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The Large-Scale Helmholtz Research Infrastructure GeoLaB

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ABSTRACT

Against the background of climate change and the geopolitical situation, the worldwide pressure mounts to reduce the dependence on fossil fuels and to accelerate the energy transition as quickly as possible. Geothermal technologies have a key role to play in supplying and storing heat. The greatest, yet untapped geothermal potential lies in the crystalline basement with important hotspots in tectonically stressed areas. New targeted, science-based strategies are the key to harness this energy under safe, sustainable, predictable, and efficient conditions. The planned GeoLaB (Geothermal Laboratory in the Crystalline Basement) will address the fundamental challenges of reservoir technology and wellbore safety for deep geothermal projects. Experiments will contribute significantly to understanding the coupled, nonlinear processes associated with high flow rates in crystalline reservoir rocks. The application and development of cutting-edge monitoring, online analysis and visualization tools will provide fundamental knowledge essential for the safe and environmentally sound operation of geothermal energy. As an interdisciplinary and international research platform, GeoLaB will collaborate with universities, industry partners, and professional associations to foster synergies. The transparent nature of the envisaged data acquisition will allow the geoscience community to participate in GeoLaB.

1 INTRODUCTION

In order to limit global warming with its severe consequences on nature, economy and society, the world community is confronted with the urgent need to make the transition to a globally sustainable energy system. The challenges as presented by the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) call for the immediate implementation of mitigation measures [IPCC, 2022]. However, economic requirements stand in the way of a rapid transformation of the energy system - also due to the current geopolitical situation. As an example of an industrialized country, less than 20% of thermal energy is generated from renewable resources in Germany [UBA, 2022]. This is especially hard for the winter months, when geothermal energy can possibly most significantly contribute to meeting the enormous demand for renewably generated electricity and especially thermal energy [Bracke, 2022].

Of the various geothermal technologies, the greatest potential lies in the crystalline basement in Central Europe, which has hardly been exploited to date, as in numerous other regions of the world. Tectonically active areas often have a particularly high potential. One of these favored regions is the abandoned rift zone Upper Rhine Graben involving the crystalline basement, hydrothermal fluid flows and significant positive temperature anomalies [Kohl et al, 2005; ‚Frey et al., 2022]. Here, in the immediate vicinity of the campus of the Karlsruhe Institute of Technology (KIT), the highest subsurface temperatures to date of over 170°C were measured at a depth of 3 km in Germany.

The EGS ("Enhanced or Engineered Geothermal Systems") technology was developed to harvest this energy in the widely available crystalline reservoirs using fractures as an underground heat exchanger [Genter et al. 2010]. A major challenge for this technology is monitoring and minimizing the associated induced seismicity in areas with seismic hazard potential, since economical operation requires high flow rates that can usually only be achieved by rock-mechanical technologies such as hydraulic stimulation. The control of seismic risk is a compulsory condition for achieving social acceptance of this technology [Meller et al. 2018]. Yet, these systems have not expanded largely, although remarkable learning curves having been reached in recent years, leading however also to the discontinuation of projects. New, science-based strategies and technologies are therefore urgently needed to exploit the geothermal potential in an economical and, at a large, reservoir-representative scale in an environmentally sound manner. Following the example of other geotechnologies, an independent and systematic scientific investigation of the relevant processes in the subsurface in large underground research laboratories is essential. It is also a prerequisite for an appropriate technology development. Under this background, the GeoLaB underground research laboratory was designed by the Helmholtz centers KIT, German Research Centre for Geosciences (GFZ) and Helmholtz Centre for Environmental Research - UFZ as a new strategic investment of the Helmholtz Association.

2 RESEARCH INFRASTRUCTURE

2.1 Underground geothermal research laboratory

GeoLaB ("Geothermal Laboratory in the Crystalline Basement") aims to scientifically address and overcome the key challenges of deep geothermal exploitation of fractured crystalline reservoirs. To reach these goals of 1) sustainable reservoir technology, 2) wellbore safety, and 3) productivity enhancement in deep crystalline reservoirs, GeoLaB is designed as an underground laboratory with access via tunnels, shafts and drifts to caverns. These are typically small caverns in which or from which the planned scientific experiments are conducted and observed (Fig. 1a).

