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Forschungslabor Geothermie

HELMHOLTZ

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GeoLaB Infrastructure Development

The GeoLaB Team: KIT, GFZ and UFZ
in cooperation with BGE and TU Darmstadt

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1 INTRODUCTION

JUDITH BREMER, THOMAS KOHL

1.1 OVERVIEW OF THE 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 resources utilizing highly permeable rock formations are currently experiencing the greatest development, as is currently being impressively demonstrated in the Munich area. However, crystalline, so-called “petrothermal” resources of the crystalline basement as predominant class of rock formations hold the greatest energy potential (Figure 1-1). 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.

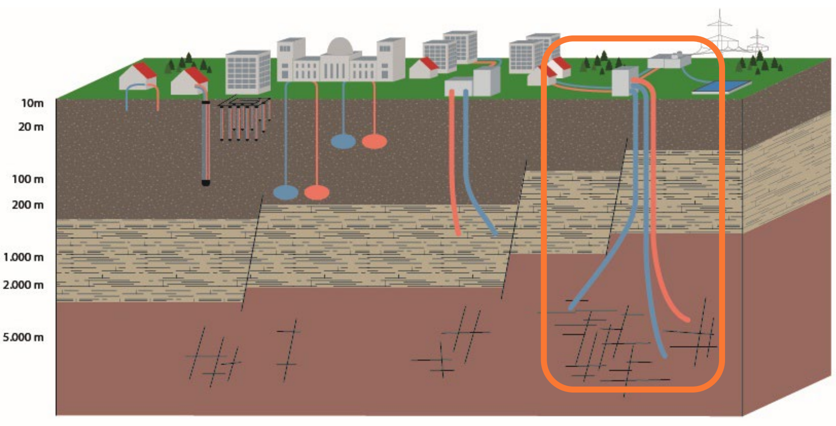

Figure 1-1: Geothermal energy systems. From near-surface and low-temperature to deep, high-temperature utilization systems. GeoLaB focuses on EGS systems in deep fractured crystalline basement rock (orange rectangle).

The GeoLaB (Geothermal Laboratory in the Crystalline Basement) 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. 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 1-2), the facility will include a gallery leading to a cavern situated under approximately 400 meters of rock (Figure 1-3). 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 1-4).

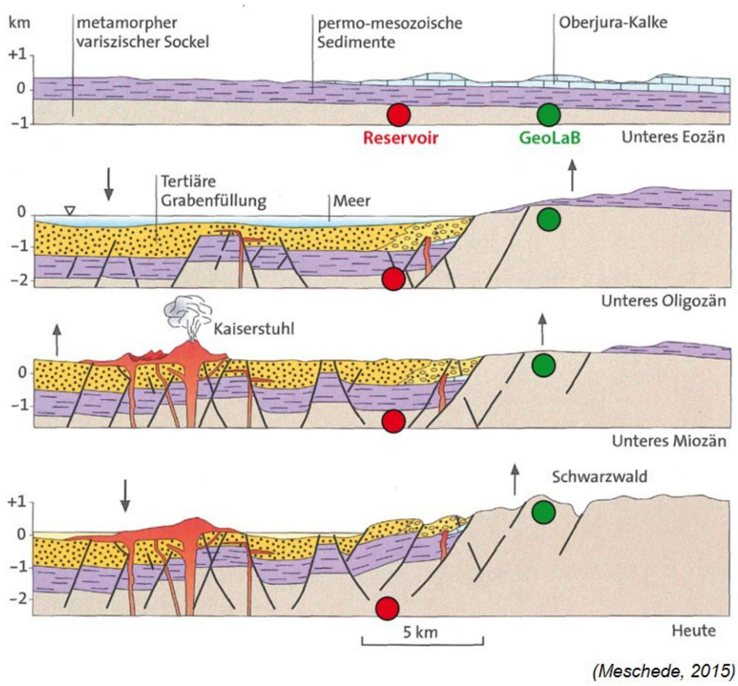

Figure 1-2: The formation of the Upper Rhine Graben (URG). In the Schwarzwald/Odenwald complex the reservoir rock of the deep URG is accessible to research.

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.

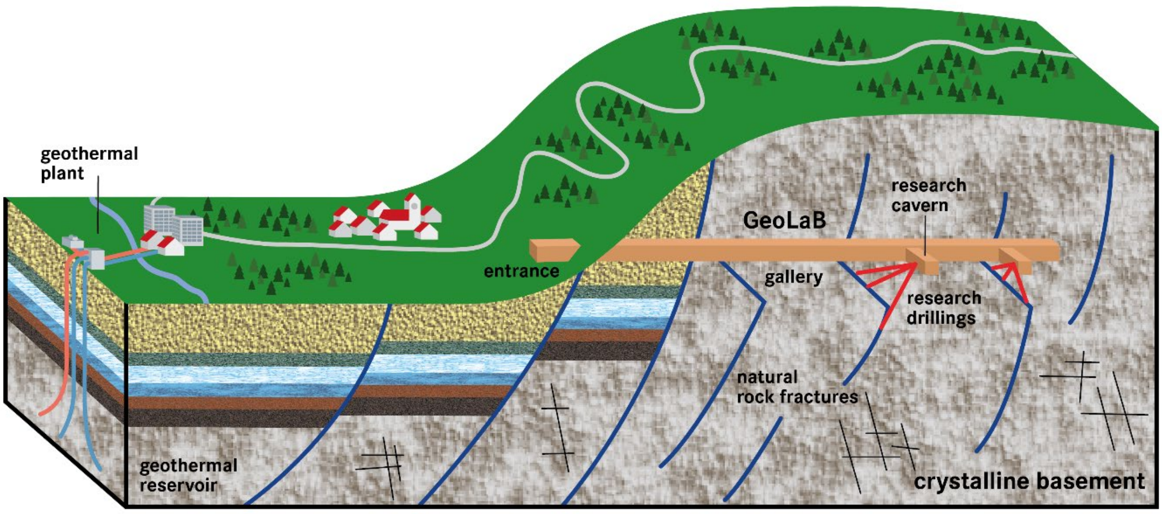

Figure 1-3: Overall setup. The GeoLaB project has been conceived for implementation in the Black Forest–Odenwald region along the Upper Rhine Graben, where elevated subsurface temperatures result in a high geothermal potential. In this mountain range, the crystalline basement rock is accessible, enabling in-situ research and observation of fluid-rock interactions across space and time.

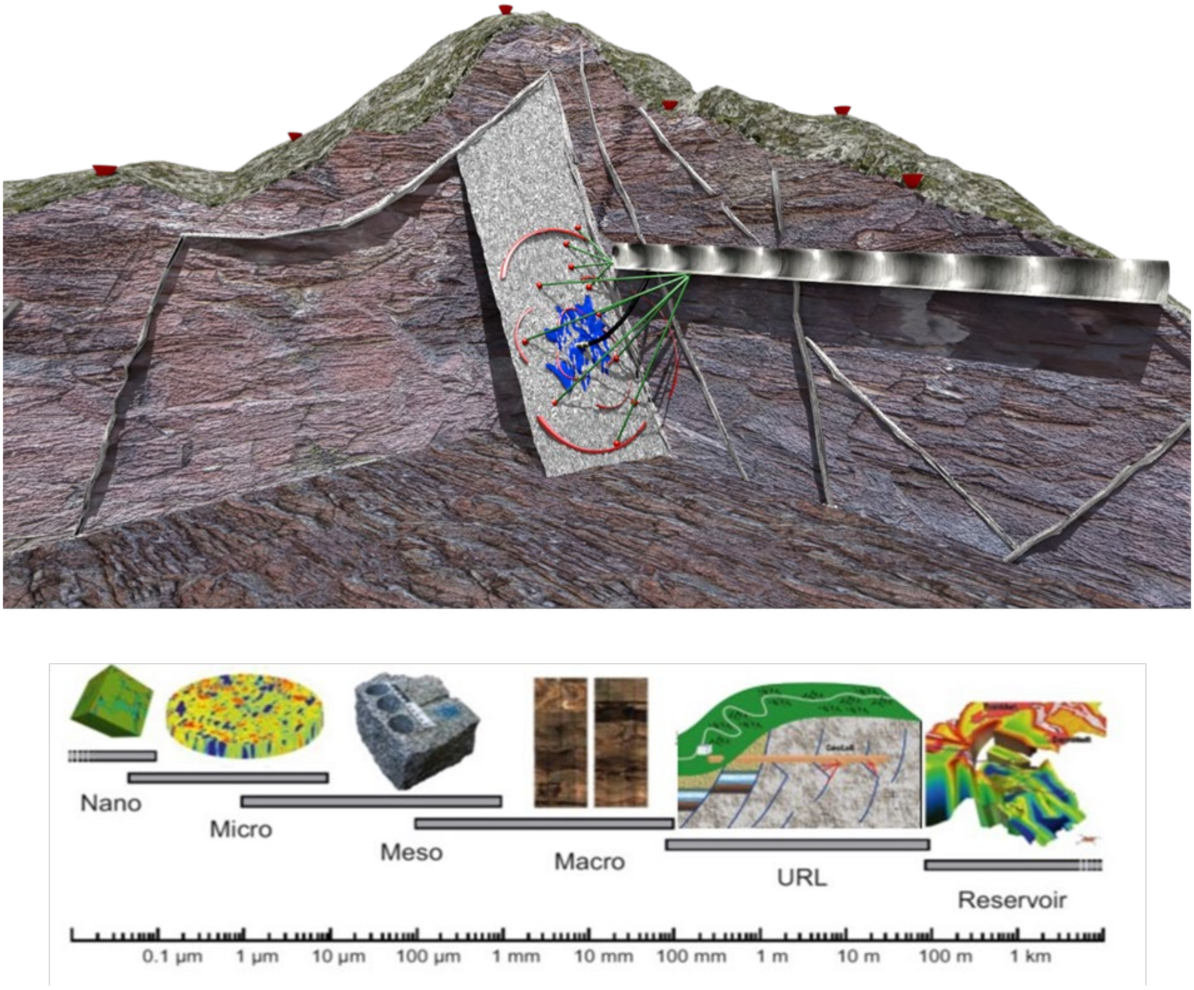

Figure 1-4: Experimental set-up. With its planned controlled high-flow experiments in fractured crystalline rock (top), GeoLaB will close the scale-gap between laboratory experiments and reservoir tests in demonstration projects (bottom).

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 1-5).

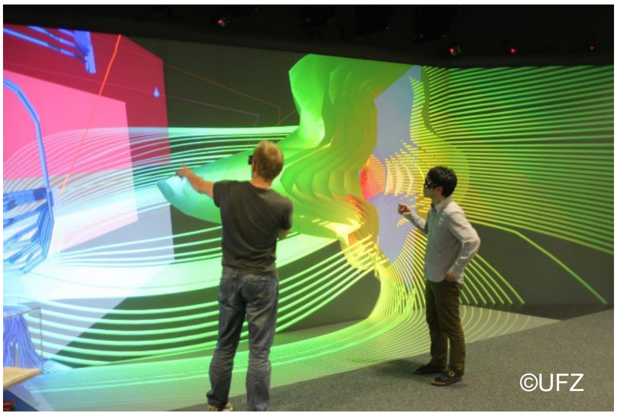

Figure 1-5: Digital twins make the underground digitally accessible and science more tangible

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.

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. In this way, long-term energy supply is combined with sustainable resource utilization in interdisciplinary research.

By scientifically addressing technological, environmental, and societal challenges, GeoLaB will play a pivotal role in advancing geothermal energy utilization and supporting the heating transition.

1.2 STATUS AND PRIORITIES FOR 2024

GeoLaB represents a competitively acquired strategic expansion investment of €35 million by the Helmholtz Association. The BGE (Bundesgesellschaft für Endlagerung) has additionally committed €15 million.

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.

The infrastructure project commenced in 2023 and comprises three phases (Figure 1-6). During the initial exploration phase, the suitability of the Tromm region in the Odenwald will be investigated and the GeoLaB test field will be established. If the various suitability criteria are successfully met, the subsequent planning and construction phases will follow. These phases will conclude with a test operation of GeoLaB, which shall then transition to the operational phase in 2032.

In the years 2023 and 2024, the exploration tasks were planned and initiated including the preparation of the first exploration well, GeoLaB-1 (GLB-1). This entailed the establishment of project management structures and workflows. Investigations were conducted with the objective of establishing a geological and hydrogeological knowledge database, which will serve as the foundation for future exploration efforts. The implementation of the Digital GeoLaB as a digital prototype and subsequently as a digital twin was initiated with the implementation of a data management system and a visualization of the Tromm region. The importance and critical function of communication with local stakeholders and beyond was demonstrated already in the initial stages of the project. Even prior to the start of the infrastructure project, the strategic-scientific development of this research infrastructure was identified as a priority. During the initial project phase, the engagement of universities resulted in the formation of a significant joint DFG initiative, and further strategic partnerships were initiated.

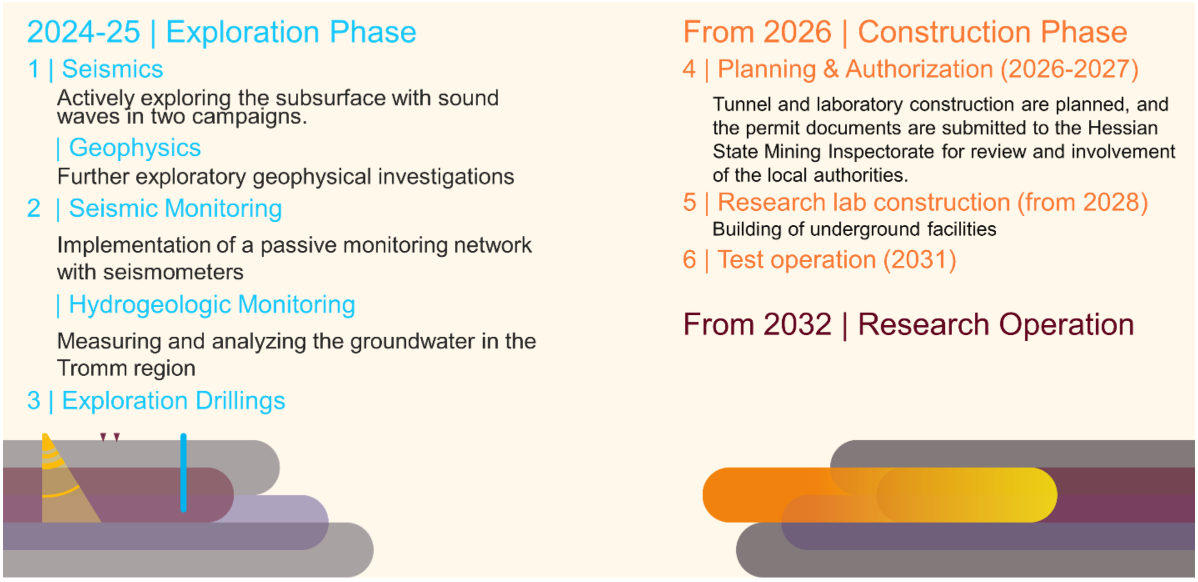

Figure 1-6: Project phases. The project phases of the complex infrastructure project GeoLaB – from exploration to operation.

2 STRATEGIC SCIENTIFIC DEVELOPMENT

THOMAS KOHL, INGO SASS, OLAF KOLDITZ, JUDITH BREMER

2.1 INITIAL SITUATION AND STRATEGIC GOALS

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[1], 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. The 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 geothermal 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

[1] Acksel, D., Amann, F., Bremer, J., Bruhn, D., Budt, M., Bussmann, G., Görke, J.-U., Grün, G., Hahn, F, Hanßke, A., Kohl, T., Kolditz, O., Regenspurg, S., Reinsch, T., Rink, K., Sass, I., Schill, E., Schneider, C., Shao, H., Teza, D., Thien, L., Utri, M., Will, H.: Roadmap Tiefe Geothermie für Deutschland I Handlungsempfehlungen für Politik, Wirtschaft und Wissenschaft für eine erfolgreiche Wärmewende” Edited by Rolf Bracke and Ernst Huenges, 2022. https://doi.org/10.24406/ieg-n-645792.

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 Enhanced Geothermal Systems (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 underground laboratory research.

GeoLaB will investigate **structural heterogeneities** and the **dynamics of hydraulic 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. Data of experiments will be shared with research centers worldwide, facilitating analysis and training the next generation of geothermal experts.

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 hydrocarbon 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. Learning from the advancements in unconventional hydrocarbon production, which successfully mitigated seismicity through innovation, GeoLaB aims to apply these lessons to the geothermal 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.

2.2 MAIN STEPS AND ACHIEVEMENTS

GeoLaB was acquired through the Helmholtz Association‘s competitive procedure for strategic expansion investments. From the outset, the strategic scientific development of GeoLaB has been based on a structured and progressive approach that encompasses preliminary research, build-up of expertise, scientific site exploration, strategic partnerships with various research groups and complementary underground research facilities, and digitalization efforts. These steps ensure that GeoLaB evolves into a state-of-the-art underground research facility for deep geothermal energy. This chapter highlights the key milestones achieved in these domains and outlines the foundation laid for future scientific advancements.

2.2.1 Preliminary Work and On-going Build-up of Expertise

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. A list of respective publications can be found in the Appendix (Chapter 10.210.2). Collectively, the publications reflect an interdisciplinary approach on studying the dynamics of fractured geothermal reservoirs.

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.

Public relations is key to any infrastructure project, and this is particularly true for GeoLaB. In inter- and transdisciplinary projects, we have developed expertise in a wide range of **public engagement**, from communication to dialogue and participation. E.g., in a co-design project, local stakeholders were involved in developing and evaluating acceptance criteria and scenarios for a sustainable heat supply of a campus. A geoethical concept for GeoLaB has been developed, with measures for research and science, environmental awareness, communication and knowledge transfer, and education. Recognizing that induced seismicity is a major factor influencing public acceptance, we have designed frameworks that empower non-experts to contribute to seismic monitoring using user-friendly tools such as plug-and-play seismometers.

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 hydrochemical 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 (Figure 2-1).

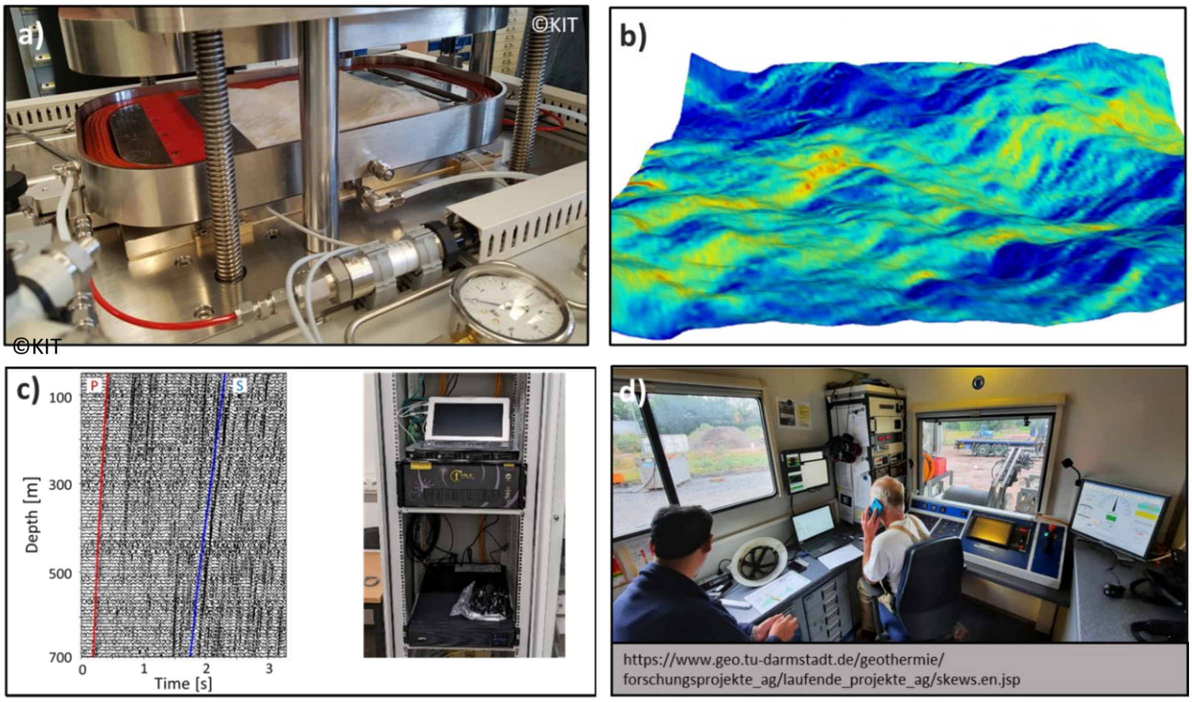

Figure 2-1: Examples of research areas of strategic relevance for the design, implementation and operation of GeoLaB: a) Hydromechanical laboratory experiments, b) Numerical simulations of turbulent flow through rough fractures, c) Advanced seismic monitoring (example of Distributed Acoustic Sensing (DAS) with interrogation unit at the Schäftlarnstraße geothermal field in Munich), d) Implementation of a geothermal storage infrastructure in crystalline rock.

2.2.2 Development of Strategic-scientific Cooperations

GeoLaB is a very complex infrastructure project that cannot be carried out by a single organization, but requires strong collaborations, for which the existing GeoLaB consortium has been established. GeoLaB also offers very extensive research opportunities. In order to fully exploit these and create necessary synergies, close involvement of the community is crucial.

On the national level, a concept was developed to **integrate university research** already into the planning and construction phases of GeoLaB. To foster scientific exchange**, DFG roundtable discussions** were held, the most recent in Leipzig (June 2023), where over 60 Principal Investigators participated in discussions on research opportunities at GeoLaB. This led to the formulation of a DFG priority program proposal under the acronym EMBRACE (pErMeaBility of fRActured Crystalline bEdrock), spearheaded by Prof. Dr. Virginia Toy (University of Mainz). Although this first proposal did not achieve the desired outcome in the first round, the feedback received will support a learning curve. A revised version is currently being prepared for re-submission in 2026. Therefore, the next round table meeting is already planned.

Several further scientific-strategic partnerships and collaborations were initiated or strengthened in 2024:

- **TU Bergakademie Freiberg** (TUBAF): Plans for structured cooperation with the Underground Research Mine "Reiche Zeche" are underway, with an agreement targeted for 2025.
- **TU Clausthal-Zellerfeld** (TUC): A research collaboration with the TUC is underway. Initial structural measures were implemented, and Prof. Dr. Ingo Sass joined the scientific advisory board of the Celle Drilling Simulator (DSC), an interdisciplinary infrastructure with a highly specialized experimental and simulation environment for experimental drilling and wellbore completion research. Such as GeoLaB, the research approach encompasses both fundamental and strong application- and transfer-orientated aspects. One key focus of this cooperation is fundamental research on improving wellbore integrity in crystalline formations for safe and efficient geothermal heat extraction.
- **Montanuniversität Leoben** (MUL), Austria: A cooperation (Prof. Dr. mont. David Misch – Energy Geoscience) on scientific hydrogen measurements and radon monitoring at the Tromm site has begun, with academic master's thesis work in progress. GeoLaB and MUL are currently working towards establishing a joint institutional research agreement.
- **DMT-Group**: In 2024, a cooperation agreement was signed to enhance seismic survey accuracy in crystalline formations. This included the acquisition of three vibroseismic trucks (1 GFZ, 2 DMT) and a 2D seismic pilot campaign in the Tromm region, with 3D MSP and VSP seismic surveys planned for 2025.
- **FORGE**: The exchange with the FORGE team was deepened, especially with respect to strategies fostering innovation, involving industry and technology transfer.
- **Bedretto Underground Laboratory**: GeoLaB is strengthening its collaboration with Bedretto through an active exchange of knowledge and experience. This includes on-site visits by GeoLaB team members to Bedretto, fostering direct insights into underground research infrastructure and experimental setups (Figure 2-2). Additionally, GeoLaB has engaged a former Bedretto researcher, who developed multi-disciplinary monitoring networks for mesoscale underground experiments, further enhancing expertise in subsurface sensing and experimental planning. Concrete plans are also underway for joint experiments in Bedretto, e.g., in the fields of sensor technology and advanced monitoring methods, aiming to refine measurement techniques and improve underground observation capabilities.

Figure 2-2: Knowledge transfer and exchange of experience: Members of the GeoLaB project team visit the Bedretto Lab of the ETH in Switzerland. Bedretto and GeoLaB, as geothermal research rock laboratory projects, have the potential to create valuable synergies.

2.2.3 Digitalization

GeoLaB has embraced digitalization as a core element of its strategic-scientific development. A key component is Virtual GeoLaB, a digital twin of the real laboratory that plays a crucial role from the planning phase onward. Building on the existing **VISLab infrastructure** at the UFZ as well as **virtual engineering** expertise and the data infrastructure **KADI4Geo** of the KIT realizing FAIR principles, it enables precise modeling and visualization of complex geothermal processes underground (Figure 2-3). Virtual GeoLaB supports infrastructure planning and construction, as well as the execution and analysis of experiments. Additionally, it enhances communication and visual analytics by making the invisible processes of deep geothermal energy comprehensible and facilitating knowledge transfer. This makes GeoLaB not only a physical but also a digital innovation hub for geosciences.

To accelerate and enhance the digital twin development, the **BMBF-funded joint project GeoDT** – Digital Twin GeoLaB is dedicated to creating a comprehensive digital twin. The project integrates geological modeling, process simulation, and data management using open-source platforms, ensuring intuitive access to complex geodata through VR-based visualization methods**.** GeoDT will build a prototype for the Tromm site and is unique in combining geoscientific and geotechnical aspects within a single digital framework. Industrial partners are already engaged in integrating digital drilling technologies into exploratory drilling, enhancing predictive modeling and operational efficiency.

GeoLaB aims to setting new standards in the digitalization of geosciences as well as underground laboratories through the targeted use of virtual reality technologies. This not only advances scientific research but also improves communication and decision-making in the GeoLaB research environment.

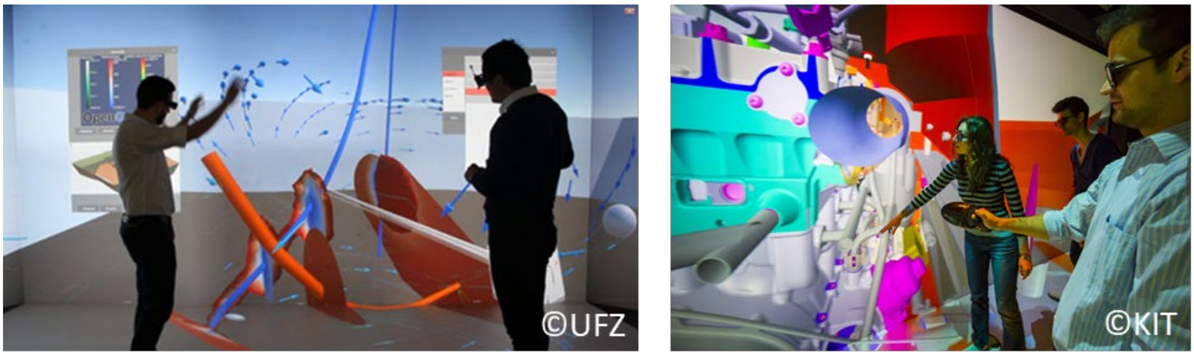

Figure 2-3: Virtual reality. Left: Visualization of temperature changes during experiments in a geothermal reservoir at the VisLab, UFZ. Right: Virtual engineering and immersive environments for education and stakeholder dialogues with PolyVR at KIT.

2.3 OUTLOOK

As this report is being finalized, the first GeoLaB exploration well, GLB-1, reached its final depth in March 2025, completing the first major milestone of the GeoLaB exploration phase. A preliminary assessment of the exploration results to date (see the Exploration chapter in this report) and the findings from GeoLaB-1 seem to support the scientific opinion that the Tromm site is technically suitable for constructing the GeoLaB facility. Without preempting the final exploration results, further strengthening the scientific justification for this site decision remains a key task for 2025/2026.

In parallel with the continued analysis of the **GLB-1**, planning of the second exploration well, **GLB-2**, has now been initiated. This second borehole will further refine the subsurface model and provide additional structural and geomechanical data. The insights gained from GeoLaB-2 will be crucial for validating the initial findings from GLB-1 and or finalizing the site suitability assessment.

A priority for the GeoLaB team is the initiation of a **DFG priority program**. The process of refining the proposal and structuring the research topics is already underway in collaboration with partners from all major German universities. The next step in 2025 involves sharpening the content, enhancing the networking between the DFG SPP and GeoLaB, and formulating the planned projects through further roundtable discussions. During the planning and construction phase of the GeoLaB tunnel facility, it is expected that the SPP will actively contribute to research preparations for experiments in the underground research laboratory (URL). The planned experiments and methodologies, developed as part of the SPP, are intended to be scaled up and implemented in the URL during the field research phase. This integrated approach will ensure that experimental designs are robust and that the transition from model-based predictions to practical, in situ applications is as seamless as possible.

The scientific community will be further engaged through the **1st GeoLaB Scientific Conference** in April 2025. This event will feature more than 60 scientists presenting creative contributions related to GeoLaB. Such engagement is expected to foster collaborative efforts and accelerate the exchange of innovative ideas across the geothermal research community.

In addition to borehole drilling and proposal development, the **scientific exploration work** will continue, e.g., with advanced seismic techniques such as 3D-MSP and VSP. GeoLaB management has also signed a letter of intent to participate in a unique airborne seismic campaign, which is expected to extend over the Odenwald. With this campaign, GeoLaB is poised to acquire a comprehensive set of airborne geophysical data that is expected to enhance our understanding of the regional subsurface characteristics.

Given the GeoLaB's scale and the diverse range of stakeholders, clear and effective **communication** from the outset is essential for its success. Additionally, geothermal technologies and research projects often face skepticism or even strong opposition. This perception of risk is further heightened by the involvement of the BGE in the implementation phase. Against this background, transparent information-sharing and open dialogue will remain crucial for this infrastructure initiative. We continue to approach this topic with great care and the necessary engagement and resources.

A further important strategic aspect is the deepening of **cooperation** and further creation of synergies **with complementary geothermal research infrastructures** such as Bedretto and FORGE. These collaborations will enable the exchange of knowledge and expertise, ensuring that the GeoLaB project benefits from best practices and innovative approaches developed in related facilities around the world.

The collaborative efforts, from drilling GLB-1 and GLB-2 to launching research initiatives and airborne surveys, demonstrate a forward-thinking strategy for realizing the GeoLaB project. The ongoing collaboration development between research institutions and industry partners will be pivotal in transforming research findings into sustainable geothermal technologies.

3
PROJECT MANAGAMENT

BASTIAN RUDOLPH

3.1 INITIAL SITUATION

The GeoLaB project, a strategic expansion investment and flagship initiative of the Helmholtz Association, was launched in 2023 as a collaborative endeavor involving KIT, GFZ, UFZ, TU Darmstadt, and BGE. GeoLaB aims to establish a globally leading underground research laboratory dedicated to advancing scientific understanding and technological development in the fields of geothermal energy, subsurface monitoring, and sustainable resource use.

The first project year was dedicated to creating the foundational structures required for successful long-term implementation. This included the development of the project's organizational framework, the initiation of key preparatory processes, and the establishment of a functional project governance system. A central milestone during this phase was the formation of formal collaboration agreements between the participating institutions, underpinned by clearly defined roles, responsibilities, and joint strategic goals.

To facilitate effective coordination and knowledge exchange across institutions and disciplines, dedicated working groups were created, addressing critical areas such as site selection, exploration planning, permitting, public outreach, and infrastructure development. Communication and project management tools, such as regular steering committee meetings, shared digital workspaces, and structured reporting formats, were implemented to support transparency, responsiveness, and operational coherence.

A comprehensive multi-criteria evaluation matrix was developed to guide the site selection process. This matrix integrated geological, geotechnical, environmental, infrastructural, and socio-political factors to ensure a robust and well-justified basis for decision-making. Following this assessment, the "Tromm" region in southern Hesse emerged as the most promising candidate for initial exploration activities.

To initiate the formal permitting process, the project team submitted an application under the German Federal Mining Act (BBergG), requesting a license for the commercial exploration of geothermal energy, lithium, and thermal brine at the Tromm site.

By the end of 2023, the project had achieved its primary objectives for the initial phase: securing institutional and legal frameworks, identifying a suitable exploration site, and initiating the permitting process. These achievements laid a solid foundation for the intensive technical and operational phases planned for the following years.

3.2 MAIN STEPS AND ACHIEVEMENTS

In 2024, GeoLaB transitioned from organizational setup to active fieldwork and implementation, marking a decisive phase in its development. The year was characterized by significant advancements in exploration activities, regulatory processes and further public engagement.

Exploration and Permitting Activities

Early 2024 saw the launch of detailed planning for a suite of exploration measures. These included:

- A **seismic campaign**,
- **Potential field geophysical surveys** (gravimetric, geoelectric, and geomagnetic),
- **Seismic monitoring** to establish environmental conditions prior to drilling,
- **Hydrogeological monitoring** to characterize groundwater flow and chemistry,
- and preparations for deep **exploration drilling**, targeting the planned boreholes GLB-1 and GLB-2.

These activities were conducted in parallel with the progression of the permitting process, as well as the tendering and contracting of service providers for field operations. The coordination of these complex and interdependent steps represented a major logistical and administrative achievement.

A key breakthrough occurred in September 2024, when the Main Operational Plan (Hauptbetriebsplan) for the exploration phase was officially approved by the responsible authorities. This regulatory green light enabled the immediate commencement of seismic fieldwork in partnership with GFZ. The first phase of geophysical surveying is now nearing completion, and drilling activities are scheduled for 2025.

At the same time, essential infrastructure was being prepared: seismic monitoring equipment was acquired and is scheduled for deployment in 2025, while hydrogeological monitoring began through cooperation with TU Darmstadt. Additional weather stations and discharge measurement installations will further strengthen the data base for environmental baseline studies.

Public Engagement and Outreach

Public participation and transparent communication with stakeholders remained a strategic priority in 2024. The project launched a comprehensive **communication strategy**, including:

- The creation of an informative website presenting key facts, project goals, timelines, and news updates,
- The distribution of flyers and printed materials in the local area,
- The organization of community events and public discussions to foster trust and dialogue.

GeoLaB also attracted widespread media coverage, including newspaper articles, interviews, and TV features. This visibility has helped position the project not only as a research effort but also as an initiative committed to environmental responsibility and public accountability.

Leadership Transition

In mid-2024, the project experienced a significant change in leadership with the departure of Prof. Dr. Eva Schill, who accepted a new role at the Lawrence Berkeley National Laboratory (LBNL) in the United States. Prof. Schill's contributions were instrumental in establishing the scientific and strategic foundations of GeoLaB. Her vision, leadership, and ability to foster interdisciplinary collaboration significantly shaped the early trajectory of the project.

While her departure leaves an important gap, the continuity of the project is ensured by the appointment of Dr. Bastian Rudolph as the new project leader in May 2024. Dr. Rudolph is committed to building on the strong foundation laid by Prof. Schill, ensuring that the project maintains its high standards and continues to move forward with strategic clarity and operational excellence.

3.3 PROJECT DELIVERY MODEL

GeoLaB's infrastructure component presents a particularly high level of complexity. Underground research construction projects inherently involve technical uncertainties, regulatory hurdles, and organizational risks. These challenges are amplified when multiple institutions are involved, and when the expectations for quality, budget, and schedule are simultaneously high.

Experience from similar infrastructure projects shows that conventional linear planning approaches often lead to delays, cost escalations, and diminished quality outcomes (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.

IPD represents a collaborative project delivery framework designed to align the interests of all stakeholders, including the client, planners, and contractors. The model encourages open communication, early involvement of all parties, joint risk management, and continuous feedback loops. These features enable more agile decision-making and foster a problem-solving culture that is particularly valuable in research construction.

To implement the IPD approach effectively, KIT secured additional financial resources for:

- The engagement of an IPD coach to guide the process and train the internal project team,
- Scientific support to evaluate and document the application of IPD 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. In 2024, the procurement process for the IPD coach was successfully completed, and preparations are underway to train the internal KIT project team. Implementation activities are set to begin in early 2025.

3.4 OUTLOOK

Looking ahead, 2025 will be a decisive year for the GeoLaB project. The key objective will be to confirm the geological and technical suitability of the Tromm site as the future location of the underground laboratory. This confirmation will be based primarily on data from the upcoming deep boreholes GLB-1 and GLB-2, supplemented by findings from seismic surveys, hydrological studies, and geophysical analyses.

Pending a positive site assessment, the project will advance into the planning and permitting phase for the construction of the underground laboratory. This phase, projected to run from 2026 to 2028, will focus on detailed engineering, safety planning, stakeholder consultations, and the approval process under relevant legal frameworks.

