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The GeoLaB URL Is Coming! Unique High Flow Experiments In Fractured Crystalline Basement Rocks

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ABSTRACT

The central European challenge for deep geothermal system is that the locations are close to dwelling areas and infrastructure. The public awareness can be higher than otherwise. There is no choice than bringing enhanced geothermal systems (EGS) systems closer to the people. To develop and demonstrate safe, sustainable and economic geothermal systems in the low permeable basement the GeoLab (Geothermal Laboratory in the Crystalline Basement) Helmholtz research infrastructure project was launched. A particular site was under investigation. The decision to erect the underground research laboratory (URL) at that particular site in SW Germany is due in March 2026. The international and interdisciplinary research platform of the Helmholtz Association focuses on the thermal-hydraulic-mechanical-chemical (THMC) processes related to explore and exploit deep geothermal reservoirs. The overarching aim of the research is a safe and ecologically sustainable use of the most important geothermal resources in Germany and worldwide. This paper reports on the status of investigation of a potential GeoLaB site.

1 OVERVIEW OF THE GEOLAB RESEARCH INFRASTRUCTURE AND ITS MISSION

The urgent need to achieve climate neutrality while simultaneously reducing dependence on energy imports presents a significant challenge. Deep geothermal energy offers a sustainable energy solution, particularly through decarbonization of the heating sector. In Germany and worldwide, the potential of deep geothermal energy is considerable. Site-dependent re-sources utilizing highly permeable rock formations are currently experiencing the greatest development, as is currently being impressively demonstrated in the Munich area. However, crystalline or petrothermal resources of the crystalline basement as predominant class of rock formations hold the greatest energy potential. In light of the urgency of addressing the climate crisis and the challenges posed by current geopolitical conditions, utilizing this resource, primary through EGS (Enhanced Geothermal Systems) technologies, could become an essential asset. Despite an impressive learning curve accomplished – not least through EGS research demonstration projects such as the European Soultz-sous-Forêts project (F) and FORGE (USA) – systematic in situ research for enhanced process understanding is required to fully harness its potential in a safe and environmentally friendly manner.

The GeoLaB concept was established to meet these needs. The envisaged underground research laboratory is designed to investigate the dynamic processes of geothermal reservoirs in space and time in a reservoir analogue as being a 4D-reservoir simulator. The goal is to contribute to the development of advanced

geothermal technologies and risk management strategies with a particular emphasis on induced seismicity, and thereby establish geothermal use in the potentially most promising resource. Potentially located in the crystalline rock of the Odenwald mirroring the reservoir rocks in the Upper Rhine Graben (Figure 1-1), the facility will include a gallery leading to a cavern situated under ap-proximately 400 meters of rock (Figure 1-2). This cavern will serve as the site for high-flow experiments to study geothermal processes under controlled conditions. GeoLaB closes the scale gap between the lab and reservoir scale (Figure 1-3).

The future research conducted at GeoLaB is designed to address fundamental questions in geothermal energy utilization in fractured crystalline rock, including the understanding of the thermal, hydraulic, mechanical, and chemical processes involved in heat and fluid transport of crystalline, petrothermal resources. These insights are expected to contribute significantly to the improvement of the safety and efficiency of EGS. Specifically, the facility will play a vital role in enhancing the understanding of induced seismicity and demonstrating measures to minimize seismic risks, thereby addressing public concerns and enabling the broader adoption of geothermal energy.