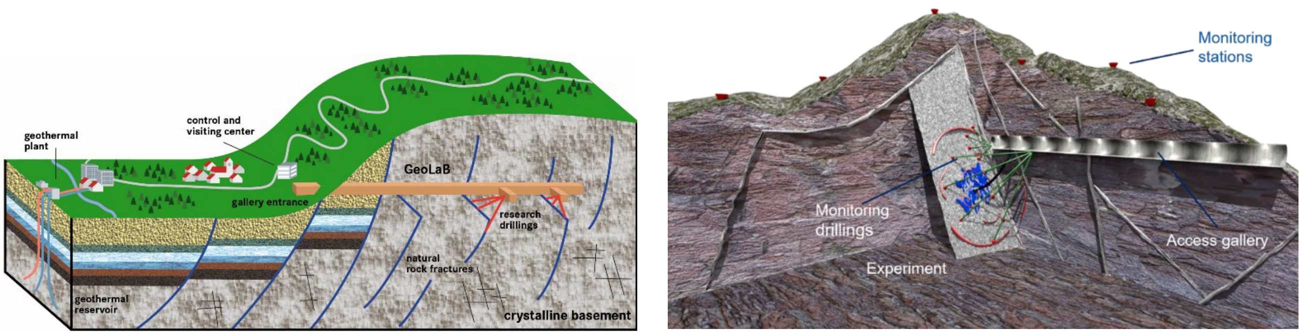

Fig. 1a (left): The schematic location of GeoLaB at the fringe of the Upper Rhine Graben, b: (right) a typical experimental setting in a cavern with specific boreholes monitoring the physical processes in a high transmissive fault / fracture zone

The Black Forest and Odenwald are suitable locations [Frey et al. 2021; Meixner et al. 2018, Bossennec et al. 2022]. Here, the rocks of the crystalline basement have been lifted up and are thus accessible for science on the "rift shoulders" of the Upper Rhine Graben in the Black Forest as well as in the Odenwald 1a). Compared to borehole and reservoir experiments from the surface, such as in the pioneering European research power plant Soultz-sous-Forêts or in FORGE (Frontier Observatory For Research in Geothermal Energy) [Simmons et al;, 2021], USA, the dynamic multiphysics subsurface processes will be observed more comprehensively and with higher resolution in 4D in the underground laboratory. (Fig.1b). In the Upper Rhine Graben and Black Forest/Odenwald, a good database and a high level of expertise has been built-up over decades by science, petroleum industry and geothermal activities. The proximity of GeoLaB in the Black Forest/Odenwald to industrial projects in the Upper Rhine Graben promotes technology transfer.

GeoLaB shall be developed as a blueprint for environmentally sound technology development in the underground. It will incorporate multiple research perspectives ranging from the geosciences, environmental sciences up to civil engineering. Already today, research disciplines such as physics, material science, geoinformatics and rock mechanics are integrated into the scientific planning resulting in a unique project setting (see below). Acceptance of renewable energy and renewable energy research necessitates an interdisciplinary approach, with research reaching out to the social sciences to address the need for supply security with sustainable resource use.

The first phase of the project began in January 2023 and will primarily consist of an exploration campaign to identify a suitable site.. The scientific and technical site criteria include the presence of a crystalline rock matrix, a fracture network with pronounced hydraulic permeability, controllable hydraulic boundary conditions for the planned flow tests, hydrothermal alteration, sufficient overburden, and a stress field that is as homogeneous as possible at depth [Schill et al. 2016]. The technical measures in the construction phase until 2029 include intensive monitoring as well as underground mining development and the construction of a control and visitor center above ground. After commissioning with the performance of reference experiments, operation of the underground laboratory is planned for at least 10 years.