Construction of the laboratory is planned to begin in 2029, with completion scheduled for 2030. Commissioning and scientific operations are targeted for 2031, marking the beginning of what is expected to be a long-term, internationally visible research platform.

The GeoLaB team remains confident and focused on its long-term vision: to establish a world-class underground research infrastructure that will provide critical insights into the sustainable use of the subsurface and contribute to the broader energy and environmental transition.

4 THE BGE INVOLVEMENT

WOLFRAM RÜHAAK, WOLFGANG KÖBE, DAGMAR DEHMER, JÜRGEN SCHAMP

4.1 INTRODUCTION

Scientific and geotechnical challenges for geosciences with societal relevance include the use of crystalline rocks for the energy transition as well as solutions for the final waste disposal. Although the required geotechnical boundary conditions for the rock are contrasted (the highest possible permeability for geothermal energy versus the maximum possible barrier effect for final disposal), there are overlaps between the areas of geothermal energy and final disposal in the field. This includes exploration, communication with the public and the construction of underground infrastructure.

4.2 THE BGE AND THE SITE SELECTION PROCESS FOR A FINAL WASTE DISPOSAL

The Federal Company for Radioactive Waste Disposal (Bundesgesellschaft für Endlagerung mbH - BGE) was established within the portfolio of the Federal Ministry for the Environment. The site selection procedure itself is carried out in accordance with the Site Selection Act (StandAG). The original version of the Act on the search and selection of a site for the repository for high-level radioactive waste of July 23rd 2013 (Federal Law Gazette (BGBl.) I p. 2553) was revisioned on May 16th 2017 (StandAG 2017) following evaluation by the repository commission and the Bundestag.

This Site Selection Act describes the principles of the Site Selection Procedure as science-based, participative, transparent, self-questioning and learning. Within the Act, BGE is responsible for the site selection procedure as the German Waste Management Organisation for nuclear waste. In accordance with Section 1 Paragraph 3 StandAG, the BGE is taking the host rocks of rock salt, claystone and crystalline rock into consideration for a final repository in Germany. In the interim report (BGE 2020), a total of 90 sub-areas were designated, of which seven sub-areas are in crystalline rock. Some properties of crystalline rock are favorable for the secure confinement of radionuclides of high-level radioactive waste over the specified period of at least one million years (Section 1 Paragraph 2 StandAG). Examples of this are the high strength, the low water solubility and the high temperature resistance of crystalline rock. However, for secure confinement of high-level radioactive waste, it is necessary that a crystalline rock complex is also sufficient homogenous and largely undisturbed. It must be ensured that fracture networks and micro-cracks do not affect the rock permeability and the barriers surrounding it in a negative way. In order to meet these extremely high geotechnical requirements for an underground infrastructure for safe final disposal, a great degree of specific expertise is indispensable.

4.3 THE PARTICIPATION IN GEOLAB

In order to conduct the site selection process, which is among others defined as a science-based and learning process, it is important to put special research efforts on the understanding of all host rock settings since the site selection process does not favor any of the three host rocks. The BGE already has profound knowledge within mining activities in rock salt and claystone, yet mining activities in crystalline rock in Germany are not within the experience of the BGE so far. Recent experiences to build a mine in crystalline bed-rock are rare in Germany, even beyond the BGE.

Therefore, it is necessary to conduct research in mining and other related exploratory technologies such as seismic and drilling with a focus on crystalline rock. In order to build up knowledge of the broad variety of aspects of the construction of underground infrastructures in crystalline rock, it is essential to carry out or participate in similar projects implementing such infrastructures. Following this approach, BGE has actively monitored and supported the planning of the first GeoLaB exploration well, to be drilled in the first quarter of 2025. Other areas of involvement include the processing of the first 2-D seismic, performed in late 2024 and the observance of various aspects of communication efforts with the local public.

The research project GeoLaB with its technical, planning and operational aspects in the course of the construction of the GeoLaB underground facility is an excellent possibility for the BGE to practice the processes and gain knowledge of the required operations in crystalline rock for the following exploration phase within the site selection process (Phase II). Furthermore, GeoLaB is not a commercial project, but a non-profit research initiative. Its primary goal is to advance scientific knowledge and provide essential insights as basis for sustainable solutions to address societal challenges. The dialogue with the population is an important part of the project throughout its duration. This is comparable to the framework conditions of the BGE and the objective of safe solutions for nuclear waste disposal. In addition, as a research project, GeoLaB is applying state-of-the-art and innovative methods in the implementation of its infrastructure. This forward-thinking approach serves as a model for best practice for similar underground infrastructure initiatives in the future. Examples of innovative methods are the use of advanced digital methods from the start of the project, including concepts of virtual reality and digital twins (see chapter 8), or the planned implementation of the principles of IPM (Integrated Project Management). All of this is very important for BGE's future site selection operations and the early participation in the drilling planning and permitting activities have already yielded notable insights and learnings.

Assuming the construction activities within the GeoLaB Project will take place in the years 2027 and following, the timing of the project fits well with the current schedule of the site selection process. The technical, planning and operational aspects during the construction of the underground laboratory mine are of great importance for the phase III of the site selection act, where such an underground mine needs to be built – even if it is unclear in which kind of rock. Therefore, BGE's participation in GeoLaB represents a unique opportunity to develop needed competencies to ensure success during the site selection process.

Further information:

https://www.bge.de/de/endlagersuche/forschung/geolab/

4.4 REFERENCES

BGE (2020): Sub-areas Interim Report pursuant to Section 13 StandAG, 436 pp., available at: https://www.bge.de/fileadmin/user_upload/Standortsuche/Wesentliche_Unterlagen/Zwischenbericht_Teilgebiete/Zwischenbericht_Teilgebiete_-_Englische_Fassung_barrierefrei.pdf (last access: 30 August 2021), 2020a

StandAG: Standortauswahlgesetz vom 5. Mai 2017 (BGBl. I S. 1074), das zuletzt durch Artikel 8 des Gesetzes vom 22. März 2023 (BGBl. 2023 I Nr. 88) geändert worden ist. StandAG.

5 GEOLOGY

JENS C. GRIMMER, DIRK SCHEUVENS

5.1 INTRODUCTION

Geothermal reservoirs in crystalline basement rocks provide opportunities and challenges for thermal energy supply. Geothermal fluids as carrier of the thermal energy are commonly produced by deep boreholes tapping fluid-bearing reservoirs. Knowledge of geometries, structures, petrophysical properties, and thermo-hydraulic-mechanical-chemical (THMC) and microbiological interactions in a geothermal reservoir is limited to the immediate vicinity of the commonly >2 km deep boreholes. Thus, modelling approaches often exhibit generic characteristics due to limited data availability. Three-dimensional insights at reservoir scale are much better achieved in underground research laboratories (URL) in combination with borehole and surface data. 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.

5.2 WORK STEPS AND CONDUCTED STUDIES

We have reviewed published and unpublished geological data of the Tromm pluton and its geotectonic position within the Odenwald Crystalline Complex, comprising geochronological, geochemical, geophysical and structural geological data in the subsequent chapters. The implementation of geological data into GIS projects is an ongoing process. An external study was commissioned by KIT on morphotectonic analyses in the southern Odenwald (Table 5.1). A stress field modelling study of the Tromm region is in progress (Table 5.1).

Table 5.1: Included studies from partners

Topic	Person	Institution
Morphotectonic analysis of the Odenwald (Report 2024-4-15)	Dr. Arnfried Becker & Richard Reinicke	Becker – Consulting geologist, 76351 Linkenheim-Hochstetten
Stress prediction for the Tromm region – part 1 (Report 2024-10-24)	Ahlers S, Reiter K, Henk A	Institute for Applied Geosciences, TU Darmstadt

5.2.1 Geological Overview of the Odenwald Crystalline Complex

The Odenwald ("Odin's Forest") Crystalline Complex is traditionally subdivided into four units (Unit I – IV), separated by shear zones displaying differences in their magmatic and metamorphic evolution (Kreuzer & Harre 1975; Lippolt 1986; Todt et al. 1995; Reischmann et al. 2001, Altenberger et al. 1990; Krohe 1991; Krohe 1992; Willner et al. 1991; Henes-Klaiber 1992; Altenberger & Besch 1993; Krohe & Willner 1995; Altherr et al. 1999; Stein 2001; Stein et al. 2022). Dörr & Stein (2019) suggested to subdivide **Unit I** into a northern part and the southern Frankenstein Massif and to discriminate the northern part as **Unit 0** due to presence of late Neoproterozoic to early Cambrian (540±8 Ma) (meta-)granitic rocks representing remnants of Cadomian basement intruded by Silurian granitic rocks. In contrast, the southern part of the Frankenstein Massif mainly consists of intermediate, basic and ultrabasic rocks of mainly gabbroic or dioritic composition, apparently lacking older continental crust components (Stein 2001). At c. 360 Ma, the gabbros intruded into a shallow crustal level in an intra-oceanic arc-type setting during south-directed subduction and caused contact-metamorphic overprint of the amphibolitic wall-rocks (Kirsch et al. 1988, Altherr et al. 1999, Schubert 1968, Willner et al. 1999).

The central and southern Bergsträsser Odenwald (Figure 5-1) are built up by granitic to dioritic plutons (c. 90 % of the area) separated by various metamorphic rocks (c. 10 % of the area) the latter forming narrow SW–NE trending zones (Stein 2001). The plutons belong to the calc-alkaline suite and are assigned to an early Carboniferous continental magmatic arc (Henes-Klaiber 1992; Altherr et al., 1999; Stein 2001; Stein et al. 2022). The central part of the Bergsträsser Odenwald („Flasergranitoid Zone") constitutes Unit II including several plutons, distinctly deformed along NE-striking left-lateral shear zones (Krohe 1991; 1992). The southern part of the Bergsträsser Odenwald constitutes **Unit III** and includes three larger, less deformed plutons (Weschnitz, Tromm, and Heidelberg; e.g., Krohe 1991). Intrusion ages of plutons in **Unit II** were determined between 354±4 Ma and 337±2 Ma and for **Unit III** between 346±1 Ma and 337±2 Ma (Stein et al., 2022).

The metamorphic rocks include greenschist- to amphibolite-grade metasedimentary rocks, metavolcanic rocks, calcsilicate marbles and orthogneisses (Stein 2001). Some metamorphic rocks include Cadomian basement rocks with similar ages as in Unit 0 (Dörr & Stein 2019). Cadomian basement rocks assign a Gondwana-origin for the Odenwald Crystalline Complex.

The NNE-trending Otzberg fault zone marks in its northern segment the boundary between the Bergsträsser and the Böllstein Odenwald (Figure 5-1) and was here active as a top-to-the W extensional (or transtensional) ductile shear zone until late early Carboniferous times (327 ±3 Ma; Hess & Schmidt 1989; Korn 1929; Grimmer et al., 2017). Multiple brittle faulting reactivation of the Otzberg fault zone is assumed since late Carboniferous times (e.g., Schälicke 1968), but the brittle deformation history of the Otzberg fault zone is as yet poorly resolved.

The Böllstein Odenwald (**Unit IV**; Krohe 1991, Figure 5-1) forms a SSW–NNE trending anticline (Figure 5-1; Altenberger & Besch 1993). It consists of an orthogneiss core with intercalated amphibolites, the latter locally exhibiting evidence to origin from retrograded eclogites, surrounded by the at least 600 m thick `schist envelope´ consisting of metasediments, metacarbonates, and metabasites (Chatterjee 1960; Altenberger et al. 1990; Altenberger & Besch 1993; Stein 2001; Will & Schmädicke 2001). Chatterjee (1960) distinguished two orthogneiss types in the core: i) a medium- to coarse-grained (leuco-) granodiorites gneiss and ii) a fine-grained granite gneiss with elevated alkali-feldspar and muscovite contents. Field observations document intrusive contacts of these granites into the granodiorite (Chatterjee 1960; Altenberger & Besch 1993). In both the gneisses and amphibolites pegmatites of granodioritic, granitic, and gabbroic compositions occur (Chatterjee 1960). The granitic protoliths of the orthogneisses intruded a continental magmatic arc collisional environment (Altenberger et al. 1990; Altenberger & Besch 1993; Reischmann et al. 2001). The amphibolites of the schist envelope outline a tholeiitic island-arc basalt signature (Altenberger et al. 1990; Altenberger & Besch 1993). All together the schist envelope can be interpreted as a volcano-sedimentary turbidite sequence deposited in a forearc basin or accretionary wedge (Altenberger et al. 1990; Altenberger & Besch 1993; Stein 2001). The intrusion of the granitic protoliths of the orthogneisses occurred during late Silurian to early Devonian times, i.e., between 425.4 ±4.1 Ma and 400 ±7 Ma (Reischmann et al. 2001; Will et al. 2021; Dörr et al. 2022).

5.2.2 Geography and Boundaries of the Tromm Pluton

At map view, the Tromm pluton is exposed as a roughly triangular-shaped body with a N-S extension of about 15 km and a maximum E-W extension of approximately 10 km in the south narrowing to the north towards zero, covering an area of c. 60 km2 (Figure 5-2; Frey et al., 2022). The Tromm pluton forms a morphologically distinct N-S trending ridge in the southeastern Odenwald reaching its highest elevation at the summit Tromm (576.8 m a.s.l.). Outcrops with the lowest elevation (< 200 m a.s.l.) can be found in the Weschnitz valley to the west of the Tromm ridge (e.g., near Mörlenbach). Hence a minimum thickness of about 350 m for the Tromm pluton can be inferred.

The poorly exposed western boundary of the Tromm pluton with the Weschnitz pluton can be followed along a line of the small towns of Krumbach, Fürth, Rimbach, Mörlenbach, and Reisen, and is largely covered by Quaternary sediments of the Weschnitz valley. The boundary between both plutons is partly marked by the NE-SW trending western branch of the Otzberg fault zone. Based on field relationships, the Tromm pluton intruded the Weschnitz pluton and thus must be younger than the Weschnitz pluton (Klemm 1933). However, conclusions are based only on few outcrops. These field observations are confirmed by modern geochronological data revealing crystallization and hence emplacement ages of 346 Ma to 343 Ma for the Weschnitz pluton (346 ± 1 Ma, 344.3 ± 0.6 Ma, 343 ± 0.6 Ma, 343.2±2.1 Ma) and of 339 ± 0.8 Ma for the Tromm pluton (Zulauf et al. 2021; Stein et al. 2022).

In the north the Tromm pluton intruded the northeasternmost parts of the Weschnitz pluton (Figure 5-2). The eastern boundary of the Tromm pluton is complex and can be separated into a northern, central, and southern segment. The northern segment of the boundary is marked by the eastern branch of the Otzberg fault zone which separates the Tromm pluton from the gneisses of the “Zwischenzone” (Nickel 1953, Nickel & Obelode-Dönhoff 1968). The termination age of the ductile shear zone activity in this area was determined by Hess & Schmidt (1989) by K-Ar biotite dating of an undeformed lamprophyre cross-cutting the fault zone. The gneisses of the “Zwischenzone” occur north of Hammelbach (Figure 5-2) with a N-S extension of ca. 8 km. They exhibit a slightly folded, originally subhorizontal foliation, steepening towards west, plunging beneath the Tromm pluton..

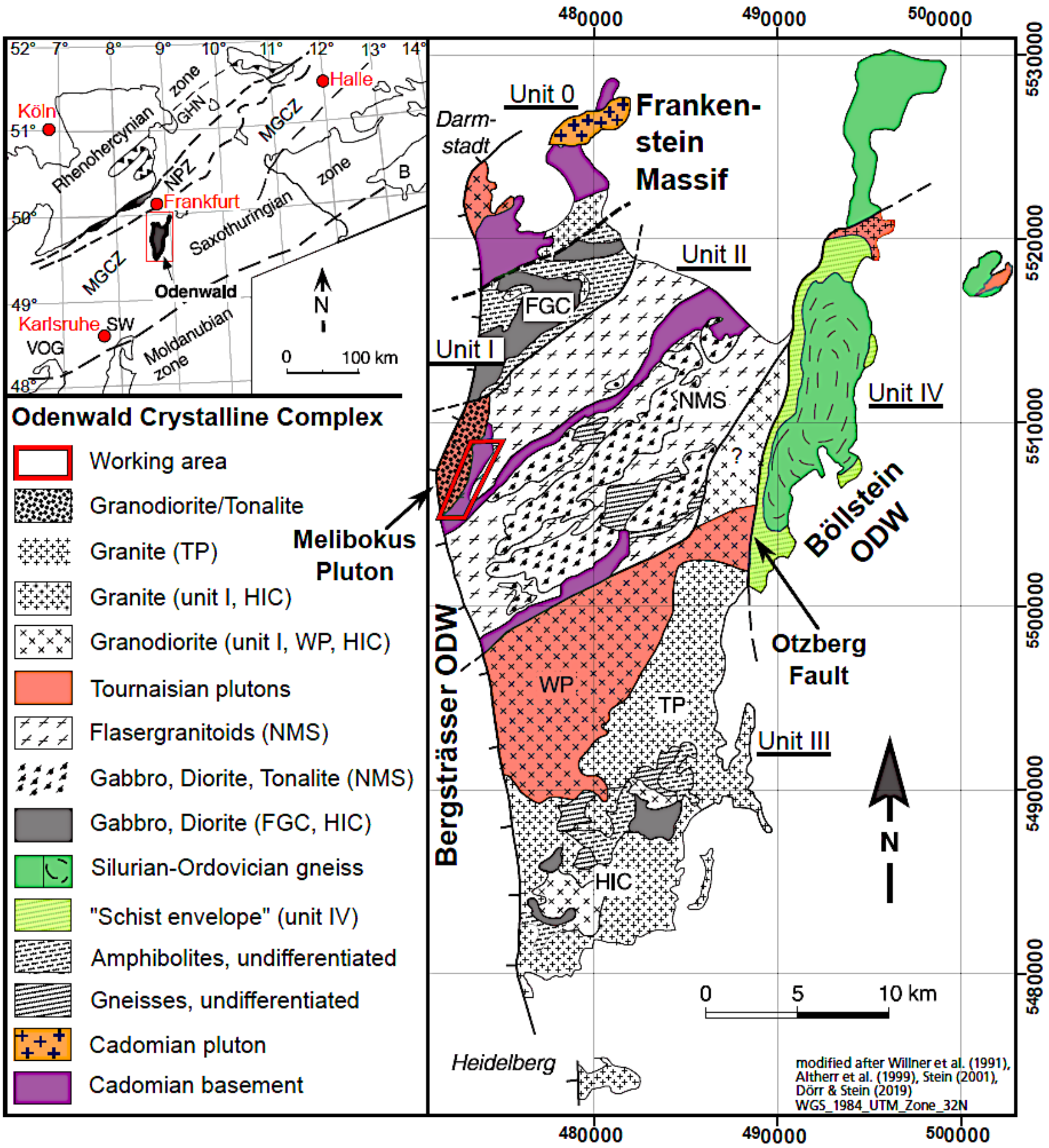

Figure 5-1: Geological overview of the Odenwald Crystalline complex (Meinaß et al., 2024).

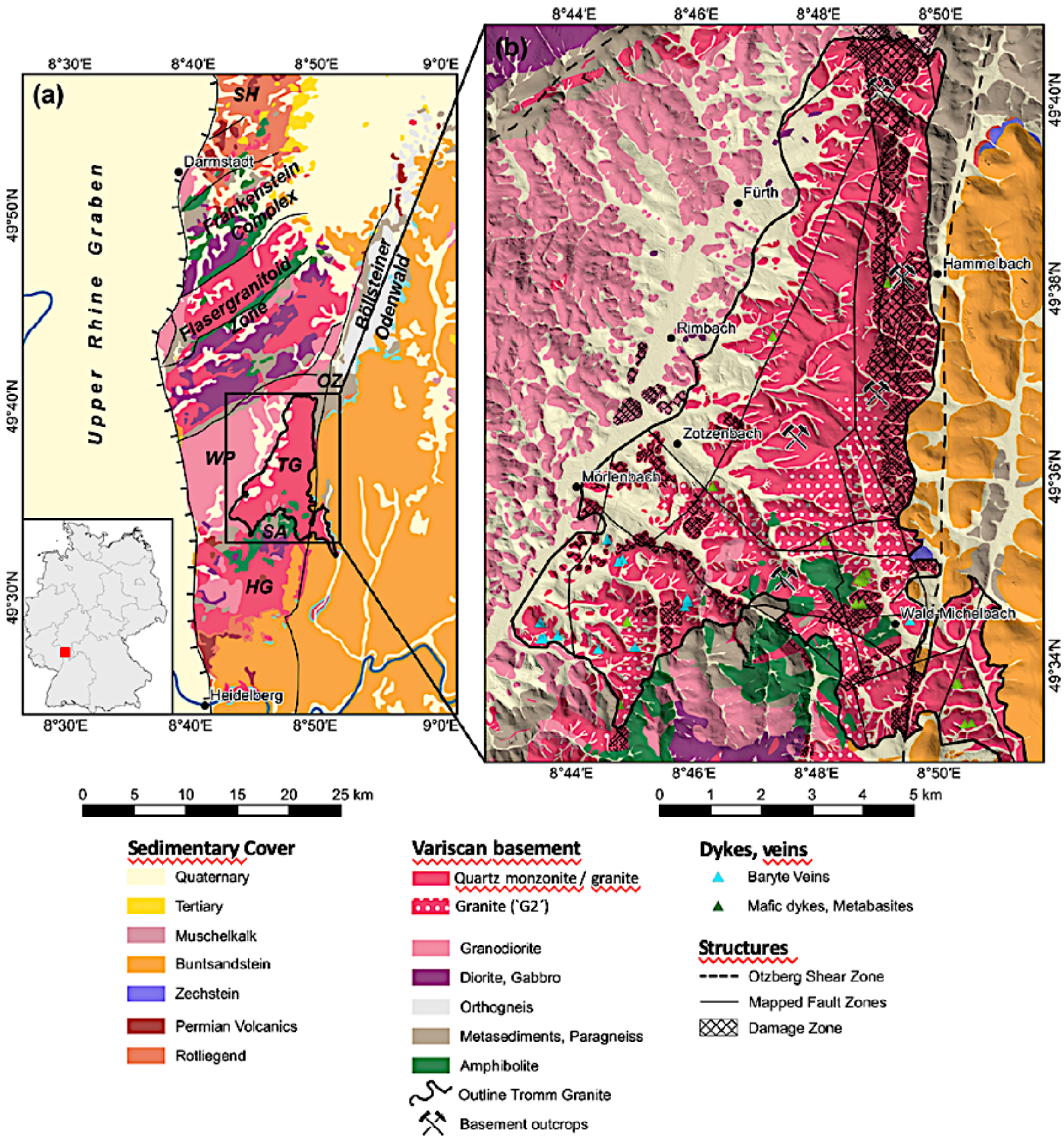

Figure 5-2: Geology of the Tromm region. Overview of the Tromm pluton and its boundaries (modified from Frey et al., 2022): (a) geological overview map of the Odenwald. (b) Geological map of the Tromm Granite in the southern Odenwald (Klemm, 1900, 1928, 1929, 1933). The fault zone map was compiled from various geological maps. HG: Heidelberg Granite, OZ: Otzberg Shear Zone, SA: Schollenagglomerat, SH: Sprendlinger Horst, TG: Tromm Pluton, WP: Weschnitz Pluton.To the east of the southern segment, small occurrences of orthogneisses documented north of Waldmichelbach also likely represent relics of the Zwischenzone gneisses. Here the granite of Wald-Michelbach (merged with Tromm pluton in Figure 5-1**Figure 5-1**) is unconformably overlain by dolomites and siliciclastics of the Zechstein Group (associated with Manganese ore deposits). To the south the displacement along the eastern branch of the Otzberg fault zone decreases and apparently dies out in the Buntsandstein Group and cannot be clearly mapped further to south in Triassic cover rocks. A likely continuation of the Otzberg fault zone in the southeastern Odenwald follows the N-S oriented Eiterbach and Steinach valleys (Schälicke 1968).

The *central segment* is also defined by the eastern branch of the Otzberg fault zone, which is poorly exposed there. However, here the Otzberg fault zone separates the igneous rocks of the Tromm pluton to the west from Permo-Triassic cover rocks to the east with poorly known composition of the crystalline basement underneath. The sedimentary cover rocks are mainly represented by formations of the Lower and Middle Buntsandstein Subgroups, but small occurrences of late Permian Zechstein Group (dolomites and siliciclastics) are present beneath the Buntsandstein Group (Nitsch & Hug-Diegel, 2020). The maximum altitude of the exposures of the Tromm pluton at a height of 576 m a.s.l. to the west of the Otzberg fault zone and the position of the basement-cover-interface at a maximum altitude of 400 m a.s.l. to the east of the fault zone imply a minimum post-Triassic throw (vertical displacement) of about 180 m with a relative downward movement of the eastern block (or a relative upward movement of the western block). The rocks of the Buntsandstein Group to the east of the Otzberg fault zone are disintegrated into fault-bounded blocks with dominating NNE-SSW and WNW-ESE striking fault zones. A westward extension of these fault zones into the Odenwald crystalline complex and especially the Tromm pluton is likely, but as yet poorly documented.

The **southern boundary** of the Tromm pluton is not well defined and the definition of an exact position is hampered by the petrographic similarity with the Heidelberg pluton (also: “Heidelberg granite”, HG or “Heidelberg Igneous Complex”, HIC) and the occurrence of partly tens of meter to km-sized blocks of older metamorphic and magmatic rocks, mainly gneisses, mica schists, amphibolites, quartzitic schists, and diorites. This rock suite is summarized as “Schollenagglomerat” in the local literature and regarded as stoped blocks or roof pendants of both Tromm and Heidelberg plutons. The Schollenagglomerat thus most likely represent relics of the crust into which the granites intruded. The contact of the Tromm pluton and the “Schollenagglomerat” is exposed in the abandoned quarry Gärtnerskopf near Ober-Mengelbach where complex contact relationships have been described (Nickel & Fettel 1985). Distinctions between Tromm and Heidelberg plutons are challenging due to similar petrography, geochemistry, and geochronology as the Heidelberg pluton has – within error – the same emplacement age as the Tromm pluton (337 ± 2 Ma; Stein et al. 2022). In summary, it needs to be emphasized that the original three-dimensional shape of the Tromm plutonic body can only be partly reconstructed owing to the offsets at its western boundary (i.e., the western branch of the Otzberg Zone) and its eastern boundary (i.e., the eastern branch of the Otzberg Zone) and the poorly defined southern boundary. The depth extents of all plutons in Unit III are essentially unknown.

5.2.3 Petrography and Textural Variations of the Tromm Pluton

The granites of the Tromm pluton are poorly exposed, and outcrops are essentially restricted to abandoned quarries and a few rock exposures along the Tromm ridge, and to outcrops in the deeply incised Weschnitz valley in the northern part of the Tromm pluton.

The granitoids of the Tromm pluton are holocrystalline and leucocratic. The major phases are K-feldspar (ca. 20-35 vol.%), plagioclase (ca. 35-40 vol.%), quartz (ca. 30-40 vol.%), and biotite (ca. 5-10 vol.%). The grain-size distribution varies from a dominating porphyric (with up to several cm large sub- to euhedral K-feldspar phenocrysts) to an equigranular microstructure (Figure 5-3,Figure 5-4). The macroscopic fabric is mainly isotropic. However, a weak shape-preferred orientation of magmatic K-feldspar and/or biotite is occasionally observed. Schlieren, cumulates, shear zones as well as microgranular mafic enclaves (MME) are not documented. Xenoliths (schist, amphibolite, diorite) ranging from decimetre to several 100 m in size are mainly restricted to the southernmost part of the Tromm pluton in the "Schollenagglomerat". Locally, smaller xenoliths exhibit disc-like shapes and show a parallel orientation of their long axes. Characteristic for the granitoids is the triad of the colours red (K-feldspar), white (plagioclase), and black (biotite). However, pure whitish to greyish varieties can also be observed. The modal composition indicates mainly a monzogranitic composition, but quartz-monzonitic or granodioritic compositions may also occur (Maggetti 1975, Nickel & Fettel 1985).

Under the polarization microscope anhedral up to 5 mm large quartz is intergrown in larger monomineralic aggregates with internal straight or curved grain boundaries. The aggregates are sometimes elongated and then define an incipient (magmatic) foliation by a preferred orientation of their long axes. Undulatory extinction and formation of subgrains is only weakly developed. Subgrain boundaries are mainly oriented parallel to the prism plane but boundaries parallel to the rhombohedral and basal plane also occur. The combination of prism- and basal-plane parallel subgrain boundaries (´chessboard pattern´) is probably the result of a weak crystal-plastic deformation under high-temperature conditions immediately after emplacement of the pluton. Partly along discrete shear zones indicators of a low-temperature deformation such as bulging recrystallization (see Stipp et al. 2002), deformation bands, and rare deformation lamellae are observed. Many quartz grains exhibit rows of fluid inclusions with different orientations.

Subhedral plagioclase (grain size: < 6 mm; An_{15-25} after Nickel & Fettel 1985) is prismatic with length-width ratios up to 4:1. A shape-preferred orientation was not detected. The plagioclases often show simple zoning with a rim with a lower anorthite content than the core. Oscillatory zoning is extremely seldom developed. Polysynthetic magmatic twinning after the albite law is ubiquitous. More rarely polysynthetic pericline twinning or single twinning is recognized. The plagioclases show occasionally brittle kinking and bending of the polysynthetic albite twins. Plagioclases are altered at various degrees by sericitization. The latter is sometimes restricted to the core or is concentrated along cleavage planes. Also, Fe-hydroxide can be observed as a secondary phase in plagioclase.

Predominantly anhedral to subhedral K-feldspar is characterized by its large grain-size (up to several cm) in the samples with a porphyric texture. They exhibit typical magmatic Karlsbad twinning, show perthitic exsolution (albite lamellae), and contain inclusions of quartz, apatite, and (euhedral) plagioclase. Microcline twinning is only incipiently developed (mainly along fractures) pointing to orthoclase as the dominating K-feldspar phase. Myrmekite is typically developed at plagioclase/orthoclase phase boundaries. As retrograde or alteration features rare chessboard albite, and a local replacement of K-feldspar by Fe hydroxide or rosette-shaped chlorite can be observed. The cloudy appearance of many K-feldspar grains is probably due to a very fine-grained sericitization.

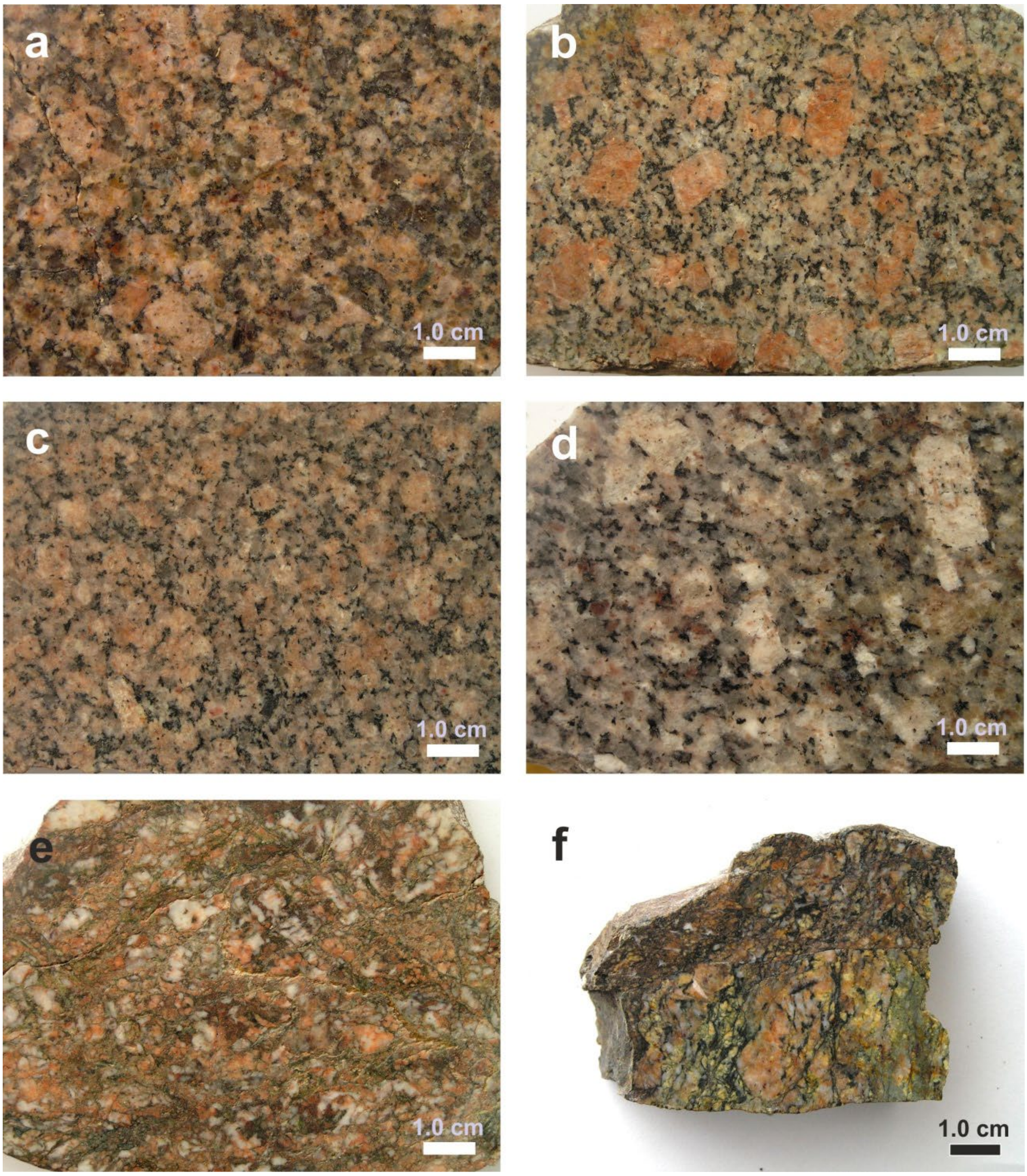

Figure 5-3: Rock samples. Photographs of representative rock slides of granites of the Tromm pluton (a-d) and cataclasites of the southern part of the Otzberg fault zone (e-f); a: abandoned quarry Borstein, b: boulders E of Brombach, c: abandoned quarry Streitsdöll, d: boulders near Jungholzhöhe, e: Weschnitz valley near Leberbach, f: abandoned quarry in Hammelbach; width of all images: 10 cm

Subhedral biotite (grain size: < 2 mm) is only a minor phase and is dispersed in the matrix with a typical tabular habit with length-width ratios of up to 5:1. Occasionally a weak shape-preferred orientation can be recognized. Biotite exhibits minor deformation by bending and kinking. It is the most intense altered mineral and often partly or completely replaced by an Fe-rich chlorite (with anomalous bluish interference colours) or white mica. Additional retrograde phases are Fe-oxide/hydroxide, leucoxene, and/or rare rutile (as sagenite grids).

