclude that only ascending deep waters can explain the phenomenon while honoring the available data. There may, however, be different explanations for the high surface heat fluxes; for instance, that two topographically driven flow regimes, southward from the Black Forest, and northward through the Mesozoic Molasse, meet in Northern Switzerland, creating the heat-flow anomaly. These could potentially form a surface-heat-flow anomaly, which would not be bound to fluids ascending along faults in the crystalline basement. Part of this project is to test these hypotheses, concerning different groundwater flow systems causing a heat-flow anomaly in the Canton Aargau (Fig. 1) by using numerical modelling. The project aims at producing model-based maps of the deep heat flow in the area as one project outcome. These maps will comprise average heat-flow values, as well as their uncertainty. This is achieved by combining (geometrical) uncertainty of geological 3D models with (parametric) uncertainty of numerical heat-transport models in a Bayesian framework (de la Varga et al., 2016; Schneeberger et al., 2017; Wellmann and Caumon, 2018).

In the following, we will describe the geological setting of the study area in more detail, and present the overall modelling workflow applied in this study.

2. GEOLOGICAL SETTING

The oldest lithological units in Northern Switzerland are grouped under the term crystalline basement. These units were strongly affected by metamorphic and structural overprinting during the variscan orogeny. Following events did not impact the structure and lithology of the basement significantly (Thury et al., 1994). Only later, in the Tertiary, the basement was affected by the development of the Upper Rhine Graben, the folding of the Jura and up-doming of the Black Forest. During the late variscan orogeny, however, the aforementioned Permo-Carboniferous trough developed in Northern Switzerland (see Figure 2). Sedimentary sequences, filling the trough, were first described by Matter (1987), who classified the lithostratigraphic series, based on core samples from four wells. These series can be categorized in three major units: (i) late Carboniferous cyclic series; (ii) early Permian fluviatile and lacustrine series; (iii) late Permian alluvial series (Naef and Madritsch, 2014).

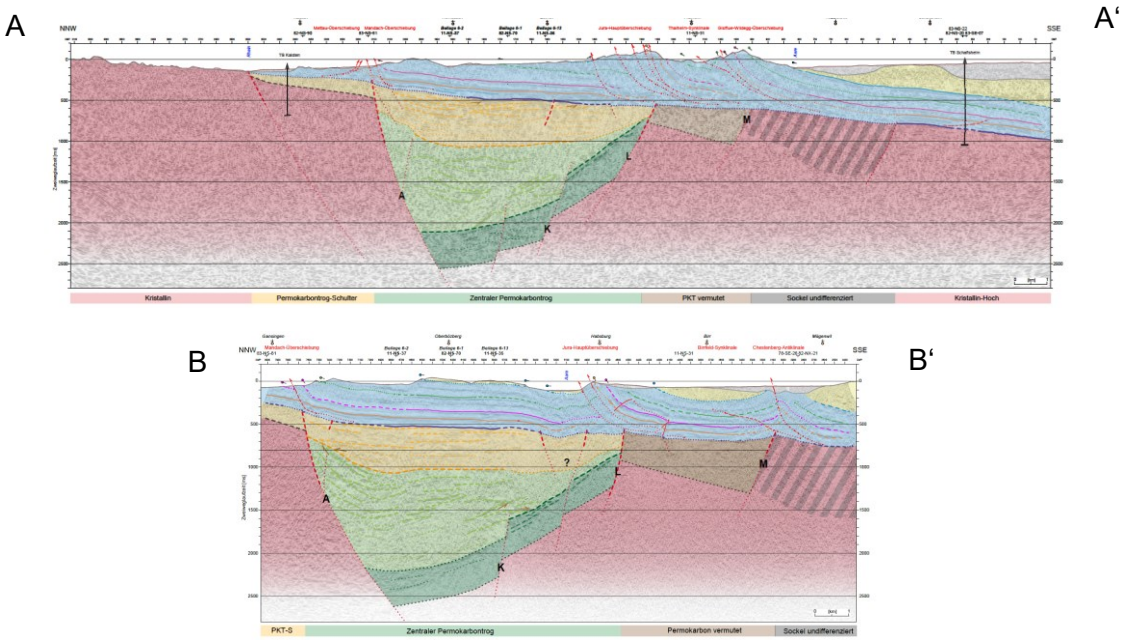

Figure 2: Geological profiles, showing an interpretation along the reflection-seismic lines 82-NF-10 (top) and 11-NS-06 (bottom) (after Naef and Madritsch, 2014). The seismic line locations are indicated in Fig. 1.

