GeoLaB - Geothermal Laboratory in the Crystalline Basement

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ABSTRACT

In view of climate change and the geopolitical situation, Europe's dependence on fossil fuels must be reduced as quickly as possible and energy transition efforts accelerated. Geothermal energy has a key role for heat provision and storage. The greatest geothermal potential is in crystalline bedrock with important hotspots in tectonically stressed areas. To better harness this energy under sustainable, predictable, and efficient conditions, new targeted, science-based strategies are needed. The planned GeoLaB (Geothermal Laboratory in the Crystalline Basement) underground research laboratory will address fundamental challenges in reservoir technology and borehole safety of deep geothermal projects. The planned experiments will contribute significantly to our understanding of the coupled, nonlinear processes associated with high flow rates in crystalline reservoir rocks. The application and development of state-of-the-art monitoring and analysis tools will provide fundamental insights that are essential for the safe and environmentally sustainable exploitation of geothermal energy. As an interdisciplinary and international research platform, GeoLaB will collaborate with universities, industry partners and professional organizations to foster synergies. The geoscientific community is invited to take part in GeoLaB.

1. INTRODUCTION

To limit global warming to 2°C above pre-industrial levels, our society is confronted with the pressing need to make the transition to a globally sustainable energy system (IPCC 2018). The newest contribution to the Sixth Assessment Report calls for the immediate uptake of mitigation actions (IPCC 2022). The current geopolitical situation makes a rapid transformation process of the energy system even more necessary. Geothermal has a great potential to contribute substantially to the enormous demand for climate neutrally and fossil fuel-freely produced electricity and, above all, thermal energy. It can play a pivotal role in the decarbonization of the energy system.

In Central Europe, as in other regions of the world, the crystalline basement offers the greatest geothermal potential, with important hotspots in areas under tectonic tension. One of these hotspots is the Upper Rhine Graben as a rift zone with hydrothermal fluid flows and significant temperature anomalies (Kohl et al. 2005). The EGS technology ("Enhanced Geothermal Systems") was developed to exploit the geothermal energy in crystalline reservoirs using fractures as a natural heat exchanger within a thermal water cycle (Genter et al. 2010). However, flow rates >10 L/s, necessary for an economic operation, typically require reservoir engineering measures such as hydraulic stimulation. A major challenge for EGS is to control and minimize the associated induced seismicity in the reservoir engineering and operation phase. This is also a necessary precondition for social acceptance of this technology. An in-depth understanding of the multiphysical, nonlinear reservoir processes is essential for respective technology developments. New science-based strategies and technologies are urgently needed to exploit geothermal potential in an economical yet environmentally sound manner. Following the example of other geotechnologies, the complex processes in the subsurface need to be studied in large-scale underground research laboratories to ensure environmental compatibility. This is the purpose of the GeoLaB underground research laboratory as proposed by the Helmholtz Centres KIT, GFZ and UFZ (Schätzler et al 2018). GeoLaB is conceived as international research platform with the aim to create synergies between disciplines and research groups.

2. CONCEPT

2.1 Infrastructure concept

The planned underground research laboratory (URL) GeoLaB ("Geothermal Laboratory in the Crystalline Basement") scientifically addresses the central challenges of EGS reservoir management in fractured rock. GeoLaB is designed as a generic underground laboratory and targets the crystalline basement of the Black Forest-Odenwald complex (Figure 1). The exposure of reservoir rocks in the graben shoulders makes them accessible to science. The target rock is at the same time representative for the crystalline basement as largest reservoir rock in the world. This allows scientific transfer to other regions. Specific criteria were defined to select a suitable location of GeoLaB in a first project phase (Schill et al. 2016).

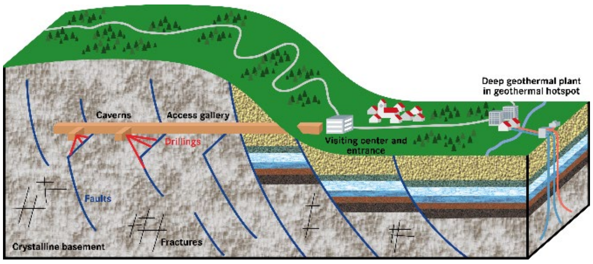


Figure 1: Schematic overall structure of GeoLaB tapping crystalline basement rock in the Schwarzwald-Odenwald complex, next to geothermal projects in the Upper Rhine Graben.