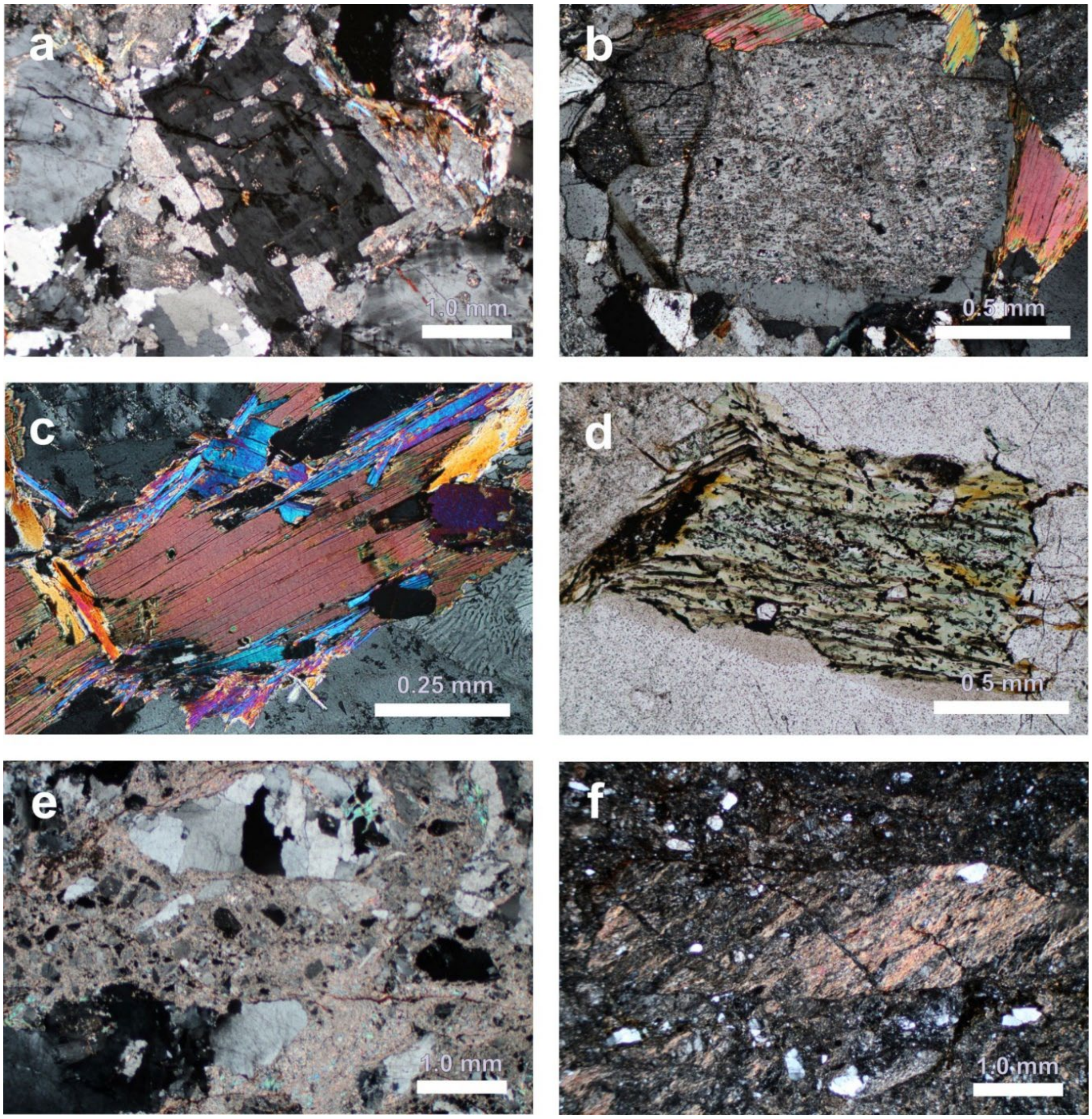

Figure 5-4: Thin sections. Microphotographs of thin sections of granites of the Tromm pluton (a-d) and cataclasites of the southern part of the Otzberg fault zone (e-f); a: zonal arrangement of euhedral plagioclase grains (altered to sericite) in large euhedral K-feldspar (crossed polarized light), b: normal zoning in plagioclase with intensely sericitized core (crossed polarized light), c: unaltered biotite intergrown with primary? muscovite, also note myrmekite formation at lower right (crossed polarized light), d: intensely altered biotite completely replaced by chlorite, rutile (as sagenite), and hematite (single polarized light), d: quartz clasts embedded in a cataclastic matrix composed of sericite, f: `phyllonitic´ fragment within cataclastic matrix (crossed polarized light).

Only in a few samples white mica (muscovite) occurs as subhedral up to 1 mm large laths which are interpreted to be of primary magmatic origin. However, most of the muscovite is much more fine-grained and represents a secondary, alteration phase. It can be observed as a replacement product of primary biotite (and muscovite), grows (radially) on different phase boundaries or along fractures, and as major alteration product of plagioclase.

Typical accessories are zircon (< 0.1 mm, with oscillatory zoning), apatite (< 0.6 mm, euhedral, mainly as inclusions in both feldspars and biotite), and primary and secondary monazite (only detected by SEM). The primary opaque phase are Fe-Ti-oxides. Secondary opaque phases comprise mainly Fe-oxide (hematite) and Fe-hydroxide. Intragranular fractures can be filled with secondary phases such as Fe hydroxide, leucoxene, calcite, white mica, and/or clay minerals.

5.2.4 Geochemistry of the Tromm Pluton

Published (Altherr et al. 1999; Henes-Kleiber 1992) and unpublished (HLNUG2 data) geochemical data of major elements of the Tromm pluton were used for classification, calculation of radiogenic heat production and zircon saturation temperatures. Major elements indicate that the Tromm pluton consists of granites and quartz monzonites in the northern and central parts („G1") and granites in the southern part ("G1" and „G2") as outlined in the TAS-diagram (Figure 5-5). Structural boundaries in the east and west, major spatial data gaps, and a limited geochemical compositional variation in both the quartz monzonite and the granites do not yet allow to identify any zonations within the Tromm pluton. The detailed contact relationships between the G1 granites and quartz monzonites and the G2 granites are not yet understood.

Tectonic discrimination diagrams indicate a (syncollisional) magmatic arc origin for the Tromm pluton (Altherr et al. 1999). Chondrite-normalized REE patterns of two samples from the Tromm pluton display significant LREE-MREE and MREE-HREE fractionations. Together with the apparent lack of Eu anomalies this indicates that fractional crystallization of plagioclase was limited and that garnet was present as a residual phase during magma segregation (Altherr et al., 1999). However, data base of the Tromm pluton is limited, as only one $^{87}Sr/^{86}Sr_i$ value was determined to 0.706 and one ε_{Nd} value of -3.5 indicate involvement of a garnet-bearing crustal source (Altherr et al. 1999).

Uranium, thorium, and potassium concentration data of 41 samples of the Tromm pluton, including also cataclastically deformed and altered samples, with an assumed average density of 2640 kg/m^3 were used to calculate first order data of the radiogenic heat production A (Figure 5-6) with the formula of Rybach (1986):

$$A[\mu W/m^3] = 10^{-5} \times \rho\ (9.52c_U+2.56c_{Th} + 3.48c_K),$$

with c_U: uranium concentration (in ppm), c_{Th}: thorium concentration (in ppm), c_K: potassium concentration (in %), and ρ: density (in kg/m^3). The mean value is 2.42 mW/m^3 (Figure 5-6), 50% of data range from 1.86 to 3.06 mW/m^3, which appear to be reasonable values. However, we want to emphasize that sampling and analyses were originally not intended to calculate radiogenic heat production as no accompanying density measurement for each sample were carried out.

We used the element Zr and major element data to achieve first estimates of the temperature of the granitic melt of the Tromm pluton applying the zircon saturation thermometer of Boehnke et al. (2013). Zircon saturation temperatures range from 690 °C to 765 °C (Figure

[2] HLNUG: Hessisches Landesamt für Naturschutz, Umwelt und Geologie

5-6) with a mean value of 727 °C (n=13). However, it must be noted that samples may be biased by inherited zircons (see Stein et al. 2022), non-representative sample heterogeneities, magma mixing and mingling processes, and (minor) alteration, which were not yet investigated in detail.

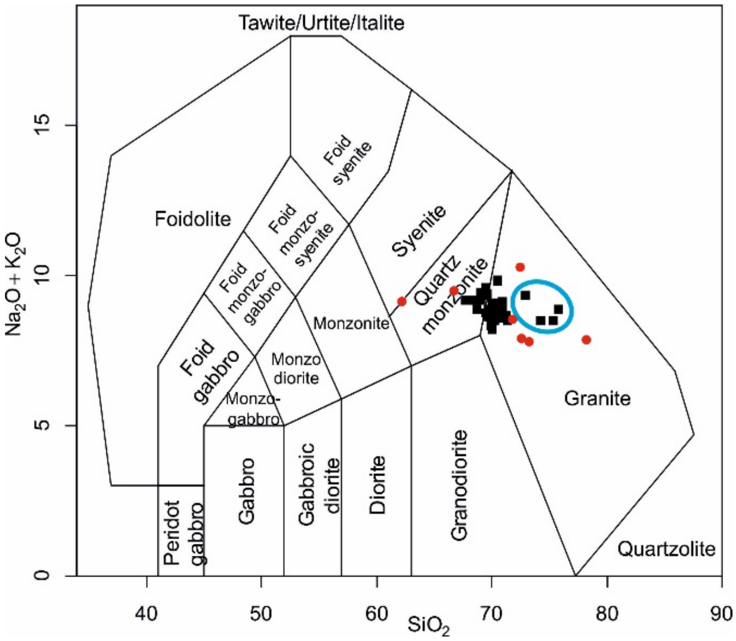

Figure 5-5: Petrography. Total Alkali vs. Silica (TAS) diagram for plutonic rocks after Middlemost (1994); black squares: granitoids of the Tromm pluton, red dots: cataclasites of the Otzberg fault zone, blue ellipse: probable younger (`G2´) granites in the southern part of the Tromm pluton.

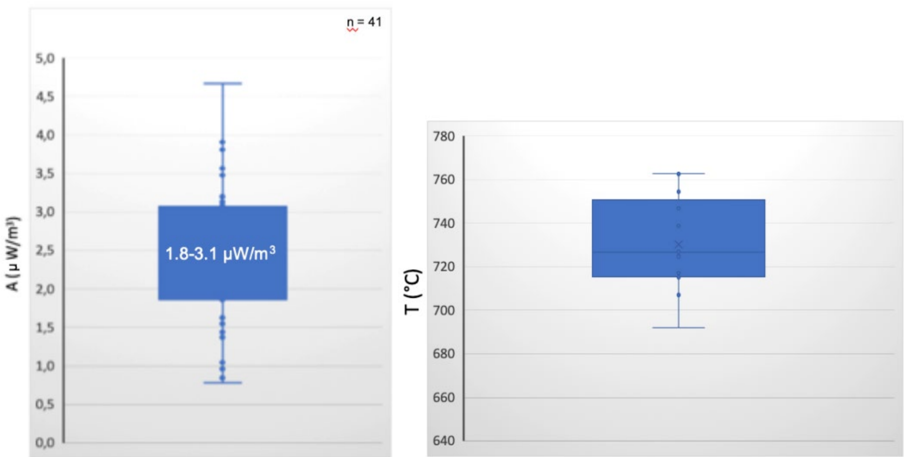

Figure 5-6: Radiogenic heat production and melt temperature estimation. Left: Box plot distribution of radiogenic heat production data from the Tromm pluton (n=41). Right: Zircon saturation temperatures (n=13).

5.2.5 Structural Geology of the Tromm Pluton

Geometry, zonations, intrusion depths and thicknesses

As already outlined in the geochemistry chapter, the Tromm pluton consists of at least two magma suites: a quartz-monzonitic suite in the central and northern Tromm pluton and a granitic suite in the southern Tromm pluton. Plutons are commonly either inverse, normally or non-zoned (Nédelec & Bouchez 2015). Geochemical data base, outcrop situation, and the, essentially structurally controlled, outline and the relatively uniform composition of the Tromm pluton makes it challenging to constrain or to exclude zonations. Intrusion are constrained with Al-in-hornblende due to pressure dependency of Al content in hornblende ("Al-in-Hbl"; Schmidt 1992). Due to the sparsity of hornblende in the Tromm pluton Al-in-Hbl data do not exist and intrusion depths of the Tromm pluton could not yet be determined by this method. However, surrounding plutons provide information that can be used to constrain first estimates: Al-in-Hbl data indicate 17.5 km to 18.6 km intrusion depth for the Weschnitz pluton (p = 0.48-0.51 MPa; Altherr et al. 1999, Zulauf et al. 2021). The slightly younger Heidelberg pluton emplaced at a depth of c. 14.9 km (p=0.41 MPa, Altherr et al. 1999). Considering the emplacement depths and ages of both the Weschnitz pluton (343-346 Ma) and the Heidelberg pluton (337 Ma), an average exhumation rate of 3 km in 7-8 Ma (= 0.4 km/Ma) can be inferred for this time span (see also Zulauf et al. 2021). Unless no new data are available, it is reasonable to assume that the Tromm pluton intruded at a comparable depth to both the Weschnitz and the Heidelberg pluton and underwent similar exhumation rates after its emplacement at 339 Ma. Gravimetric data have not yet been analysed to constrain thicknesses (or depth ranges), root (or feeder) zones or original geometries of the Weschnitz, Heidelberg, and Tromm plutons, which thus remain essentially unknown. Intrusion depths >13 km may suggest rather lopolithic or hybrid (lacco-lopolithic) plutons as laccoliths occur preferentially in shallower crustal levels (Figure 5-7).

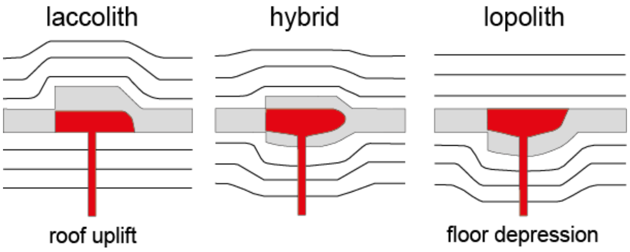

Figure 5-7: Estimation of intrusion depth. Schematic illustration of lopoliths and laccoliths as idealized and generalized endmembers and their different emplacement modes by either floor depression or roof uplift (modified from Cruden 1998). Commonly associated transtensional-extensional stress fields for magma ascent and emplacement are not considered in this sketch.

The regional distribution of the Bouguer anomalies shows gravimetric gradients along the SE-, SW-, NW-, and E boundaries (northern and southern segments) of the Tromm pluton. The northern boundary is gravimetrically indistinct and gradually as well as the central segment of the eastern boundary (Figure 5-8Figure 5-8). The relative gravimetric high in the southern Tromm pluton cannot neither clearly assigned to the Schollenagglomerat nor to the G2-granites and currently remains poorly understood.

The aeromagnetic survey of the Tromm pluton reveals large variations of the magnetic field, varying from -22.5 to +67.5 nT (Figure 5-9). Patterns cannot straightforwardly be correlated with gravimetric anomalies. Some positive magnetic anomalies along the southern margin of the pluton can be clearly assigned to mapped amphibolites and diorites of the Schollenagglomerat (Figure 5-9, Frey et al. 2023). The distinct positive anomaly in the central part of the Tromm pluton may be interpreted by the presence of primary ferrimagnetic minerals, not or poorly affected by alteration, while the magnetic lows indicate absence of ferrimagnetic minerals, either due to primary petrographic variation or due to secondary alteration. However, the causes generating these variable positive magnetic highs and lows need to be studied in more detail.

Hyper-solidus fabrics

Granitoids are apparently isotropic at first glance, but emplacement processes commonly induce hyper-solidus fabrics, preserved in the crystallized magmas. These hyper-solidus fabrics may be overprinted by sub-solidus fabrics caused by deformation, alteration, and/or metamorphism. An established method to unravel hyper-solidus fabrics is the measurement of the anisotropy of the magnetic susceptibility (AMS; e.g., Améglio et al. 1997; Bouchez 1997; Nédélec & Bouchez 2015). For the Schollenagglomerat („xenoliths") and the plutons of Unit III Greiling & Verma (2001) published the first and as yet only AMS data, but did not refer their samples to the commonly used rock units (Weschnitz, Tromm, Heidelberg plutons) and also do not provide geographic coordinates of their samples, which leaves some uncertainties along boundaries on assignment of few data to the respective pluton. Modern AMS studies commonly produce six to nine specimens from one sample of one sampling location to cover the statistical variation that results from heterogeneities in (coarse-grained) granitic rocks. Greiling & Verma (2001) commonly measured one to three, commonly two specimens from one sample for their AMS measurements. Four samples contain obviously magnetite and accordingly show higher values for the mean susceptibility (K_{mean}). The Weschnitz pluton is characterized by steep (63-89°), (E)NE-(W)SW striking magnetic foliations, both NNW- and SSE-dipping, and a uniform subhorizontal to shallow (15-28°, one exception of 56°) ENE-plunging magnetic lineations. The corrected degrees of anisotropy P´ are < 1.1 (or <10%) for samples lacking or containing only little magnetite. However, only few samples were as yet analysed for their magnetomineralogy.

Magnetic foliations of the Tromm pluton dip steeply to the (E)SE. Trends of magnetic lineations outline shallow to moderate plunges to both NE and SW directions. The degree of magnetic anisotropy is generally larger (P´<1.17) than in the other two plutons. Mean magnetic susceptibilities are generally below 600 x 10^{-6} Si-units indicating preferentially paramagnetic behaviour and the lack of (or very little) ferrimagnetic minerals (such as magnetite), but some specimen outline presence of magnetite and a higher mean magnetic susceptibility (Figure 5-10). Greiling & Verma (2001) suggest that primary (titano-)magnetite was partly altered to (ilmeno-)hematite to explain the large scatter of mean magnetic susceptibilities.

In spite of the large variety of investigated rocks in the Schollenagglomerat magnetic fabrics outline relatively similar patterns: Magnetic foliations dip shallowly to NW-SW with shallow W- to WSW-plunging magnetic lineations. The degrees of anisotropy (P´< 1.65, max at 2.36) outline the highest values in Unit III.

Mean susceptibilities of the Heidelberg pluton are <500 x 10^{-6} SI units and paramagnetic behaviour is expected. Magnetic fabrics of the Heidelberg pluton differ from the Tromm and Weschnitz plutons displaying generally low degrees of anisotropy (P´< 1.06) and magnetic foliations dipping with 26° to 46° to the NE. Magnetic lineations plunge shallowly to subhorizontally to the NW. Magnetic fabric data thus may be used to distinguish between the Heidelberg and Tromm plutons, which show no well-defined boundary (as stated earlier).

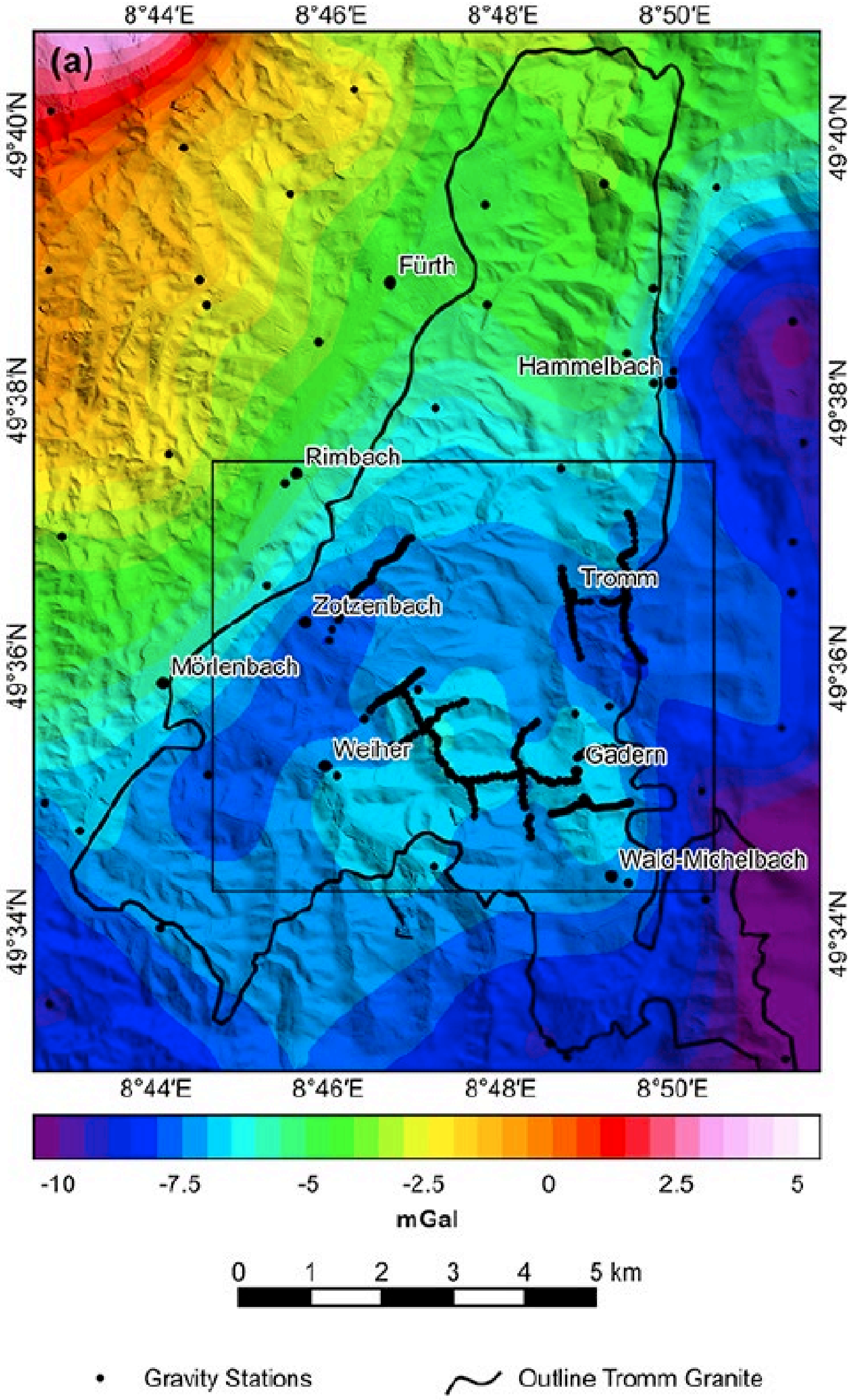

Figure 5-8: Complete Bouguer anomaly map of the Tromm pluton (Frey et al. 2022).

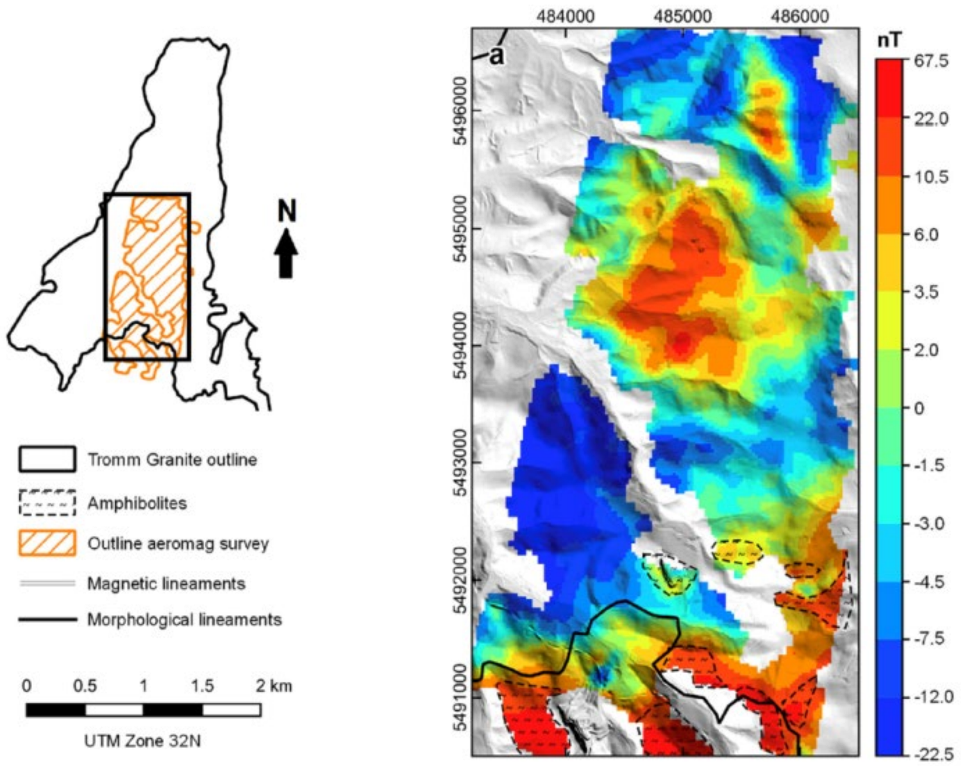

Figure 5-9: Results of the aeromagnetic survey from the Tromm pluton. (a) magnetic anomalies after reduction to the pole (RTP) at 70 m above ground and with a lateral resolution of 25 m (from Frey et al. 2022).

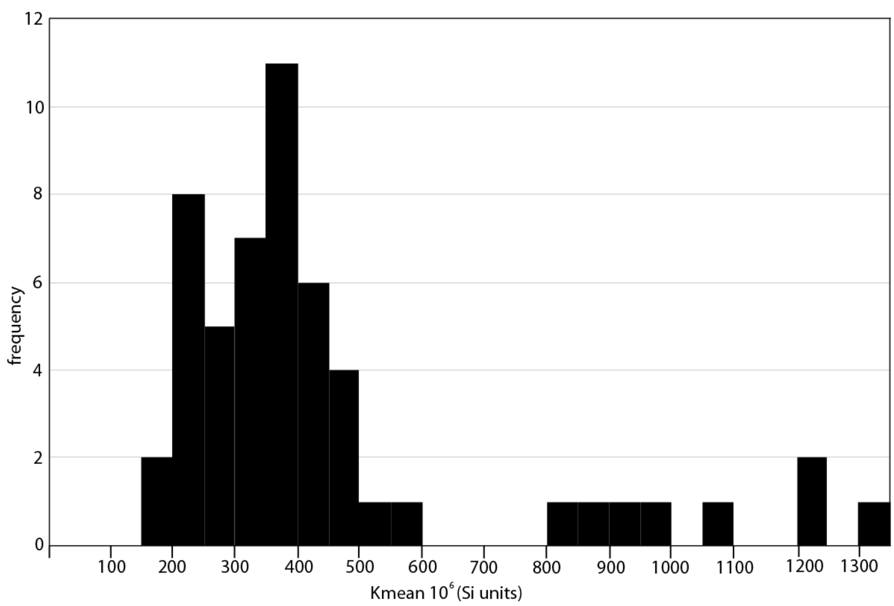

Figure 5-10: Mean magnetic susceptibilities. Distribution of mean magnetic susceptibilities (K_{mean}) of the Weschnitz, Tromm, and Heidelberg plutons indicating that the majority of all specimen (n=53) outline paramagnetic behaviour, but few samples with K_{mean} >500 x 10^{-6} show contributions of relic ferrimagnetic minerals; i.e., magnetite, not completely altered by oxidation. Four data points with K_{mean} >4000 x 10^{-6} were not shown for reasons of illustration. Data compiled from Greiling & Verma (2001).

Post-emplacement (sub-solidus) development

After its emplacement at 339 Ma the Tromm pluton was affected by several tectono-magmatic events.

Magmatic events

Especially in the southern part of the Tromm pluton the coarse-grained granite is intruded by veins and small stocks of a medium- to fine-grained (grain size < 1-2 mm) biotite-poor granite (Klemm 1929, 1933). This granite has its largest regional distribution around the town of Wald-Michelbach and was termed granite of Wald-Michelbach by Klemm (1900). Besides this granitic variety numerous small-scale (maximum several dm wide) veins and dikes of aplitic or pegmatitic appearance can be observed in the field. Both are characterized by granitic compositions, low abundance of mafic minerals (e.g., biotite), and the occurrence of primary muscovite (especially in the pegmatites). Additional accessory minerals that can be found in the pegmatites are tourmaline and rare beryl. Pegmatites exhibit sometimes fine-grained (aplitic) rims and/or pure quartz accumulations in the centre. The orientation of the dikes is variable and occasionally complex networks can be observed in outcrops (e.g., Klemm 1929). Most veins are undeformed but some pegmatites are associated with small-scale shear zones where they probably acted as a mechanically weak zone until their complete solidification (e.g., quarry Streitsdöll). Under the polarization microscope the sheared pegmatites are characterized by a bimodal grain-size distribution of quartz (probably due to rotation recrystallization) and plagioclase (due to solution-precipitation creep?) and the development of white mica fish. Especially the mica fish exhibit an indistinct shape-preferred orientation defining a weak sub-solidus foliation. As accessory phases chloritized biotite, apatite, zircon, monazite, and an opaque phase could be observed. The age of the aplitic and pegmatitic dikes is unknown, but emplacement immediately after the intrusion of the Tromm pluton is likely, possibly representing its residual melts.

Lamprophyres are restricted to the northern part of the pluton (especially in the Weschnitz valley around Leberbach) and also occur in the adjacent gneisses of the Zwischenzone (Hess & Schmidt 1989). Here they form up to 10 metres thick steeply inclined dikes that can be followed for several hundreds of metres along their N-S to NNE-SSW strike direction. They are best exposed in abandoned quarries to the SE of Leberbach (where the lamprophyres intruded gneisses of the Zwischenzone. In these quarries it can be observed that the dikes exhibit chilled margins (`Salbänder´) against their wall rocks with a pronounced finely laminated (magmatic?) foliation. The latter is oriented parallel to the contact zone of the dike. The lamprophyres were termed malchites in the older literature (after the mountain summit Malchen = Melibocus, e.g., Klemm 1933). They are mainly characterized by high amounts of biotite representing minettes in modern terminology. A recent geochemical analysis of the lamprophyre near Leberbach is published in Soder (2017). Two lamprophyric dikes in the Odenwald Crystalline Complex have been dated. Zulauf et al. (2021) revealed an emplacement age of 342 ± 1 Ma (U-Pb titanite) for a spessartite that intruded the Weschnitz pluton, and Hess & Schmidt (1989) determined a $^{40}Ar/^{39}Ar$ biotite age of 327 ± 3 Ma (K-Ar: 328 ± 7 Ma) for an undeformed lamprophyre that intruded the northernmost part of the Tromm pluton. However, geochronological data of lamprophyric dikes from the Spessart Crystalline complex yielded emplacement ages of 334-323 Ma and 297-295 Ma (von Seckendorff et al. 2004) indicating that generation of K-rich magmas was active over a time span of more than 40 Ma or was active during two distinct phases. Lamprophyres and other K-rich magmatites are widely distributed in the Variscan orogen and are attributed to partial melting of a metasomatized heterogeneous mantle (with elevated K_2O/Na_2O ratios; Soder & Romer 2018) where the additional heat was produced by upwelling of hot asthenosphere associated with detachment of the lithosphere at the end of the Variscan orogeny (von Seckendorff et al. 2004). The preferential N-S orientation of the lamprophyric dikes indicates a lithosphere-scale, post-orogenic E-W extension (e.g., Grimmer et al. 2017).

A later magmatic event is represented by acid volcanics south of the Tromm pluton (`quartz porphyr of the Eiterbachtal´, Klemm 1929). The volcanic rocks are relics of a previously larger, early Permian rhyolitic lava flow on already exhumed crystalline basement to the south of the Tromm pluton (Klemm 1929). Larger early Permian volcanic activity is documented between Heidelberg and Weinheim at the western margin of the Odenwald Crystalline complex where several hundred meters thick lava flows, pyroclastites, and ignimbrites were deposited on crystalline basement rocks. Major parts of the Odenwald Crystalline Complex lack Permian red beds as the area comprises a Permian swell separating the Kraichgau trough in the southeast and the Saar-Nahe basin in the northwest.

The latest magmatic event in the Odenwald is documented by late Cretaceous – early Cenozoic mafic-ultramafic rocks of the Southern Central European Volcanic Province (S-CEVP; Binder et al., 2023). In the southwestern part of the Tromm pluton, south of Zotzenbach, a small occurrence of a “basaltic” dike (not dated) was reported by Klemm (1929). SW of Darmstadt few Oligocene-Miocene basaltic rocks (e.g., the Otzberg volcanic center) were dated by the K-Ar method (Lippolt et al. 1975). However, K-Ar age data of basaltic rocks need to be considered with caution due to possible alteration and excess Ar (Binder et al. 2023).

<u>Exhumation and hydrothermal overprint</u>

The Tromm pluton intruded at 339 Ma at a depth of approximately 15-18 km (as outlined in previous sections) into a probably already hot crust due to previous intrusion of the Weschnitz pluton. The low pressure – high temperature metamorphism in Unit III with a transient geothermal gradient of about 50 K/km (see Willner et al. 1991) has been dated at 342 Ma and 332 Ma by U-Pb zircon on two gneisses (Todt et al. (1995). The metamorphic age of 332 Ma (from the quarry Hohe Hecke near Kallstadt) is younger than the intrusion ages of the unmetamorphosed Weschnitz, Tromm, and Heidelberg pluton, and is attributed to contact metamorphism associated with a younger yet undated intrusion phase (Stein et al. 2022). Coupling emplacement ages to emplacement depths it can be shown that exhumation of Unit III already took place during the Viséan at a rate of about 0.4 km/Ma (as outlined in previous sections). Assuming a constant exhumation rate and starting with the intrusion depth of 15 km of the Heidelberg pluton at 337 Ma, Unit III should have been completely exhumed at ca. 300 Ma. K-Ar (Kreuzer & Harre 1975, data recalculated, see Schubert et al. 2001) and $^{40}Ar/^{39}Ar$ (Schubert et al. 2001) amphibole cooling ages for Unit III fall into a range between 336 Ma and 326 Ma. Assuming a constant geothermal gradient of 50 K/km (which is probably an overestimation) and a closure temperature of 550°C for the K-Ar system in amphibole

(Harrison et al. 1985) an exhumation rate of 4 km in about 8 Ma (= 0.5 km/Ma) can be calculated confirming the considerations above. However, Henk (1995) calculated higher initial exhumation rates of 1.3 km/Ma for the entire Bergsträsser Odenwald by geothermal modelling. Further cooling and exhumation are indicated by a ^{40}Ar/^{39}Ar white mica age of 327 ± 1.6 Ma (Leyk et al. 2001) and K-Ar biotite ages between 328 Ma and 324 Ma (Kreuzer & Harre 1975). They indicate a temperature drop below 350 °C and 300 °C (closure temperatures for K-Ar in muscovite and biotite, respectively) after constant cooling (Stein et al. 2022) in the Serphukovian (i.e., c. 331 – 323 Ma). Final exhumation and exposure at the surface were achieved at ca. 300 Ma to 295 Ma (Henk 1995) because clastic sediments (and acid volcanics) of the Rotliegend were unconformably deposited on top of the crystalline basement (e.g., Zwischenzone gneisses in the vicinity of Erzbach). However, at other localities dolomites of the Zechstein sediments or sandstones of the Lower Buntsandstein directly, unconformably overlay the basement (for example around Wald-Michelbach) indicating that the sediments of the Rotliegend (and also Zechstein) were (re-)eroded or never deposited. The dolomites of the Zechstein, associated with Mn-ore mineralizations, exhibit a maximum thickness of several tens of meters. Subsequently Triassic and Jurassic sediments with an overall thickness of several hundreds of meters accumulated on top of the crystalline basement.

During Jurassic times the Odenwald crystalline basement was affected by an intense hydrothermal overprint, which likely caused the widespread observed sericitisation in the Tromm pluton and is responsible for the generation of metal-bearing hydrothermal veins at temperatures of more than 250 °C (Burisch et al. 2017). For the Tromm pluton, metal-bearing hydrothermal veins were not documented. Different vein types with more than 100 documented minerals (mineralienatlas.de) are documented in the active quarry `Viadukt´ near Mackenheim, located in the `Schollenagglomerat´ SW of the Tromm pluton. On the other hand, quartz and baryte veins (with a thickness up to a few meters) are probably widely distributed within the Tromm pluton. A WNW-ESE striking baryte vein at the northern slope of the summit Eselstein cross-cuts (without offset) the Otzberg fault zone and can also be found in the sandstones of the Buntsandstein Group to the east of the fault zone (Klemm 1928, Klemm 1929). Hence, at least this baryte vein must be post-Buntsandstein in age and younger (Miocene?) than the tectonic activity along the eastern branch of the Otzberg fault zone. In contrast to other parts of the Odenwald Crystalline Complex the baryte veins of the Tromm pluton are not silicified (i.e., replaced by quartz). Other hydrothermal precipitations (for example quartz, baryte, calcite, hematite) are likely associated with the movements along the Otzberg fault zone and will be described below.

In contrast to Burisch et al. (2017), Wagner & Storzer (1975), based on fission-track data, concluded that Mesozoic temperatures for the crystalline rocks of the Odenwald never exceeded 240 °C and fall into a range between 150 °C and 240 °C. Post-Jurassic cooling through the partial annealing zone of apatite is heterogeneous for the Odenwald Crystalline Complex pointing to a later exhumation of the Unit III with respect to the Unit II (Wagner & Storzer 1975): Unit III is characterized by the youngest AFT ages (n=9) varying from 69 Ma to 76 Ma whereas Unit II is characterized by the oldest AFT ages (n=9) in the Odenwald crystalline complex varying from 91 Ma to 105 Ma. The SW-NE striking boundary between Unit II and Unit III, trending along the schist-belt between Heppenheim, Lindenfels, and

Reichelsheim, likely localize structures causative for the relative younger uplift of Unit III (Figure 5-11). Unit IV, east of the Otzberg zone, displays AFT ages (n=3) varying from 80 Ma to 88 Ma. The observed fission-track age data are obviously related to Cretaceous-Palaeogene tectonic activities in west-central Europe (Eynatten et al., 2021; Voigt et al., 2021; Binder et al., 2023): Late Cretaceous NE-directed contractional basin inversion in central Europe is constrained from 95 Ma to 75 Ma, followed by a phase of dynamic topography from 75 Ma to 55 Ma and accompanied by intrusion and extrusion of minor nephelinitic-basanitic volcanic rocks and their differentiates. The southern Taunus and Odenwald regions were in a rather central position of this uplift which caused significant erosional removal of Mesozoic rocks that previously covered Permian redbeds, volcanics, and the pre-Permian crystalline basement (Böcker et al., 2017).