2.2 Reservoir simulator for controlled high flow experiment in crystalline rock

GeoLaB provides the first opportunity to scientifically study the coupled, nonlinear processes of fractured geothermal reservoirs in space and time. Geothermal reservoirs can so far only inadequately be described as highly complex dynamic and coupled systems. This is especially true for petrothermal reservoir formations. Instead, a number of highly simplifying physical assumptions are made to model the thermal-hydraulic-mechanical-(bio)chemical (THMC) processes that occur during the upgrading of a reservoir and the operation of a deep geothermal system in the subsurface. This applies, for example, to fracture geometry, fluid mechanics at rough surfaces, or shear [Egert et al. 2021]. In addition, the parameters required for prognostic modeling are subject to large uncertainties due to the lack of data and benchmarking experiments.

To overcome these limitations, the experimental setup of GeoLaB (Fig. 3) focuses on controlled high-flow experiments (CHFE) in fractured crystalline rock. They are key to achieving GeoLaB's main scientific and technological objectives:

1) Description of hydraulic processes in flowed fractured media under high flow rates.
2) Experimental validation of multi-scale THMC processes.
3) Development and calibration of safe stimulation technologies to minimize induced seismicity and seismic risk.
4) Development of risk management strategies including safe and efficient well installations using innovative monitoring approaches.

GeoLaB's experimental scale as an underground research laboratory is designed to be between laboratory and reservoir scale. It thus bridges the gap between nano- to macro-scale experiments of samples or subsystems and full-scale reservoir experiments, e.g., in research power plants. With its conception as a generic underground laboratory, GeoLaB aims to transfer the results not only to the geothermal projects in the Upper Rhine Graben, but also to other regions worldwide. In this context, cooperation with other underground laboratories such as the Äspö Hard Rock Laboratory, the Bedretto Underground Laboratory for Geosciences and Geoenergies (Hertrich et al. 2019), the Grimsel Test Site, or FORGE plays an essential role in linking the scientific findings across scales. GeoLaB, in addition to the URLs mentioned above, is designed to perform insitu experiments over a permeability gradient between the homogeneous rock mass and permeable fracture zones of up to more than six orders of magnitude.

All tests in GeoLaB will be continuously observed and monitored by high-resolution measurements in fan-shaped boreholes and by monitoring stations in the near and far vicinity. This will result in a comprehensive 4D benchmark dataset of THMC parameters. A high importance for the development of new computational solutions schemes is closely linked to the experimental data, resulting in particular from the physical and geometrical complexity of the subsurface systems. It can be assumed that many of the existing mathematical solution schemes cannot adequately predict the behavior and that new methods based on AI concepts need to be developed. The expected advancement in numerical methods will require validation data derived from reactive hydro-mechanical experimentation. This, in turn, should lead to new strategies to optimize and design an experimental setup or predict the physicochemical behavior in the subsurface based on new characterization methods of an existing setup. In this way, future energy production from the crystalline subsurface or the use of crystalline rock for bulk storage should become more predictable.

2.3 Digital Twin „Virtual GeolaB“

The totality of data collected in GeoLaB opens up the opportunity for an understanding of processes of unprecedented complexity and holds the potential for new modeling approaches and predictive models. The expected volume of data will be so large that "big data" methods will be necessary to address the associated challenges. Machine learning methods will be required to fully exploit the potential of the entire data set for process understanding and modeling. The extremely high computational requirements for realistic simulations make artificial intelligence and high-performance computing essential for the simulation platform. In addition, new methods of scientific visualization, such as virtual reality and augmented reality, are necessary.