In the URL, individual caverns will be accessed via an approx. 1 km long access tunnel, in which controlled high-flow experiments are to be carried out. Ideally, GeoLaB will be located near a large fault zone (Meixner et al. 2018; Frey et al. 2021). For the establishment of GeoLaB, KIT (as coordinating Helmholtz center and representing the partners GFZ and UFZ) and BGE (German federal company for radioactive waste disposal) enter into a cooperation.

With this set-up, GeoLaB strives for

1) the efficient and safe management of fractured reservoirs,
2) cutting-edge multi-disciplinary and multi-process research with visualization concepts,
3) developing new benign environmental strategies for subsurface installations and
4) transparent interaction with public, shareholders and decision makers.

2.1 Experimental concept

GeoLaB aims at scientific investigations of coupled, non-linear processes in fractured reservoirs associated to high flow rates of EGS plants. These thermal-hydraulic-mechanical-(bio)chemical (THMC) processes of geothermal reservoirs as dynamic and highly complex systems cannot be described adequately yet. Instead, a number of simplifying, often inappropriate physical model assumptions are made regarding, e.g., the fracture geometry, fracture intersections as hydraulic pathways, matrix alteration, fluid mechanics on rough surfaces, and shearing (Egert et al. 2021). Furthermore, the necessary parameters for forecast modeling are subject to great uncertainties due to the lack of a database.

To overcome these limitations, the experimental set-up of GeoLaB (Figure 2) focuses on “controlled high flow rate experiments” (CHFE) in fractured rock. They are key to reach the main scientific aims of GeoLaB:

1) Description of hydraulic processes in fractured media under high-flow conditions
2) Experimental validation of multi-scale THMC processes
3) Mitigation of induced seismicity and seismic risk by developing and calibrating smart stimulation technologies
4) Development of risk management strategies including save and efficient borehole installations using innovative monitoring concepts.

The experiments in GeoLaB will be continuously monitored by measurements in fan-shaped boreholes (Figure 2). This results in a comprehensive 4D data set of THMC parameters.

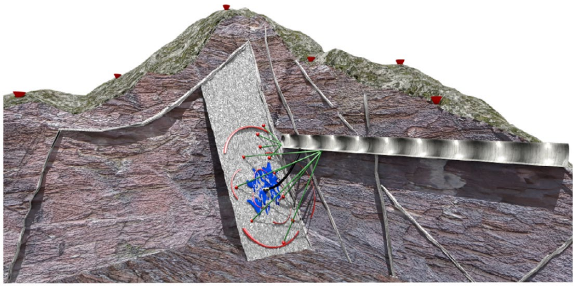


Figure 2: Experimental set-up with a comprehensive sensor network allowing 4D monitoring of CHFE.

In terms of experimental scale, GeoLaB, as an URL, is located between the laboratory/small field-scale and the reservoir scale (Figure 3). Thus, it bridges the gap between nano to meso/macro scale experiments of samples or subsystems and full-scale reservoir experiments.

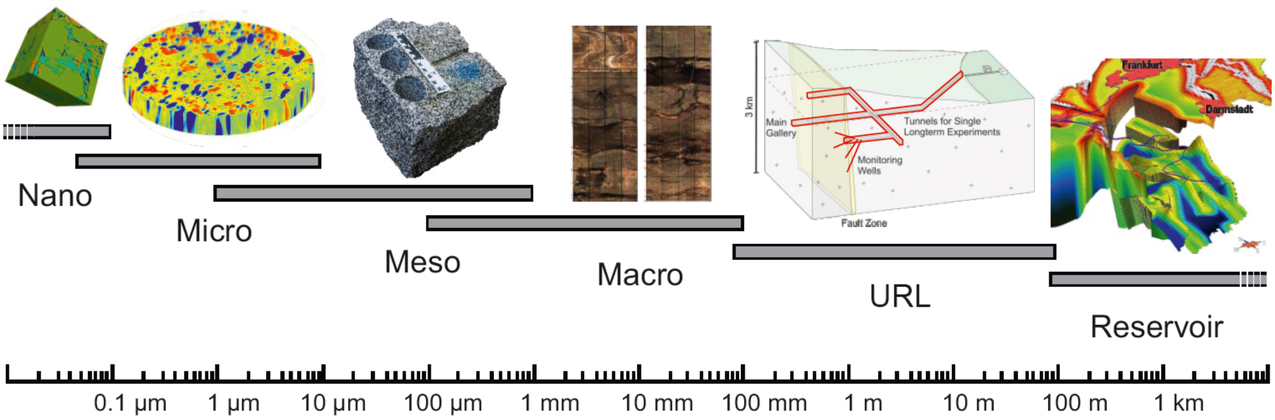


Figure 3: Categorization of the experimental scale of GeoLaB.