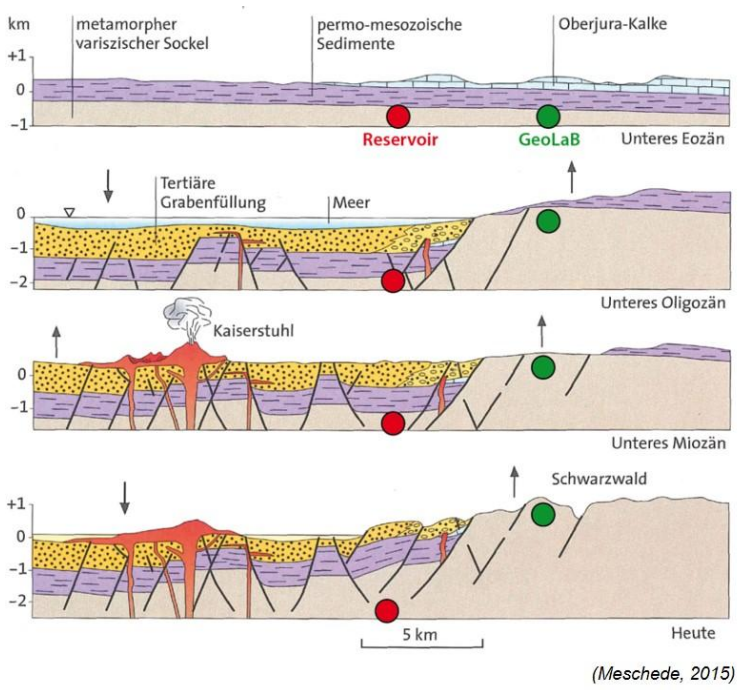


Figure 1-1: The formation of the Upper Rhine Graben (URG). In the Black Forest/Odenwald complex the reservoir rock of the deep URG is accessible to research.

Moreover, GeoLaB underscores the practical application of research and the implementation of findings in operational projects. This encompasses the facilitation of discourse with the public and the contribution to the development of regulatory processes that are pivotal to the acceleration of the deployment of geothermal technologies in urban and industrial contexts. The objective of the research laboratory is to provide actionable knowledge to facilitate the integration of geothermal energy into the energy transition.

The digitalization constitutes a fundamental aspect of the GeoLaB approach. The implementation of advanced data management systems, virtual engineering reality and immersive virtual reality accompanies the planning and later the construction of the research infrastructure. It will also support the efficient planning and evaluation of experiments. The utilization of virtual reality tools will facilitate the visualization and comprehension of complex underground processes, thereby also enhancing the transfer of knowledge and fostering public understanding.

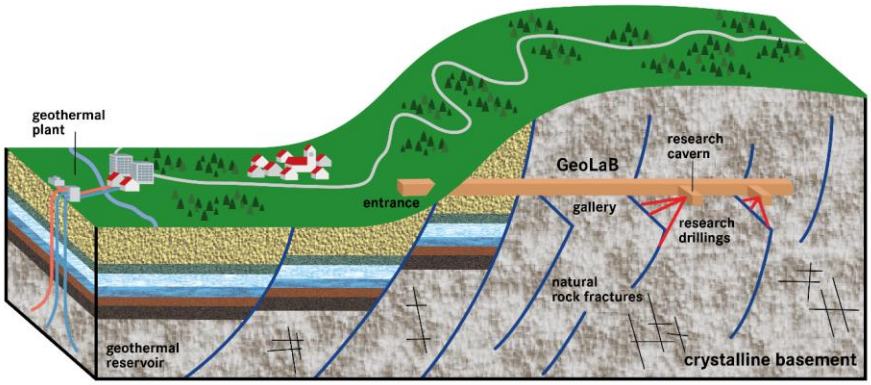


Figure 1-2: Overall setup. The GeoLaB project has been conceived for implementation in the Black Forest–Odenwald region along the Upper Rhine Graben, where elevated subsurface temperatures result in a high geothermal potential. In this mountain range, the crystalline basement rock is accessible, enabling in-situ research and observation of fluid-rock interactions across space and time.

As an interdisciplinary and international research platform, GeoLaB intends not only to advance scientific knowledge and foster innovation, but it also contributes to education and training of the next generation of experts. It supports the development of future researchers and technicians while promoting collaboration between academic institutions, industry, and regulatory bodies. Dialogue and collaboration with the various stakeholders are key aspects of its mission.