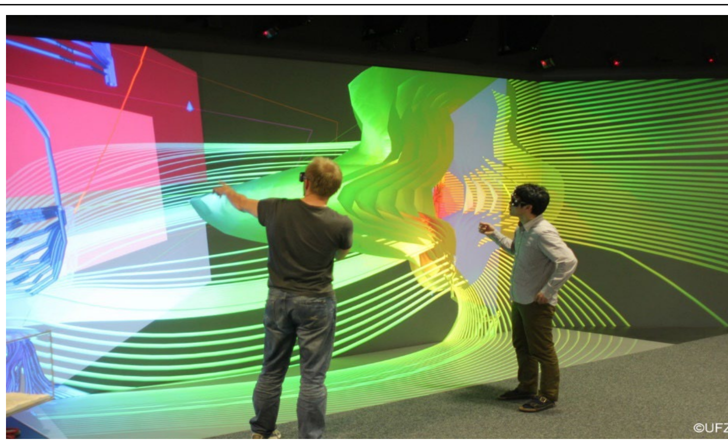

Fig. 2: The virtual GeoLaB concept

Against this background, a "Virtual GeoLaB" is to be realized. It is used for visual analysis and data storage. The starting point for this is the visualization center VISLab [Bilke et al. 2016; Rink et al. 2022] (Fig. 2). This digital twin of the GeoLaB will accompany the development of the research infrastructure already in the construction phase and support the scientific investigations, including planning, analysis, and documentation, in the operation phase. This concept, which already includes the planning phase, is new for a research infrastructure. The virtual GeoLaB will also play an important role in communication with stakeholders, decision-makers and the public.

3 EXPERIMENTAL DESIGN

Focusing on geothermal relevant processes, the experimental design of GeoLaB has multiple objectives. First, it will cover the typical challenges in underground reservoirs with a characterization of the distribution of properties 8e.g. Bossennec et al. 2021], including their anisotropy, alteration, or chemical precipitation. Basically, the experiments rely on comparatively small hydro-mechanical pulses to monitor the reservoir system. In certain experiments, chemical pulses are also part of the workflow. In the next step, the perturbation will be stepwise increased to understand the system response under the new conditions. Clearly, the experimental state will not be reset to the initial values. This variation can be considered to be a minor stimulation of the underground. For example, if the flow rate is increased further, the physical complexity should become apparent: the analyses will have to address the non-linear hydraulic regimes that are a current research topic under laboratory-scale settings. or analyses have to deal with possible mechanical variation due to the lowering of the effective stress magnitude. Whereas the first aspect should result into Navier-Stokes approaches, the second will address the fracture mechanics. The observation of reactive processes between mineral rock matrix and geothermal fluids may bring quantifications of the change of hydro-mechanical properties in a non-linear and transient way. Under these conditions, the targeted complexity of GeoLaB is getting clear: the parametrization of the 3D underground will also result in understanding the dynamic conditions in a reservoir.

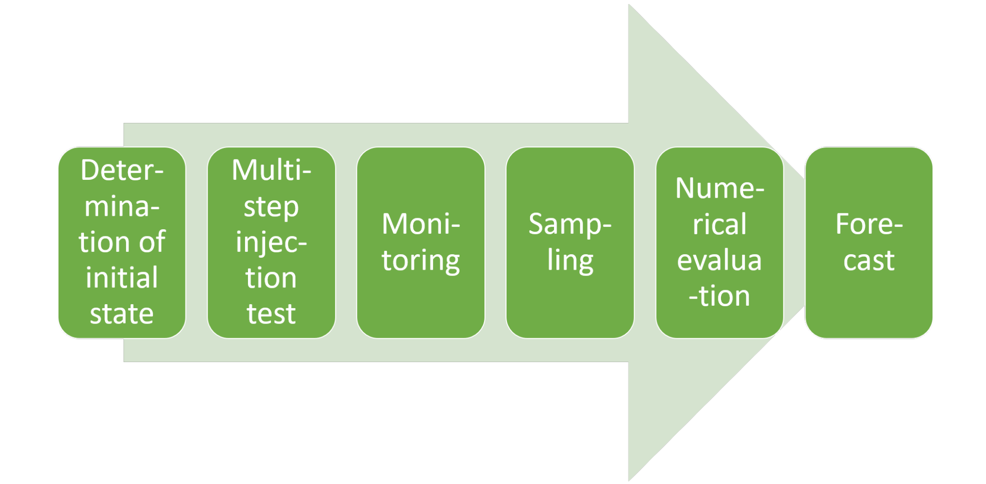

Fig. 3: Typical stepwise experimental and numerical assessment in the GeoLaB reservoir

Fig.3 shows an example of a possible experimental workflow. The variation of a perturbation can be extended to singlet / doublet injection, to hydraulic, thermal, or chemical variation, and to the design of different monitoring methods or locations. In a multistage procedure, when e.g., fluids are injected at different rates, the impact can be visualized through extensive monitoring of the hydrogeological conditions as well as geophysical and geomechanical parameters. Tracers reveal flow paths and velocities and, in the case of functional nano-tracers, the physical conditions of the sampled rock volume. Core sample investigations allows conclusions to be drawn about geomechanical and petrological parameters, and the stress state is determined. Finally, the measured disturbed conditions are compared with the original system state. The experiment is modeled numerically with the goal of validating, calibrating, and defining the flow regime. A synthesis allows the next step towards prediction through forward simulation of the hydro-mechanical processes.