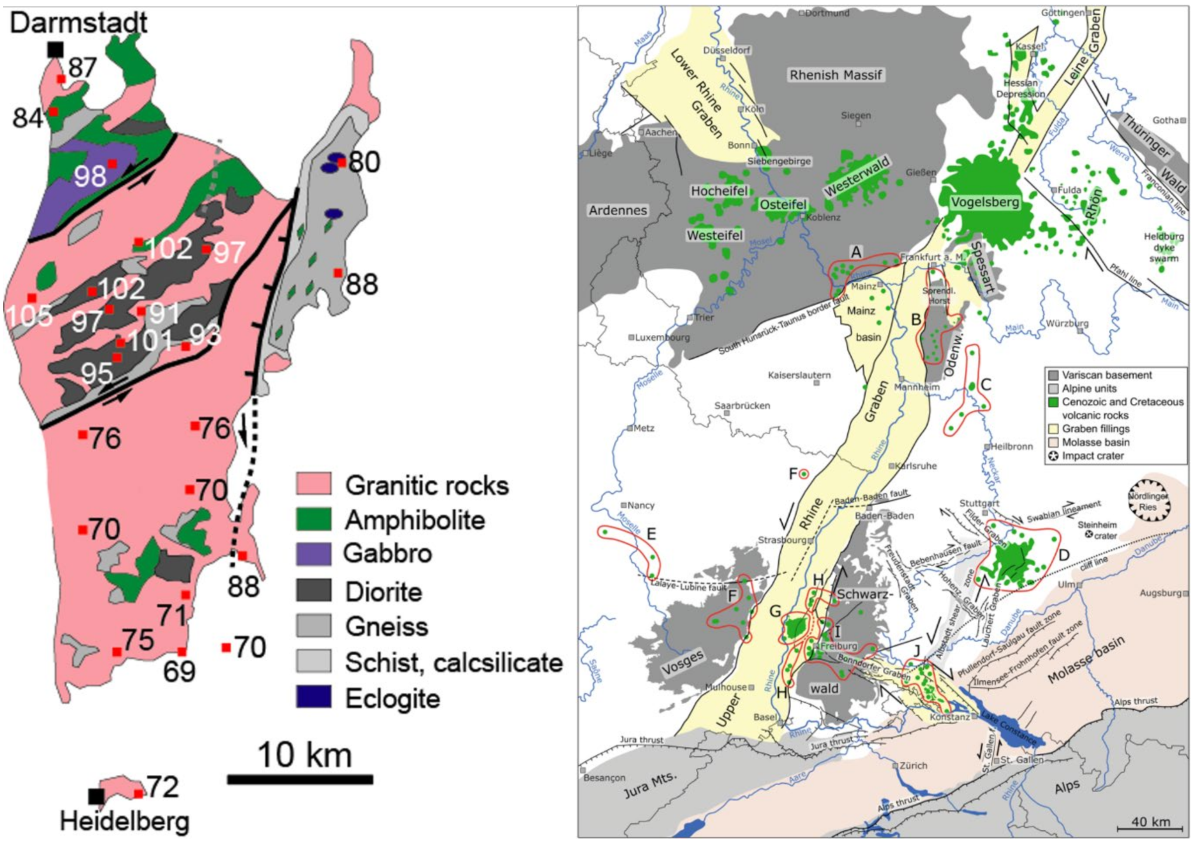

Figure 5-11: Geology. Left: Apatite fission track ages in the Odenwald Crystalline Complex in the different units. Data from Wagner & Storzer (1975). Right: Map of late Cretaceous-Eocene and late Oligocene-Miocene Southern Central European Volcanic Province (SCEVP) with the different subareas A-J. Subareas in the Taunus (A), Odenwald (B), and Kraichgau (C) host nephelinitic and basanitic volcanic rocks with ages varying from 73 Ma to 47 Ma (Binder et al. 2023).

In the Paleogene, contemporaneous with the intrusion and extrusion of primitive mafic-ultramafic volcanics, and the (re-)activation of fault zones a further phase of hydrothermal activity occurred in the Odenwald Crystalline Complex at c. 60 Ma, U-Pb on calcite II, Burisch et al. 2017). Exhumation through the lower limit of the apatite partial annealing zone (T = 40-60 °C, Rana et al. 2021) finally took place about 40 Ma ago. Jurassic rocks in pipe breccias of the c. 70 Ma old phonolites of the Katzenbuckel (Schmitt et al., 2007), SE of the Odenwald, intrusive into rocks of the Upper Buntsandstein Subgroup, document removal of >500 m of Mesozoic cover rocks since that time (Geyer et al., 2011).

Otzberg (fault) zone

Especially at its western and eastern margins the Tromm pluton is intensely affected by brittle deformation associated with the tectonic activity of the Otzberg fault zone. To the north of the Weschnitz valley between Brombach and Leberbach an undeformed lamprophyre crosscuts the cataclasites of the Otzberg fault zone within the Tromm pluton. The dike has been dated by the $^{40}Ar/^{39}Ar$ and K-Ar method on biotite and reveals an age of 327 ± 2 Ma and 328 ± 7 Ma, respectively (Hess & Schmidt 1989). This indicates that at least in this area cataclastic deformation must be older than 327 Ma and younger than 339 Ma (intrusion age of the Tromm pluton, see above). Furthermore, from the K-Ar biotite cooling ages of Kreuzer & Harre (1975) between 328 Ma and 324 Ma (recalculated) for Unit III it can be concluded that the cataclastic deformation must be active at temperatures around or above the closure temperature for the K-Ar system in biotite (T = ca. 300 °C, Harrison et al. (1985)). This in turn implies that cataclastic deformation took place at a depth of approximately 10 km (assuming a normal geothermal gradient) and at the brittle/ductile transition for quartz-dominated lithologies. The comparatively high temperatures during this cataclastic event are substantiated by the microstructures of the cataclasites (neo-crystallization of biotite, dynamic recrystallization of quartz; Hess & Schmidt 1989).

However, in the above-mentioned abandoned quarry to the SE of Leberbach it can be observed that the steeply dipping 010° striking contact between the lamprophyre and the gneisses of the Zwischenzone is strongly affected by brittle deformation with the development of distinct slickensides and sub-horizontal striations associated with displacement along a fault with oblique-slip sinistral kinematics. This indicates that at least some brittle deformation must have occurred after the emplacement of the lamprophyres.

The brittle structural inventory within the Tromm pluton has been investigated by Schälicke (1968, 1969, 1975) in considerable detail. For outcrops in the northern part of the Tromm pluton (north of the Weschnitz valley between Brombach and Leberbach) mainly SSW-NNE striking steeply inclined slickensides with dip-slip lineations are overprinted by sinistral SSW-NNE striking fault zones. Even younger are sub-horizontal slickensides with top-to-the-WNW kinematics (Schälicke 1968). From the age relationships described above it can be assumed that the near vertical displacement occurred before the emplacement of the lamprophyres and the formation of the sinistral fault zones is younger in age.

If the Permian rhyolites that crop out along the southernmost (eastern branch: Eiterbach valley, western branch: SW of Birkenau) and northernmost parts (E of Groß-Umstadt) of the Otzberg fault zone are associated with tectonic movements along the fault zone or just use zones of weakness for magma ascent is unclear at the moment.

Further age constraints for the activity along the Otzberg fault zone come from the eastern branch of the southern part of the fault zone. Here in the area between Hammelbach and Wald-Michelbach the fault zone is characterized by N-S striking, steeply inclined and according to the geological map 1:25000 Blatt Lindenfels (Klemm 1932) cataclasites separate the

Tromm pluton in the west from clastic sediments of the Buntsandstein to the east. Given the maximum altitude of exposures of the Tromm pluton at the Tromm summit (577 m a.s.l.) and the altitude of the basement-cover unconformity at Affolterbach at c. 380 m a.s.l. a minimum post-Buntsandstein displacement of 200 m with relative downward movement of the eastern block can be inferred. In apparent contradiction to this conclusion are observations by Schälicke (1968) from outcrops at Hammelbach who describes steeply to the W dipping SSE-NNW to SSW-NNE striking fault planes that exhibit W-side-down kinematics and hence must be interpreted as W-dipping normal faults. This discrepancy can be resolved if one assumes that the final displacement that positioned the clastic sediments of the Buntsandstein next to the Tromm pluton was achieved by a not exposed discrete fault zone that is located in the depression between Hammelbach, Scharbach and the western end of Kocherbach and is now hidden by Quaternary sediments. In the eastern branch of the Otzberg fault, additionally E-W striking and steeply S dipping fault planes with an oblique-slip dextral component can be observed (Schälicke 1968). They are younger than the W-dipping normal faults.

Displacement along the eastern branch of the fault zone in post-Buntsandstein times is probably coupled to the formation of a mosaic of blocks within the Buntsandstein area (see Backhaus & Bähr 1987). The blocks are mainly bounded by SSW-NNE- and WNW-ESE-trending steeply inclined fault zones and movement along the fault zones is probably associated with minor tilting of the blocks (as evidenced for example by the increase in altitude of the Variscan unconformity from about 260 m a.s.l. near Oberschönmattenwag to about 380 m a.s.l. near Aschbach along a distance of ca. 4 km).

The structural inventory of the western branch of the southern part of the Otzberg fault zone was investigated by Schälicke (1968). Typical for the western branch are SSW-NNE oriented steeply inclined slickensides with a sinistral sense of shear. In the boundary region between the Tromm pluton and Heidelberg pluton Schälicke (1968) describes different outcrops with cataclasites and brittle fault zones that are aligned in a SSW-NNE direction and interprets this as a further fault zone (`Westrandparallelzone´). This fault zone is aligned parallel to the western branch of the Otzberg fault zone which is located within the Weschnitz valley further to the west (with a distance of about 2 km), largely covered by Quaternary sediments. A former excellent outcrop (now behind a wire mesh fence) of the western branch is located to the SW of Rimbach at the road B38. Here numerous approximately N-S striking and steeply to the W or E dipping slickensides with moderately to the N plunging slickenlines were exposed within the Weschnitz pluton exhibiting mainly oblique-slip sinistral kinematics (Schälicke 1968). To the south the western branch of the Otzberg fault zone diminishes in the area of Birkenau. Comparable to the eastern branch W-E striking mainly steeply dipping fault zones with unknown strike-slip kinematics represent a younger tectonic event of probably Tertiary age (Schälicke 1968). Reactivation of older fault planes or formation occasionally causes the opening of fractures under an extensional stress field. The voids can be filled partly or completely by a late generation of calcite or quartz. Brittle deformation along the southern part of the Otzberg fault zone (western and eastern branch) is accompanied by the precipitation of secondary minerals such as quartz, hematite, and calcite.

Lineament and outcrop analyses

The fracture network of the Tromm pluton was recently investigated by lineament analysis of digital elevation models (DEM) covering the entire Tromm pluton (Frey et al. 2022), by gravity measurements (Frey et al. 2022) and a drone-based aeromagnetic survey (Frey et al. 2023) in the central part of the pluton, and by a combined LiDaR and 2D profile analyses of five outcrops in the Tromm pluton and the adjacent Otzberg fault zone (Figure 5-12,Figure 5-13; Bossenec et al. 2022, Frey et al. 2022).

Whereas a regional analysis using SRTM data (SRTM = Shuttle Radar Topography Mission) with a resolution of 1 arcsec (c. 27 m) reveals dominating W-E and WNW-ESE striking lineaments, a more detailed analysis using the digital elevation model with a resolution of 1 m (DEM1) exhibits a near random orientation of the lineaments with a minor peak in the WNW-ESE direction. The dominant W-E to WNW-ESE strike direction of the lineaments probably coincides with the W-E striking fault zones (slickensides) described by Schälicke (1969).

The fracture analyses of five different outcrops of the Tromm pluton and the Otzberg fault zone by LiDaR measurements reveal a comparatively homogeneous joint distribution pattern for the outcrops that were not or only little affected by obvious brittle deformation (quarries Streitsdöll, Borstein, Ober-Mengelbach). In general, two orientation maxima could be determined with the major maximum striking NNW-SSE and a minor maximum with a WSW-ENE strike direction (Figure 5-13; Bossenec et al. 2022, Frey et al. 2022).

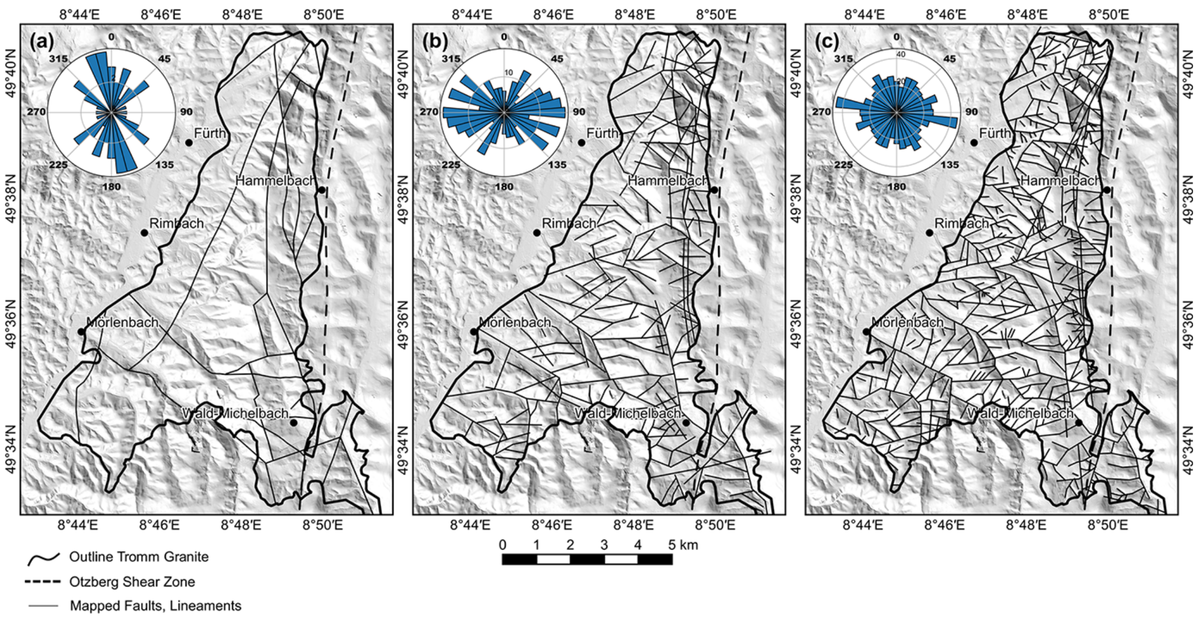

Figure 5-12: Lineament analysis. Summary of the lineament analysis in the Tromm Granite area of Frey et al. (2022): (a) compilation of mapped faults from various geological maps (b) lineament analysis using SRTM data with 1 arcsec resolution (c) lineament analysis of DEM1 data.

The first maximum is broadly parallel to the main orientation of mapped geological faults in the area, but both maxima do not coincide with the orientation of the lineaments derived by DEM analysis (Frey et al. 2022). Outcrops exposing cataclastically overprinted rocks are assigned to the Otzberg Zone (Weschnitz valley, Hammelbach) the fracture patterns outline orientation maxima trending E-W to NW-SE and NE-SW. However, neither the fracture pattern at Hammelbach nor at Weschnitz valley can be correlated with the main orientation of the slickensides described by Schälicke (1968, 1969) from these outcrops. Taken the existing data together, a comprehensive understanding of the orientation of faults, slickensides, and joints within the Tromm pluton has not been achieved yet.

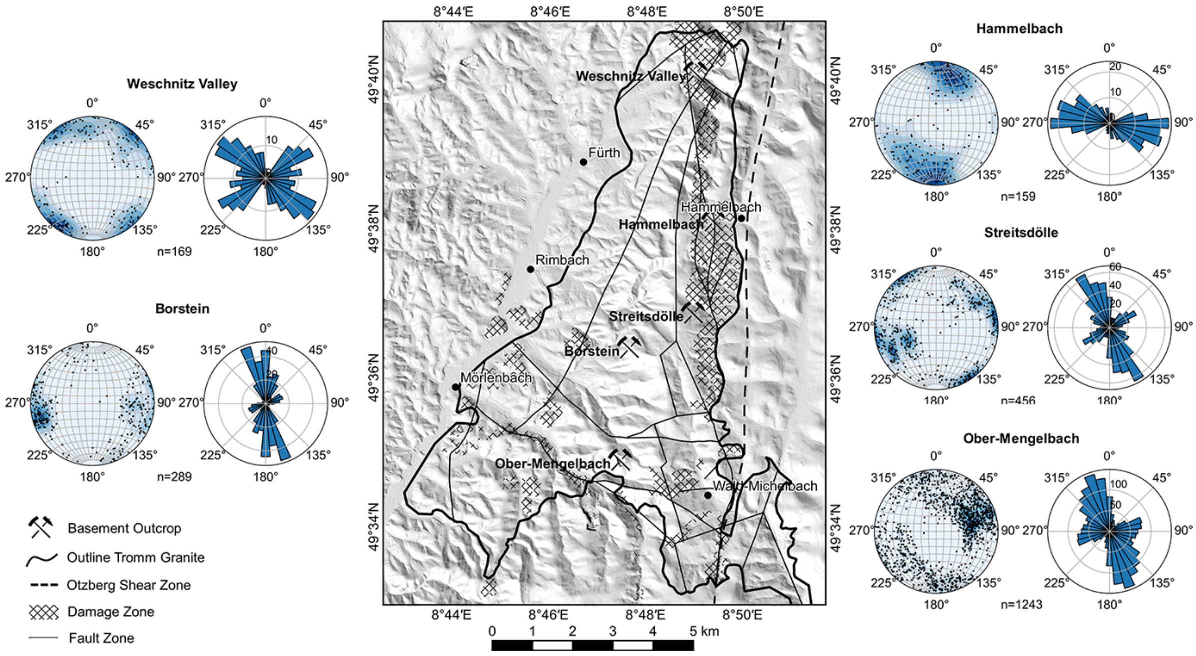

Figure 5-13: Outcrop analysis. Summary of outcrop analyses with RIEGL VG 400 lidar instrument in the Tromm pluton and cataclasites of the Otzberg Zone (from Frey et al. 2022).

The DEM5 lineament analysis of Becker & Reinicke (2024) encompasses the entire southern Odenwald with preferred lineament orientations trending NNE-SSW and NW-SE. For the Tromm pluton the preferred lineament orientation is NW-SE (Figure 5-14).

The lineament frequency (lineaments per km^2) and lineament density (lineament length per km^2) of the Tromm pluton is relatively high if compared to the other distinguished units, but lower than in the Weschnitz pluton.

In the quarry Ober-Mengelbach an as yet unpublished fault plane analysis was carried out in summer 2016 by the principal author when the water table in the quarry was relatively low and more parts of the quarry were accessible. The quarry exposes both the Schollenagglomerat and the Tromm pluton (as outline earlier). To the east it is limited by a steeply W-dipping 3-5 m thick cataclastic zone in which the rocks were intensively altered, likely representing a major, regional fault zone. The quarry exposes several faults with kinematic indicators (mineral fibers, slickensides, Riedel shears, offset relations). Fault-slip data are heterogeneous and were subdivided into four subsets that are kinematically compatible (fault populations FP 1-4;Figure 5-15). For the major steeply W-dipping cataclastic fault zone the kinematics could not be determined due to intense alteration and rock decomposition and possible multiphase deformation. The fault zone strikes parallel with steep dipping sinistral strike-slip faults grouped as FP 1 and thus may be a sinistral strike-slip zone (Figure 5-15). This major fault zone was displaced dextrally by c. >5 m by a SW-dipping oblique normal fault of FP 3, which thus must be younger. However, no relative or absolute age could be as yet constrained.

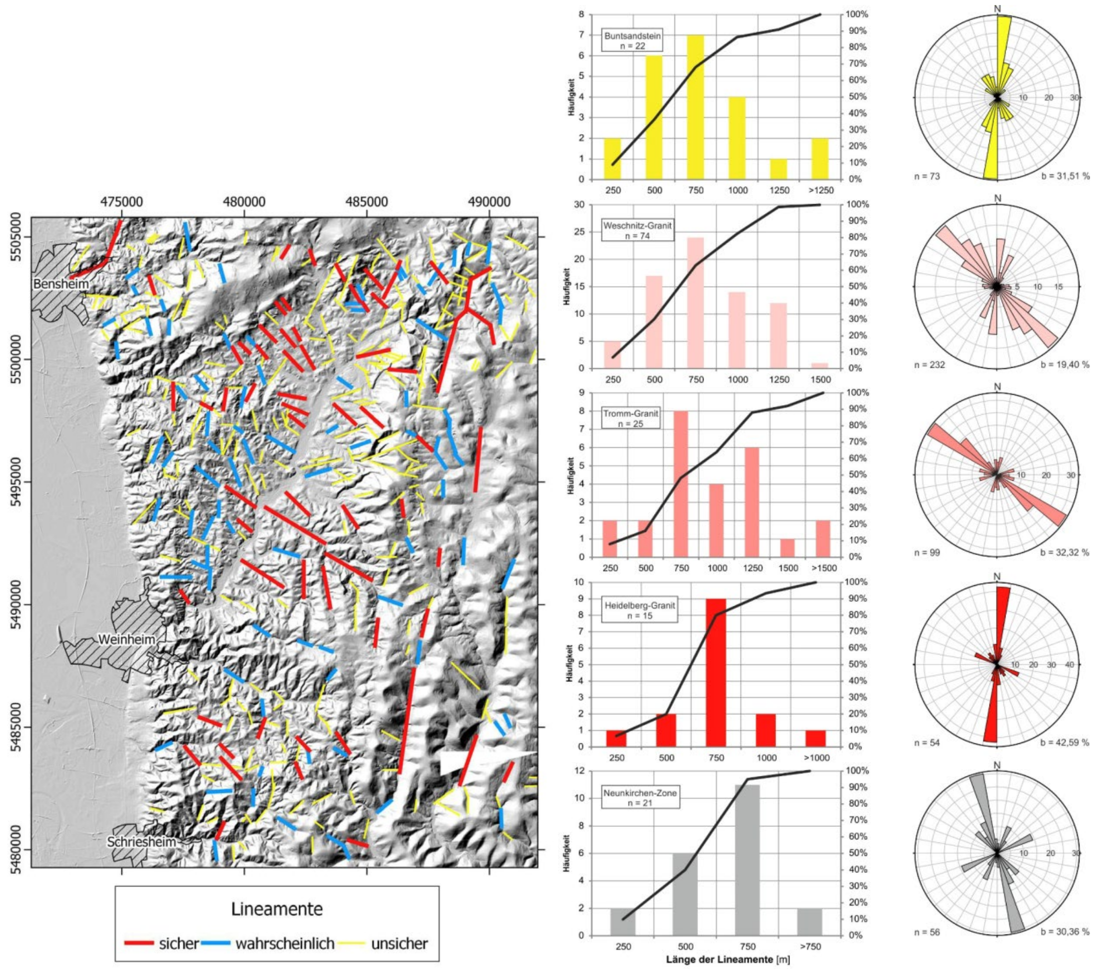

Figure 5-14: Lineament uncertainty and statistics. Left) Mapped lineaments of Becker & Reinicke (2024) based on a DGM5, subdivided into the categories highly likely (sicher), likely (wahrscheinlich), unlikely (unsicher). Right) lineament length frequency diagram and orientation distribution statistics.

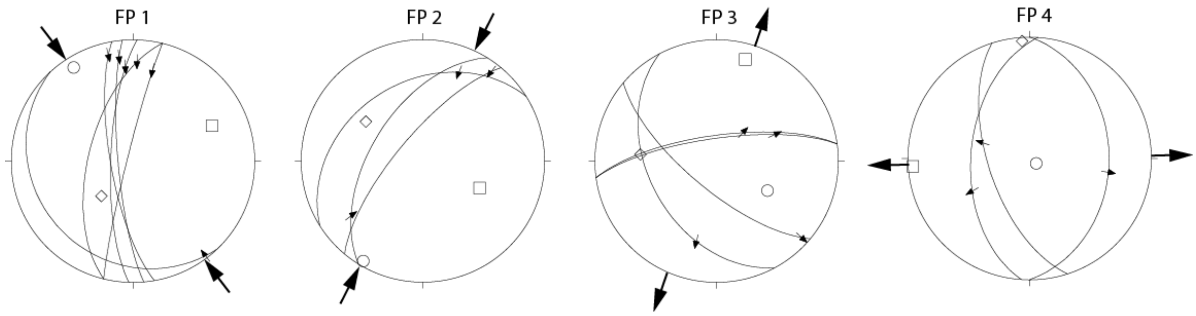

Figure 5-15: Fault-slip data from the quarry Ober-Mengelbach subdivided into four fault populations (FP 1-4).

5.3 KEY FINDINGS AND CONCLUSIONS

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 (likely younger `G2´) granite suite in the south. However, little is known on basic pluton characteristics: thicknesses, root zones, original geometries, zonations, 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 geometry, petrogenesis, and internal structure.

Outcrops in the Tromm pluton (Borstein, Streitsdölle, Ober-Mengelbach) 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.

In summary, a lot of detailed and distributed observations and data of variable quantity and quality exist for the Tromm pluton and surrounding areas on post-emplacement brittle faulting. A well developed and coherent kinematic understanding of the deformation history is essentially lacking. To achieve this relative and absolute age constraints of deformation are needed.

5.4 NEXT STEPS

The next work steps will be carried out in i) the field, ii) on borehole data (logs), iii) and core material of the GLB-1 borehole.

1) Structural analyses along the eastern branch of the Otzberg Zone in the Permo-Triassic cover rocks to constrain post-Permian deformation. Datable material linked with structures/deformation (e.g., calcite fibers, veins, fault gouge) will be sampled for radiometric dating of deformation.

2) FMI analysis of the GLB-1 borehole and development of a Discrete Fracture Network (DFN) in areas of interest.

3) Targeted geochemical, mineralogical, textural and geochronological analyses of Tromm pluton to improve understanding of petrogenesis, emplacement, deformation, and alteration.

4) An improved AMS study will be carried out on drill cores of the GLB-1 borehole to unravel vertical hyper-solidus fabric variations and sub-solidus development.

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6 HYDROGEOLOGY

CHRISTOPH SCHÜTH

6.1 INTRODUCTION

6.1.1 Rational for Hydrogeological Studies

The surrounding municipalities in the Tromm region operate local water suppliers, which mainly have their extraction facilities in the valleys surrounding the Tromm mountain range. In the west of the Tromm, this is particularly the Weschnitz valley with the municipalities of Fürth, Rimbach, Zotzenbach and Mörlenbach, and in the east the valleys of the Ulmenbach with the municipalities of Grasellenbach and Wald-Michelbach. The associated aquifers are fed by local groundwater recharge from precipitation, but in particular also by inflowing water from the Tromm mountain range. This means that the construction and operation of the underground laboratory could potentially have an impact on these water resources (Figure 6-1).

The hydrogeological situation in particular requires comprehensive investigation, as crystalline rock bodies such as the Tromm Pluton are of minor relevance from a water management point of view and have therefore not been investigated in detail for such purposes. This also applies to the Tromm Pluton, for which only very limited information is available from boreholes. It is generally assumed that the crystalline rock below a typical granular disintegration zone has low permeabilities, which are correspondingly less water-bearing. Numerous springs can also be found in the higher areas of the Tromm, which suggest near-surface runoff of infiltrating rainwater with short residence times.

However, it must be clarified to what extent the crystalline basement participates in the water cycle of the catchment areas surrounding the Tromm. In particular, whether relevant quantities of water flow from the deeper parts of the crystalline basement to the valley aquifers in comparison to the granular disintegration zone near the surface, and also whether the catchment areas that can be defined above ground on the basis of the elevation profiles are congruent with the underground catchment areas. It should be noted that fissure systems in the crystalline basement can have flow directions that deviate locally from the overall system due to their spatial orientation.

Due to the downward sloping access shaft, the main cavern of the underground laboratory will be located well below the western and eastern valley levels. However, it is not known whether and how productive fissure systems will be encountered during the excavation of the access shaft. It is therefore possible that substances affecting the water quality could flow into the downstream located aquifers during or after the construction work. If this were the case, extensive dewatering measures would be necessary, both to keep the access shaft and the main cavern dry, but also to prevent the outflow of water affected by the construction and operation of the underground laboratory.

The hydrogeological investigations can provide valuable information on the role of the Tromm Pluton in the overall hydrogeological system by obtaining hydraulic, hydrochemical and hydrological data. This should ensure that the construction and operation of the under-ground laboratory does not have a negative impact on the surrounding areas relevant to the local water supply, or that appropriate measures can be taken to protect them.

6.1.2 Hydrogeological Framework

From a hydrogeological perspective, the Tromm mountain range in the area of the study site forms a water divide. On its western side, the terrain falls quite steeply from the highest elevation of the Tromm summit at around 577 m down to the Weschnitz valley, with heights of around 150-200 m in the southern valley locations. In the east, the terrain in the transition to the Bunter Sandstone Odenwald is much flatter, with heights of around 250-300 m in the southern valley locations. The Weschnitz drains the western area towards the Upper Rhine Graben, and accordingly to the Rhine, while in the east the Ulfenbach, named Laxenbach after its confluence with the Finkenbach downstream, drains the eastern area into the Neckar (Figure 6-1Figure 6-1).

As a crystalline rock body, the Tromm pluton typically should have only low to extremely low hydraulic conductivities. This assumption is also made in the report “Groundwater in Hesse, Issue 2 - Odenwald and Sprendlinger Horst” published by the Hessian State Agency for Nature Conservation, Environment and Geology (HLNUG). However, a quantification of permeabilities or other hydraulic parameters in the deeper areas of the pluton is not yet possible, due to the lack of data. Measured values of the apparent or intrinsic permeability of the granite from Weinert et al. (2020) range between 10^{-15} m^2 and 10^{-18} m^2, and porosity values are assumed to be between 0.1 and 2.1 %.

The rock itself is therefore more or less hydraulically impermeable, but the rock permeability should be higher, as fissures are expected in the granite, especially in the area of fault zones, such as the Otzberg fault zone. There may also be fissures close to the surface in a relaxation zone with water pathways, although this zone should only extend to a depth of a few tens of meters. The fissure widths and densities should decrease rapidly towards depth. Therefore, in the crystalline basement, a low effective porosity can only be expected in the area near the surface.

A weathering layer in the form of a granular disintegration zone is formed above the solid rock, in which an unconsolidated aquifer (pore aquifer) of medium to moderate hydraulic permeability can be formed. This zone is the main aquifer in the Crystalline Odenwald. The groundwater moves downslope in this weathered zone, which is usually only a few meters thick. A large proportion of the seeping precipitation most likely then generates interflow to the numerous springs on the slopes with only a short time delay, without reaching the bedrock.

In the quaternary fluviatile unconsolidated sediments of the river valleys, particularly on the western side of the Tromm, pore aquifers of medium to moderate hydraulic permeability have developed. The groundwater either flows into them from the fissures in the crystalline rock or is flowing downhill in the slope debris and the granular disintegration zone. To a lesser extent, groundwater recharge of the valley aquifers is also generated by percolating precipitation in the absence of alluvial loam.

The HLNUG[3] report on the hydrogeology of the Odenwald and the Sprendlinger Horst states that data from 1,748 boreholes/measuring points can be evaluated for the Crystalline Odenwald. For the Crystalline Odenwald, 1,056 data on groundwater levels were available. In the Crystalline Odenwald, most of the monitoring wells have an average groundwater table of up to 5 meters below surface. Groundwater table depths between 20 and 40 m were found at 23 monitoring sites, and 74 m at one site.

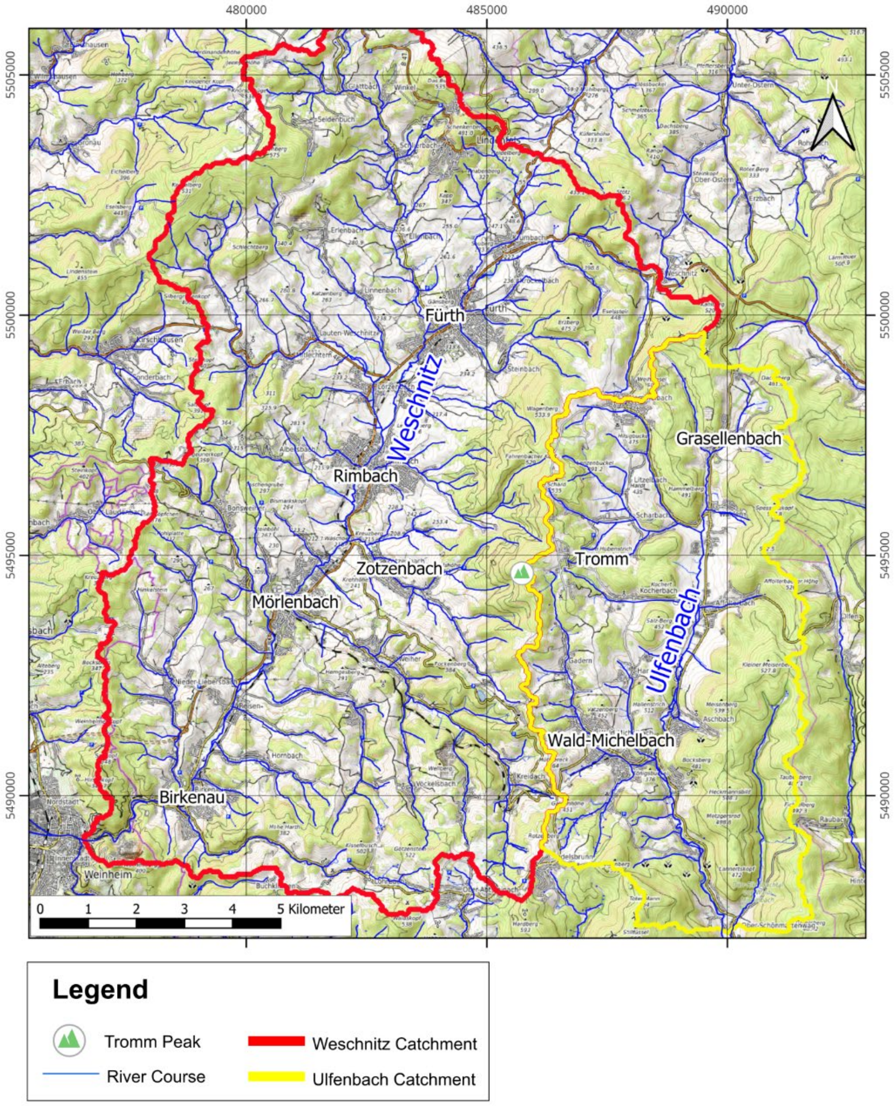

Figure 6-1: Tromm mountain range as a water divide. In the west, the Weschnitz forms the receiving watercourse and drains to the Rhine Valley, in the east the Ulfenbach forms the receiving watercourse and drains, later called Laxenbach after merging with the Finke.

Artesian groundwater conditions were not encountered at any of the boreholes. The low values for the depths to the groundwater table also indicate that the granular disintegration

[3] Hessian Agency for Nature Conservation, Environment and Geology

zones of the crystalline rocks are water-bearing and that there is only low permeability below. It should be noted that only a few boreholes reached a depth of more than 100 m (n=35). The influence of the Otzberg fault on the hydrogeological conditions is not documented.

6.1.3 Water Protection Areas and Other Protected Zones

Water protection areas are frequently found in the Tromm area and its surroundings, as the local communities generally operate their own water supply. In the wider study area, almost 20 km² are designated as protected areas, which corresponds to more than 25% of the total area where an exploration license is requested. Figure 6-2 shows the protected areas, but not all of these are relevant to the planned activities in the central part of the Tromm.

In addition, a fauna-flora habitat (FFH) stretches from the Tromm mountain ridge to the west. The underlying European Habitats Directive aims to conserve biodiversity in such an area. To this end, a favorable conservation status of the species and habitat types of interest is to be restored or maintained. One means of achieving this is the establishment of a system of protected areas designated according to uniform criteria (Natura 2000).