While unit (iii) was cored in all studied wells, the deeper units (i) and (ii) were only encountered in one and two wells, respectively. Overall, the classified lithofacies reflect the paleo-climatic transition from a seasonally humid, in the Carboniferous and early Permian, to a more arid climatic environment in the middle and late Permian (Naef and Madritsch, 2014). Mesozoic facies in Northern Switzerland mainly comprise marine and evaporitic sequences, which partly form the basal décollement of the folded Jura (Laubscher,

1961, 1973, 1997; Sommaruga, 1999; Sommaruga et al., 2017), one of two structural regions in the Alpine foreland. The other region is the Molasse Basin (here we only look at the Plateau Molasse), which comprises Cenozoic sediments overlying Mesozoic sequences. The lithologies of the Molasse Basin can be divided into four major stratigraphic units which reflect shallow marine to fluviatile-continental sedimentary settings (Pfiffner et al., 1997).

3. MODELING WORKFLOW

One component of this project is to develop an integrative, adaptive, and reproducible workflow which comprises four major steps (Fig. 3). Data preparation is the initial step of the workflow. This step comprises a multitude of tasks, however, not all available data for a region are equally usable. For instance, in addition to available digital data, multiple sources of legacy data exist, and multiple sources, be they digital or analogue, often adhere to different data standards or nomenclatures. Homogenization and standardization of data is thus one essential task in the first step of this project. We follow the approach of Strasky et al. (2016), who developed a lithostratigraphic lexicon of Switzerland, with the aim of harmonizing the existing lithostratigraphic nomenclature. Many different approaches exist for data handling in the geosciences, as, for example, shown in a special issue in GeoResJ (Wyborn et al., 2015). A classic approach in data-based geological model building is sequential, meaning a geological model is iteratively improved by implementing new data, once it is available. Corbel and Wellmann (2015) propose a different, hypothesis-based approach. In their method, an iteratively built geological model does not necessarily have to fit single data points, but it is also used to test data. Their approach enables a modeler to distinguish between (model-)consistent data and (for the model) unusable data.

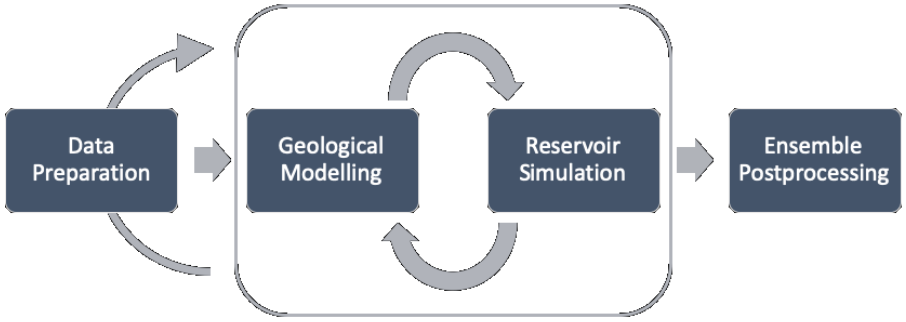

Figure 3: Simplified depiction of the intended project workflow, based on four major steps.