Underground research laboratories fulfill the important task of bridging the scale gap between laboratory type measurements and reservoir-scale observations in boreholes. Especially for rock mechanics, scale effects with their impact on fracture mechanics, tensile strength, or fluid interaction (…) represent key aspects. These are a well-known limitation in forecasting mechanical processes in subsurface rock since they may exhibit tremendous changes in strength when varying the sample sizes. The non-linearity of the processes thus indicates that the scale-gap is not only defined from the well-known geometrical restrictions of the observations, but also from the physical restrictions applied from limited scale of the process condition (like flow rate). Important clues could be provided by monitoring of acoustic emissions or micro-seismicity alongside with detailed hydraulic sensoring in the 3D volume. Only through systematic experimental settings can these processes be quantified. The experiments will considerably extend the on-going research on induced seismicity by adding real reservoir conditions.

In terms of chemical reaction of the experimental fluid scale of it plays an important role. Reactions and crystal species may change over an extended reaction flow path in an URL compared to lab scale approaches. Those reactions can modify the mechanical properties of the fracture system. URL are required to quantify those phenomena to be modelled in a reservoir scale.

4 POTENTIAL BEYOND GEOTHERMAL RESEARCH

4.1 Research opportunities for further disciplines

In addition to its central importance for deep geothermal energy, the crystalline also has significance for other geotechnologies. Understanding the complex processes and derived strategies for the controlled exploitation of deep reservoirs is important, especially with regard to induced seismicity and borehole integrity. Applied geotechnology issues could relate, for example, to the use of artificial intelligence in exploration technology, fracture behavior, drilling techniques, or wellbore safety. Underground infrastructure in development and operation offers opportunities to develop efficient techniques for shaft sinking and roadway driving, innovative sensor technology, smart pumping systems, and risk management methods. GeoLaB promotes digitalization in geotechnologies and allows developments and applications of artificial intelligence and virtual reality methods, as well as Industry 4.0.

GeoLaB also offers experimental opportunities in the field of material science, e.g., regarding the development of corrosion-resistant materials. GeoLaB *per se* includes the perspective of environmental sciences. In addition, GeoLaB lends itself to studies in environmental systems analysis and geoecology, especially in the fields of hydrogeology and hydrology, geochemistry, and geobiology. The rock laboratory in Äspö, for example, demonstrated the valuable insights that an underground laboratory can provide into the interactions between the geosphere and the biosphere [Leefmann et al. 2015].

GeoLaB is conceived as a multidisciplinary research platform that also offers research and development opportunities for issues that go beyond geothermal energy, and offers corresponding cooperation opportunities such as those already realized by BGE, the German federal company for radioactive waste disposal, and knowledge transfer in the field of mining.

4.2 GeoLaB as a platform for dialogue and participation

In Germany and worldwide, the lack of acceptance by citizens is a major hurdle to the construction of large-scale infrastructures. This aspect is therefore also an obstacle to the implementation of the energy transition with the introduction of new technologies and the construction of new infrastructures. This is especially true for geothermal projects, which have often provoked resistance from the public in recent years. Increasing the acceptability of new technologies on a sound scientific basis is therefore a prerequisite for geothermal energy to become a cornerstone of a future sustainable energy supply.

It is a prerequisite that GeoLaB involves the social sciences. In its dialog and participation concept, GeoLaB focuses on transparency and offers citizens opportunities for active participation. GeoLaB goes even further than typical research institutions and follows a geoethical concept [9]. Geoethics places the geosphere and human society in context and proposes principles for responsible and sustainable management of the geosphere. Following these guiding principles, GeoLaB takes action in four areas:

- research and science
- environmental awareness
- communication and knowledge transfer
- education.