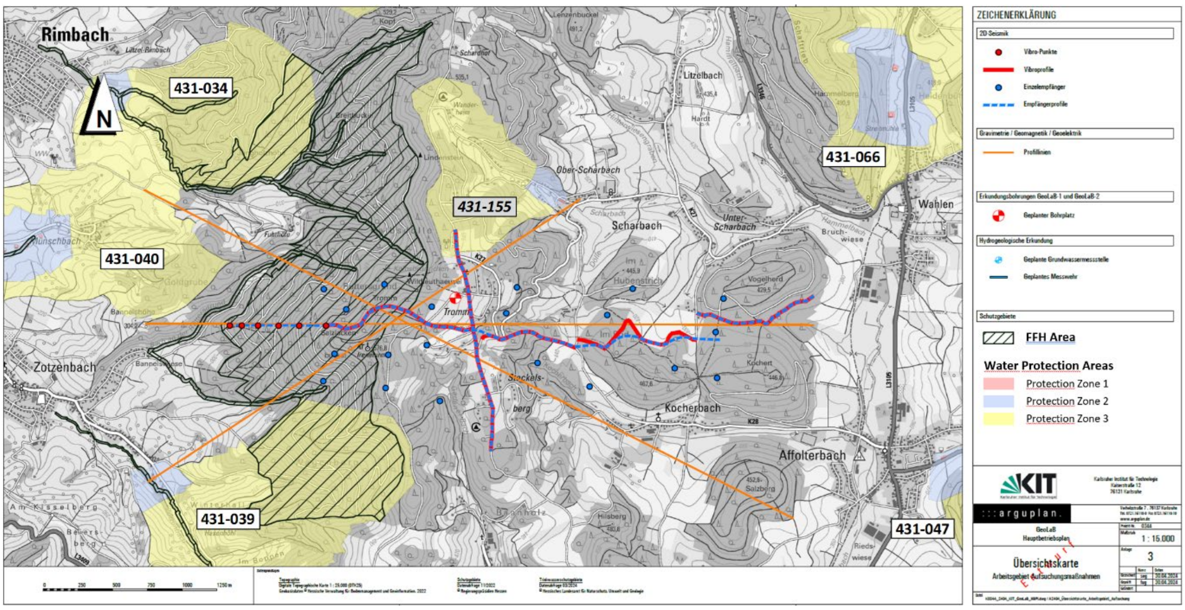

Figure 6-2: Protection areas. Locations of the water protection areas and the FFH area close to the Tromm peak. Map and information on the water protection areas obtained from GruSchu database of HLNUG (https://gruschu.hessen.de/mapapps/resources/apps/gruschu/index.html?lang=de). Pink line represents the location of the planned geophysical investigations.

Closer to the highest peak of the Tromm several water protection areas have been defined, particularly on the western side. The corresponding protection area reports are available, as provided by HLNUG. The water protection area 431-034 (Wüstenwiese-Rimbach well), 431-040 (Münschbachertal-Rimbach well), 431-039 (Zotzenbach-Rimbach well) have been established, as have the somewhat more distant protection areas on the eastern side: 431-066 (Grasellenbach well and springs) and 431-047 (Afolterbach-Wald-Michelbach springs). The protected area 431-155 (spring 10, Scharbach-Grasellenbach) is still in the process of being designated. These relevant water protection areas and the FFH area are shown in Figure 6-2.

6.2 WORK STEPS AND CONDUCTED STUDIES

The aim of the work carried out was to create a basis for implementing a monitoring system based on the data collected. This should enable to monitor the potential influences of the activities in the GeoLaB context on the groundwater resources in the target area and the connected catchments used for public water supply.

As the exact location of the access tunnel to the GeoLaB underground laboratory has not yet been determined, no monitoring system directly related to it can be developed at this stage. However, an initial spatial analysis was carried out on the basis of the GeoLaB planning status and the existing database. In addition, new data were collected on hydrochemical parameters. Based on this, installations are to be proposed that can already generate relevant data regardless of the location of the access tunnel that is determined later.

One reasonable assumption is that the access shaft will be located on the western side of the Tromm mountain range, as the difference in height between the Tromm summit and the point where the shaft should begin is significantly larger there than on the eastern side. In order to achieve the highest possible overburden of the shaft end point, the starting point must also be close to the latitude of the summit. Considering this, a digital elevation model was first used to delineate above-ground catchment areas, particularly on the western side of the Tromm and evaluate their locations based on the prospective shaft entrance points.

6.2.1 Hydrochemical Analyses

In the area of the Tromm mountain range 16 wells and 20 springs were sampled in order to obtain a first overview of the hydrochemical conditions in the study area. The sampling took place on both the east and west sides of the Tromm and also included the water catchments of the water supply companies. Besides field parameters, major anions and cations, trace elements as well as stable water isotopes were analyzed.

As an example, in Figure 6-2 the total dissolved solids concentrations (TDS - mg/l) of the water samples are displayed.

As expected, the TDS contents are low, particularly in the springs in higher elevations. Low TDS contents of less than 100 mg/l are also found on the eastern side of the Tromm pluton and in the adjacent sandstone. Such TDS contents are characteristic of crystalline rocks and may also indicate short residence times in the subsurface, particularly at higher locations. Higher TDS contents of up to about 400 mg/l are limited to the western side of the Tromm mountain range and here are found in the wells which are used for public water supply.

Sampling of wells and springs currently continues to get time series of various parameters for later comparison with values obtained during the construction and operation of the GeoLaB.

6.2.2 Analyses of a Digital Elevation Map

A digital elevation model (DGM1) was obtained from the Hessian Authority for Soil Management and Geoinformation (HVBG). As an intermediate step, the flow directions and the potential flow paths of surface runoff were calculated from the DTM1 so that the calculated flow paths correspond approximately to the flow paths obtained from the 1:25,000 topographic map (TK25) or from the digital landscape model (DLM). From this, the watershed between Weschnitz (draining to the Rhine) and Ulfenbach (draining to the Neckar) was first calculated over a large area. This runs along the ridge of the Tromm.

As the cavern should have an overburden of at least 400 m if the GeoLaB is realized, it should be located at an altitude of about 170 m above sea level in the area below the Tromm summit or even lower (Tromm summit 577 m - 400 m = 177 m). This elevation level is significantly lower than the valley floors in the Ulfenbach valley east of the watershed, which lie at 250 - 300 m above sea level. For this reason, smaller-scale catchment areas were only calculated for the western side of the Tromm towards the Weschnitz valley. A total of 5 catchment areas were identified on the west side of the Tromm (Figure 6-4).

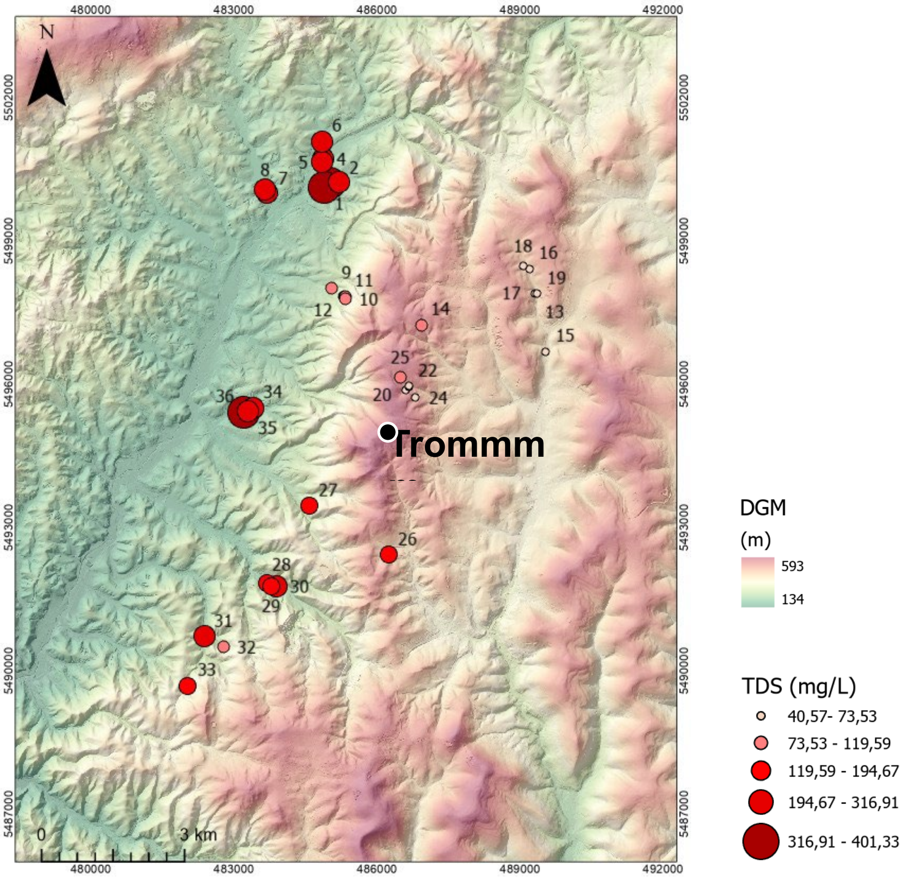

Figure 6-3: Location of springs and wells in the study area. These were sampled and determined TDS content.

It can be seen that catchment areas 3 and 4 should be considered more closely. This results from the locations of the possible shaft entrances for access to the GeoLaB, which are located in particular in sub-catchment 3 and are potentially also very close to catchment 4. The different possible shaft courses are taken from the collection of GIS files from the UFZ data repository.

It should be noted here that the water protection areas 431-034 (Wüstenwiese-Rimbach well), 431-040 (Münschbachertal-Rimbach well) and 431-039 (Zotzenbach-Rimbach well) with the corresponding catchments are also located in these two sub-catchments.

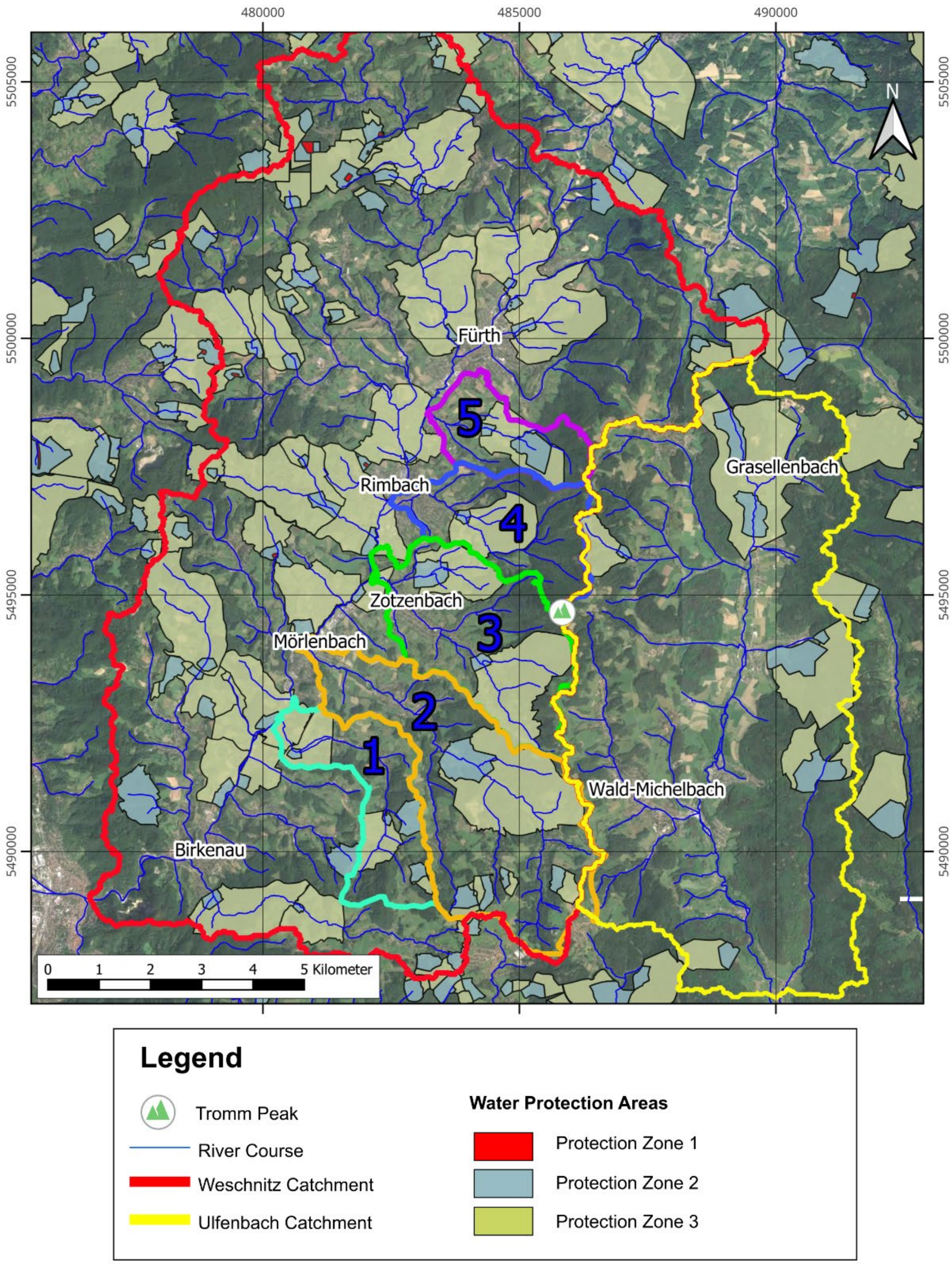

Figure 6-4: Catchment areas. Five different catchment areas on the western side of the Tromm were distinguished, which drain the area towards the Weschnitz.

6.2.3 Monitoring Approach

The hydrological monitoring of a catchment are ideally leads to water balances. For this purpose, both the input, in this case rainfall, and the output, i.e., the runoff from a catchment area, must be determined. In order to generate this data, monitoring stations must be set up in the catchment area (weather stations, discharge measuring stations). With the data collected in this way and further information on the geological conditions in the subsurface, the hydraulic properties of the subsurface, numerical models can then be created that can describe the current state, but also provide an outlook on the effects of measures in the catchment area.

In the two catchments 3 and 4 potential locations for discharge measurement stations were already identified in field surveys to get data sets later used in water balance calculations of the sub-catchments. In order to be able to describe the catchment areas identified from the digital elevation model in more detail, 70 points of hydrogeological interest (springs, wells, water reservoirs) in catchment areas 3 and 4 were also identified from the TK25 or during field inspections (Figure 6-5).

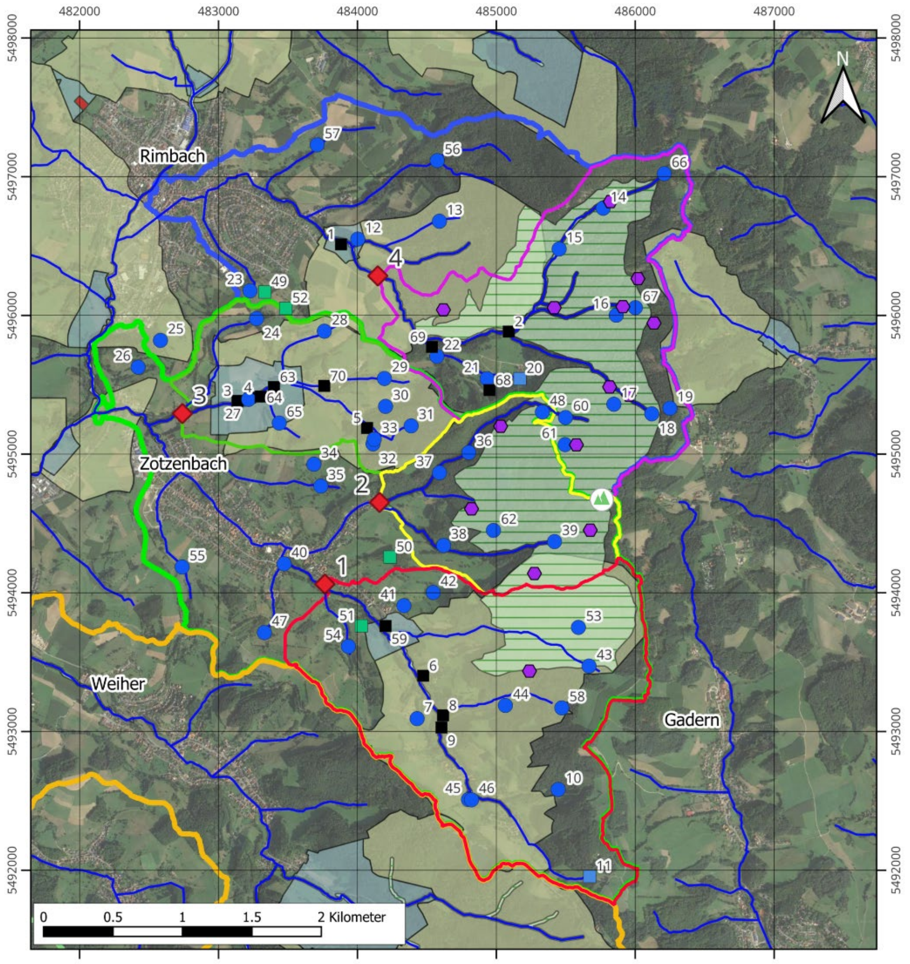

Figure 6-5: Measuring stations. "Water Point Inventory" (springs, wells, water reservoirs) in the relevant catchment areas 3 and 4 on the west side of the Tromm, as well as the location of 4 possible discharge measuring stations.

6.2.4 Installation of a First Weather Station

In addition to the discharge measuring stations, weather stations, or at least precipitation measuring stations, are required to further assess the hydrological/hydrogeological situation and to estimate water balances in the sub-catchment areas. Therefore, a fully equipped weather station has already been set up in the area of the Tromm summit and here on the grounds of the Odenwald Institute (Figure 6-6).

It is planned to install further precipitation stations and rainfall collectors at least in catchment areas 3 and 4.

Figure 6-6: Installed weather station close to the Tromm summit.

6.3 CONCLUSIONS AND OUTLOOK

From the review of the current data on the hydrogeological situation in the Tromm area, conclusions can be drawn that contribute to the planning and implementation of an effective monitoring system. It must be noted, however, that the final location of the access shaft is still not known. However, by narrowing down the possible area for the access shaft, monitoring installations can already be carried out now, which will then have to be supplemented by groundwater wells.

The basic idea is that water balances must be determined for the potentially later affected areas for the documentation of the initial state, which can be used as a reference for later investigations in the construction phase and during operation of the underground laboratory. Water quality data should also be generated here in order to document the native groundwater chemistry and to identify potential geogenic or anthropogenic backgrounds in order to be able to identify later influences of the construction phase and the operation of the laboratory on the groundwater quality. The following conclusions can be drawn from these basic assumptions, also with regard to a second project phase:

- The western side of the Tromm is the most likely starting point for the access shaft to the underground laboratory.
- On the western side of the Tromm, two catchment areas can be defined which are potentially influenced by the construction of the access shaft.
- A total of 3 water protection areas are located in these two catchment areas, namely 431-034 (Wüstenwiese-Rimbach well), 431-040 (Münschbachertal-Rimbach well) and 431-039 (Zotzenbach-Rimbach well)

- To determine water balances, it is proposed to set up 4 automated discharge measuring stations and 4 precipitation measuring stations with rain collectors in this area.
- The measurement campaigns started to generate a hydrochemical characterization of groundwater, springs and surface waters must be continued, also on the eastern side of the Tromm. In addition to the parameters to be collected in the field, laboratory analyses for main anions/cations, trace elements including rare earth elements, anthropogenic contaminants, as well as water isotopes and isotopes for determining the age of water must be carried out. Monthly sampling campaigns are proposed for basic parameters, as well as event-based automated sampling at high resolution, e.g., hourly, particularly for questions relating to the discharge behavior of springs and surface waters.
- Installation of groundwater level loggers at suitable wells, in consultation with the water suppliers

A data exchange was agreed with the municipalities and local water suppliers, which, together with the data generated in a second project phase, should also provide additional information on potential locations for new groundwater monitoring wells. The basic idea here is to install groundwater monitoring wells with a depth that penetrate the loose sediments, the granular disintegration zone of the crystalline bedrock, and the upper area of the bedrock in the upstream area of the relevant catchment areas.

This will generate data on the structure of the subsurface, and thus on the overall hydrogeological system, which is absolutely essential for the planned development of numerical flow and transport models.

7 EXPLORATION

FIORENZA DEON, STEFAN LÜTH, INGO SASS, NADINE HAAF, ULRIKE HOFFERT, HARALD MILSCH, RÜDIGER GIESE, GÜNTER ZIMMERMANN, DORIT KÖNITZ

7.1 INTRODUCTION

The working group planning/exploration focuses the activities on the Tromm (Odenwald) exploration following different approaches. From the surface to the subsurface we aim to understand the granitic rock bodies, the fractures, shear zones, alteration and faults (Otzberg fault) in the area. The overall scope is to determine the sustainability of the Tromm location for the realization of the GeoLaB underground research laboratory. By means of several disciplines such as geology, geophysics, petrology and geochemistry valuable information are being gathered for a better knowledge of the Tromm region. The group is coordinated by Dr. Fiorenza Deon (GFZ) and Prof. Dr. Christoph Schüth. Several colleagues from the different partner institutions (GFZ-KIT) and TUDa work pro-actively in the exploration strategy and the implementation of each single step in the direction of the site selection. The working group has synergies with the group technique given the exploration drilling and the core sampling pro-gram which is planned for the beginning of 2025.

The main activities of the group will be described in the next paragraph along with the results achieved so far.

7.2 WORK STEPS AND CONDUCTED STUDIES

7.2.1 Mineralogy-petrology: Characterization of Outcrop Rocks

The samples were collected based on the accessibility, exposure and alteration of the outcrops in the Tromm area. The samples from the Streitsdöll quarries and the samples from the Tromm village are considered as closer example of the Tromm granite. Rock samples from 4 different locations were investigated by the following means.

X-ray powder diffraction

The rock samples (Figure 7-1, sample TR001) were crushed to powder and analyzed in order to determine the modal mineral composition, following the procedure described in Deon et al. 2022. Scope of this investigation is to get the mineral abundances of the rock samples. The sampling locations are shown in the map modified after Frey et. al. 2022.

The interpretation of the XRD patterns was completed semi-quantitatively while the quantitative interpretation with the Rietveld method is on-going. Figure 7-2Figure 7-2 shows an XRD pattern from a typical Tromm granite. Given the paragenesis and the detected mineral concentration the example shown below can be considered as unaltered fresh Tromm granite. The sample was selected because there is no indication of hydrothermal alteration given the mineral composition. Thus, this lithological unit is feasible for the construction of the underground research laboratory.

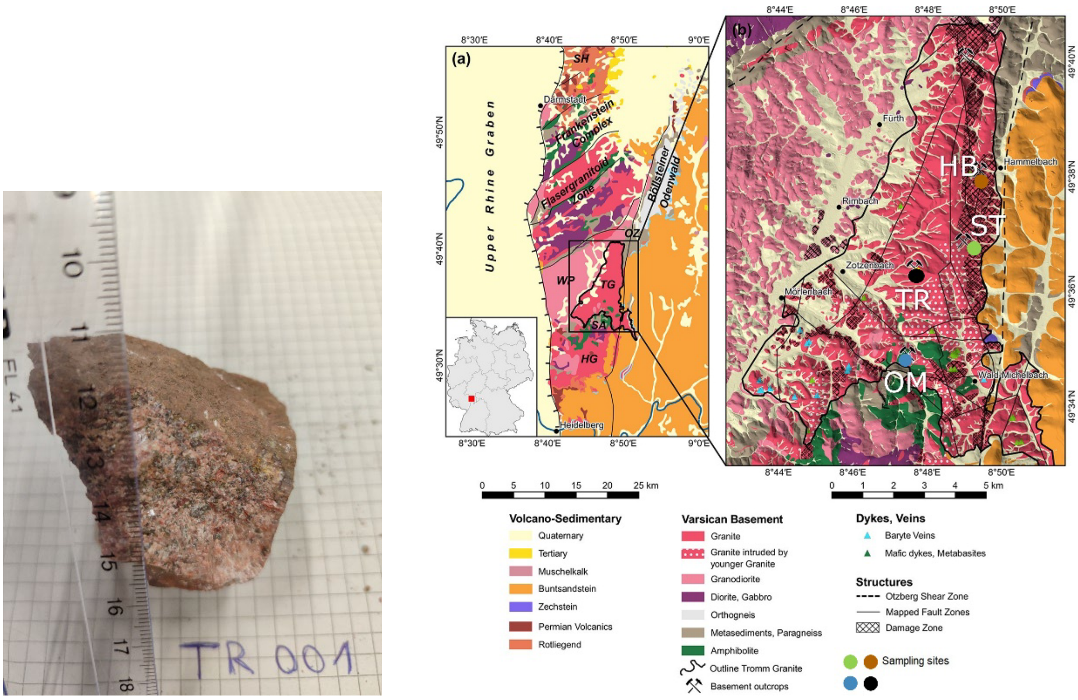

Figure 7-1: Rock sampling. Rock sample collected in the Tromm village, sample Tromm 1. The fresh unaltered surface shows plagioclases, feldspars and micas. Beside the geological map (modified after Frey et. al. 2022) with the sampling sites.

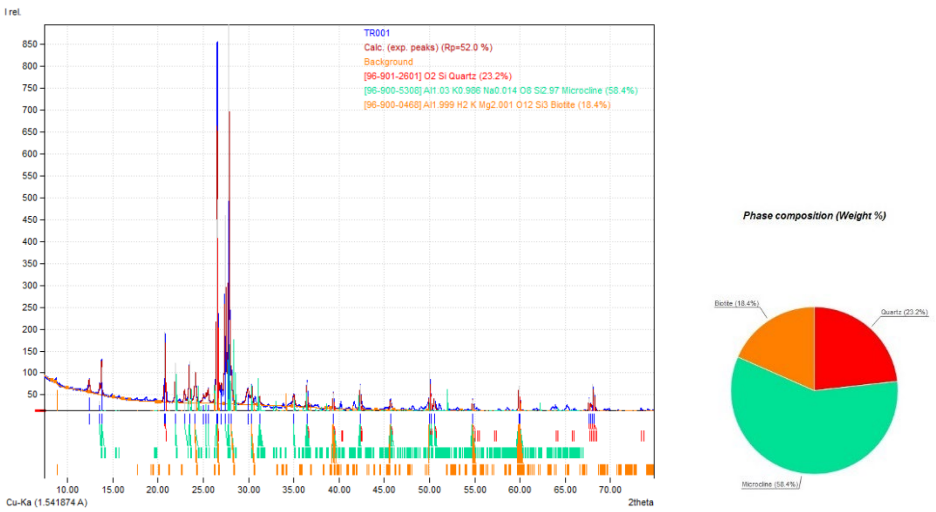

Figure 7-2: XRD analysis. XRD pattern of the sample TR001. The semi-quantitative mineral quantification indicates quartz (main peak 26.4° 2ϴ), plagioclase-feldspar (in the interpretation microcline given the best fitting structure 27.8° 2ϴ) as dominating mineral species. Micas (main peak 8.9° und 12.3° 2ϴ) were detected. The amount of mica might be overestimated given the preferred orientation.

Electron microprobe

Ultra-polished thin sections were prepared and analyzed at the EMP. Secondary Electron images confirm the mineral composition detected with XRD (Figure 7-3) and indicate the occurrence of hydrothermal alteration as well as microfractures (Deon et al. 2024). This microscale information should be further investigated in terms of orientation and texture. Moreover, these results are only limited to surface outcrop sample. An extensive analytical program will be implemented on the cores which will be gained from the exploration drilling in the beginning of next year.

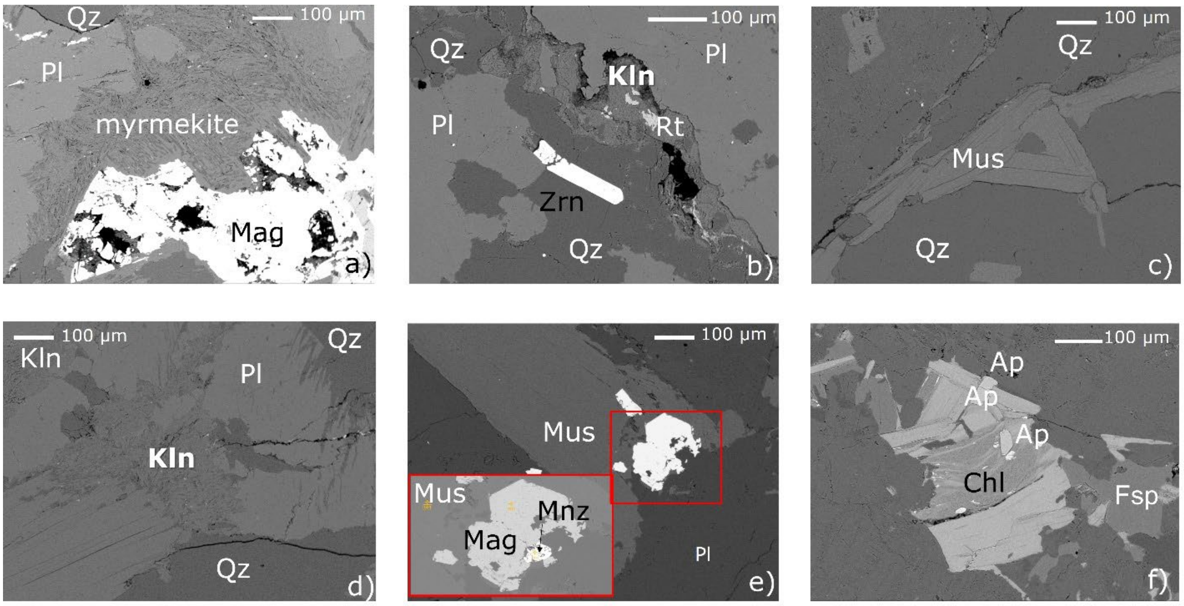

Figure 7-3: Electron microprobe. A selection of SE (Secondary Electron) images acquired with the electron microprobe. a) ST001: myrmekite structures, i.e., inclusion of quartz in plagioclase (Pl) indicating tectonic induced metasomatism. The structures follow the magnetite (Mag) rims. b) HB002: well-formed zircon (Zrn) embedded in quartz (Qz). Kaolinite (Kln) occurring in the fracture indicate the occurrence of hydrothermal alteration. Rutile (Rt) is an accessory phase. c) ST002: a triangular muscovite (Mus) embedded in quartz. d) ST002: small kaolinite (Kln) grains likely formed form the alteration of plagioclase (Pl). e) ST002: muscovite (Mus) grain including magnetite (Mag) and monazite (Mnz). The latter offers the possibility to perform in-situ geochemical dating and investigate REEs concentration. f) OM001: Chlorite (Chl) with large apatite (Ap) grains.

X-ray fluorescence – ICP-MS

All rock samples were geochemically investigated. The major oxides were analyzed via X-ray fluorescence while the trace elements with ICP-MS. These analyses indicate the geochemistry and the precise rock type based on the major oxides.

7.2.2 Flow-Through-Experiments

In order to provide supporting evidence for the selection of a location for the site, experiments were conducted on granite samples from the Odenwald/Tromm region, specifically outcrops taken from the Streitsdöll quarry. The aim of the investigation was to quantify possible mineral precipitation during the extraction of fluid through the rock formation, which could result in potential environmental toxicity. This was disproved in the laboratory experiments.

In order to achieve this objective, a newly developed apparatus, designed and built at the GFZ Potsdam, was first utilised. The flow-through experiments were conducted using groundwater samples from the Streitsdöll spring in the Tromm (Figure 7-4). Prior to and following the flow-through experiments, the main components and traces in the fluid were analysed using ICP-MS (mass spectrometry) and IC (ion chromatography) in order to quantify the fluid-rock interactions. Additionally, the rock samples were characterised in detail (see the X-ray powder diffraction and electron microprobe section).

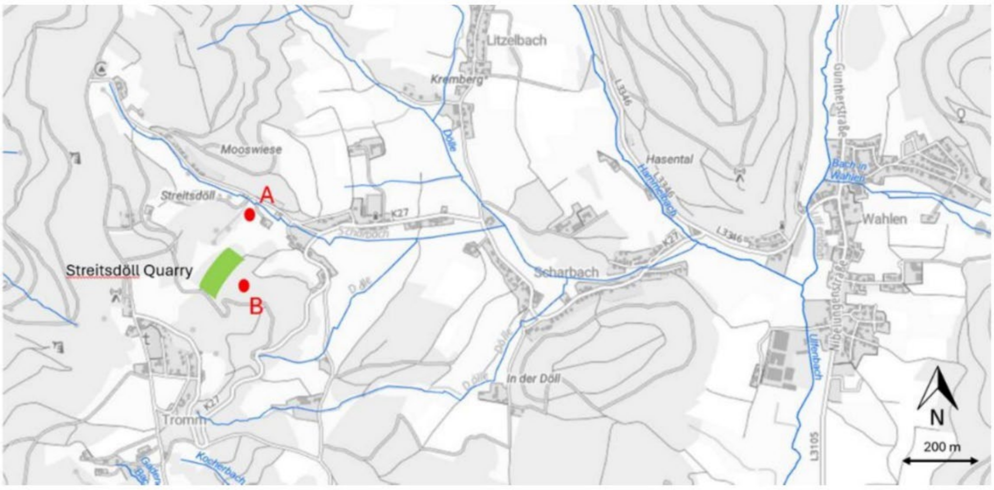

Figure 7-4: Geographical location of the spring rooms A+B (red) and the Streitsdöll quarry (green) (modified after HLNUG, 2023).

At GFZ Potsdam, the rock samples were cored to a diameter of 30 mm and cut to a length of 40 mm. The ends of the cylindrical samples were polished. Optically, the Streitsdöll rock samples could be assigned to three different varieties (see Figure 7-5). The samples of each of these varieties were subjected to a series of flow-through experiments at three different temperatures. In each case, one sample was archived as a reserve sample.

APPARATUS FLOW-RIA

Flow-RIA is a flow-through apparatus developed and constructed at the GFZ Potsdam for the investigation of fluid-rock interactions (Figure 7-6). The apparatus enables the study of fluid flow through a rock sample in a cell at temperatures of up to 200°C and a confining pressure of up to 20 MPa, with the fluid capable of exerting a pore pressure of up to 2 MPa. The flow cell containing the rock sample is placed in an oven. A pump delivers the fluid at a set flow rate from a reservoir through the rock sample into a container. The confining pressure is applied by nitrogen. A pressure relief valve ensures a constant pore pressure and discharges the fluid from the pore system. This setup was financed by the GFZ Innovation Fund 2022 and supplemented and modified for the measurements using funds from the GeoLaB project.

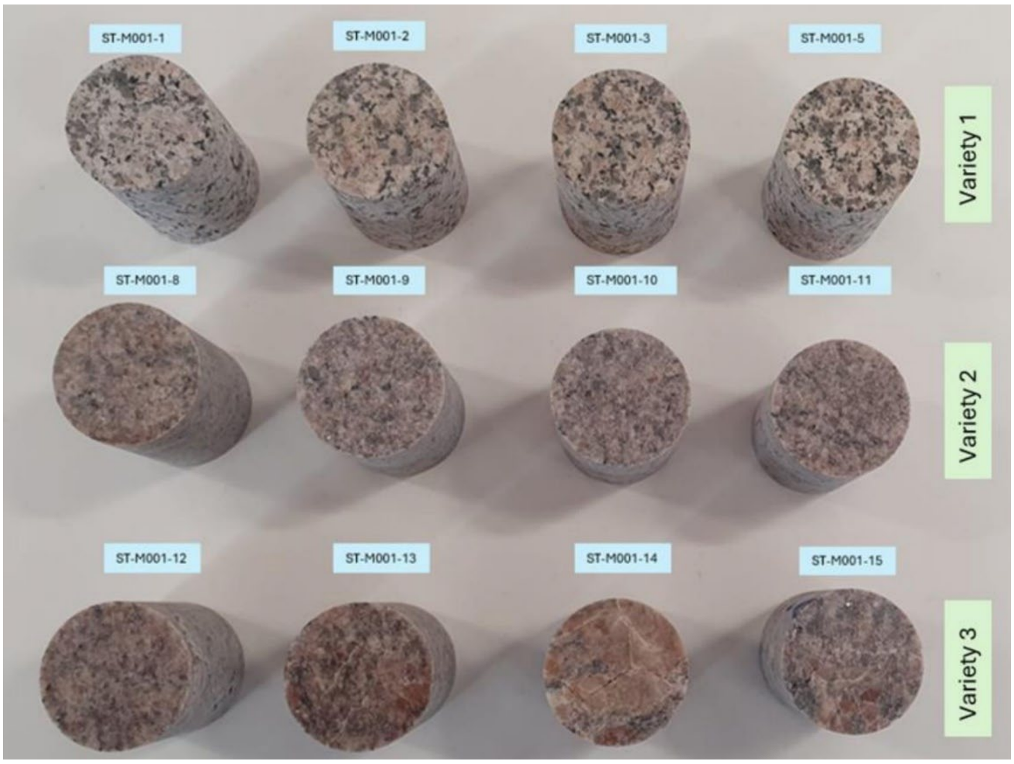

Figure 7-5: Cored and preparated rock sample series of the Streitsdöll outcrop with visible rock composition differences (picture by Maximilian Dietze).