Steps two and three, namely "Geological Modelling" and "Reservoir Simulation", are an iterative process, where a suite of different geological model hypotheses are evaluated by numerical simulation of heat- and mass-transport in the geological model. A modelling workflow, which will be set up for different hypotheses, is shown in Figure 4. Starting from a conceptual geological model (i.e. a hypothesis), a 3D geological model is generated in an implicit modelling framework, described in Section 3.1. The geological model is discretized and implemented in a simulation framework, presented in Section 3.2, to yield a numerical reservoir model. If the reservoir simulation can be calibrated to existing, consistent temperature and heat-flow data, the numerical reservoir model and simulation parameters will be stored. The parameters will then be changed within their probability range, and a new iteration is started.

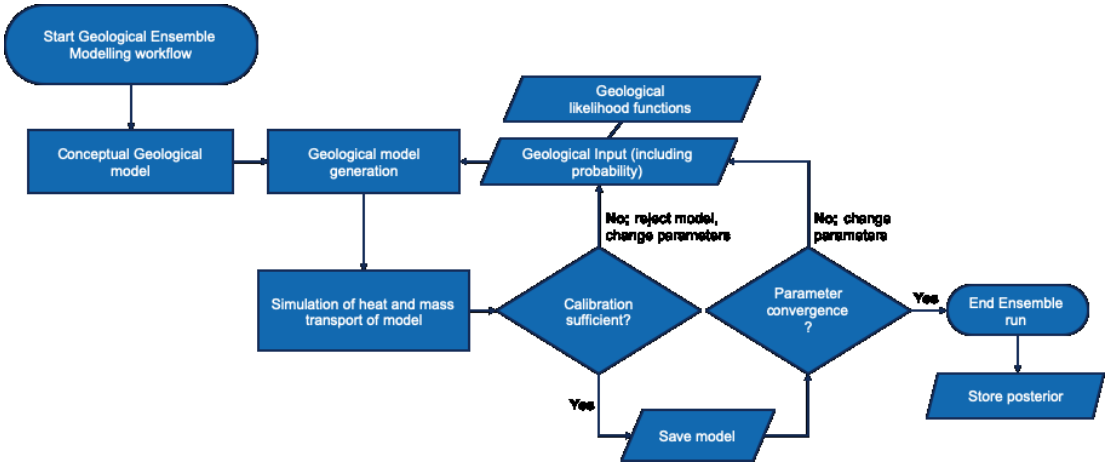

Figure 4: Planned modelling workflow, applied in this study to yield a posterior ensemble of possible geological models with corresponding ranges of expected petrophysical parameters.

Once a parameter convergence is reached, the saved set of reservoir models are evaluated in the fourth step of the project workflow, called "Ensemble Postprocessing". Having a conditioned ensemble of models fitting measured data has multiple advantages over the classical single, iteratively refined model. For instance, ensembles, based on different underlying hypotheses, can be evaluated more easily in terms of their spatial uncertainty. Further, subsurface temperatures, assessed by a model ensemble, provide an interval of expected temperatures, compared to a single, average temperature value at a certain depth. Such information is valuable for geothermal development projects.

3.1 Geological modelling approach

For modelling the spatial geometry of geological structures and lithologies, we use an implicit potential-field approach (Lajaunie et al., 1997; Wellmann & Caumon, 2018), implemented in the open-source software GemPy (de la Varga et al., 2019). In this approach, geological interfaces are treated as equipotential surfaces of a potential field, whose shape is determined by cokriging between data points in space, which are associated with a certain gradient of the potential field. The geological analogue to these data points and gradients are, for example, contact points between lithostratigraphic units and their orientation in space, respectively. Other features of a geological model, such as faults, are modelled similarly, but considered as discontinuous drift functions in the cokriging algorithm (de la Varga et al., 2019). In Figure 5, we show exemplarily the two input data types, interface points (colored circles) and orientation points (black arrow heads), and the resulting discretized 2D model of a Permo-Carboniferous trough, based on seismic interpretations by Naef and Madritsch (2014).