This is a novel approach to the development of a research infrastructure, accompanied by the social sciences in inter- and transdisciplinary projects.

5 CONCLUSIONS AND OUTLOOK

To unlock the full potential of deep geothermal energy, basic research is necessary. The crystalline basement represents the world's largest geothermal resource. On the one hand, its environmentally sound exploitation and efficient, safe, and sustainable operation is one of the greatest challenges in geotechnology research; on the other hand, its solution offers a huge application potential due to the location-independence of this resource.

A sustainable geothermal use of the crystalline basement for the energy transition requires scientific investigations in an underground laboratory. GeoLaB allows in-situ experiments in reservoir-like conditions as well as direct observation of complex processes in space and time. GeoLaB thus enables the necessary basic research (e.g., on constitutive laws, flow behavior in fracture networks under high flow rates, fracture behavior) and applied research (e.g., on borehole integrity, reservoir engineering, or economic considerations).

Environmentally sound technology development can ensure sustainable utilization strategies and thus make a significant contribution to the security of supply and heat transition. GeoLaB aims at the development of strategies for the safe use of geothermal energy, such as the minimization of seismic risks and thus a controlled and efficient management of the crystalline bedrock. GeoLaB thus provides the scientific basis for the social acceptance of this technology.

As a holistic research platform, GeoLaB offers cutting-edge research and creates synergies for the development of economically relevant geotechnologies. As the only new development of an underground laboratory in Germany and one of a few worldwide, GeoLaB enables the development of valuable knowledge for the development of large underground infrastructures with innovative methods (incl. virtual reality). GeoLaB provides a forum for citizen dialogue and participation, as well as collaboration between universities, federal institutions, and, last but not least, industry. Thus, GeoLaB creates a link between science, economy, and society.

The GeoLaB research infrastructure creates a controlled research environment in which theories and technologies can be developed and tested. Representatives from science and explicitly from industry are invited to contribute their own ideas and to collaborative projects. In this way, GeoLaB has the potential to become a nucleus for scientific breakthroughs that enable technological innovation. The Continental Deep Drilling Program (KTB), the Soultz-sous-Forêts research power plant, and, more recently, FORGE demonstrate the impact of geo-research infrastructure on science and technology development, as well as how partnerships with industry and technological developments within the research infrastructure can generate positive feedback processes.At present, technological progress, technologies and strategies for risk minimization, and new dialog and participation concepts are urgently needed in deep geothermal energy in order to effectively shape the necessary disruptive transformation process from a hydrocarbon-based to a sustainable and future-proof energy system.

REFERENCES

Bilke, L., Fischer, T., Helbig, C.; Krawczyk, C., Nagel, T., Naumov, D. et al.: TESSIN VISLab—laboratory for scientific visualization. Environ Earth Sci, 72 (10), (2014), pp. 3881–3899. https://doi.org/10.1007/s12665-014-3785-5.

Bossennec, C.; Frey, M.; Seib, L.; Bär, K.; Sass, I. Multiscale Characterisation of Fracture Patterns of a Crystalline Reservoir Analogue. Geosciences (2021), 11, 371. https://doi.org/10.3390/geosciences11090371

Bossennec, C.; Seib, L.; Frey, M.; van der Vaart, J.; Sass, I. Structural Architecture and Permeability Patterns of Crystalline Reservoir Rocks in the Northern Upper Rhine Graben: Insights from Surface Analogues of the Odenwald. Energies (2022), 15, 1310. https://doi.org/10.3390/en15041310

Bracke, R., and Huenges, E. (Hrsg.): Roadmap Tiefe Geothermie für Deutschland I Handlungsempfehlungen für Politik, Wirtschaft und Wissenschaft für eine erfolgreiche Wärmewende, (2022), 37 p. https://doi.org/10.24406/ieg-n-645792.

Egert, R., Nitschke, F., Gholami K., Maziar, and Kohl, T.: Stochastic 3D Navier-Stokes Flow in Self-Affine Fracture Geometries Controlled by Anisotropy and Channeling, Geophysical Research Letters, 48 (9), (2021). https://doi.org/10.1029/2020GL092138.