Figure 4 illustrates exemplary a possible key experiment: the injection of cold water in a fault zone. Detailed measurements describe the initial state. Water is injected at different rates in a multi-step procedure. Extensive monitoring reveals variations in hydrogeological conditions, geophysical parameters, and stress and strain. Tracers highlight flow paths and velocities, and in case of messenger nano tracers, physical conditions of the sampled rock. Coring allows conclusions about geomechanical fault parameters. The stress state is defined. The measured perturbed conditions are compared to the initial system state. The experiment is modeled by numerical simulation with the aim of validation/calibration and definition of the flow regime. A synthesis allows the next step towards forecasts by forward simulation of hydraulic-mechanical processes.

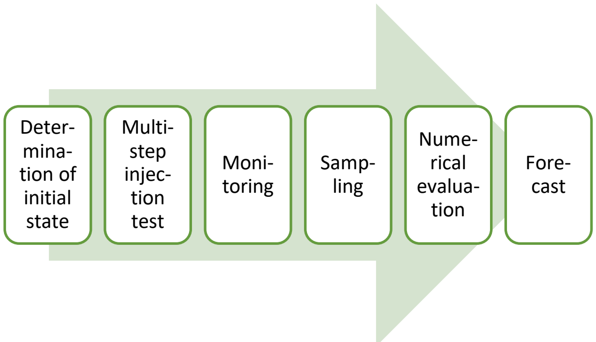


Figure 4: Outline of an exemplary injection experiment.

2.3 Virtual GeoLaB

The expected data volume and process complexity will be huge. New machine learning methods will be necessary to cope with the associated challenges. The extremely high computational effort required for realistic simulations makes artificial intelligence and high-performance computers indispensable for the simulation platform. In addition, new methods of scientific visualization such as virtual reality and augmented reality are necessary.

Against this background, a "Virtual GeoLaB" will be realized. It will serve for visual analysis purposes and as a visual data repository of GeoLaB. The visualization center VISLab (Bilke et al. 2014; Figure 5) provides a starting point. This digital twin of GeoLaB will accompany the development of the research infrastructure already in the set-up phase and support scientific investigations including planning, analysis and documentation in the operation phase. The virtual GeoLaB will also play an important role in communication with stakeholders, decision makers and the public.

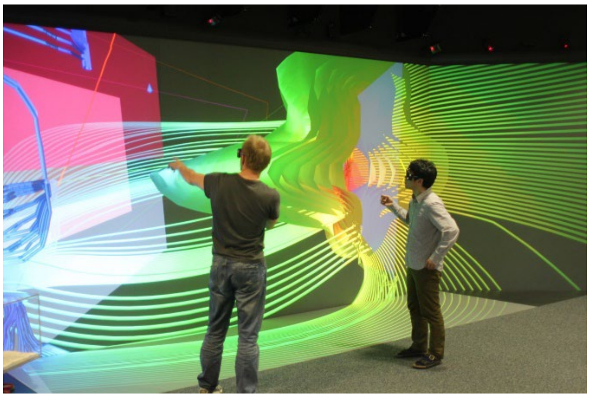


Figure 5: Vizualization center VISLab.

4. INCORPORATION OF SSH

In Germany and worldwide, lack of acceptance by citizens is a major hurdle for the establishment of large infrastructures. This aspect is therefore also an obstacle to the realization of the energy transition with the introduction of new technologies and the construction of large new infrastructures. This is especially true for geothermal projects, which have often provoked opposition of citizens in the last years. Rising acceptance is thus a precondition for geothermal energy becoming a cornerstone of a future sustainable energy mix.

It is therefore only consistent that GeoLaB incorporates "Social Science and Humanities" (SSH). In its SSH concept, GeoLaB sets a focus on transparency and offers citizens opportunities for public participation. Within the SSH activities, GeoLaB goes even further and follows a geoethical concept (Meller et al. 2018). Geoethics sets geosphere and human society into a context and suggests principles for a responsible and sustainable usage of the geosphere. Following these guard rails, GeoLaB takes measures in four areas:

- Research and science
- Environmental consciousness
- Communication and knowledge transfer
- Education.