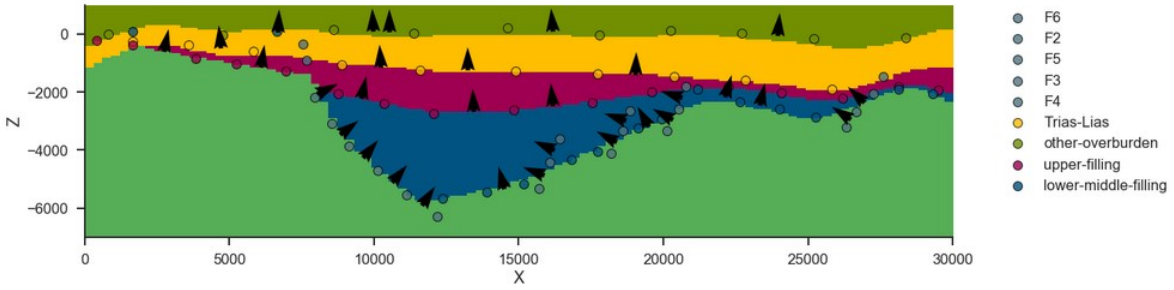

Figure 5: First iteration of a 2D geological model based on the interpretation of seismic line 11-NS-06 (Fig. 2 bottom) by Naef and Madritsch (2014). Key features, such as the major graben fault (marked with A in Fig. 2 bottom), can easily be modelled, while other features are more difficult (e.g. unconformities or strong folding). The plotted circles are the interface points, colored by lithological unit. F2 to F6 in the legend represent interface points of the five different faults in this model. The black arrow heads mark implemented orientations, with the head pointing orthogonal to the dip.

In addition to the basic 3D-modelling capabilities of GemPy, it provides straight-forward functionalities for stochastic modelling in a Bayesian framework. This is an important feature, as it enables the modeler to constrain a variety of possible model realizations, which exist due to uncertain input data, based on existing geological knowledge (see Figure 4). For instance, the probability of characteristics of geological features, such as a fault dip, can be conditioned, based on the modeler's experience. Thus, this modelling approach honors uncertainty in input data, while also considering geological knowledge (as likelihood functions), yielding a conditioned probability distribution of geological models.

3.2 Modelling fluid mass and heat transfer

The results of the geological modelling process, i.e. the geological structures, are transferred to a framework for simulating fluid mass and heat transfer. We chose the MOOSE framework (Gaston et al., 2009) as simulation framework, as it (a) is licensed as an open-source software, (b) provides flexible usability, and (c) is highly parallelized, using PETSc (Balay et al., 2019). While (b) and (c) are preferable for more complex numerical models of geothermal reservoirs, (a) is a precondition for an easily reproducible and open workflow. MOOSE provides a porous flow module which comprises all necessary governing equations for simulating fluid mass and heat transport in a geothermal reservoir system. Figure 6 shows a preliminary, purely conductive, heat-transport simulation of the geological model shown in Figure 5.

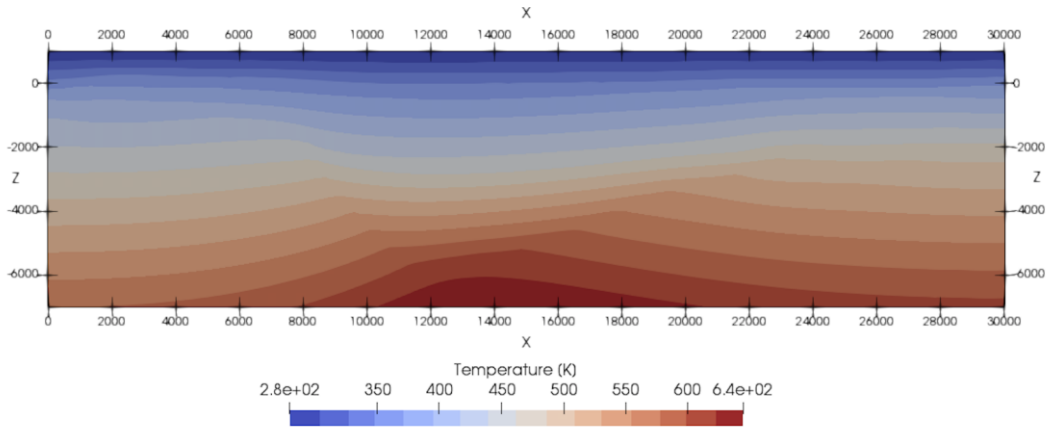

Figure 6: First, preliminary, purely conductive temperature field of the modeled geological cross-section. The shape of the graben system can be inferred, due to the different thermal conductivities of the lithological units.