Frey, M., Bär, K., Stober, I., Reinecker, J., van der Vaart, J., and Sass, I.: Assessment of deep geothermal research and development in the Upper Rhine Graben. Geothermal Energy 10 (1), (2022), https://doi.org/10.1186/s40517-022-00226-2.

Frey, M., Bossennec, C., Seib, L., Bär, K., and Sass, I.: Interdisciplinary Fracture Network Characterization in the Crystalline Basement: A case study from the Southern Odenwald, SW Germany, Solid Earth Discussions, (2021), 1-35.

Genter, A., Evans, K., Cuenot, N., Fritsch, D., and Sanjuan, B.: Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of enhanced geothermal systems (EGS), Comptes Rendus Geoscience, 342 (7-8), (2010), 502–516. https://doi.org/10.1016/j.crte.2010.01.006.

Hertrich, Marian; Gholizadeh Doonechaly, Nima; Krietsch, Hannes; Ma, Xiaodong; Nejati, Morteza; Plenkers, Katrin; Shakas, Alexis; Driesner, Thomas; Loew, Simon; Maurer, Hansruedi; Meier, Peter; Saar, Martin O.; Wiemer, Stefan; Giardini, Domenico; Bedretto Deep Underground Laboratory for Geoenergies - a new Interdisciplinary Research Facility (2019); Proc. AGU Fall Meeting 2019, San Francisco, CA, USA, December 9-13, 2019 H14D-01

IPCC, (2022): Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, et al. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926

Kohl, T., Signorelli, S., Engelhardt, I., Andenmatten Berthoud, N., Sellami, S., and Rybach, L.: Development of a regional geothermal resource atlas, Journal of Geophysics and Engineering, 2 (4), (2005), 372–385, https://doi.org/10.1088/1742-2132/2/4/S11

Leefmann, T., Heim, C., Lausmaa, J., Sjövall, P., Ionescu, D., Reitner, J., Thiel, V.: An Imaging Mass Spectrometry Study on the Formation of Conditioning Films and Biofilms in the Subsurface (Äspö Hard Rock Laboratory, SE Sweden). Geomicrobiology Journal, 32 (3-4), (2015), S. 197–206. https://doi.org/10.1080/01490451.2014.910570.

Meixner, J., Grimmer, J. C., Becker, A., Schill, E., Kohl, T.: Comparison of different digital elevation models and satellite imagery for lineament analysis. Implications for identification and spatial arrangement of fault zones in crystalline basement rocks of the southern Black Forest (Germany). Journal of Structural Geology, 108, (2018), 256–268. https://doi.org/10.1016/j.jsg.2017.11.006.

Meller, C., Schill, E., Bremer, J., Kolditz, O., Bleicher, A., Benighaus, C., Chavot, P., Gross, M., Pellizzone, A., Renn, O., Schilling, F., and Kohl, T.: Acceptability of geothermal installations. A geoethical concept for GeoLaB, Geothermics, 73, (2018), 133–145. https://doi.org/10.1016/j.geothermics.2017.07.008.

Rink, K., Şen, Ö.O., Schwanebeck, M., Hartmann, T., Gasanzade, F., Nordbeck, J., Bauer, S., and Kolditz, O.: An environmental information system for the exploration of energy systems, Geothermal Energy, 10 (4), (2022), https://doi.org/10.1186/s40517-022-00215-5

Schill, E, Meixner, J., Meller, C., Grimm, M., Grimmer, Jens C., Stober, I., and Kohl, T.: Criteria and geological setting for the generic geothermal underground research laboratory, GEOLAB, Geothermal Energy, 4 (7), (2016), https://doi.org/10.1186/s40517-016-0049-5.

Simmons, S. F., Moore, J., Allis, R., Kirby, S., Jones, C., Bartley, J., et al., and Fischer, T.: A revised geoscientific model for FORGE Utah EGS Laboratory. Proceedings, 43rd Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, CA (2018).

UBA (Umweltbundesamt) based on AGEE-Stat, 03 / 2022. https://www.umweltbundesamt.de/sites/default/files/medien/384/bilder/dateien/6_abb_anteil-ee-eev_2022-03-25.pdf