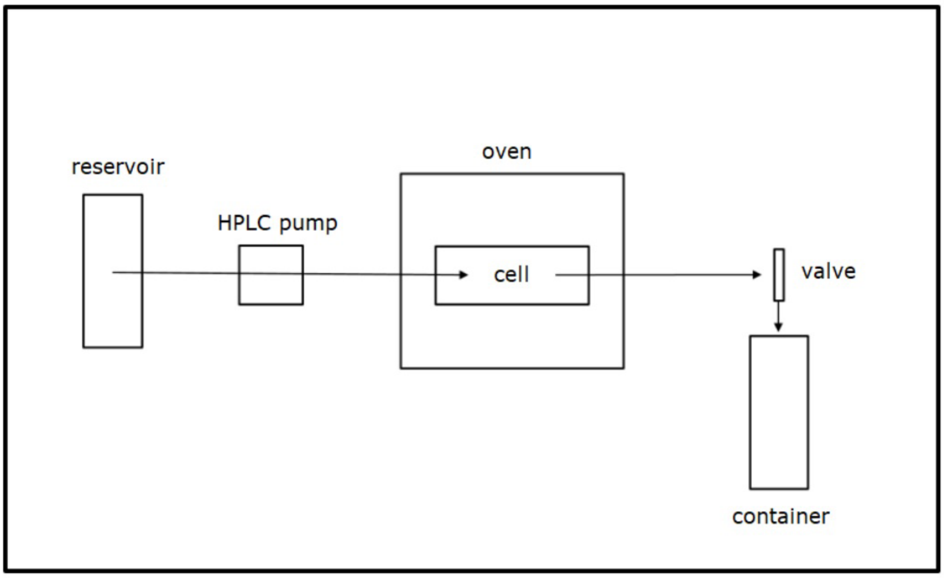

Figure 7-6: Schematic illustration of the flow-through apparatus developed and constructed at the GFZ.

Experimental Procedures

The samples were subjected to a split tensile strength test (Brazilian test) on the MTS apparatus at the GFZ Potsdam. This resulted in a crack in the rock samples, which was used for the flow-through experiments.

Each sample was placed in the measuring cell of the flow-through apparatus and continuously flowed through at 50, 100 or 150°C for one week. The fluid was circulated through the rock sample to allow for the enrichment of precipitating components.

Fluid Analysis

The study used a comparative approach to investigate the dissolution behaviour of rock and water samples, focusing on the concentrations of dissolved elements present in the influent and effluent fluids. The fluid samples were analysed using ICP-MS (mass spectrometry) and IC (ion chromatography) at Technical University of Darmstadt. While temperature did not generally affect dissolution, the solubility of calcium was found to be temperature dependent in all experiments.

In addition, magnesium, strontium and bromine tended to adsorb onto the rock, while potassium, fluorine, chromium, manganese, nickel, copper, arsenic, rubidium, molybdenum, silver, tin, cesium and lead tended to dissolve into the solution. The results are shown in Figure 7-7 and Figure 7-8.

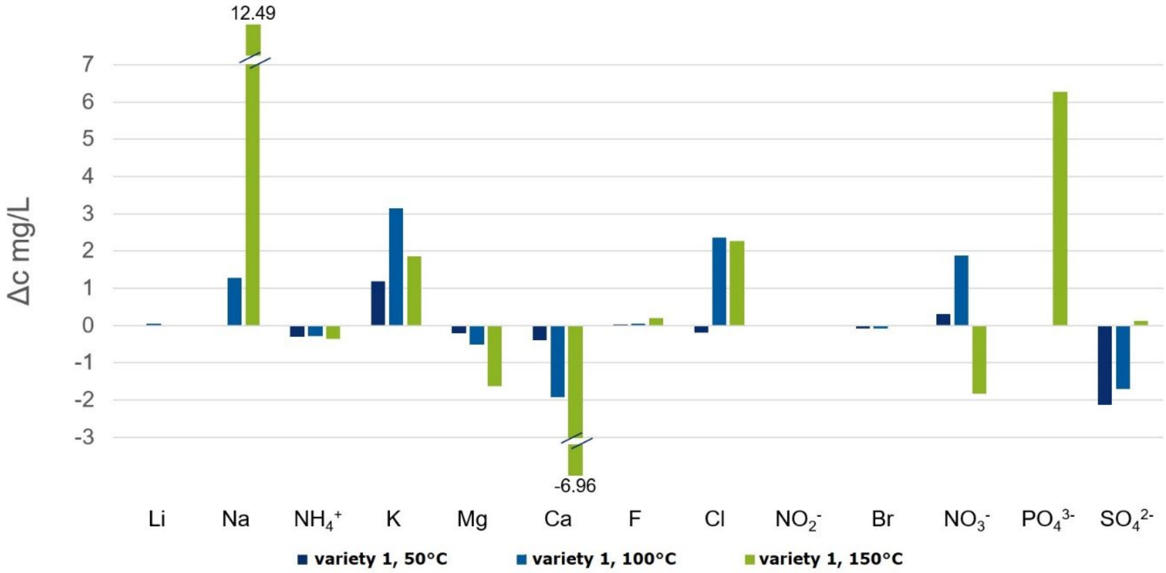

Figure 7-7: Concentration changes of the main and minor components in the fluid (mg/L) compared to the input fluid (normalized to 0).

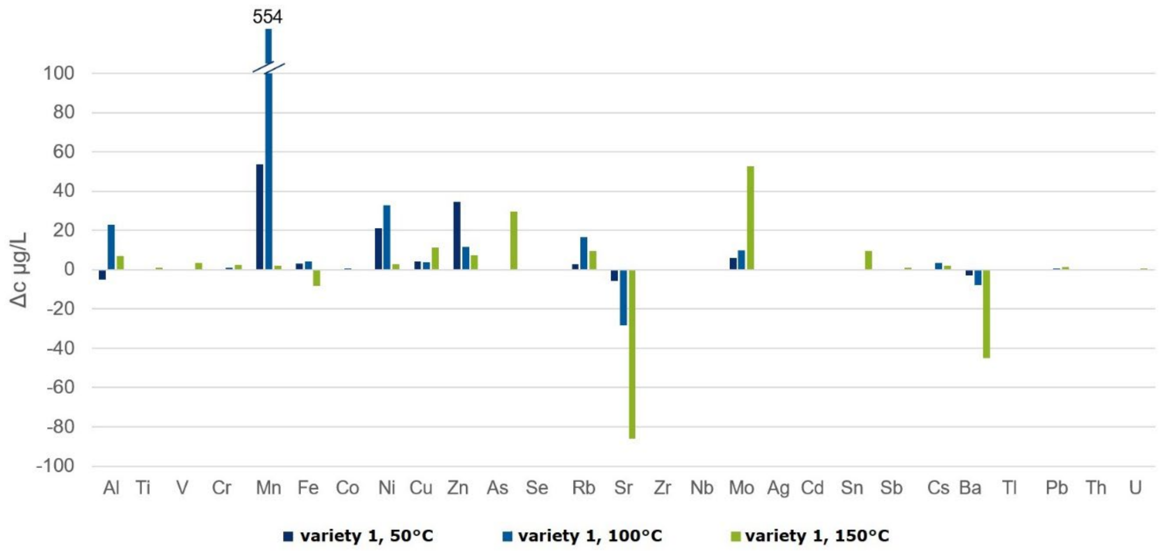

Figure 7-8: Concentration changes of the trace components in the fluid (µg/L) compared to the input fluid (normalized to 0).

7.2.3 Potential Geophysics

The scope of services presented here relates to the exploration of the Tromm license area using geophysical potential methods, specifically gravimetry, geomagnetics, and direct current geoelectrics (ERT). The aims of the investigations are:

1. to generate geophysical subsurface models based on the measurements and geological studies (results from gravimetry, geomagnetics and ERT).
2. identification of fractures and tectonic faults (from geomagnetics and ERT)
3. characterization of fractures and tectonic faults in terms of their hydraulic properties (from gravimetry and ERT).

The tendering process was conducted in spring/summer 2024.

Scope of the Measurements

The scope of work is divided into two phases and includes:

- Gravimetric Measurements: 3,500 measurement points, including base station measurements.
- Geomagnetic Measurements: 3,500 measurement points.
- DC Electrical Resistivity Measurements (ERT): 50 km of measurement profiles.

All measurements must be carried out within the defined GeoLaB subarea. The gravimetric and geomagnetic measurement points must be aligned within a tolerance radius of less than 1.0 m to a maximum of 10 m. ERT profiles are to follow the gravimetric and geomagnetic measurement points.

Phased Execution of the Measurements

The investigation will be carried out in two phases:

Phase 1:

- Measurements will be taken along six predefined profiles (see Figure 7-9).
- The goal is to identify potential fractures and tectonic features.
- The results from this first phase will form the basis for the detailed measurements in Phase 2.

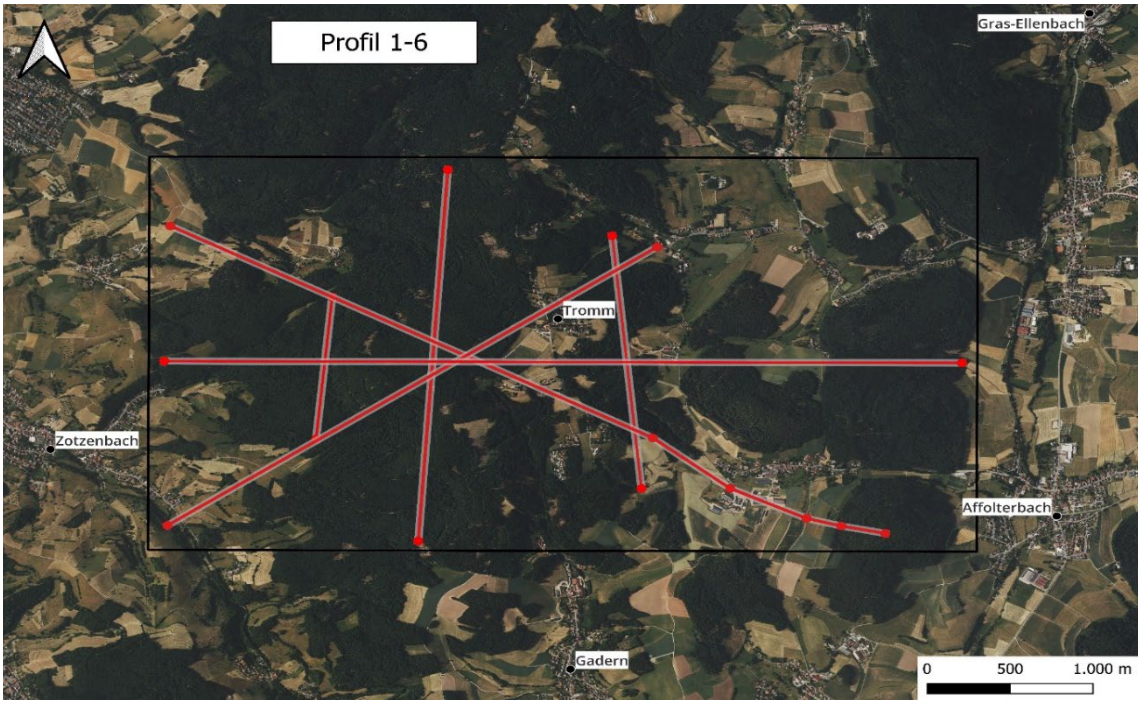

Figure 7-9: The six planned profiles for phase 1.

Phase 2:

- The measurements will be expanded based on the results of Phase 1.
- A broader range of measurements will be carried out with increased density of measurement points to provide more detailed information about fault zones and their properties.

The overall time schedule is shown in Table 7.1. The first seismic milestone, S-MS1, was obtained in August 2024. S-MS2 is expected end of the year/ early next year.

Table 7.1: Timetable.

Milestone	Specification	Time frame
S-MS1	Kickoff meeting between KIT and contractor	4 weeks after contract
S-MS2	Final report for phase 1 with presentation	3 months after contract
S-MS3	Preparation and realization: workshop between KIT and contractor to plan phase 2	4 weeks after MS2
S-MS4	Final report with presentation for phase 2	10 months after contract

SPECIFICATIONS OF THE MEASUREMENT METHODS

The technical specifications are summarized here:

1. Gravimetry:
   - High accuracy measurements with a tolerance range of <1 µGal.
   - Calibration through a base station three times daily.
   - Repeated measurements of at least 10% of the points for quality assurance.

2. Geomagnetics:
   - Measurement of total field anomalies with an accuracy of ≤0.2 nT.
   - Installation of an automatically recording base station to correct the magnetic variation field.

3. ERT:
   - Multi-electrode measurements with at least 48 active, digitally controlled electrodes.
   - Induced polarization (IP) must be considered to enhance the characterization of conductivity and chargeability.

Planning Phase 1

The company Geopyhsik GGD, Gesellschaft für Geowissenschaftliche Dienste m.b.H., was contracted for the initial phase of the project. GGD has two sub-contractor GGL, Geophysik und Geotechnik Leipzig GmbH, and the terratec geophysical services GmbH & Co KG.

S-MS1 (Seismic Milestone 1) was successfully completed on 22nd August 2024. During the planning of Phase 1, several unforeseen challenges arose, most notably the issue of African Swine Fever (ASP). Additionally, the permit process encountered delays, largely due to complications such as outdated inhabitant data and local resistance to the project.

ASP African Swine Fever (ASP) Impact

The outbreak of ASP necessitated adjustments to the planned profiles. Measures were taken to comply with veterinary regulations, including a restriction on conducting measurements in forested areas outside of designated paths and routes to prevent the spread of the disease.

Permit

The company IPS Celle was contracted to support the permitting process. The permit approval process significantly prolonged the planning phase. This delay required further modifications to the profiles to align with the regulatory requirements and the evolving situation on-site. As seen in the Figure 7-11: Permit overview with green, red and grey areas with a positive or negative permit, respectively. Grey areas mean no additional info of the owners available. The yellow line is part of the Vibroseis campaign and was used as an alternative for profile 1C. In Figure 7-11Figure 7-11, some areas are red colored with no permit, so for example, we shifted profile 1C south to cover more of the eastern area.

Carrying Out Phase 1: Gravity Measurements

A total of 349 measurement points were recorded during the gravity survey in October 2024 using the CG-6 Autograv™ Gravity Meter from Scrintex. Of these, 302 points were measured using Differential GPS (DGPS), and 42 points were measured using tachymetry, both with the Trimble R10 and the appropriate antenna.

Carrying Out Phase 1: ERT measurements

ERT measurements started mid of November 2024 and are ongoing. The measurements are carried out using a Syscal system from IRISI Instruments. A test measurement determined the optimal electrode array for the survey area.

Comparing Wenner-Schlumberger and Dipole-Dipole configurations, the latter was selected for better vertical resolution (see Figure 7-14).

Carrying Out Phase 1: Geomagnetic measurements

The geomagnetic measurements in Phase I will be carried out continuously early in 2025 along the planned profiles, i.e., one measurement every approx. 10 seconds. This allows significantly denser data to be obtained for each profile without additional effort, thus eliminating or drastically reducing the risk of a locally falsified measured value at an insulated measuring station.

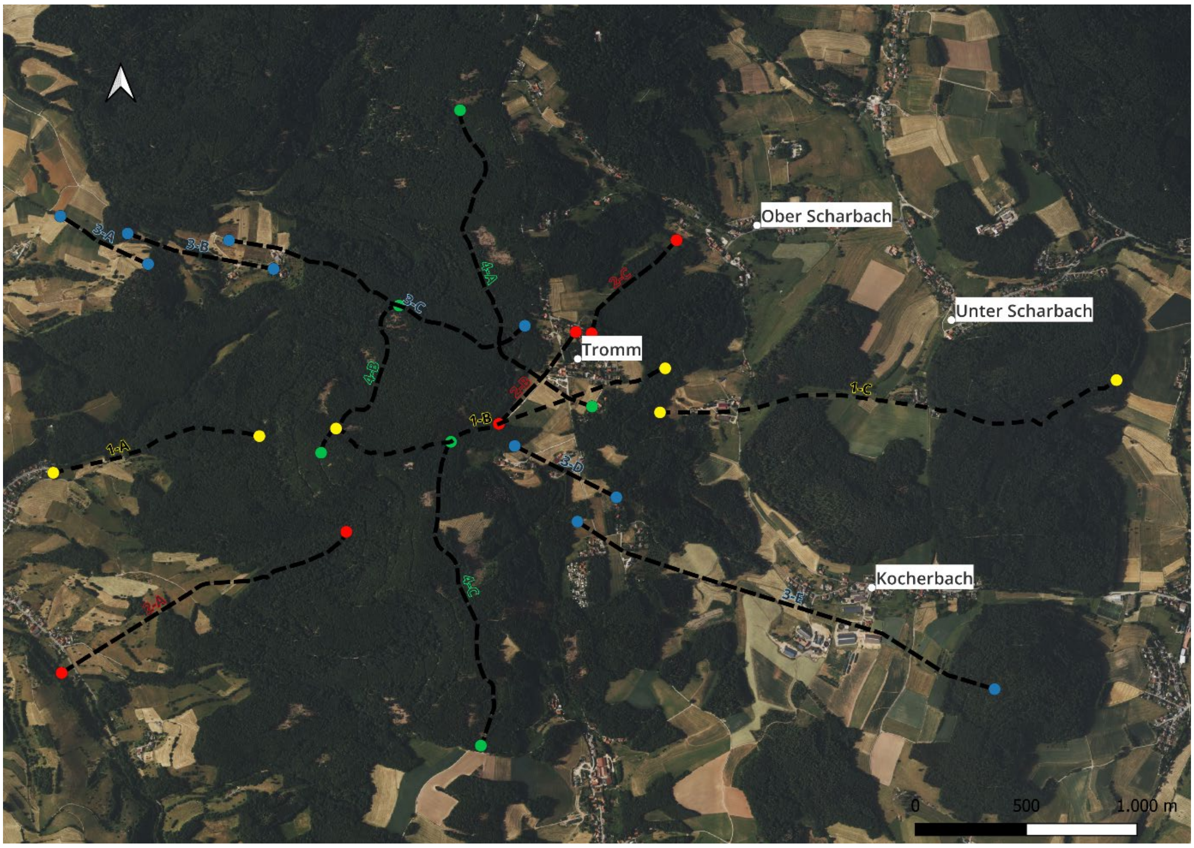

Figure 7-10: The profiles were adapted to the ASP regulations.

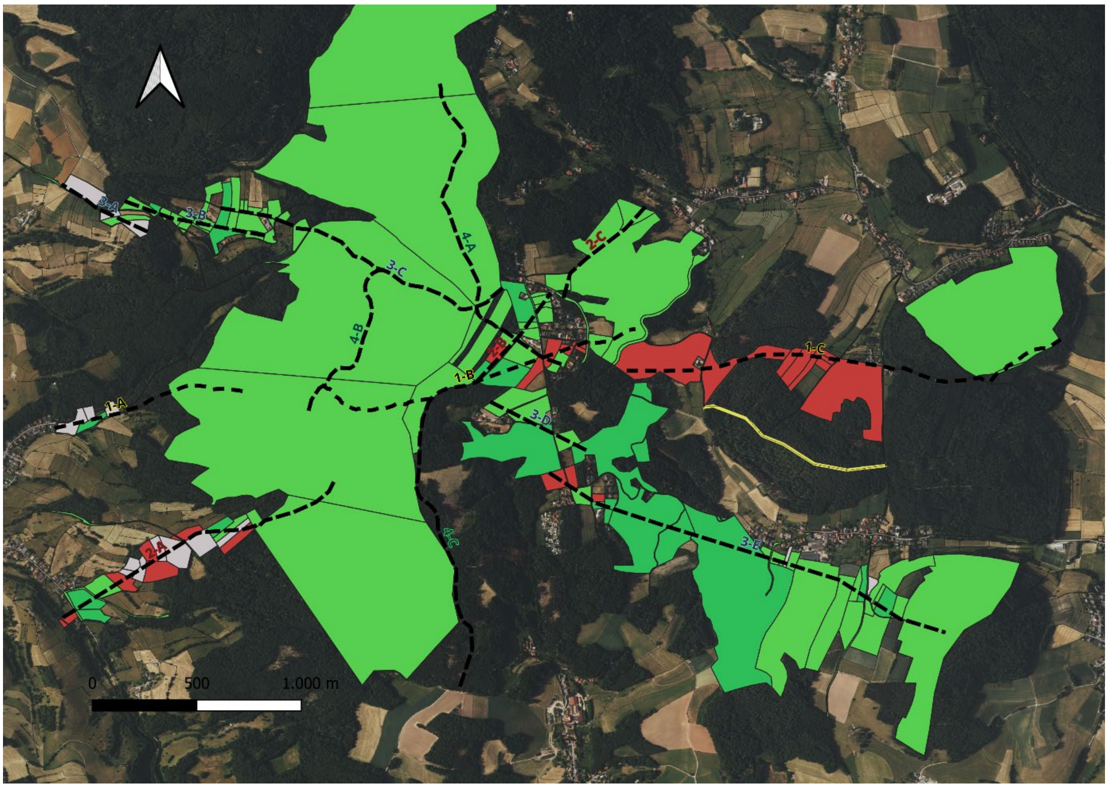

Figure 7-11: Permitting. Permit overview with green, red and grey areas with a positive or negative permit, respectively. Grey areas mean no additional info of the owners available. Yellow line is part of the Vibroseis campaign and was used as an alternative for profile 1C.

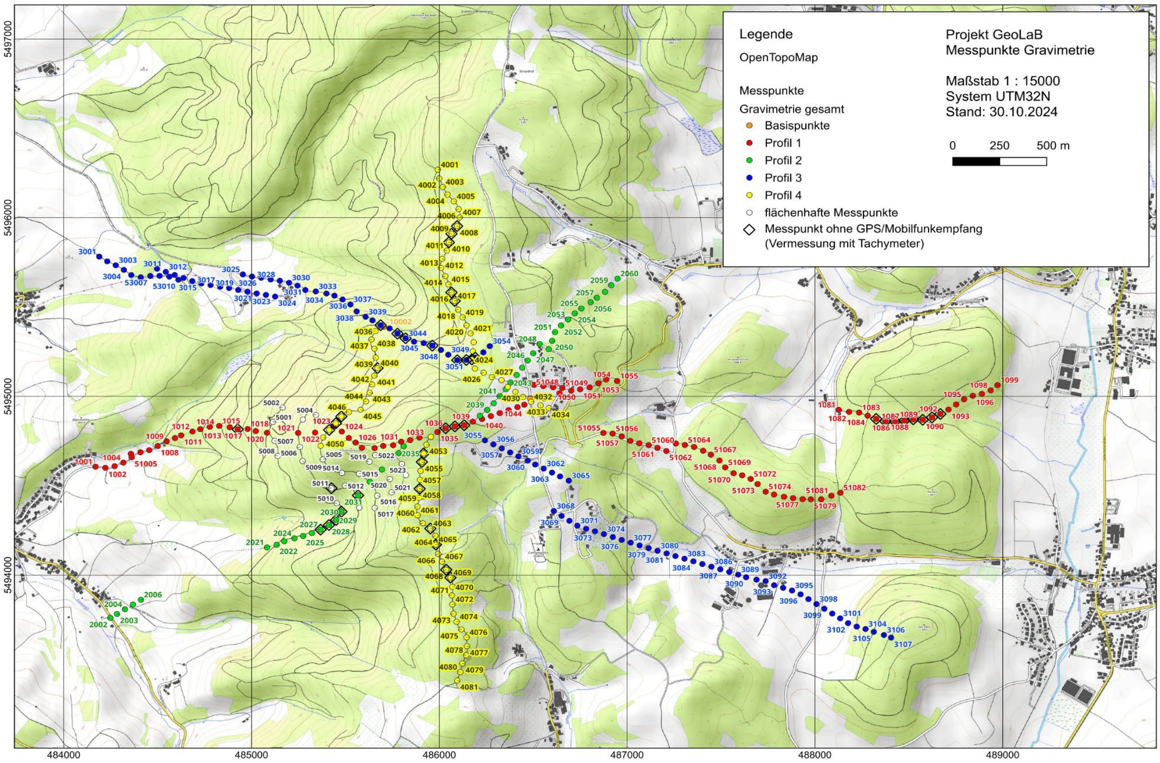

Figure 7-12: Measured gravity points

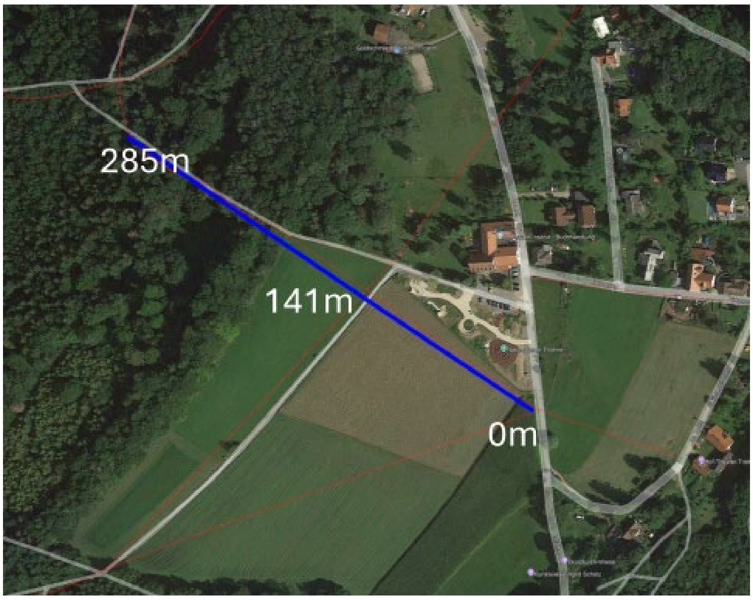

Figure 7-13: Test profile layout (left) with Syscal unit installation (right).

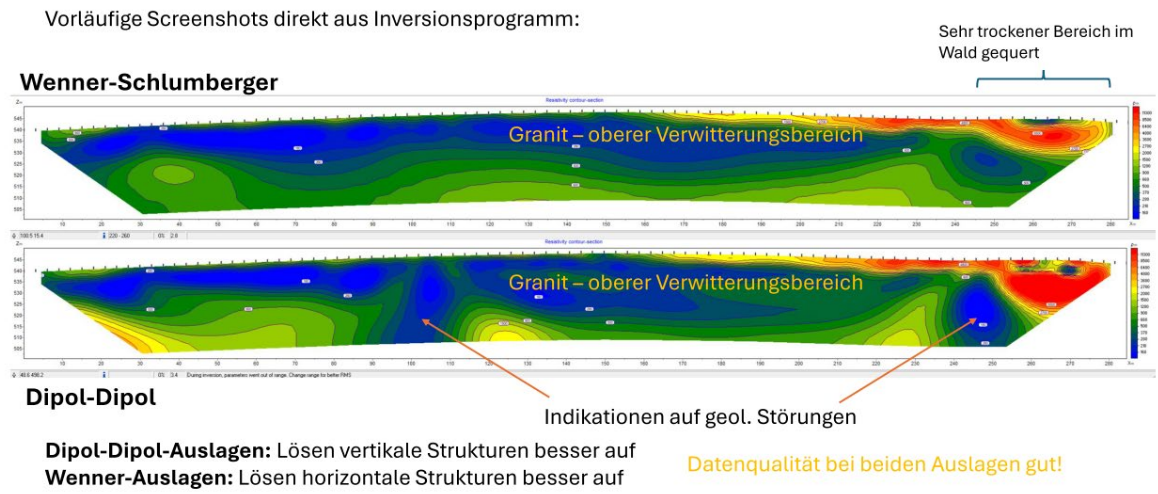

Figure 7-14: Test results — Wenner-Schlumberger vs. Dipole-Dipole configurations.

7.2.4 Pilot Seismic: Motivation and Aim of the Survey

The Tromm Granite is a potential site of the GeoLaB Underground Rock Laboratory which is planned to provide an experimental platform for in-situ research in the context of the petrothermal use of geothermal energy. According to the current state of knowledge, the Tromm Granite is more or less unfaulted, with an increasingly faulted and fissured transition (“damage zone”) at its Eastern margin while approaching the Otzberg Fault Zone. This setup would be ideal for an underground gallery in the unfaulted Tromm Pluton, providing access to highly permeable rock units enabling experiments investigating high flow rates in such permeable rocks.

The field survey consisted of two perpendicular vibro-seismic profiles, one short profile (~1.6 km) in North-South direction, one longer profile (~4.3 km) in East-West direction. Additional autonomous seismic stations were deployed at a lateral distance to these profiles in order to achieve additional 3D-coverage for a tomographic imaging of the region. A map overview of the survey is given in Figure 7-15.

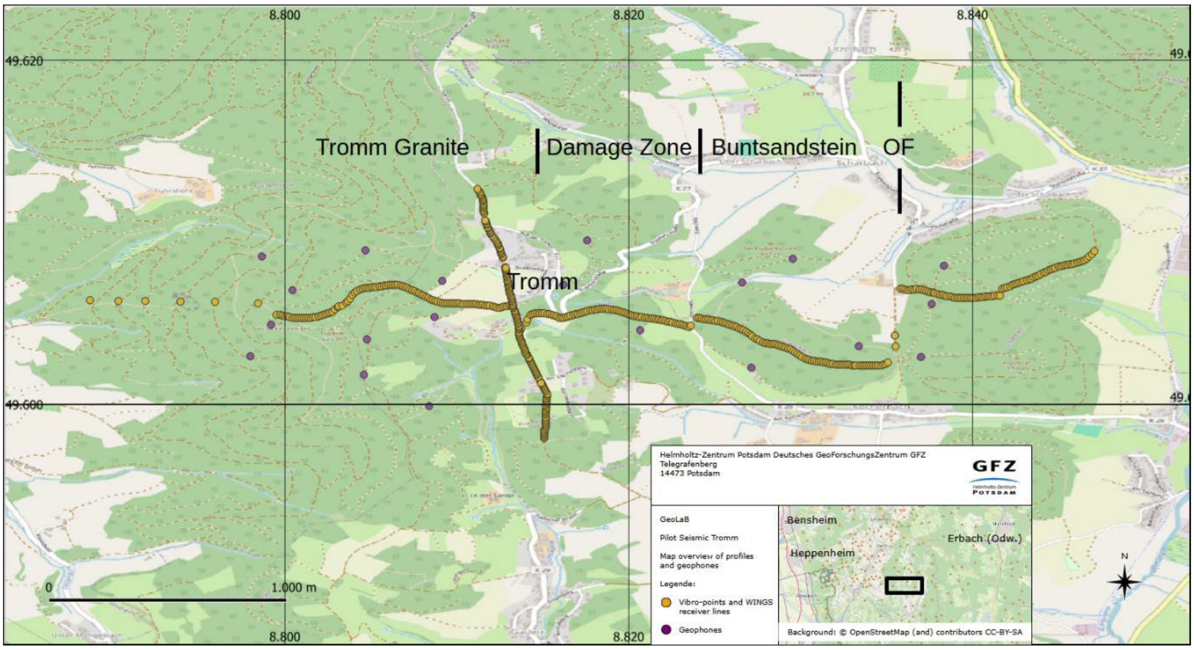

Figure 7-15: Seismic profiles. Map overview of seismic profiles and additional geophone positions of the pilot seismic survey. The main geological units covered by the seismic profiles are indicated (Tromm Granite, Damage Zone, Buntsandstein, Otzberg Fault (OF)).

The western part of the East-West acquisition profile is covering the potential location of the GeoLaB underground gallery, and the central and eastern parts of that profile are crossing the transition zone from the presumably unfaulted Tromm Pluton into the fissured eastern margin of the Pluton. The Otzberg Fault Zone is located within the eastern end of the E-W acquisition profile. The main task of this seismic survey is to provide data for an initial imaging of this transition from the Tromm Granite towards the Otzberg Fault Zone. This initial site characterization will also provide valuable baseline information for a more detailed 3D seismic investigation which is foreseen to be acquired for planning the GeoLaB underground gallery, once the decision has been made to build this gallery at the Odenwald (Tromm) site.

This technical field report is summarizing the field work progress and is providing first insights into the acquired data (including brute stacks of the two reflection profiles).

Time line of the survey

Table 7.2: Summary of main field activities per day.

Date	Activities	Remarks
Wed, 18.09.2024	Routine sounding for warfare materials; crew mobilization	
Thur, 19.09.2024	Sounding for warfare materials, crew safety instructions and survey kick-off meeting, topographical surveying of vibro points N-S profile, surveying and deployment of receiver points for parameter test	
Fri, 20.09.2024	Parameter test (one vibro point, variation of source sweep parameters), deployment of receivers on profiles and geophones, HR press visit on site.	
Sat, 21.09.2024	Surveying and deployment cont., evaluation of parameter test	
Mon, 23.09.2024	Acquisition on N-S profile, mining office visit on site	Delay due to technical problems with GFZ vibrator vehicle (solved), N-S profile acquired incompletely
Tue, 24.09.2024	Acquisition on E-W profile (starting in E), KIT shot documentary material (drone, camera)	
Wed, 25.09.2024	Acquisition on E-W profile finished, completed acquisition on N-S profile, collection of all receivers and geophones	
Thur, 26.09.2024	Crew demobilization	

Crews and parties involved

KIT (Project Lead GeoLaB, owner of mining law, public relations): on each day of field work, at least one representative of KIT was present at the survey site (B. Rudolph, N. Neuwirth, N. Haaf, K. Schätzler).

GFZ (Project Lead Seismic Survey, geophone acquisition, field crew support): during the complete field work period a GFZ core field team was on site (S. Lüth, F. Deon, R. Giese, G. Zimmermann, N. Schmidt, I. Sass (part-time)), during the deployment phase, three more GFZ members were on site (K. Jaksch, U. Hoffert, P. Guericke).

TU Darmstadt (field crew support): two members of TU Darmstadt joined the deployment phase (H. Elokl, F. Wang).

DMT GmbH & Co KG (Vibro source operation, topographic surveying, data acquisition on profiles): 6 crew members performed the field work (W. Lukas, D. Puljek, G. Dudek, A. Rybicky, W. Postel, Z. Coltescu).

IPS Celle (Permitting): (T. Hafner)

Terrasond Kampfmittelräumung GmbH (warfare materials sounding) (Mr. Mauermann, Ms. Brucker)

Description of the acquisition equipment

As a seismic source, the Inova Univib 326 was used (~115 kN peak force). The seismic source vehicle is owned by GFZ, and it is operated by DMT personnel.

The seismic data acquisition was performed on the profiles using nodes of the Sercel Wing System. The system consists of autonomous nodes with a MEMS accelerometer and GPS clock synchronization (DMT). In addition, 20 three-component geophones (4.5 Hz) and Omnirecs Data Cubes (GFZ) were deployed along the East-West-Profile with a lateral distance to the central profile of ~100 m – 500 m in order to achieve additional 3D coverage for 3D seismic tomography. Sources and receivers used for the data acquisition are shown in Figure 7-16 and Figure 7-17.

Figure 7-16: Seismic vibration source vehicle Inova Univib and Sercel Wings seismic recorder.

Figure 7-17: 3-Component geophone and Cube3 recorder (GFZ).

PARAMETER TEST

In order to find an optimal sweep signal and to optimize the trade-off between fast acquisition progress and high data quality (signal-noise ratio), a parameter test was performed on Friday, September 20 in the morning (9:19 h – 10:11 h). The sweep parameters tested were: force, start and end frequencies, number of stacks, and sweep length. Table 7.3 is showing the range of parameters tested.

The parameter test was performed along profile 2402 (N-S line) using one vibration point at the northern end of the line and 89 Wings receivers at 20 m station interval. Figure 7-18 is showing the distribution of source and receiver points used during the parameter test. After the test program was finished, the 89 Wings recorders were collected and sent to Münster for transcribing and processing the data. The data were made available on Saturday, September 21 in the morning and analyzed on Saturday. It was decided to use the following sweep parameters:

Option 1 (High Force): Freq. 10-180 Hz, 5 sweeps stacked, 16 s sweep length, taper cos, start 0.3 s, end 0.3 s, 80% force.

Option 2 (Low Force): Freq. 10-180 Hz, 5 sweeps stacked, 16 s sweep length, taper cos, start 0.3 s, end 0.3 s, 40% force.

Table 7.3: Parameter test program.