This is a novel approach of a research infrastructure and accompanied by social sciences.

5. DISCUSSION

The multiphysical processes involved in geothermal production in the low-enthalpy reservoirs of EGS projects have not been sufficiently investigated and understood to optimize EGS technology in terms of sustainability, safety and efficiency and to bring it to market. Systematic reservoir-scale investigations of key issues related to hydraulic processes and induced seismicity are needed, as are new concepts for reservoir configuration. It is extremely difficult - if not impossible - to study the associated processes under the complexity of a 5 km reservoir. It requires access to a typical reservoir structure in a URL with a 4D sensor network, which greatly extends the power of 1D data in deep boreholes. As in other geoscientific disciplines for which specific research programs have been established, special study sites are required for geothermal energy.

Given this necessity, GeoLaB is proposed as first reservoir simulator for deep geothermal energy sustainably exploiting the abundance of energy available in the largest geothermal resource rock, the fractured crystalline. GeoLaB is a unique URL. Existing URLs often address questions of barrier properties of host rocks, typically in connection with nuclear repository research (NEA 2013). GeoLaB targets the opposite problem, namely the best possible permeability of the reservoir rock with a high fracture density and an extensive fracture network.

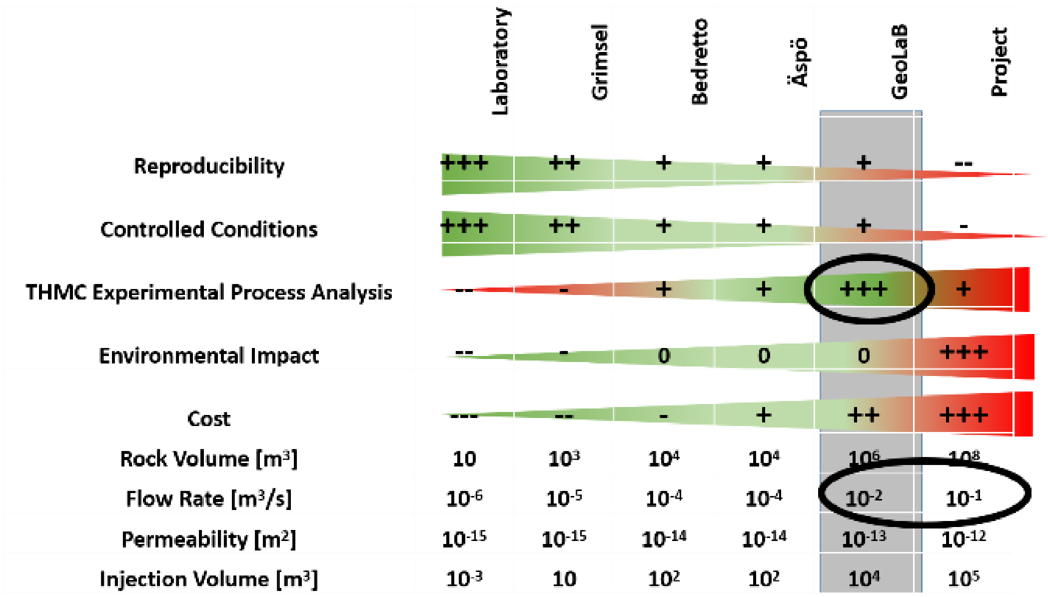
The planned experiments will allow detailed in-situ observations in space and time for the first time. A worldwide unique dataset will be created that will allow specific and more reliable parametrizations. This is expected to contribute significantly to our fundamental understanding of the THMC processes associated with operating conditions of EGS.

Describing the complex processes in numerical models that overcome the limitations of current typical models and enable predictions to estimate reservoir behavior constitutes a crucial step. Therefore, GeoLaB has a special focus on the extension of constitutive flow laws at higher flow rates. With the planned experiments, experimental determinations and the verification in 3D of hydrodynamics (e.g. Navier-Stokes laws) and hydromechanics (e.g. triggering and propagation of microseismicity) in the fractured crystalline basement are possible for the first time at high flow rates. Thus, dynamic and coupled processes, e.g., variability of the stress field in space and time, can be experimentally determined under reservoir-like conditions for the first time.