The shape of the graben structure can be seen in the temperature field, due to the different thermal conductivities of the graben-filling sediments and the crystalline basement rocks. As bottom boundary conditions, we applied a specific heat flux of 135 mW m^{-2}, which reflects the average value expected along this profile, based on the map by Medici and Rybach (1995), as can be seen in Figure 1.

The top mean annual surface air boundary condition is set to 5.5 °C, approximately the 40-year average (1980-2019) mean annual temperature in northern Switzerland.

4. OUTLOOK

With its nature as a pilot study, the methods developed and implemented in this project, should be flexible and integrative, such that they can easily be adapted to other, similar projects in the future, for instance in other Cantons of Switzerland. Existing geological models, such as GeoMol (GeoMol Team, 2015), will be considered and merged with the model hypotheses in the presented modelling workflow. With similar studies in the future, this could potentially contribute to a nationwide model-based representation of the subsurface. The generated models and simulations in this project may provide insights into the nature of the heat flow anomaly in Northern Switzerland and test the hypothesis that upward migration of deep geothermal fluids, along structural pathways, is the origin of this particular heat flow anomaly. Further, model-based maps of the deep geothermal heat flow in the project area will be publicly available and of use for potential geothermal development projects in the region.

REFERENCES

Abdelfettah, Y., Schill, E., Kuhn, P.: Characterization of geothermally relevant structures at the top of crystalline basement in Switzerland by filters and gravity forward modelling. Geophysical Journal International, **199** (1), (2014), 226–241.

Balay, S., Abhyankar, S., Adams, M., Brown, J., Brune, P., Buschelman, K., … MAY, D.: PETSc Users Manual. Argonne National Laboratory, (2019).

Corbel, S., and Wellmann, J. F.: Framework for multiple hypothesis testing improves the use of legacy data in structural geological modeling. GeoResJ, **6**, (2015), 202-212.

Gaston, D., Newman, C., Hansen, G., and Lebrun-Grandie, D.: MOOSE: A parallel computational framework for coupled systems of nonlinear equations. Nuclear Engineering and Design, **239**(10), (2009), 1768-1778.

GeoMol Team (2015): GeoMol – Assessing subsurface potentials of the Alpine Foreland Basins for sustainable planning and use of natural resources – Project Report, 188 pp. (Augsburg, LfU).

Lajaunie, C., Courrioux, G., and Manuel, L.: Foliation fields and 3D cartography in geology: principles of a method based on potential interpolation. Mathematical Geology, **29**(4), (1997), 571-584.

Laubscher, H. P.: Die Fernschubhypothese der Jurafaltung. Eclogae Geologicae Helvetiae, **54**, 221–280, (1961).

Laubscher, H. P.: Jura Mountains. In K. A. De Jong & R. Scholten (Eds.), Gravity and tectonics (pp. 217–227). New York: Wiley, (1973).

Laubscher, H. P.: The décollement hypothesis of the Jura folding after 90 years. Bulletin of Applied Geology, **2**(2), (1997), 167–182.

Leu, W.: Permokarbon-Kartenskizze (Rohstoffe). Kompilation eines GIS-Datensatzes auf der Basis von bestehenden Unterlagen (Bereich Schweizer Mittelland). Nagra Arbeitsber. NAB 08-49, (2008).

Matter, A.: Faciesanalyse und Ablagerungsmilieus des Permokarbons im Nordschweizer Trog. Eclogae Geologicae Helvetiae, **80**(2), (1987), 345-367.

