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The Helmholtz Research Infrastructure GeoLaB: A Test Field for Exploration of Fractured Reservoirs

Thomas Kohl[1], Judith Bremer[1], Bastian Rudolph[1], Eva Schill[2], Katharina Schätzler[1], Fiorenza Deon[3], Jens Grimmer[1], Said Kamrani-Mehni[3], Stefan Lüth[3], Karsten Rink[4], Nico Neuwirth[1], Christoph Schüth[5], Olaf Kolditz[4], Ingo Sass[3]

[1]Karlsruhe Institute of Technology (KIT), Kaiserstrasse 12, 76131 Karlsruhe, Germany, [2]Lawrence Berkeley National Laboratory, Berkeley, California, [3]Helmholtz Centre for Geoscience – GFZ, Potsdam, Germany, [4]Helmholtz Centre for Environmental Research – UFZ, Leipzig, Germany, [5]Technical University Darmstadt, Darmstadt, Germany

thomas.kohl@kit.edu

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ABSTRACT

Deep geothermal energy, particularly from crystalline systems, holds significant promise as a clean and sustainable energy source, but it also presents a unique set of challenges in terms of exploration, technological development, and risk management. The GeoLaB project is at the forefront of efforts to unlock this potential, aiming to advance our understanding of crystalline geothermal reservoirs through high-resolution experiments conducted at an Underground Research Laboratory (URL) scale. By leveraging state-of-the-art technologies and methodologies, GeoLaB seeks to provide critical insights into the dynamics of these deep reservoirs and improve the management of induced seismicity, a key concern in the development of geothermal energy from crystalline basement rocks.

In addition to its direct research focus, GeoLaB is strategically positioned to create synergies with other large-scale geothermal initiatives, such as the Utah FORGE project, enabling the exchange of knowledge, data, and best practices. This collaborative approach is essential for accelerating the technological advancements necessary to make deep geothermal energy a reliable and scalable energy source. GeoLaB's research is focused on several critical aspects of reservoir dynamics, including fluid flow, heat transfer, and the impact of deep geothermal activities on the surrounding environment, especially with respect to induced seismic events.

The current exploratory phase of GeoLaB is centered on the verification of the Tromm region as a suitable site for further development. This involves an extensive program of geophysical surveys, drilling operations, and detailed geological and hydrogeological analyses to gather the data necessary to assess the region's geothermal potential. These field activities are being supported by cutting-edge digital modeling tools, including the development of a digital twin, which is playing a pivotal role in planning, advanced simulations, and visualizing the complex subsurface conditions of the region.

The digital twin is a key component in ensuring that the project moves forward with a high degree of precision and foresight. By simulating various geological scenarios and operational conditions, the digital twin allows researchers and engineers to predict the behavior of the reservoir under different exploration and development strategies. This helps to identify potential challenges and risks early in the process, ensuring that mitigation measures can be implemented before they become critical issues.

Overall, the GeoLaB project is making significant strides in addressing the scientific, technological, and operational challenges of harnessing deep geothermal energy from crystalline reservoirs. By combining high-resolution experiments with advanced digital modeling and collaboration with other large-scale research initiatives, GeoLaB is well-positioned to contribute valuable knowledge and innovations that will help unlock the vast untapped potential of deep geothermal energy. The ongoing infrastructure development, combined with the comprehensive exploratory activities in the Tromm region, will pave the way for future breakthroughs in the sustainable and efficient use of geothermal resources. As these efforts continue to unfold, they will provide valuable insights not only for geothermal energy production but also for the broader field of underground energy resources.

1. INTRODUCTION

While sedimentary geothermal systems are a promising starting point for geothermal energy development (Bracke et al., 2022), crystalline rock formations, which are widespread throughout Central Europe and the United States, hold the most significant geothermal potential. In central Europe, the Upper Rhine Graben stands out, offering exceptional thermal conditions—temperatures exceeding 180°C at just 3 km depth. This places the region on par with other world-class geothermal anomalies, such as the Great Basin in the western United States, which has been at the forefront of geothermal development for decades. Despite these favorable conditions, geothermal development in the Upper Rhine Graben has remained far behind the progress made in the Great Basin. A critical factor contributing to this gap is the challenge of induced seismicity, which has been exacerbated by past events such as the seismic incidents in Basel, Landau, and Vendenheim. These events led to stringent regulations that have hindered further geothermal exploration and exploitation in the region. As a result, practical expertise in Europe has diminished over time, even as significant advances have been made in risk assessment and mitigation strategies.