Mitigating the risk of induced seismicity by developing smart stimulation and operating procedures requires understanding the underlying geomechanical processes. Closely associated to this topic are scale effects. These are a well-known limitation in describing mechanical processes in the subsurface (Brady and Brown 2006): Varying the sample size under laboratory conditions can lead to significant changes of processes and fields under laboratory conditions. Moreover, a considerable gap exists between laboratory and real scale conditions. GeoLaB can help to close this gap; this has also relevance to the theory of geomechanics in general.

It shall be noted that experiments must be planned carefully in an anticipatory manner since experiements may change parameterizations of the investigated rock in the URL, and the intial state may not be reached again after completion of the experiment. This fact has the consequence that experiments are not necessarily reporducable. This is in contrast to laboratory experiments.

Figure 6 classifies the above presented and discussed characteristics and opportunities of GeoLaB with respect to laboratory, similar URLs, and industrial EGS plants. This compilation also illustrates the uniqueness of GeoLaB as geothermal URL tailored to the requirements of geothermal research.



	Laboratory	Grimsel	Bedretto	Äspö	GeoLaB	Project
Rock Volume [m³]	10	10^3	10^4	10^4	10^6	10^8
Flow Rate [m³/s]	10^{-6}	10^{-5}	10^{-4}	10^{-4}	10^{-2}	10^{-1}
Permeability [m²]	10^{-15}	10^{-15}	10^{-14}	10^{-14}	10^{-13}	10^{-12}
Injection Volume [m³]	10^{-3}	10	10^2	10^2	10^4	10^5

Figure 6: Characteristics of GeoLaB compared to those of laboratory experiments, other URLs and operative projects (adapted from Doetsch et al 2018)

GeoLaB offers a multidisciplinary research platform for the international research community. In Germany, it is currently the only new large-scale URL. This also allows the consideration of requirements for modern infrastructures in the URL design. This situation holds R&D opportunities, e.g., for environmental system analysis, materials science, or digitization (Big Data, artificial intelligence, Industry 4.0, virtual reality), beyond geothermal research.

Transparency is seen as a central characteristic of GeoLaB. It is supposed to have a dialogue platform character in order to foster exchange of scientists and stakeholders from economy, politics, administration and society. Scientific and non-scientific platforms will provide open access to data and results as far as possible. At the same time, this concept ensures a certain quality control of GeoLaB projects.

Providing information, offering transparency, fostering dialogue, and enabling participation and involvement shall rise trust and confidence towards geothermal research and technology. Following measures of responsible research in the geoethical sense, aims not only to promote the acceptance of GeoLaB itself. It also – and more importantly – aims to increase the acceptability of the deep geothermal technology according to societal standards of sustainability and safety, and to improve the overall perception of geothermal energy as a reliable renewable energy source.

6. CONCLUSIONS

GeoLaB as first specific reservoir simulator for deep geothermal energy investigations offers a large potential for geothermal research. GeoLaB is designed as a generic underground laboratory in crystalline rock at the edge of the Rhine Graben, one of the most important geothermal hotspots in Central Europe. GeoLaB is an analogue site representative of the most widespread geothermal reservoir rock, the crystalline basement. Findings will be transferable to other crystalline reservoirs to a large extent.

The development of future geothermal application concepts in crystalline rock profits strongly from international cooperation; therefore, international collaborations shall be fostered and synergies enabled. GeoLaB is conceived as an integrated platform for research, development, teaching, and communication. It holds a high potential for innovation in the creation of environmental standards and safety research, as well as in the development of a communication standard for geothermal energy. The use and development of comprehensive and cutting-edge observation and assessment methods lead to findings that are of great importance for the safe and ecologically sustainable use of geothermal energy.

The experimental and structural opportunities of the URL enable effects beyond EGS and geothermal research. An overall impact is expected that is comparable to the last large geoscientific infrastructure project, the KTB, and that goes beyond geothermal research. GeoLaB is relevant for several fields of geosciences and the development of strategies to subsurface use by geotechnologies in general. As a research and innovation platform, GeoLaB offers ideal conditions for teaching and training the next generation of scientists, geotechnical experts and decision-makers.

Scientists worldwide are invited to collaborate and participate with own ideas and projects. This way, the large infrastructure project GeoLaB will become a nucleus of scientific breakthroughs enabling technological innovations. Technological progress, risk mitigation and new SSH concepts in geothermal are urgently needed to shape the necessary disruptive transformation process from a hydrocarbon-based to a sustainable and future-proof energy system.

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