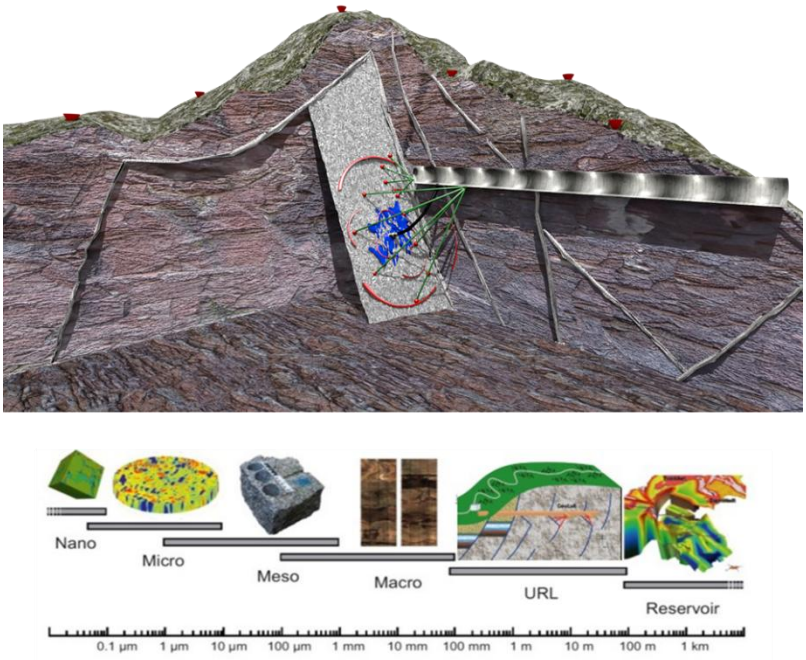


Figure 1-3: Experimental setup. With its planned controlled high-flow experiments in fractured crystalline rock (top), GeoLaB will close the scale-gap between laboratory experiments and reservoir tests in demonstration projects (bottom).

GeoLaB is conceived as a joint research infrastructure of the Helmholtz research fields “Energy” and “Earth and Environment”. Only if both perspectives come together in GeoLaB can environmentally friendly technology development succeed. By scientifically addressing technological, environmental, and societal challenges, GeoLaB will play a pivotal role in advancing geothermal energy utilization and supporting the heating transition.

The GeoLaB initiative is coordinated by the Karlsruhe Institute of Technology (KIT). The Helmholtz partners are the Helmholtz Centre for Geosciences (GFZ) and the Helmholtz Centre for Environmental Research (UFZ). The development is closely coordinated with the university partner TU Darmstadt as regional expert. The BGE is involved, primarily in an observer role, in the exploration, planning and construction phases, with the aim of acquiring expertise in establishing underground infrastructures.

2 STRATEGIC SCIENTIFIC DEVELOPMENT

Germany's energy transition relies on a secure and sustainable supply of both heat and electricity. With heating accounting for nearly 60 % of total energy consumption, the demand for thermal energy is a crucial factor. Annually, this demand amounts to approximately 1,400 TWh, underscoring the need for innovative and efficient solutions for thermal energy provision.

The heat demand ranges from low to high temperatures, from cooling and space heating to industrial high-temperature process heat. Contrary to power production, the most important heat sources are currently still fossil fuels. Thus, the heating transition remains one of the biggest challenges of the energy transition, and a transformative, partly disruptive, approach is necessary.

Deep geothermal energy offers a significant opportunity to contribute to this goal. A German 2022 Deep Geothermal Roadmap highlighted, that hydrothermal technologies alone open up a market potential of around 25 % of the total heat demand in Germany. This can be tapped using today's state-of-the-art deep drilling and process technology, which has a high level of technological maturity (TRL 6 - 9). In addition to the hydrothermal potential, there is a vast amount of untapped geothermal energy in the crystalline basement, the so-called petrothermal reservoirs, as well as the potential of large seasonal underground heat storage systems. However, realizing the petrothermal potential requires addressing key challenges related to resource exploration, technological advancement, and public acceptance.

While sedimentary systems offer a promising starting point for geothermal use, crystalline rock formations, prevalent throughout Central Europe, harbor the highest geothermal potential due to their elevated temperatures. The Upper Rhine Graben, with its exceptional thermal conditions (exceeding 180 °C at 3 km depth), rivals world-class non-volcanic geo-thermal anomalies like the Basin and Range systems in the western US. Despite this potential, and the extensive research conducted in both regions over the past 40 years, geothermal development in the Upper Rhine Graben has lagged significantly behind the Basin and Range, which boasts over 400 MW of geothermal electricity production. Induced seismicity raised public concern, fueled by past events like those in Basel, Landau, and Vendenheim, and led to cancellation of projects, stringent regulations and hindered progress. This has resulted in a decline of practical expertise, even as research into risk assessment has advanced.

However, recent advancements, including dramatic cost reductions in drilling, innovative EGS exploitation schemes, and progress in reservoir engineering, particularly in the US, underscore the need for renewed focus and innovation. This is where GeoLaB comes into play. Conceived over a decade ago, GeoLaB aims to increase process understanding, develop risk mitigation strategies and bridge the gap between innovation and public acceptance, unlocking the vast potential of deep crystalline geothermal resources.

Today, the few geothermal plants based on EGS in the Upper Rhine Graben are mostly linked directly or indirectly to fluid flow in crystalline systems. The geothermal systems, including Soultz-sous-Forêts, Rittershoffen, Landau, and Insheim, demonstrate the viability of utilizing fractured crystalline formations, even if indirectly. The extensive data gathered from the 5 km deep Soultz reservoir has provided valuable insights into the behavior of hydro-thermalized zones within crystalline rock. Building on this foundation, GeoLaB will take a closer look at the fractured heat exchange areas, pioneering a new approach to under-ground laboratory research.