Test	FFID	Frequency (Hz)	Stacks	Sweep Length (s)	Force	Param-eter
1	6	10-150	5	16	20%	Force
2	12	10-150	5	16	30%	
3	18	10-150	5	16	40%	
4	24	10-150	5	16	50%	
5	30	10-150	5	16	60%	
6	36	10-150	5	16	70%	
7	42	10-150	5	16	80%	
7	42	10-150	5	16	80%	Start Fre-quency
8	48	12-150	5	16	80%	
9	54	15-150	5	16	80%	
10	60	10-100	5	16	80%	End Fre-quency
11	66	10-120	5	16	80%	
12	72	10-150	5	16	80%	
13	78	10-180	5	16	80%	
14	82	10-150	3	16	80%	Stacks
15	88	10-150	5	16	80%	
16	96	10-150	7	16	80%	
17	106	10-150	9	16	80%	
18	112	7-150	5	16	80%	Start Fre-quency
19	118	10-150	5	32	80%	Sweep length

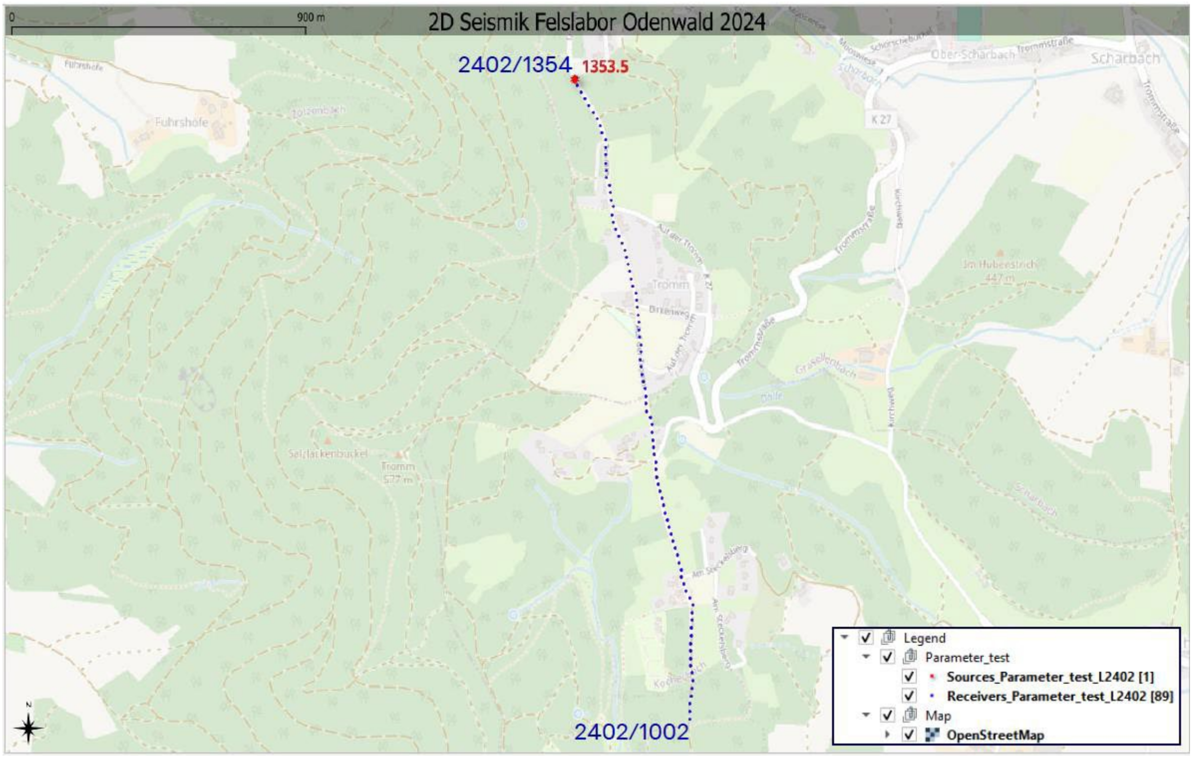

Figure 7-18: Setup of source and receiver points for the parameter test (DMT Report).

Seismic acquisition

The seismic acquisition was performed along three profiles (2401, 2402, 2403), of which 2403 indicates only the six source points on the western flank of the Tromm mountain. They are the westward extension of profile 2401 aiming at providing some imaging coverage on the western flank of the Tromm mountain. Due to the topographic conditions, and due to restrictions related to the mitigation of the African Swine Fever (ASF), it was not possible to deploy seismic receivers along this part of the E-W profile. The map shown in Figure 7-21 is giving an overview of the source and receiver point distribution on the profiles, and Table 7.4 is summarizing the seismic acquisition along the profiles. Figure 7-22 shows a map of the 20 geophone stations which were continuously recording throughout the whole campaign for 3D tomographic imaging.

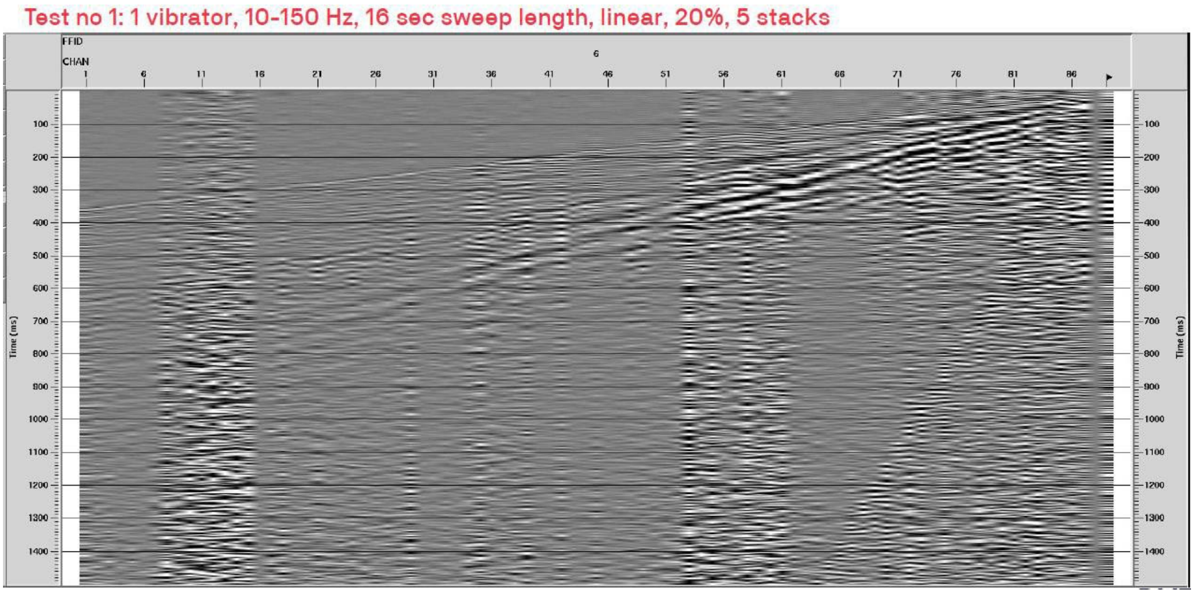

Figure 7-19: Shot gather of parameter test, example of "bad" data quality (very low force applied).

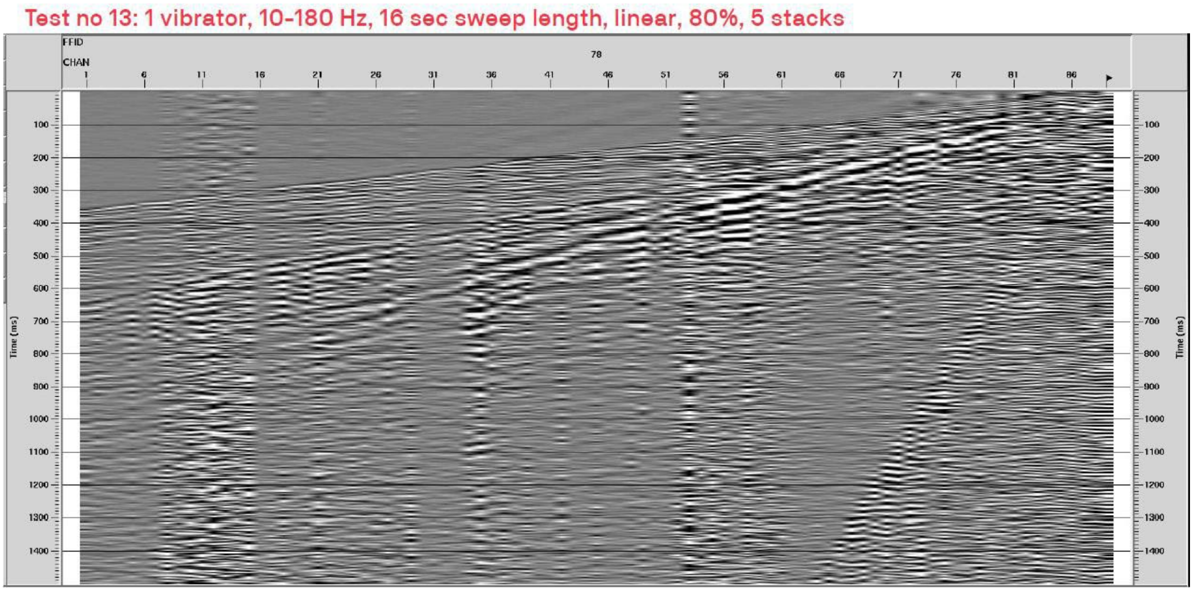

Figure 7-20: Shot gather of parameter test. The sweep parameters of this gather were used for production.

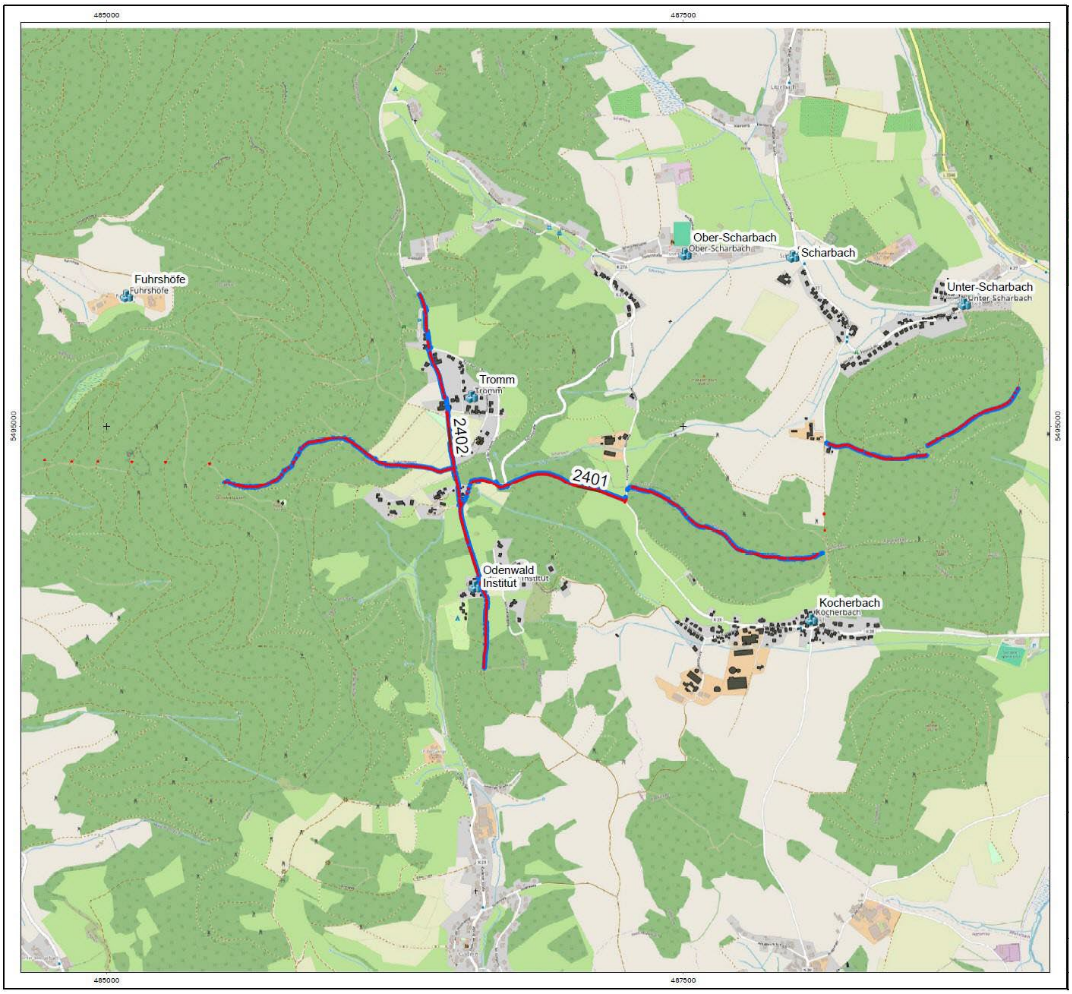

Figure 7-21: Map of source (red dots) and receiver (blue dots) locations on the profiles (DMT report).

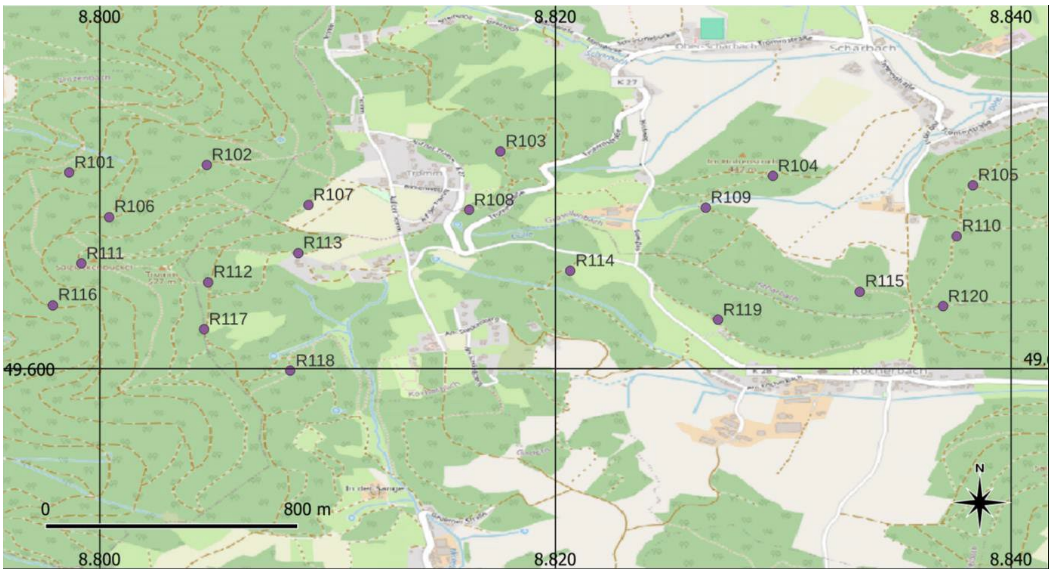

Figure 7-22: Map view of 20 3-component geophones and data cube stations with station names.

Table 7.4: Detailed summary of the acquisition along the three profiles and on the array of GFZ geophones.

Line number	2401	2402	2403	GFZ array
Orientation	W - E	NW - SE	W - E	areal
Number of receiver points	687	330	0	20
Nominal receiver station interval	5 m	5 m	n.a.	n.a.
Sampling rate	500 Hz	500 Hz	n.a.	400 Hz
Number of source points	342	160	6	n.a.
FFIDs (uncorrelated, unstacked records)	899 – 2950 (N = 2052)	119 – 898 & 2987 – 3166 (N = 960)	2951 – 2986 (N = 36)	
Nominal source point interval	10 m	10 m	n.a.	
CDP bin size	2.5 m	2.5 m	n.a.	

Brute stack

The generation of an initial brute stack as part of the field QC processing was performed by the DMT after the end of acquisition. The following relatively simple processing sequence was applied (DMT report):

- Geometry Setup
- Geometry Check
- Elevation Statics
- True Amplitude Recovery
- Spiking Deconvolution
- AGC
- Velocity Analysis
- NMO Stack, FX Deconvolution

The resulting brute stack sections of the E-W profile (2401) and the N-S profile (2402) are shown in Figure 7-23 and Figure 7-24. The reference datum of the sections is 600 m (slightly above the highest position along the profiles), the replacement velocity for the elevation static correction is 3000 m/s.

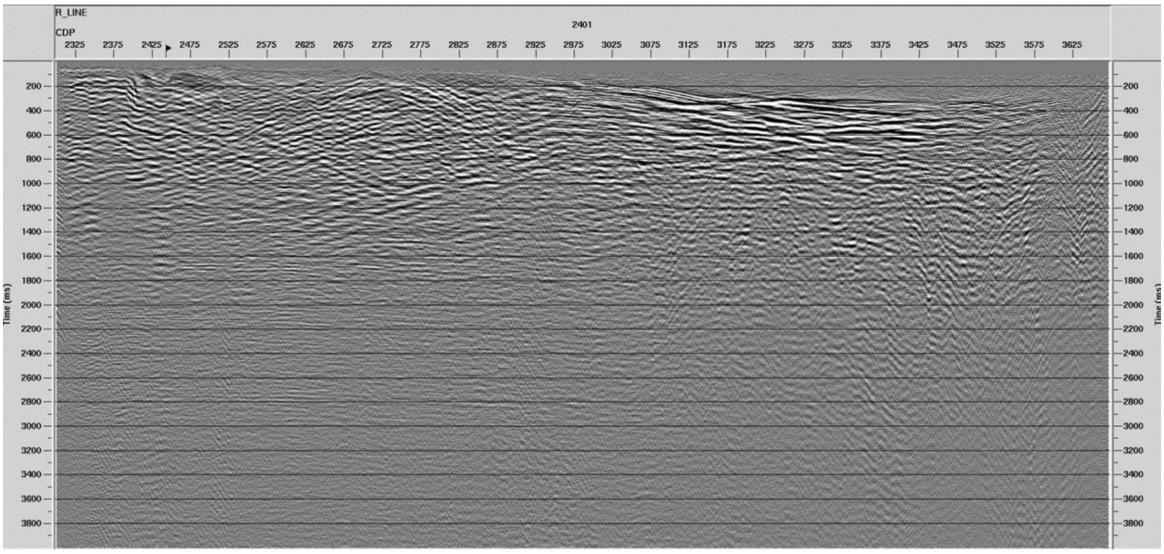

Figure 7-23: Brute stack line 2401. The CDP interval is 2.5 m.

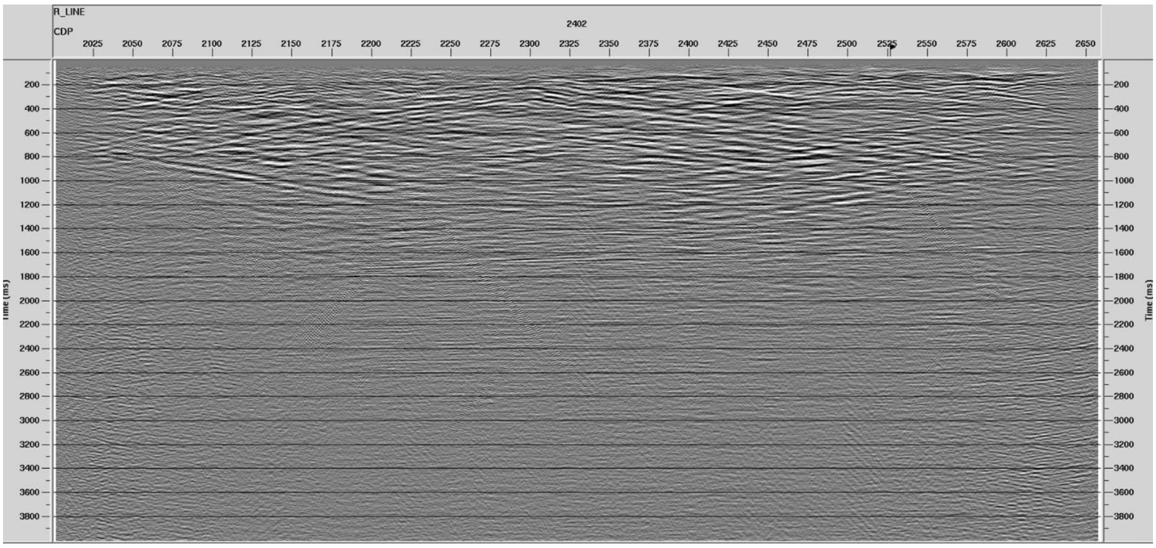

Figure 7-24: Brute stack line 2402. The CDP interval is 2.5 m.

References and materials used

DMT report: QC Report 2D Felslabor Odenwald, DMT

QC Office. Summary of parameter test, DMT.

7.3 KEY FINDINGS AND CONCLUSIONS

Potential geophysics

Since measurements will continue until December 2024 and MS2 has not yet been achieved, the results and interpretations are not included in this annual report. The next steps involve completing the measurements and achieving MS2, followed by planning and executing Phase 2 of the geophysical campaign (MS3).

Preliminary results seismic

Preliminary imaging results are shown in Figure 7-25 and Figure 7-26. Both Figures show a map view of the acquisition geometry along the western part of the E-W profile at the top, and a stacked and time-migrated section at the bottom, respectively. In the western part of the stacked section (Figure 7-25) several almost linear reflection events, dipping westward, are visible. Two strong events are marked ("A" and "B"). The eastern part of this section is characterized by less reflection events from below 200 ms Two-Way-Time, but one strong reflector at shallow depth (150 – 200 ms). The post-stack-time-migrated image (Figure 7-26) shows that the reflection events A and B from the stacked section have been concentrated to smaller lateral extension (~300 – 500 m) and shifted eastward, due to the westward dip of the reflectors. These two reflection events may be caused by heterogeneities within the Tromm Granite, potentially related to features of the "Damaged Zone" at the eastern edge of the Tromm Granite. The upper boundary of reflector A can be estimated to be located at approximately 400 m – 450 m depth below the surface (assuming an average P-wave velocity of ~5 km/s for that depth interval). A more detailed interpretation will be possible when final migration results, velocity models, and, ideally, results from complementary geophysical observations are available.

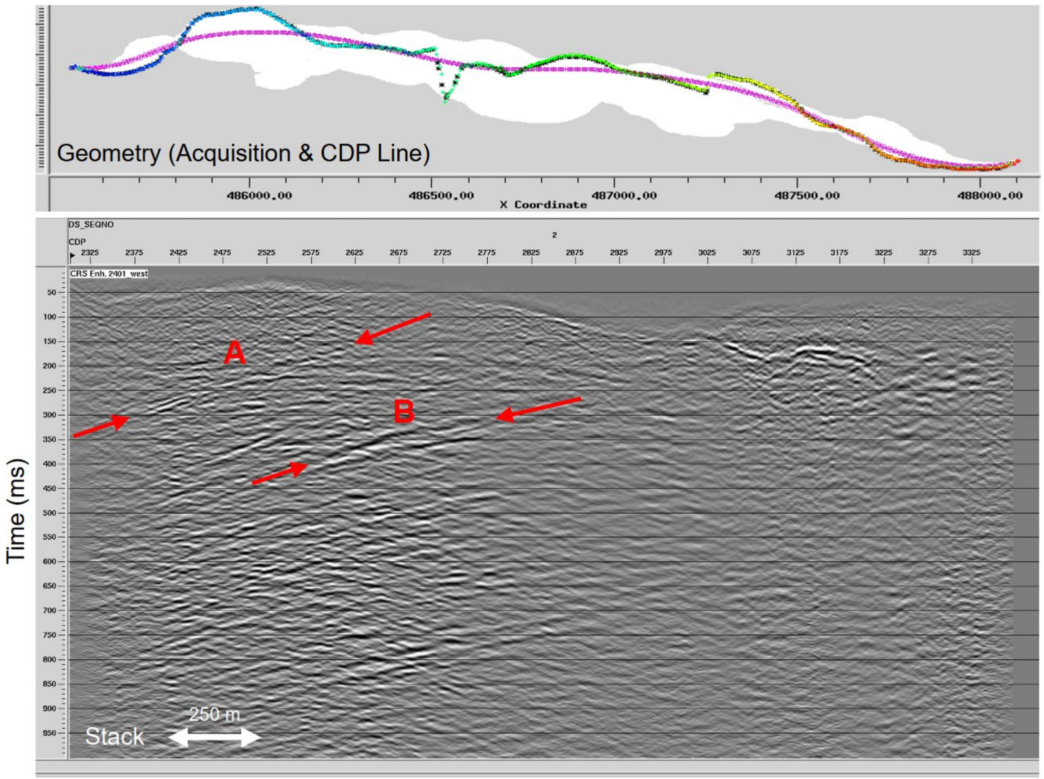

Figure 7-25: Seismic analysis. Map view of the acquisition geometry (source and receiver positions) and the CDP line (top) and stacked section of the western part of profile 2401 (E-W). Arrows indicate two strong almost linear reflection events ("A" and "B"), dipping westward. The CDP interval is 2.5 m.

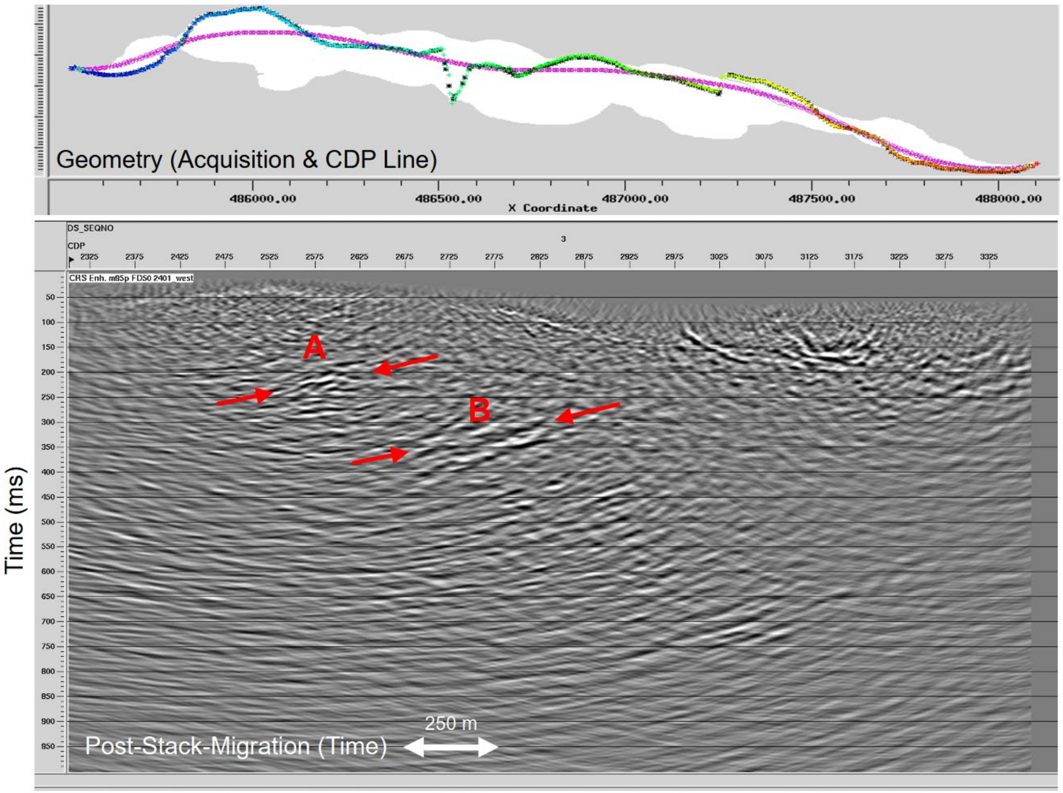

Figure 7-26: Seismic analysis. Map view of the acquisition geometry (source and receiver positions) and the CDP line (top) and post-stack-migrated section of the western part of profile 2401 (E-W). Arrows indicate the two strong almost linear reflection events (“A” and “B”), also indicated in the stacked section, now after migration.

7.4 NEXT STEPS

7.4.1 Petrology

The samples of Streitsdöll reveal pegmatitic structures with large k-feldspar grains (up to 1 cm). These structures and geochemical features (SiO_2 excess) will be further investigated. A complete set of analyses on the cores from the GLB-1 well will be conducted in 2025 and will provide a comparison of the petrology and geochemistry of the surface samples (Deon et al. 2025).

7.4.2 Fluid-rock Interaction

Potential environmental impacts were assessed by comparing the dissolved chemical levels to drinking water regulations (TrinkwV). The concentrations of arsenic and chromium exceeded limits in only one sample each, indicating that fluid-rock interactions at the Streitsdöll site are unlikely to lead to groundwater contamination.

7.4.3 Geophysics

In order to monitor earthquake activity around the drilling site (GLB-1) and the surrounding area, seismometers will be installed in early January 2025, before any drilling begins. This seismic monitoring is primarily intended to contribute to the preservation of evidence in the event of possible seismicity in connection with drilling work and subsequent formation testing. In addition, the data from these stations will help to establish a permanent seismological network around the planned boreholes and future rock laboratory. One part of the future seismic monitoring will be, in addition to stations deployed at the surface, borehole seismometers in order to achieve an enhanced detection of micro-seismicity in the underground. Initially, a total of four seismometer stations will be set up in the village of Tromm in the vicinity of the drilling site.

7.4.4 Exploration Well

The exploration well GLB-1 will start in the beginning of 2025. The plan is to do a full coring to 500m deep inside the crystalline rock bodies. A cover of quaternary sediments is expected in the first shallow layers of the drilling. This exploration well is unique as it is the first at such depth in the area. It will deliver for the exploration phase of GeoLaB an outstanding dataset on the subsurface on top of the pilot seismic data. Beside an ample monitoring and logging program, cores will be sampled. These will deliver basic information about the crystalline rock bodies, their mineralogy, the presence of fractures, occurrence of hydrothermal alteration and the integrity of the expected granite-granodiorite at depth. The core samples will undergo a wide investigation and experimental workflow in order to determine the mineral assemblage, permeability, porosity (MTS) thus enabling the GeoLaB team to acquire insights on the subsurface.

The requirements, plan and details of the drilling are described in the Statement of Requirement (SOR) attached to this document.

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8
DIGITAL GEOLAB

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8.1 INTRODUCTION

The GeoLaB project is fostering aspects of the Helmholtz Information and Data Science initiative (Incubator) by building a Virtual GeoLaB as a “digital twin” of the real underground research laboratory. This digital approach of Virtual Labs is unique in geosciences and will affect other disciplines in “Earth and Environment” and “Energy”, underpinning the added value of the GeoLaB for both research areas and beyond. The key aspects of the Digital GeoLaB working group and, thus, the digital twin, are the implementation of a data transfer and storage system as well as creating visualization applications for the GeoLaB project to create a three-dimensional digital reproduction of the real laboratory containing all available datasets that can be interactively accessed.

8.2 WORK STEPS AND CONDUCTED STUDIES: DATA MANAGEMENT

8.2.1 KADI - The Karlsruhe Data Infrastructure

For data management, we employ the Karlsruhe Data Infrastructure (KADI). Comparing existing solutions implemented at the various research centres as well as the required resources for implementing a new system, it became obvious early on that KADI offered the most flexible solution and would fulfil the requirements for data storage for large and long-term research projects. Advantages that resulted in selecting KADI included how easy it was to upload and download data, create or copy records, the flexibility for assigning metadata, specifying access rights for groups or individuals, and being able to maintain a directory-tree-like structure for the whole data collection.

The current implementation of KADI is called “Kadi4Mat” and focusses on applications in the material sciences. A more geoscientifically focussed implementation called “Kadi4Geo” is currently in development. In general, KADI is a generic and open-source virtual research environment that can be used for the management of any type of research data within different research disciplines and use cases. Kadi4Mat is being developed as part of several research projects at the Karlsruhe Institute of Technology (KIT). The goal of Kadi4Mat is to combine the ability to manage and exchange data with the possibility to analyse, visualize and transform certain types of data. For datasets stored within KADI, heterogeneous workflows can be defined and executed via an application programming interface (API). In this way, a customisable framework is created that facilitates good research data management practices and collaboration between researchers. [1]

8.2.2 The GeoLaB Metadata Template

KADI stores data in so-called "records". A record is a set of metadata with one or more files attached. Storing metadata is important, especially in large collections, to be able to find specific datasets and have information about describing the data. In KADI, metadata information can be defined individually for each record. Alternatively, templates can be defined, so metadata is consistent across several data sets. For storing metadata within GeoLaB, a number of important criteria were considered:

- Metadata should adhere to an existing standard
- Minimising the effort of adding metadata to datasets
- Having a defined set of necessary metadata to have required information about any given dataset

After considering multiple existing metadata standards, e.g., ISO19115 [2] or CSDGM [3], the working group decided to employ the DublinCore Metadata Elements [4], which is a de-facto standard also published as ISO 15836. DublinCore consists of just 15 elements:

Table 8.1: DublinCore metadata terms

Content	Intellectual Property	Instantiation
Title	Creator	Date
Subject	Publisher	Format
Description	Contributor	Identifier
Type	Rights	Language
Relation		
Coverage		

Also, DublinCore is compliant with the INSPIRE directive (Infrastructure for Spatial Information in the European Community) of the European Community [5,6], defined to improve access to spatial data, e.g., in environmental sectors. DublinCore has not been defined for geospatial data in particular. A metadata element "Reference System" was added as this is required information in other geospatial standards. Also, an element "Responsible Party" was added that may or may not be identical with the Creator or Publisher. Especially for publicly available datasets, this represents a person – e.g., the original uploader – who can serve a person to talk to when questions about a dataset occur. Finally, a field "Dataset Category" was added to allow for a finer categorisation than the very general options of "Type".

To simplify adding metadata, pull-down menus giving a closed set of options were added wherever possible, namely for "Dataset Category", "Reference System", "Language", "Format", and "License". In addition, the Reference Date can be selected using a calendar

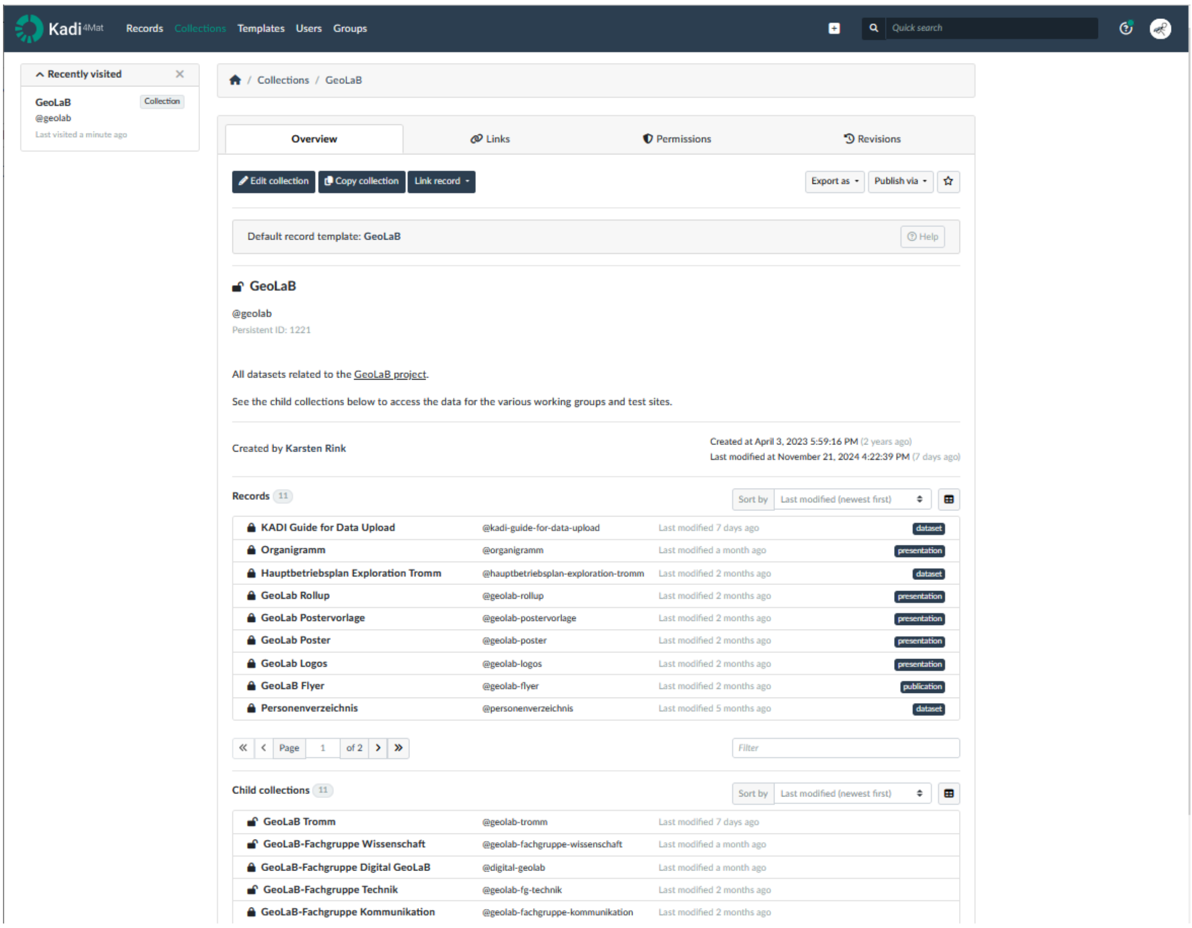

Figure 8-1: KADI4Geo. The GeoLaB-Collection as displayed by the KADI data management system. The collection contains a description, a number of general datasets relevant for all members (such as poster templates, logos, etc.) and the subcollections containing geodata, data of the working groups, presentations, etc**.**

widget and Rights can be added by selecting from a pool of users and predefined groups. To further simplify adding multiple datasets with similar properties, metadata sets can be copied, so only a minimum of information needs to be adjusted when creating new records.