However, recent technological advancements are rekindling interest in geothermal resources in crystalline rocks. Notably, dramatic reductions in drilling costs, coupled with innovative Enhanced Geothermal Systems (EGS) exploitation strategies and improvements in reservoir engineering—particularly in the United States—highlight the potential for a renewed focus on deep geothermal energy development. These breakthroughs underscore the importance of innovation and investment in the geothermal sector to realize the vast potential of deep geothermal resources. Expanding the approaches tested in EGS Collab (Kneafsey et al., 2025) at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, under the lead of Lawrence Berkeley National Laboratory prior to the Utah FORGE site, this is where the GeoLaB project steps in, offering a unique opportunity to bridge the gap between reservoir-scale applications and laboratory-scale experiments, thus unlocking the geothermal potential of crystalline basement formations.

GeoLaB is a collaborative effort led by the Karlsruhe Institute of Technology (KIT) that involves partnerships with the GFZ German Research Centre for Geosciences, the Helmholtz Centre for Environmental Research (UFZ), the Federal Company for Radioactive Waste Disposal (BGE), and the Technical University of Darmstadt. Conceived over a decade ago, GeoLaB is an ambitious research infrastructure aimed at advancing our understanding of deep geothermal resources in crystalline rocks. With a €50 million investment, GeoLaB is developing an URL in the Odenwald massif, near the Rhine Graben, to investigate the physical and chemical interactions within deep geothermal reservoirs. This facility will serve as a real-field, 4D reservoir simulator, providing a dynamic environment for experiments that complement the industrial EGS development in central Europe. GeoLaB's experiments will be conducted in interconnected caverns accessed via a central main gallery, and the project will explore several key aspects of geothermal energy production, including structural heterogeneities in the reservoir, the dynamics of hydraulic fracturing and fluid injection, and the long-term stability of the geothermal system. One of the key goals of GeoLaB is to advance our understanding of the interactions between fluids, rocks, and induced seismicity in deep geothermal reservoirs. By focusing on these critical dynamics, GeoLaB aims to identify strategies that can improve the efficiency and sustainability of geothermal energy production while minimizing seismic risks.

The project has made significant progress since its inception, with drilling and exploration wells already underway in the Odenwald massif. This initial phase, which includes comprehensive geophysical data acquisition, is set to continue until the beginning of 2026. Following this, the planning and permitting process for the main gallery will begin, with drilling and commissioning scheduled to start in 2029. GeoLaB is expected to become fully operational by 2032, at which point it will become one of the leading research facilities for deep geothermal systems in Europe.

THIS MANUSCRIPT PROVIDES AN UPDATE ON THE €50 MILLION GEOLAB PROJECT, WHICH IS DEVELOPING AN UNDERGROUND RESEARCH LABORATORY (URL) IN CRYSTALLINE BASEMENT ROCK (KOHL ET AL., 2023). 2. EXPLORATION

A comprehensive multi-criteria catalogue had been created to assess potential exploration areas, considering geological, geotechnical, political, and environmental factors. This evaluation identified the "Tromm" field in the State of Hesse as the primary exploration site. In compliance with the German Federal Mining Act (BBergG), the formal permitting process was initiated by submitting a permit application to the relevant authorities, seeking approval for the commercial exploration of geothermal heat, brine, and lithium in the "Tromm" field. The aim of the current exploration phase is to demonstrate the suitability of the Tromm region as a prospective site for the future research laboratory infrastructure. Baseline measurements and monitoring measures have been and are being carried out to demonstrate the suitability of the site and to minimize the environmental impact of the operation.

2.1 Geology

The Tromm pluton is regarded as a relatively uniform granitic body in the Odenwald Crystalline Complex providing favourable pre-conditions for controlled high-flow experiments, poorly influenced by geological boundary conditions that are too complex. Therefore, we have reviewed the current status of primary and secondary geological features and properties in the Odenwald crystalline complex to summarize not only the current status of knowledge, but also to identify knowledge and data gaps and future research demand.