Mazurek, M., Hurford, A. J., and Leu, W.: Unravelling the multi-stage burial history of the Swiss Molasse Basin: integration of apatite fission track, vitrinite reflectance and biomarker isomerisation analysis. Basin Research, **18**(1), (2006), 27-50.

Medici, F., and Rybach, L.: Geothermal map of Switzerland 1995:(heat flow density) (No. 30). Commission Suisse de géophysique, (1995).

Naef, H., and Madritsch, H.: Tektonische Karte des Nordschweizer Permokarbontrogs: Aktualisierung basierend auf 2D-Seismik und Schweredaten. Nagra Arbeitsbericht NAB 14-017, (2014).

Pfiffner, O. A., Erard, P. F., and Stäuble, M.: Two cross sections through the Swiss Molasse Basin (lines E4-E6, W1, W7-W10). Deep structure of the Swiss Alps. Results of NRP, **20**, (1997), 64-72.

Rybach, L., Eugster, W., and Griesser, J. C.: Die geothermischen Verhältnisse in der Nordschweiz. Eclogae geologicae helvetiae, **80**(2), (1987), 521-534.

Schneeberger, R., de La Varga, M., Egli, D., Berger, A., Kober, F., Wellmann, F., and Herwegh, M.: Methods and uncertainty estimations of 3-D structural modelling in crystalline rocks: a case study. Solid Earth, **8**(5), 987-1002, (2017).

Schärli, U. and Kohl, T.: Archivierung und Kompilation geothermischer Daten der Schweiz und angrenzender Gebiete. ISSN 0253-1186, Swiss Geophysical Commission (Beiträge zur Geologie der Schweiz: Geophysik, Nr. 36), (2002).

Sommaruga, A.: Décollement tectonics in the Jura foreland fold-and-thrust belt. Marine and Petroleum Geology, **16**, (1999), 111–134.

Sommaruga, A., Mosar, J., Schori, M., and Gruber, M.: The role of the Triassic evaporites underneath the North Alpine Foreland. In Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins (pp. 447-466). Elsevier, (2017).

Strasky, S., Morard, A., and Möri, A.: Harmonising the lithostratigraphic nomenclature: towards a uniform geological dataset of Switzerland, Swiss J Geosci **109**(2), (2016), 123-136. https://doi.org/10.1007/s00015-016-0221-8

Swiss Federal Office of Energy: https://www.bfe.admin.ch/bfe/en/home/policy/energy-strategy-2050.html, retrieved 28/06/2019

Thury, M., Gautschi, A., Mueller, W.H., Vomvoris, S., Mazurek, M., Naef, H., Pearson, F.J., and Wilson, W.: Geology and hydrogeology of the crystalline basement of Northern Switzerland Synthesis of regional investigations 1981-1993 within the Nagra radioactive waste disposal programme (NAGRA-NTB--93-01). Switzerland, (1994).

de la Varga, M., Wellmann, F.: Structural geologic modeling as an inference problem: A Bayesian perspective. Interpretation, 4 (3), (2016), SM1–SM16. doi: https://doi.org/10.1190/INT-2015-0188.1

de la Varga, M., Schaaf, A., and Wellmann, F.: GemPy 1.0: Open-source stochastic geological modeling and inversion. Geoscientific Model Development, **12**(1), (2019), 1. doi:http://dx.doi.org/10.5194/gmd-12-1-2019

Weber, C.: Energie Strategie 2050: Die Rolle der Geothermie im total revidierten Energie-Gesetz. Presentation at Schweizer ORC-Symposium 2018, (2018).

Wellmann, F., and Caumon, G.: Chapter One - 3-D Structural geological models: Concepts, methods, and uncertainties. Advances in Geophysics, **59**, (2018), 1-121.

Wyborn, L., Hsu, L., Lehnert, K. A., & Parsons, M. A.: Guest Editorial: Special issue Rescuing Legacy data for Future Science., GeoResJ, **6**, (2015), 106-107.