GeoLaB will investigate structural heterogeneities and the dynamics of hydraulic and chemical injections, develop risk mitigation strategies and address public perception. By integrating geoscientific, data science, and social science research, GeoLaB aims to foster science-based, informed decision-making and build public trust. Since GeoLaB is state financed data will be accessible to research partners worldwide.

A core element of GeoLaB's mission is developing highly skilled professionals capable of navigating the complex thermal-hydraulic-mechanical-chemical processes in fractured rock. Furthermore, GeoLaB will focus on designing safe and efficient geothermal production strategies tailored to specific geological and mechanical conditions. Just as the hydrocar-bon industry has evolved to exploit unconventional resources, geothermal energy must also demonstrate its ability to deliver cost-competitive thermal and electrical energy. GeoLaB will drive innovation by supporting fundamental research into new analytical techniques for characterizing structural and geological constraints, leading to improved resource assessments and stimulation strategies.

Unlike the sparsely populated Basin and Range in the U.S., the densely populated Upper Rhine Graben, like most regions in Europe, necessitates careful consideration of induced seismicity. GeoLaB will prioritize the evaluation of seismicity related to fluid injection and circulation. Participation initiatives in environmental monitoring aim to promote transparency and build confidence in the technology.

The non-commercial nature of GeoLaB allows for flexible experiment adjustments, including halting operations if necessary, enabling the quantification of micro-seismicity and the development of tailored injection protocols. Learn-ing from the advancements in unconventional hydrocarbon production, which successfully mitigated seismicity through innovation, GeoLaB aims to apply these lessons to the geo-thermal context.

Germany's energy future demands flexible and reliable resources. Geothermal energy, particularly from deep crystalline systems, offers compelling opportunities. GeoLaB will leverage the knowledge and experience gained from complementary underground field laboratories and research facilities, particularly Soultz-sous-Forêts, FORGE and Bedretto, and global geothermal operations for specific research to characterize the dynamics of underground rock formations and ensure safe and sustainable production. The exploration borehole being drilled at the beginning of 2025 in the Odenwald marks an exciting first step in this endeavor.

3 EXPLORATION

Several years before the start of the GeoLaB infrastructure implementation phase, the project partners KIT, GFZ, UFZ, and TU Darmstadt have started to pre-explore the Black Forest and Odenwald area with respect to its general scientific suitability for GeoLaB and to refine its concept. Moreover, they have built up expertise in several fields relevant for the exploration and implementation phase as well as future experiments in GeoLaB. These works cover a broad range of geoscientific, engineering and social scientific disciplines, including the characterization of geothermal fluid systems, virtual reality and visualization techniques, numerical modeling, the development of innovative tracer technologies, site surveying methods and seismic monitoring, and drilling.

One focus of the work is to analyze the suitability of a potential GeoLaB in the Black Forest and Odenwald as a reservoir simulator for deep fractured reservoirs in the Upper Rhine Graben. Therefore, intensive geological investigations in the Upper Rhine Graben and its graben shoulders have been undertaken to delineate the subsurface structures, fault networks, and fracture systems. E.g., satellite imagery for lineament analysis were analyzed in the Black Forest and Odenwald. Site selection criteria were developed. This site selection process is critical, as it determines the feasibility and long-term success of GeoLaB.

A further central theme is the development and application of numerical modeling techniques to advance process understanding and investigate fluid flow and heat transfer processes in geothermal reservoirs. Inventive and unique microstructure simulations delve into the intricate interplay of geological, mechanical, and fluid dynamics phenomena to gain insights into subsurface reservoirs at the microscopic scale.

We addressed the challenge of simulating turbulent flow through rough rock fractures with complex void spaces by stochastic mapping and 3D Navier-Stokes flow simulations and developed an innovative workflow to model and characterize preferential flow paths in rough-walled shear fractures. Finite element simulations explore the impact of permeable fault zones on system performance. Structural and fracture network analyses of crystalline reservoir analogues in the Odenwald and Upper Rhine Graben further enhance the understanding of permeability patterns in geothermal reservoirs. Further studies illustrate how uncertainty quantification and machine learning methods are employed to optimize models and enhance predictions for geothermal systems.