The Tromm pluton appears to be composed of at least two magma suites: a prevailing quartz-monzonite suite in the central and northern part of the Tromm pluton and a granite suite in the south. However, little is known on basic pluton characteristics: thicknesses, root zones, original geometries, zonation, magma differentiation processes, petrogenesis, and emplacement. Geochemical and isotope as well as geophysical and structural data and modelling approaches are needed to achieve a better understanding of the Tromm pluton. Outcrops in the Tromm pluton show preferred NNW-orientation of fractures presumably displaying high dilation tendencies within the regional stress field, hence enabling infiltration of meteoric fluids into crystalline basement. Hydrochemical data from fluids tapped by wells and springs in the lowlands around the Tromm ridge, the exploration well Tromm-1, and the future gallery will help to verify this.

To characterize outcrop rocks, rock samples were analyzed with regard to mineralogy and petrology by XRD power diffraction, electron microprobe, and X-Ray fluorescence. Flow-Through-Experiments were carried out to quantify possible mineral precipitation during the extraction of fluid through the rock formation.

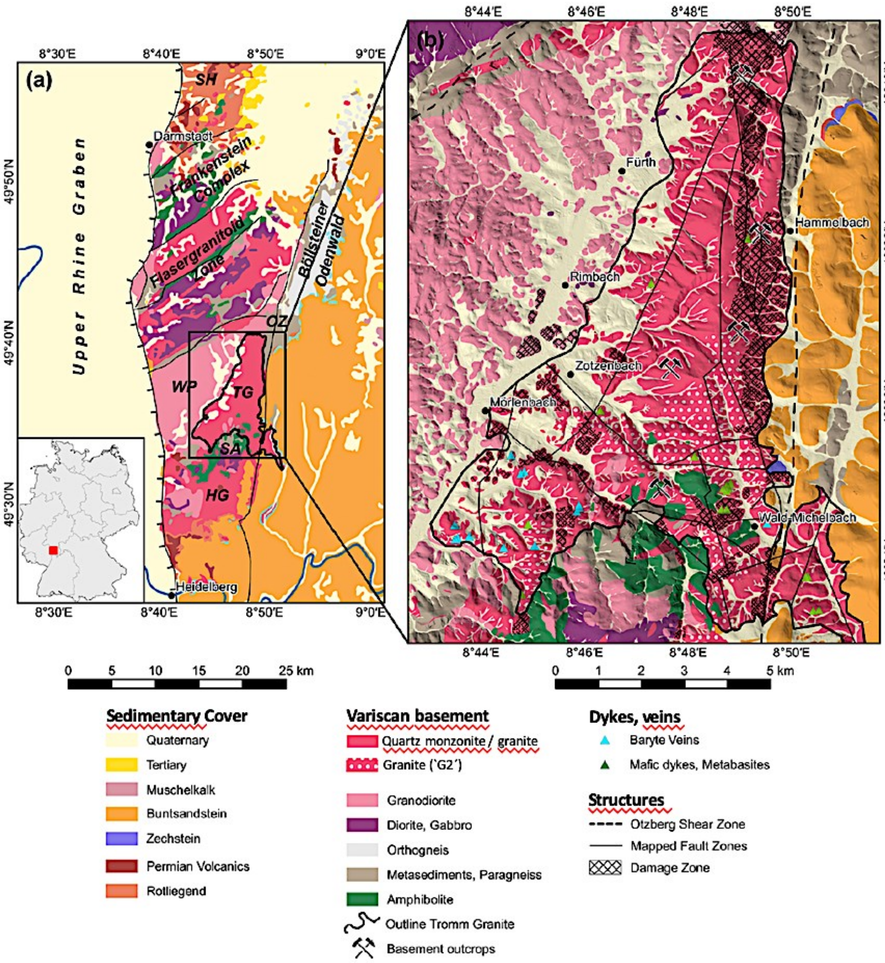

Figure 1: Overview of the Tromm pluton and its boundaries (modified from Frey et al., 2022).

2.2 Hydrogeology

For the construction of the GeoLaB underground research facility, it is essential to clarify the extent to which the crystalline basement participates in the water cycle of the surrounding catchment areas. Specifically, there needs to be an understanding of whether significant volumes of water flow from the deeper parts of the crystalline basement to the valley aquifers, especially in comparison to the influence of the granular disintegration zone near the surface. Additionally, it is important to assess whether the catchment areas delineated above ground based on elevation profiles are congruent with the underground catchment areas. This knowledge will be critical for understanding potential hydrological impacts resulting from the operation of GeoLaB.

