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GeoLaB – an URL for Geothermal Energy is on its way

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ABSTRACT

GeoLaB (Geothermal Laboratory in the Crystalline Basement) constitutes a novel underground research infrastructure (URL), presently in its exploration and confirmation of site suitability phase, tailored to investigate coupled thermal, hydraulic, mechanical, and chemical (THMC) processes in fractured crystalline rock and advance understanding and implementation of Enhanced Geothermal Systems (EGS). Located in Germany, GeoLaB aims to bridge the gap between laboratory research and field-scale geothermal applications. This paper presents the scientific exploration progress, strategic development, and project management framework of GeoLaB. As a collaborative initiative between leading Helmholtz Centres and academic partners, GeoLaB represents a cornerstone for Europe's sustainable heating transition and international geothermal innovation. Through its interdisciplinary approach and integration of digital technologies, the project will contribute to safer, more efficient geothermal development and fosters global partnerships to advance renewable energy science.

1. INTRODUCTION The imperative to achieve climate neutrality while ensuring a secure and sustainable energy supply has brought geothermal energy into sharp focus within the discourse on low-emission energy provision. With thermal energy demand accounts for nearly 60% of Germany's total energy consumption alone, transitioning to sustainable and reliable, base-load capable energy sources is critical. Among these, deep geothermal systems in fractured crystalline basement rock offer a high-energy-density, low-carbon solution with significant spatial potential for urban and industrial environments. However, the broad implementation of Enhanced Geothermal Systems (EGS) remains constrained by persistent knowledge gaps, uncertainties in reservoir behaviour, and societal concerns—most notably regarding induced seismicity

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GeoLaB (Geothermal Laboratory in the Crystalline Basement) has been established to address these critical challenges. Currently in its initial exploration and confirmation of site suitability phase, which precedes the subsequent planning and permitting, and construction phases, GeoLaB is envisioned as a permanent, large-scale underground research infrastructure (URL) to investigate coupled thermo-hydro-mechanical-chemical (THMC) in-situ processes under controlled, high-flow in-situ conditions. Situated in the thermally anomalous tectonic regime of the Upper Rhine Graben, the planned facility aims to further the fundamental understanding of deep Geothermal Energy and develop new technological standards for EGS while fostering public engagement and stakeholder confidence through transparency and interdisciplinary cooperation. The facility will support Germany's energy transition goals and contribute to the broader European and global decarbonization agenda by enabling research that closes the scale gap between laboratory experiments and field applications.

2. MAIN SECTION

2.1 Scientific and Strategic Goals

GeoLaB's scientific agenda is predicated in the need for reliable, data-driven insights into deep geothermal reservoir behaviour within fractured crystalline formations. The planned facility as a versatile platform to facilitate cross-disciplinary, in-situ experimentation under realistic hydraulic and thermal boundary conditions. Four primary research domains form the conceptual backbone of the initiative:

- **Coupled THMC Processes:** The facility will enable high-resolution analysis of thermally, hydraulically, mechanically, and chemically coupled processes. In-situ experiments will examine transient interactions among heat flow, fluid transport, stress regimes, and chemical

alteration—in crystalline rock, anchored in preliminary modelling, data from boreholes, and field campaigns.

- **Induced Seismicity and Risk Management:** GeoLaB’s concept integrates real-time seismic monitoring and probabilistic risk modelling and will therefore play a vital role in enhancing the understanding of induced seismicity and demonstrating measures to minimize risks, providing a roadmap for future mitigation strategies.
- **Reservoir Stimulation and Optimization:** Preparatory numerical studies and analogue field experiments will be used to explore hydraulic stimulation approaches and optimize flow behaviour .
- **Digital Innovation and Simulation Validation:** The digital GeoLaB twin is already under active development. Providing a virtual proxy for the physical laboratory, allowing simulations and design validations to proceed simultaneously with site characterization.

By articulating its strategic research priorities in this early stage, GeoLaB establishes the epistemic, technical, and institutional foundations necessary for a scientifically credible and operationally scalable geothermal laboratory infrastructure.

2.2 Project Management and Organizational Framework

The project management framework of GeoLaB is deliberately aligned with the dynamic requirements of a complex, large-scale infrastructure initiative in its early-stage development. During the ongoing exploration phase, efforts focus on coordination of interdisciplinary research, technical and legal risk assessment, stakeholder engagement, and regulatory scoping in accordance with the Federal Mining Act (BBergG).

Milestone-Based Approach: The project employs a milestone-based project logic, structured into the following sequential phases:

- Exploration (2023–2025): Site screening, non-invasive geophysics, stakeholder dialogue, and the drilling of two deep boreholes (GLB-1 and GLB-2) form the basis for geological and hydrogeological characterization.
- Planning and Permitting (2025–2027): This phase will include the submission of regulatory documents, detailed infrastructure design, and environmental assessments under mining and construction law.
- Construction (from 2028): Subject to regulatory approval, construction of the underground laboratory, above-ground facilities, and supporting infrastructure is scheduled to commence.
- Operation (from 2030): Upon commissioning, GeoLaB will function as a long-term experimental platform for EGS-related process research and monitoring, as well as for research and development in adjacent scientific and engineering fields such as drilling, monitoring technologies, engineering innovations, and remote sensing.