These simulation studies are complemented by experimental flow experiments on a lab scale. An example is the DFG-funded F4at Lab, a hydromechanical laboratory at KIT, designed to address unresolved questions on hydraulics, transport, and fluid chemistry, especially for high Reynolds number flows. The unique setup includes a 3D scanner, 3D printer, thermal conductivity meter, and hydraulic test rig. Natural rock surfaces are scanned to quantify roughness parameters, and 3D-printed fracture samples are used for hydraulic tests. The F4aT lab allows experiments on rough fracture surfaces under high geothermal flow rates, leading to turbulence-like flows. Numerical and experimental findings enhance our understanding of fluid flow dynamics in fractured reservoirs.

The investigation of geothermal fluid origins and evolution also plays an important role. Studies in this area explore the chemical and physical processes that influence fluid characteristics, contributing to a better understanding of how these systems form and evolve over time.

In addition to simulation and modeling, studies focused on experimental and field investigations of geothermal systems. For instance, the interaction of geothermal fluids with surrounding rocks was explored. Other studies emphasized real-time seismic monitoring techniques to enhance the understanding and management of geothermal systems.

Geophysical surveys, including seismic studies and aeromagnetic data acquisition, form the backbone of the exploration phase. Advanced methods are needed to map the intricate geological structures and to identify regions with geological conditions required for GeoLaB. The insights gathered from conducted surveys were essential for pinpointing potential regions that meet the criteria for establishing an underground laboratory.

Seismic data acquisition methodologies were refined, enhancing seismic data migration and interpretation through the ‘Vibroseis’ exploration technique. These efforts laid the groundwork for collaborations with GFZ and DMT, particularly in combining multiple geophysical methods to detect small-scale heterogeneities and elevated permeabilities in crystalline bedrock. Moreover, TU Darmstadt led efforts to test and train 4D borehole tomographic methods.

These advanced techniques will also become integral to the next steps of the project. Numerical modeling, enhanced by machine learning and uncertainty quantification methods, will simulate fluid flow and heat transfer, providing predictive insights into its behavior. Similarly, Distributed Acoustic Sensing (DAS) with fiber optics will provide continuous, real-time monitoring of the subsurface, allowing for the immediate detection of any changes. Real-time monitoring is a cornerstone of GeoLaB, enabling continuous observation of underground processes through advanced sensing and seismic monitoring techniques. This real-time feedback is crucial for ensuring the safety, efficiency, and scientific impact of GeoLaB experiments.

Future experiments in GeoLaB could also benefit from innovative tracer technologies. KIT in-house developed functional nanoparticle tracers, engineered with improved dispersion stability and tailored sorption properties, could be used to track fluid pathways and assess transport mechanisms in the subsurface. These experiments will complement the modeling and monitoring efforts, leading to a comprehensive understanding of the system’s dynamics.

The UFZ has established its leading role in digital innovation in geosciences, with a focus on developing VISLab, a high-performance visualization infrastructure for geoscientific modeling. Their work integrates virtual reality (VR) technologies to enhance the understanding of complex underground processes and is a starting point for the digital twin of GeoLaB. A key application of their VR research has been the Mont Terri Rock Laboratory, for which immersive digital models were developed to simulate and analyze experiments and subsurface behavior in geological formations. These VR models support experimental planning, real-time data visualization, and interactive analysis, enabling scientists to explore underground environments in unprecedented detail.

Expertise in site surveying, in infrastructure implementation in crystalline rock (Odenwald grandiorite and granite) and in its experimental operation was demonstrated in the BMWK-funded SKEWS project at a campus of the TU Darmstadt. Three 750 m deep borehole heat exchangers build the world's first medium-deep borehole energy storage. Accompanying scientific studies by TU Darmstadt and GFZ focus on advancing geothermal energy storage and subsurface characterization in crystalline bedrock formations. They include the development and validation of new thermal energy storage models and integrating it into energy systems.

A continuous thermal and hydro-chemical monitoring is carried out via three nearby groundwater monitoring wells during the building and operating phase to quantify the systems impact on the near surface aquifer. The operating and monitoring results will be used to improve and validate existing numeric simulation tools. SKEWS is part of several joint projects, including the EU H2020 project PUSH-IT, and therefore one of the nuclei for future collaborations for GeoLaB.

Overall, the GeoLaB initiative embodies a holistic approach to geothermal research, where cutting-edge technologies and interdisciplinary methods converge to drive efficient and safe renewable energy solutions.

4 REFERENCE

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