Baseline measurements and hydrogeological monitoring have been ongoing since July 2024, with the primary goal of tracking any changes in the groundwater system that could be induced by or influence the operation of the facility. Initial hydrogeological investigations have provided important insights into the groundwater characteristics in the Tromm granite. These early findings indicate that, at higher altitudes, the groundwater is predominantly Mg-SO_4(HCO_3)-water. In contrast, lower elevations, such as valleys, feature groundwater that is primarily Ca-HCO_3, with an increase in total dissolved solids (TDS). The Quaternary deposits in the region are particularly influential, as they significantly affect the concentrations of calcium and hydrogen carbonate in the groundwater samples from the western part of the study area.

The analysis of groundwater samples has also revealed clear anthropogenic influences, with elevated levels of phosphate and nitrite. These findings suggest that human activities are contributing to changes in groundwater composition, possibly due to pollution or industrial discharge. The sulfate content in the groundwater seems to be influenced by sulfuric acid in exhaust gases, while disturbed nitrate and sulfate reduction patterns are likely attributed to the aerobic conditions present in the groundwater system. Further analysis of metals has shown a positive correlation with TDS content, and elevated concentrations of iron (Fe), manganese (Mn), copper (Cu), cobalt (Co), zinc (Zn), and uranium (U) were detected in a significant portion of the groundwater samples, again suggesting anthropogenic impacts.

Rare earth elements (REEs) also provide valuable insights into the groundwater chemistry. The concentrations of REEs are pH-dependent, leading to distinct signature curves for each well and spring. Interestingly, springs exhibited higher total concentrations of REEs, with light REEs showing slight enrichment compared to heavy REEs. A consistent positive europium (Eu) anomaly was observed across all groundwater samples, likely resulting from the weathering of potassium feldspar in the crystalline rock. Furthermore, an altitude-dependent gradient in the depletion of stable isotopes δ^2H and δ^{18}O was noted, indicating variations in the water's source and history.

While these findings offer valuable information, they also highlight that crucial questions regarding the watershed and groundwater dynamics remain unresolved. Specifically, the results suggest that the groundwater in the western part of the study area likely shares a common genesis with the higher elevations of the Tromm Plateau, transitioning from a Ca-(HCO3)SO4 composition to a Ca-HCO3 composition due to additional mineralization. Moreover, a distinct hydrochemical signature marks the transition from the Tromm granite to the Buntsandstein-Odenwald boundary. However, the study was unable to derive hydrochemical patterns that could conclusively indicate mixing or transition zones, which are critical for understanding subsurface water flow.

2.3 Exploration well GLB-1

Currently the first exploration borehole GLB-1 is being drilled. This borehole aims at proofing the necessary stress condition that are needed in the experimental part of the GeoLaB. In order to carry out controlled high flow experiments, fractures need to be favorably oriented for reactivation in the ambient stress field (Schill et al., 2016). This is an intrinsic pre-requisite of GeoLaB. Since the stress field orientation across the European crystalline basement is highly variable, no specific stress field can be chosen, but a favorable reactivation potential has to be considered instead. Since the geothermal resources occur in normal or strike-slip regimes rather than thrust fault regimes, we may consider the latter as less favorable. Non-representative, atypical stress perturbation resulting from, e.g. the glacial rebound should be avoided. In mountain regions, significant perturbations of the regional stress field pattern by local topography need to be taken into account. To avoid such additional variation in the stress field that biases future experiments with respect to reservoir condition, for the GeoLaB design, it is strived for a maximum variation in magnitude of the principal stress of <10 %. Depending on the topography of a potential URL site, a minimum depth below terrain level has to be considered.The next GLB-2 borehole shall already be drilled with a noticeable dog-leg in Q2 2025, depending on the results of GLB-1.

Figure 2: Preparation of the drill site for the first exploration well GLB-1 with the drilling site being protected with a noise barrier and the drilling rig.

2.4 Geophysical exploration

In 2024, a crucial first step was taken with the completion of a 2D seismic survey aimed at exploring the geological structures beneath the surface, particularly to delineate fault zones. This seismic survey serves as a foundational component in the larger effort to understand the subsurface conditions in preparation for future exploration and construction activities. Additionally, plans are already in motion for a more comprehensive 3D seismic survey that will provide a more detailed, three-dimensional understanding of the geological framework. Beyond seismic surveys, additional geophysical methods were initiated in 2024, including gravimetry, magnetics, and electrical resistivity tomography (ERT).