Governance and Transition Preparation : In anticipation of the complex challenges associated with subsurface laboratory construction, procurement strategies, risk mitigation protocols, and staffing structures are being established to enable a seamless transition from the current Exploration phase to the subsequent Planning and Permitting stage.

Project coordination is led by the Karlsruhe Institute of Technology (KIT), in collaboration with the Helmholtz Centres GFZ and UFZ and the TU Darmstadt, our university partner. A structured hierarchy ensures scientific rigor and strategic coherence:

Executive and Scientific Advisory Boards: The executive board integrates institutional leadership with external advisory input and comprises representatives of the core institutions and external scientific advisors. It ensures strategic coherence and scientific excellence. An international scientific advisory board guides research priorities and normative, ethical frameworks..

Working Groups (WGs): Specialized working groups are responsible for the key project domains: Planning (WG-P), Technical Implementation (WG-T), Communication and Engagement (WG-C), Science (WG-S) and Digital Innovation (WG-CS). Each group includes members from all institutions, with designated leads. A dedicated Project Office GeoLaB was also established.

Integrated Project Delivery (IPD): Recognizing the inherent uncertainties in underground infrastructure projects, and the limitations of conventional linear planning, GeoLaB has adopted the Integrated Project Delivery (IPD) model. This collaborative delivery framework synchronizes interests across all stakeholders—clients, planners, and contractors—through early-stage involvement, transparent communication, and joint risk ownership. These features enable more agile decision-making and foster a problem-solving culture that is particularly valuable in research construction. (Weinmann et al. 2024)

Experience from similar infrastructure projects underscores IPD’s capacity to minimize cost escalations and timeline overruns. compared to conventional linear planning approaches (Groß et al. 2024). Recognizing this risk, and acknowledging that KIT’s experience with underground laboratory construction is limited, a strategic decision was made to adopt the Integrated Project Delivery (IPD) model for GeoLaB.

KIT has secured targeted funding to engage a professional IPD coach for process facilitation and internal capacity building, as well as Scientific

evaluation support of IPD's institutional integration within the KIT project management environment.

These investments not only support the current project but are also intended to build institutional learning capacity for future complex infrastructure undertakings. The procurement of the IPD coach was finalized in 2024; implementation begun in 2025.

Legal and Regulatory Coordination: The permitting process under the German Federal Mining Act was formally initiated in 2023. A specialized legal and regulatory team ensures procedural compliance with safety, environmental, and labor legislature to align GeoLaB's development with statutory frameworks for subterranean research construction.

2.3 Exploration Progress and Site Characterization

The ongoing exploration and site characterization phase constitutes a pivotal component of the GeoLaB initiative, providing the empirical basis for design decisions and regulatory assessments. This phase commenced in 2023 with the development of a multi-criteria catalogue integrating geological, geotechnical, environmental, infrastructural, and socio-political parameters to enable a transparent and evidence-driven site selection process.

Three candidate regions were initially identified: the northern Black Forest, the southern Black Forest, and the Odenwald. Following a comprehensive review of existing geological and geophysical datasets—coupled with early-stage consultations involving stakeholders, regulatory authorities, and local communities—the Odenwald region was selected as the preferred target for intensified investigation. Following the decision mentioned above, a publicly tendered and scientifically coordinated exploration campaign was launched, spearheaded by a collaboration of leading geoscientific institutions and specialized contractors. It employed a suite of advanced geophysical methods, including gravimetric, geoelectrical, and geomagnetic surveys, to delineate near-surface heterogeneities and regional structures. A 2D seismic survey was conducted to resolve deeper stratigraphy and guide borehole positioning.

In early 2025, the first vertical research borehole, GLB-1, was successfully drilled. This milestone marked a significant achievement for the project, yielding valuable core samples and in-situ logging data, which now inform a refined geological site model encompassing lithological architecture, fracture distribution, thermal properties, and fluid migration pathways. This model is being continuously updated through the integration of legacy data and field measurements. providing comprehensive understanding of the site's geological and hydrogeological framework.

The next major step involves the planning and drilling of a second, deviated borehole—GLB-2, designed to provide additional insights into the site's structural configuration and hydraulic permeability. GLB-2 will serve as a critical validation step for the geological model and inform the final decision regarding the suitability of the Odenwald site for hosting the future underground laboratory.

Collectively, these efforts represent a rigorous and transparent approach to site evaluation, ensuring that any subsequent phases of planning, permitting, and construction are founded on robust, scientific and traceable knowledge as well as communal engagement

3. CONCLUSIONS

GeoLaB stands at a decisive inflection point within the lifecycle of a multi-decade research infrastructure initiative. While the physical construction of the facility has yet to begin, the ongoing Exploration phase has already generated substantial scientific and procedural value. Key achievements include the establishment of a robust geological knowledge base, the implementation of digital modeling frameworks, the activation of interdisciplinary governance structures, and the cultivation of stakeholder dialogue.

Forthcoming priorities include the drilling of the second deviated borehole (GLB-2), finalization of the site suitability assessment, and the preparation of regulatory documentation and technical specifications for the Planning and Permitting phase. The scientific insights, methodological tools, and institutional arrangements developed thus far constitute the essential foundation upon which the subsequent realization of a high-performance underground research laboratory will be built

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