Figure 3: Seismic vibration source vehicle Inova Univib and Sercel Wings seismic recorder used in the first seismic campaign.

3. DIGITAL TWIN DEVELOPMENT

The GeoLaB project is advancing the development of a Virtual GeoLaB as a digital twin of the planned and the prospective physical underground research laboratory. Virtual GeoLaB offers assistance in the areas of infrastructure planning and construction, and later in planning, conducting and analyzing experiments.

Central to the Digital GeoLaB efforts is the establishment of a data transfer and storage system and the creation of visualization tools to build a fully interactive, three-dimensional digital representation of the laboratory, integrating all available datasets. Developing methods for a suitable visualization of the various categories of data will become essential for working with the data on an interdisciplinary level. The Virtual GeoLaB will provide support for researchers when analyzing or verifying their data. This is particularly relevant for large datasets, such as lineament analysis data or the results of numerical simulations. Digital twins of the experiments will be shared globally, facilitating analysis and training the next generation of geothermal experts.

4. CONCLUSIONS

A core element of GeoLaB’s mission is to cultivate a new generation of highly skilled professionals equipped to navigate the complex thermal-hydraulic-mechanical-chemical (THMC) processes in fractured rock. This expertise is crucial not only for advancing geothermal energy production but also for addressing the multi-disciplinary challenges associated with subsurface energy systems. By training scientists and engineers in these complex interactions, GeoLaB aims to ensure that the geothermal sector has a steady stream of talent capable of overcoming the technical hurdles of deep geothermal resource extraction.

Additionally, GeoLaB will focus on developing safe and efficient geothermal production strategies that are tailored to the specific geological and mechanical conditions of each site. Just as the unconventional hydrocarbon industry has evolved to deliver cost-competitive thermal and electrical energy, geothermal energy must also demonstrate its potential for affordable, large-scale energy generation. Through its cutting-edge research, GeoLaB will support the development of geothermal systems that can compete with traditional energy sources, driving the industry towards commercialization and long-term sustainability.

At the heart of GeoLaB’s strategy is a commitment to innovation. This will be achieved by supporting fundamental research into new analytical techniques for characterizing subsurface conditions, particularly the structural and geological constraints that govern fluid flow and energy extraction. By improving our understanding of fractured rock dynamics, GeoLaB will play a pivotal role in advancing stimulation strategies, potentially unlocking new geothermal reservoirs that were previously considered inaccessible or uneconomical.

The densely populated Upper Rhine Graben presents unique challenges that differentiate it from more sparsely populated regions like the Great Basin. In particular, the potential for induced seismicity due to fluid injection and circulation requires careful consideration. GeoLaB will prioritize the evaluation of seismicity, using real-time monitoring systems to assess and mitigate seismic risks. Drawing lessons from the unconventional hydrocarbon industry—where advancements in drilling and fluid management have successfully mitigated seismic events—GeoLaB will apply similar innovative techniques in the geothermal sector to minimize the risk of induced seismicity while maximizing energy production.

GeoLaB’s efforts will also build on the collective experience gained from underground research facilities worldwide. By leveraging this knowledge, GeoLaB will contribute to a deeper understanding of the dynamics of underground rock formations, which is essential for ensuring both the safety and sustainability of geothermal energy production. This collaboration with global geothermal operations ensures that GeoLaB remains at the forefront of geothermal research, informed by the latest advances in underground resource management.

The flexibility of GeoLaB’s infrastructure will allow it to explore a wide range of innovative concepts. Dedicated caverns, along with the potential for future surface and subsurface drilling, will enable the testing of advanced ideas such as geothermal energy storage. In addition, GeoLaB will investigate the co-extraction of valuable resources, such as lithium, alongside geothermal energy production, thus contributing to the growing field of sustainable, multi-use resource management. These efforts will not only enhance the economic viability of geothermal operations but also ensure that geothermal energy plays a key role in the broader transition to a sustainable, low-carbon energy future.

In summary, GeoLaB is poised to lead the way in overcoming the technical, environmental, and economic barriers to large-scale geothermal energy production. By combining cutting-edge research with practical, field-based experiments and fostering collaboration across disciplines, GeoLaB will ensure that geothermal energy becomes a reliable, cost-competitive resource for the global energy market..

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