8.2.3 Data Management Structure and Datasets

As previously mentioned, datasets are stored within so-called records, each of which can contain one or more files, allowing the user to connect multiple closely related files with one set of metadata. In addition, multiple records can be grouped into collections. Each collection has a name and description and separate user rights. Also, a collection can in turn include (sub-)collections, allowing for a directory- or tree-like structure that can be intuitively navigated and allows for a separation of records into multiple groups while still belonging to one larger project. Any record or collection can be set to be either “visible” – i.e., findable by any user in KADI, no matter the project they are assigned to – or be “private” – i.e., only visible to members of the GeoLaB group or one of its sub-groups.

The complete collection of datasets related to the GeoLaB project is one of multiple data collections within KADI. To provide a clear classification of the data, this collection currently contains eleven subcollections. These include:

- Subcollections for working groups
  - GeoLaB Wissenschaftlich Technischer Lenkungsausschuss
  - GeoLaB-Fachgruppe Digital GeoLaB
  - GeoLaB-Fachgruppe Exploration
  - GeoLaB-Fachgruppe Kommunikation
  - GeoLaB-Fachgruppe Technik
  - GeoLaB-Fachgruppe Wissenschaft
- Subcollections for potential sites for GeoLaB
  - Blauen
  - Omerskopf
  - Tromm
- A subcollection containing presentations
- A subcollection containing publications

The (sub-)collections for potential sites contain geoscientific datasets, while the collections for the individual working groups contain mostly minutes of group meetings and presentations shown during those meetings. However, each working group can decide on its own what to store within their respective collection. The collection for the Communication group presents a special case here, as it also contains material for outreach and public affairs, such as flyers and posters with general information on GeoLaB as well as the official GeoLaB logos and templates for presentations and posters, relevant for everyone working within the project.

As of October 2024, the GeoLaB data collection consists of 292 unique records containing significantly more than 300 datasets, as some records contain multiple datasets within a single record. Examples of that are the records for historical orthophotos or seismic campaign data. Table 8.2;Table 8.3;Table 8.4 and Table 8.5 give an overview of geoscientific data collected for the three potential sites. It should be noted that the collection for the Tromm site has been updated regularly over the past year, while the collections for the two sites in the black forest just include the result of an initial data research. Significantly more datasets have become available for these regions over the past months and the respective data collections will be updated in the future if necessary.

Like records can be categorised into collections, users can be categorised into groups. For the GeoLaB-project, a general GeoLaB-Members group has been defined, currently consisting of 40 persons. In addition, for each working group a representative group in KADI has been defined, allowing, for instance, these users to have administration or editor rights on records in their own working group while only having member rights everywhere else. Here, member rights grant only access to view and download the data, while editors can also change the data and administrators can create and delete datasets.

Table 8.2: List of vector datasets in the GeoLaB-Tromm collection. The abbreviation "AG" signifies the field of activity within the project (Arbeitsgebiet).

Dataset type	Dataset	Extent	Source
Adminitrative data	ATKIS Digitales Basis-Landschaftsmodell	Hessen	HVBG
	Verwaltungsgrenzen	AG / Hessen	HVBG
	Ortschaften	AG	
	Liegenschaftpläne	Hessen	
	Amtliche Hausumringe	Hessen	HVBG
Protection areas	Biosphärenreservate	AG / Hessen	HLNUG
	Biotopkartierung, Biotope und Biotopkomplexe	AG / Hessen	HLNUG
	Fauna-Flora-Habitate	AG / Hessen	HLNUG
	Geschützte Biotopkomplexflächen	AG / Hessen	HLNUG
	Landschaftsschutzgebiete	AG / Hessen	HLNUG
	Naturparke	AG / Hessen	HLNUG
	Naturschutzgebiete	AG / Hessen	HLNUG
	Vogelschutzgebiete	AG / Hessen	HLNUG
	Wasserschutzgebiete ALK	AG / Hessen	HLNUG
	Wasserschutzgebiete TK25	AG / Hessen	HLNUG
Bodenflächenkataster	Bodeneinheiten	Hessen	HLNUG
	Bodenflächenkataster 1:5000	Hessen	HLNUG
	Bodenhauptgruppen	Hessen	HLNUG
	Ertragspotential	Hessen	HLNUG
	Feldkapazität	Hessen	HLNUG
	Nitratrückhaltevermögen	Hessen	HLNUG
	Nutzbare Feldkapazität	Hessen	HLNUG

	Standorttypisierung Biotopentwicklung	Hessen	HLNUG
Project-related boundaries	Begrenzung Arbeitsgebiet	AG	GeoLaB Team
	Begrenzung Aufsuchungserlaubnis	AG	GeoLaB Team
	Begrenzung Arbeitsgebiet Seismik	AG	GeoLaB Team
Geological data	Geologische Übersichtskarte GÜK300	Hessen	HLNUG
	GÜK 300 Tektonik	Hessen	HLNUG
	Bohrungen	AG	HLNUG
	Steinbruchdaten	AG	HLNUG
	Dünnschliffkataster	AG	HLNUG
	Isohypsenplan	AG	GeoLaB Team
	Flurstücke Potentialgeophysik	AG Seismik	GeoLaB Team
	3D Tomography Stations	AG Seismik	GeoLaB Team
	Empfängerprofile	AG Seismik	GeoLaB Team
	Vibropunkte/Vibroprofile	AG Seismik	GeoLaB Team
	Profile	AG Seismik	GeoLaB Team
	Planung Schachtverläufe	AG Seismik	GeoLaB Team

Table 8.3: List of raster datasets in the GeoLaB-Tromm collection. The abbreviation "AG" signifies the field of activity within the project (Arbeitsgebiet).

Dataset type	Dataset	Extent	Source
SRTM data	DEM 90m	AG	NASA
DGM1	DGM1-Birkenau	AG	HVBG
	DGM1-Fürth	AG	HVBG
	DGM1-Grasellenbach	AG	HVBG
	DGM1-Heppenheim	AG	HVBG
	DGM1-Mörlenbach	AG	HVBG
	DGM1-Reichelsheim	AG	HVBG
	DGM1-Rimbach	AG	HVBG
Orthophotos	Google	AG	BKG
	DOP20-Birkenau	AG	HVBG
	DOP20-Fürth	AG	HVBG
	DOP20-Grasellenbach	AG	HVBG
	DOP20-Heppenheim	AG	HVBG
	DOP20-Mörlenbach	AG	HVBG
	DOP20-Reichelsheim	AG	HVBG
	DOP20-Rimbach	AG	HVBG
Topographische Karte	DTK25	AG/Hessen	HVBG
Liegenschaftspläne	Nordgrenze_Flurgrundstücke	AG	HVBG
	Landes und Kommunalflächen	AG	HVBG
	Zotzenbach_Eigentumsverhältnisse	AG	HVBG
Historische Luftbilder	1945 - 4 Luftbilder 1:40 000	AG	HVBG

	1935 – 4 Luftbildpläne 1:25 000	AG	HVBG
Schummerung	Schummerung Frey		GeoLaB team
	Schummerung Neuwirth		GeoLaB team

Table 8.4: List of remaining datasets (non-vector and non-raster) in the GeoLaB-Tromm collection. The abbreviation "AG" signifies the field of activity within the project (Arbeitsgebiet).

Dataset type	Dataset	Extent	Source
Geologie	Hessen3D	Hessen	HLNUG
	Schichtenverzeichnis	AG	HLNUG
	Morphotektonische Analyse Odenwald	AG	B-bG
	Bohrprofile Tromm	AG	AninA GmbH
Gebäudemodelle	LOD2	AG	
Liegenschaftskataster	Bestandsdaten	AG	
QGIS Projekte	Aeromagnetic dataset from the Tromm Granite in the southern Odenwald		GeoLaB team
	Geologie Tromm		GeoLaB team
	Structural network analysis from outcrop analogues of the crystalline Odenwald		GeoLaB team
	Interdisciplinary Dataset on the Fracture Network of the Tromm Granite, Southern Odenwald, SW Germany		GeoLaB team

Table 8.5: List of datasets in the GeoLaB-Omerskopf- and GeoLaB-Blauen-collections. Many of the datasets are covering the whole German state of Baden-Württemberg (BW) and thus belong to both collections.

Dataset type	Dataset	Extent	Source
Protection areas	Biosphärengebiete	BW	LUBW
	Fauna-Flora-Habitate (FFH)	BW	LUBW
	Geschützte Biotope	BW	LUBW
	Gewässer-Basisein-zugsgebiete	BW	LUBW
	Landschaftsschutzge-biete	BW	LUBW
	Moorkarte	BW	LUBW
	Nationalparke (NLP	BW	LUBW
	Naturdenkmale (END, FND)	BW	LUBW
	Naturparke	BW	LUBW
	Naturschutzgebiete	BW	LUBW
	Quellenschutzgebiete	BW	LUBW
	Stehende Gewässer (AWGN)	BW	LUBW
	Vogelschutzgebiete (SPA	BW	LUBW
	Waldschutzgebiete	BW	LUBW
	Wasserschutzgebiete	BW	LUBW
Administrative data	Gemarkungsüber-sichtskarte 1:350 000	BW	LUBW
	Kreiskarte 1:200 000	BW	LGL BW
	Verwaltungskarte 1:350 000	BW	LGL BW
	ATKIS Basis-DLM Ver-waltungsgrenzen	BW	LGL BW
Waterways	Fließgewässer (AWGN)	BW	LUBW

Maps	Landnutzung nach Landsat	BW	LUBW
	Schummerungskarte 30m	BW	LUBW
	Höhendarstellung mit Schummerung und Gewässerbeschriftung	BW	LGL BW
	Physische Karte 1:500 000	BW	LGL BW
Omerskopf	GÜK300 Geologische Einheiten Omerskopf	BW	LGRB BW
	GÜK300 Tektonik O-merskopf	BW	LGRB BW
	GK25-Datenblatt8212 Buehl	BW	LGRB BW
	GK25-Datenblatt7314 Buehl	BW	LGRB BW
	GK25-Datenblatt7315 Buehl	BW	LGRB BW
	DGM1-Omerskopf	BW	LGRB BW
	Bohrdaten Region O-merskopf	BW	LGRB BW
Blauen	GÜK300 Geologische Einheiten Blauen	BW	LGRB BW
	GÜK300 Tektonik Blauen	BW	LGRB BW
	GK25-Datenblatt8211 Blauen	BW	LGRB BW
	GK25-Datenblatt8212 Blauen	BW	LGRB BW
	DGM1-Blauen	BW	LGRB BW
	Bohrdaten Region Blauen	BW	LGRB BW

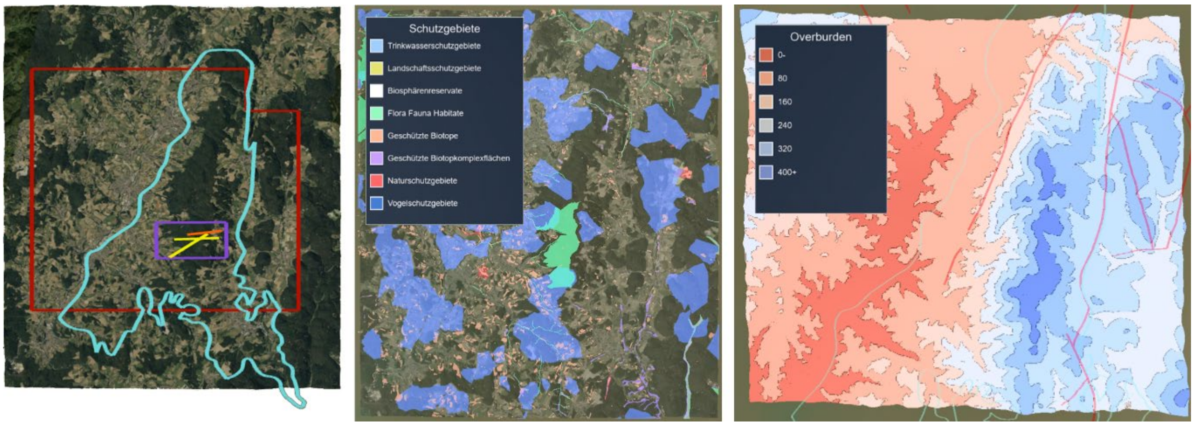

Figure 8-2: Map views. Top down view on the Tromm region: (a) prospecting region (red) and Tromm boundary (cyan) (b) protection areas, (c) overburden and faults.

8.3 WORK STEPS AND CONDUCTED STUDIES: VISUALIZATION

8.3.1 Unity Scene

For a 3D visualization of the Tromm region, we employ a workflow originally developed for building virtual environments for energy storage [7,8]. This workflow has been modified and is continuously expanded to acquire, transform, integrate and visualize heterogeneous datasets from a variety of resources (see Table 8.2, Table 8.3 and Table 8.4) in the scope of GeoLaB. The resulting application can be employed for data exploration and the intuitive presentation of campaigns at the Tromm site. This 3D scene will be the basis for an interactive digital twin of this region, integrating geoscientific, administrative and campaign data and serve as an application for data verification and knowledge communication.

A 3D visualization of the prospecting area has been modelled using the DGM1 digital elevation model as well as raster data such as satellite images or maps to serve as textures for this 3D Surface. For geographical context, this is embedded into a geographical overview of the whole of Germany, presented in a much coarser resolution. All integrated datasets used in this study have been projected into the UTM zone 32N coordinate system (EPSG:25832) to allow for a concurrent visualization. Surface data has been tessellated to represent a 3D model of the region as well as several specific locations, such as the site for test drillings, with their elevation properties.

For the prospecting area, a variety of administrative data is overlaid on the topographic surface for an overview of settlements, boundaries and environmental protection areas within the region. This data includes district centres, district boundaries, property boundaries, parcels, land use, urbanisation and building models within the area (see Figure 8-2).

Regarding geological data, the study includes two geological overview maps (the official GÜK300 map provided by the HLNUG as well as a more detailed map created by the GeoLaB staff), geological layers provided by the Hessen3D dataset [9] and a collection of boreholes available from the HLNUG with their correct depth and width, thus enabling their properties to be explored alongside the surrounding geological structure from a subsurface perspective (see Figure 8-3). In addition, we included fault lines, seismic profiles, possible tunnel locations, overburden data and more. All available data acquired through ongoing seismic and hydrological campaigns, alongside the digital layout of the prospective tunnel system will be integrated as they become available and support the planning stage of the project. For example, the two exploration drillings GLB-1 and GLB-2 planned near the urban district Tromm of the Grasellenbach municipality are already shown based on the current plans for the drilling site (see Figure 8-4).

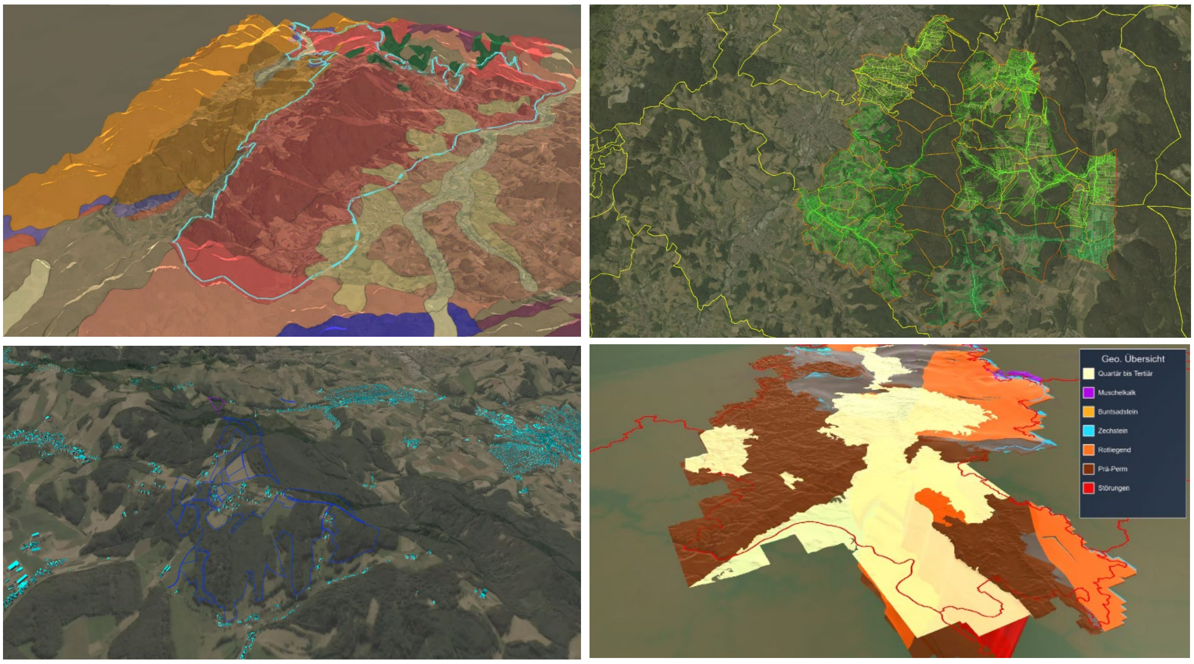

Figure 8-3: Data visualization. Examples for data visualization for the Tromm region: (a) geological overview map (b) property boundaries (c) 3D building models (d) geological layers of the Hessen3D dataset.

We utilise ParaView[4] and the OpenGeoSys Data Explorer[5] as a visualization framework to convert, import and integrate a collection of heterogeneous data, experiment and numerical simulation results from various resources into Unity[6], where we can adjust visibility properties and viewpoint perspective to build a visual storyline out of the available data. Beside datasets and experiment results, real-time measurements retrieved by data loggers and sensors can be linked to specific structures to be displayed by user interactions. In the same way, it is possible to attach descriptive documents, images, videos and websites to any 3D object. The visualization framework enables the presentation of datasets and measurement results using

4 https://www.paraview.org/

5 https://www.opengeosys.org/

6 https://unity.com

a visually appealing storytelling technique alongside such descriptive visual aids to provide information for knowledge transfer activities for stakeholders and the public.

The current state of the visualization study is demonstrated in a short video available on YouTube: https://youtu.be/TQIF9pR7MCA

8.3.2 Web-based Prototype for a Digital Twin

In addition to the 3D visualization implemented in Unity, which at this point is primarily suited for presentation and knowledge transfer purposes, the Digital GeoLaB group is working on a browser-based 3D visualization that will be expanded into a highly adaptable interactive prototype for a digital twin of the underground laboratory.

Figure 8-4: Visualization of the drilling site near the village of Tromm. (a) top-down view, (b)isometric view showing the planned boreholes

After testing a number of different open-source approaches based on "trame"[7], we have decided to utilise the "paraview-trame-components"[8] which enables a full ParaView visualization server to communicate with a web-based client to visualize the scenes running online on the server within a browser. As a browser-based tool, this application can be easily used by anyone without installing additional software. Due to the connection to a ParaView server, it becomes feasible to visualize large amounts of data independent of the local hardware. Finally, using a Python interface this can be integrated into Jupyther Notebooks[9], which can be advantageous for data science in heterogeneous and distributed environments.

Using this framework, it becomes possible to create standard visualizations of specific collections of datasets (e.g., sensors, geo-contexts, tunnel systems, simulation results etc.) and provide these for researchers without the need of setting up complex visualization software or to learn a programming language like Python, while still allowing for interactive modifications of the visualization such as applying predefined filters or adjusting the parameterisation of existing filters. Examples of such modifications include changing the visibility or colour of specific datasets, adjusting contour surfaces or clipping planes or creating specific views for the evaluation of selected datasets. While these features are currently employed to support the planning stage of GeoLaB, the main goal is to enable the visualization for planning and

[7] https://www.kitware.com/trame/

[8] https://github.com/Kitware/paraview-trame-components

[9] https://jupyter.org

verification of underground experiments once the underground laboratory is built. This will support researchers by providing an interactive visual tool for data exploration, verification and outreach activities.

Based on the current implementation, the online application can run in two different modes: The first mode is to generate or extend a scene via a specifically tailored user interface to support the user. Tests and user evaluations are planned to choose the most intuitive way of setting up complex visualization scenarios. The second mode is a viewer to visualize parts of the digital twin for analysis and verification based on the methods defined in the first mode. Besides the implementation of a suitable user interface, we started to look at heterogeneous geodata which needs to be automatically transformed to fit the VTK formats in order to be integrated into the visualization of the digital twin using ParaView. This poses a number of challenges, for example the missing z-coordinate of 2D shape files or the face that GIS data is often represented using boundary representations, which leads to the problem of tesselating the data for creating a 3D representation. The outcome depends on how a particular algorithm represents and transforms the boundary into simplicial complexes, which are required for rendering surfaces or volumes in 3D. This is a nontrivial problem and a unique transformation cannot be guaranteed since it depends on the method used. At this point, the issue of connecting different data sources has not been addressed yet. However, a connection of the framework to KADI or other databases will be addressed in the future.

8.4 NEXT STEPS

As new datasets are continuously acquired in the scope of GeoLaB, both the data management system (DMS) and the data visualization need to be updated accordingly. Examples of this include the integration of data acquired during the recent seismic, hydrological and potential geophysics campaigns as well as the two drillings planned for the near future. Here, uploading data into the DMS has the highest priority as this step ensures that datasets become available to all researchers within the project.

Developing methods for a suitable visualization of the various categories of data will become essential for outreach activities and for working with the data on an interdisciplinary level. The implemented methods will ensure a wider understanding of datasets for non-experts and 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.

In addition to handling the datasets, there is a number of technical developments that will be addressed: Regarding the DMS, an automatic testing and preprocessing of datasets during upload will save the team a significant amount of work. Advantages here include the at least partial extraction of metadata from datasets, projection into the agreed upon geographic coordinate system, checking the validity of files, providing previews of datasets within the DMS, integrating external databases for use within the project and much more. To ensure easy access to the data, the advantages of setting up web servers and providing standardized web services, e.g., as defined by the Open Geospatial Consortium, will be investigated.

Considering visualization activities, the (semi-)automatic conversion of geodata into suitable formats will save time during the preprocessing stage and both the Unity-framework and the browser-based visualization setup will benefit from this step. The overall application development will for now focus on the browser-based approach, as this concept seems more suitable for a productive framework used by researchers during their actual work. As outlined in section 8.3.2, the development of an intuitive user interface and interaction methods are currently being prioritized to provide a first working prototype that will be the basis for further developments in close cooperation with domain scientists.

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9 COMMUNICATION

KATHARINA SCHÄTZLER, JUDITH BREMER

INTRODUCTION

Given the scale of the GeoLaB project and the range of stakeholders involved, effective communication from the beginning is critical to its success. Impactful communication and public relations are a prerequisite for achieving the first GeoLaB milestone. Furthermore, geothermal technologies or research projects are frequently met with skepticism or even outright rejection, making information and dialogue even more important in this infrastructure project. This perception of risk is exacerbated by the involvement of the Federal Company for Final Disposal (BGE). The BGE aims at gaining experience in the exploration and excavation of underground laboratories. The complexity of the infrastructure project is reflected in the communication concept and requires the design and implementation from various perspectives and with diverse expertise. We therefore involve scientists, communication experts, risk communication specialists and specialized graphic designers. Transparency, making science tangible, taking concerns and ideas expressed seriously and enabling participation are among the key objectives of the concept.

Communication in GeoLaB is the responsibility of the spokesperson communication, supported by the communication expert group. This group consists of communication and public relations experts from the three participating Helmholtz Centers and the BGE. Since March 2023, online meetings convened and organized by the spokesperson have taken place every 14 days, and weekly if necessary. Through these joint meetings, the members of the expert group are actively involved in the development of communication strategies and measures for all GeoLaB communication topics. The communications team is strengthened by the risk communication agency “team ewen”, a subcontractor that has been supporting local communications work in particular since March 2024.

9.1 WORK STEPS AND CONDUCTED MEASURES

Since the authorization procedure for the exploration measures started and investigations in the frame of the exploration started on site, the primary objective in 2024 was the dissemination of information about GeoLaB to the public and network building. This was achieved through the organization of information events and the distribution of informational flyers. Additionally, information events were held for municipal councils, and discussions were initiated and facilitated. GeoLaB was represented at markets, including the "Gassenmarkt" and "Rimbacher Herbst", and an excursion was conducted. The website was specifically designed to be even more citizen-centered. Local press and media work continued, and the first social media posts were published. In detail, the following working steps were accomplished:

- Socio-economic analysis and specific site assessment resulting in a list of stakeholders
- Refinement of the communication concept and planning
    - Development of a graphical co-operate design
    - Conceptualization of the envisaged future dialogue platform (“Forum”)
- Development of a risk communication concept
- Media monitoring
- Realization of dialogue events (e.g., market stands, excursion)
- Development of communication materials
    - Citizen-oriented revision of the website and creation of an own subdomain
    - Development of an online newsletter
    - Social media posts
    - Distribution of flyers on several topics
    - Conceptualization of a drilling site info point
    - GeoLaB film development

The following sections will provide a more detailed description of some of these work packages.

9.1.1 Socio-economic Analysis and Communication Concept Refinement

The conceptualization process began with a socio-economic analysis to identify stakeholders, framework conditions, current media attention and the prevailing level of conflict. The concept builds upon early information as people often feel ill-informed and may rely on rumors. It is therefore important to communicate information in a clear and understandable way, supported by graphic processing. However, this is challenged by a dynamic overall project schedule with multiple dependencies and short-term adjustments typical for infrastructure projects of this complexity. Transparency is given a high priority. Discussing also potential negative impacts, such as waste and traffic, from the outset may help to build trust. Conveying the dimensions of the project in a tangible way, using concrete examples and everyday comparisons, makes the scope more comprehensible. Addressing the benefits is essential, not only in abstract terms for the country, but also specifically for the region and local communities. Finally, activating strong regional networks can effectively disseminate information and foster community support.

Communication is offered among differing channels and with various communication modules. These include personal contacts in dialogue events, thematic excursions and participation in local events such as markets, press releases, and digital tools such as newsletter, website and social media. The envisaged forum is a public round table offering the opportunity for in-depth dialogue on specific topics. Certain target groups will be explicitly invited to each forum, but it shall be open to all others. Ideally, the forum will be a place for appreciative monitoring of the project and a seismograph for critical developments in the region.

The concept is complemented by science education incentives for local schools and a citizen science approach to involve interested residents in the environmental monitoring of the infrastructure project. In later project stages, this is also intended to serve as a platform for the co-creation for scientific-technological solution approaches to enhance the transformative impact of GeoLaB.

9.1.2 A Corporate Design for GeoLaB

A modular design concept was developed for the new corporate design (Figure 9-1) in cooperation with “team ewen” and particularly the graphic agency “3f design” specialized in science communication. The corporate design uses the color palette of Helmholtz as the umbrella organization, which should remain recognizable. However, it extends the color palette by a few more colors that match GeoLaB and emphasize its characteristics. It visualizes the GeoLaB infrastructure schematically and very simplified as a tunnel in a mountain. The design conveys that GeoLaB is intended to bring light into the proverbial darkness. It also highlights the complexity of the underground and the respective research as well as the location of the experiments in the rock.

Figure 9-1: Impressions of the corporate design of GeoLaB as implemented by *3f design*.

The corporate design is used as basis for a variety of templates including flyers, posters, letters, PowerPoint presentations and social media posts. The logo consists of a word mark and a figurative mark. The latter is inspired by a globe and a tunnel into the Earth.

9.1.3 Development of Information Material

Based on the corporate design, information material in the form of texts and graphics was developed and used for flyers, website and posters with local residents as main addressees.

A basic flyer with core information on the GeoLaB project was developed in July 2024 in cooperation with *team ewen* and *3f design,* and distributed to the households of the communities mainly involved in the exploration phase around the Tromm. This flyer, titled *"Fascination Geothermal Energy",* presents GeoLaB as a unique underground research laboratory dedicated to advancing geothermal energy technologies[10]. It highlights how GeoLaB enables scientists to explore safe, sustainable, and efficient geothermal systems. The flyer emphasizes the importance of geothermal energy in the transition to renewable energy sources and invites the public to experience the excitement of scientific discovery.

Two further flyers were produced and circulated in the run-up to the seismic campaign[11] (Figure 9-2) and in the course of the geophysical measurements[12]. They explained the purpose of the measurements, basic principles of the measurement methods, effects for local residents and contacts for the population.

The website was restructured and the texts revised, not least in response to feedback from local stakeholders. It has been placed as a subdomain of the Helmholtz website[13] to reflect its status as a joint Helmholtz large-scale infrastructure across Helmholtz centers and research fields.

In order to explain the basic concepts behind GeoLaB to laypersons, a series of consecutive graphics has been created (Figure 9-3). With respect to the graphics made for the scientific community, they convey the essential aspects of the project. The starting point is a sketch of a geothermal plant in the fractured crystalline subsurface using the geological situation of the Upper Rhine Rift Valley as an example. The second picture shows the overall set-up of the Upper Rhine Graben and the Odenwald as a graben shoulder. This is where the crystalline bedrock comes to light and is accessible to scientists for in-situ experiments and 3D observations. The sketch also shows the proportions of geothermal reservoirs of geothermal plants and the relatively smaller test area of GeoLaB. The third image zooms into the underground laboratory and shows the main gallery and the basic elements of the experimental setup with fractures, research boreholes for experimental injections and sensors.

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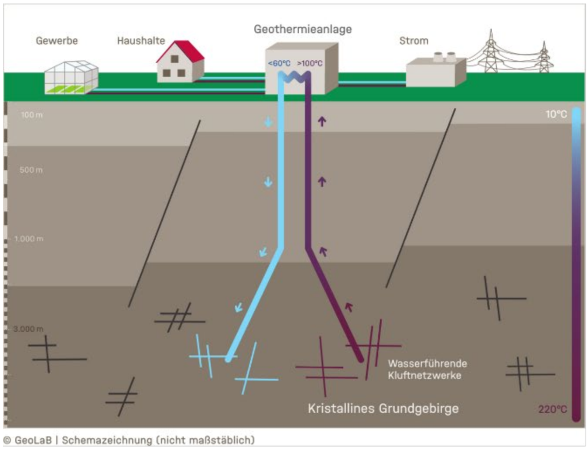
[13] https://geolab.helmholtz.de/

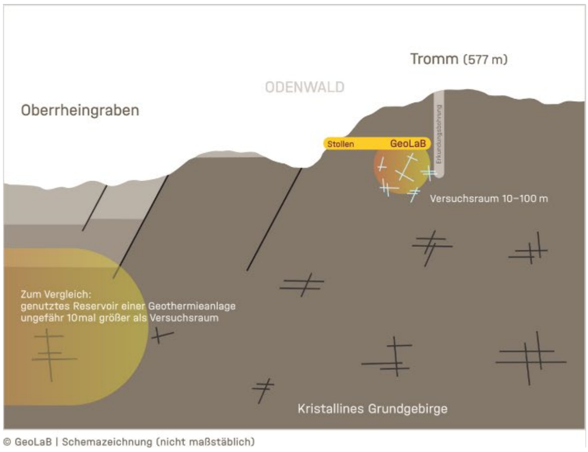
Figure 9-2: GeoLaB seismic flyer. It informs about the seismic campaign taking place in autumn 2024. The flyer uses the new corporate design developed in 2024.



◀ Concept of deep geothermal plants in the fractured crystalline basement

◣ Bottom left: GeoLaB in the mountain range along the Upper Rhine Graben, where the crystalline basement rock is accessible to research and 3D observations

Zoom into the underground research lab with its gallery, fractures and experimental set-up▼



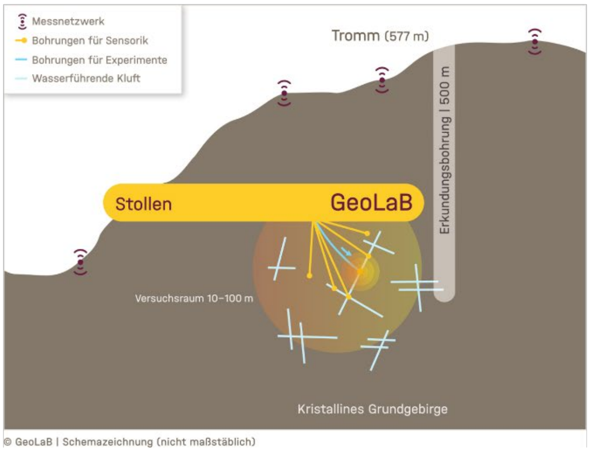


Figure 9-3: GeoLaB explanatory graphics. These sketches were designed in collaboration with *3f design* to explain the concepts and core elements of GeoLaB to laypeople.

9.1.4 Dialogue Events

Gassenmarkt

The seismic truck was the centerpiece of the GeoLaB stand at the ‘Gassenmarkt’ on September 8, 2024. The all-day GeoLaB representation was organized with the truck, posters, roll-ups, flyers and two experimental cases on rock properties, as well as a large number of staff from the GeoLaB team (Figure 9-4).

The GeoLaB information stand was very well attended on the day. The 6-person team had numerous conversations about GeoLaB in general and seismics in particular. The majority of questions were neutral to interested, while a smaller group of citizens were critical of the project.

Figure 9-4: Market place dialogue. At the Gassenmarkt, visitors were encouraged to interact with the GeoLaB team and ask questions. The highlight was the GFZ seismic truck, which was used to carry out the first seismic campaign a few days later.

Seismic Excursion

The seismic excursion for citizens on September 14 was the central information event for the seismic measurement campaign. Posters and the website were used to invite the public to spend two hours on a Saturday morning learning about the seismic survey. The program of the event was designed with short keynote speeches at several stations with plenty of room for questions and answers from the public. A short walk was organized to approach the seismic truck, which produced vibrations from time to time. The aim was to dispel fears of seismic measurements by making the shaking of the truck tangible and providing comprehensive information.

The excursion was very well attended with around 90 people (Figure 9-5). The citizens asked many questions, most of which related to the entire GeoLaB project. The ‘walk’ format was very successful, as it kept the situation lively and enabled many small discussions with individual citizens. No significant opposition arose. Among the visitors was a group of critics, primarily concerned with the potential GeoLaB tunnel construction site and groundwater protection.

Figure 9-5: Technical excursion. During the seismic excursion, the operation of the seismic truck was explained and demonstrated. Its vibrations were measured with a seismometer and visualized.

Rimbacher Herbst

The information stand at the Rimbacher Herbst, an exhibition of tradesmen in the municipality of Rimbach on October 13, served to inform citizens about GeoLaB in general and to present the exploration measures in autumn (Figure 9-6). The organization and implementation were similar to the Gassenmarkt in Wald-Michelbach, but without the seismic truck, as the seismic survey had already been completed by this time.

A group of residents expressed their concerns about the infrastructure project. The concerns centered on a reduced quality of life and the destruction of the natural landscape.

Figure 9-6: Market stand. At the GeoLaB booth at the Rimbacher Herbst, small experiments were used to demonstrate the differences in rock properties. The GeoLaB team was available for questions and discussions.

9.1.5 Media Presence

Print media – Initiatives and continuous analyses

Early on, press initiatives were supported to raise awareness of GeoLaB and its upcoming events. Journalists were invited to attend. Issues important to the local community were also covered by the press.

To monitor public perception, regular analyses of media coverage are conducted using press clippings. Regional media coverage (print media) is analyzed by the risk communication agency “team ewen”. Since March 2024, articles containing the words ‘geothermal energy’ or ‘GeoLaB’ have been reviewed and analyzed with regard to newspaper, authors, title, number of words, the existence of pictures, newspaper section, and the form of presentation. The content is also subject to evaluation: What is the topic of the article? What positive and negative aspects are covered and discussed? What is the tone of the article? Which actors are mentioned in the article?

A total of 193 relevant articles were identified and analyzed. Aside from the usual summer dip, the monthly distribution was fairly even. Most of the articles were published in the Frankfurter Rundschau and the local papers Bergsträsser Anzeiger and Odenwälder Zeitung. These were mainly medium-length pieces with images, written by newspaper editors, and featured in the 'Local/Regional' section.

Overall, the thematic focus of the articles is typically on the expansion of infrastructure and local politics. In ~10% of cases, the focus is directly on GeoLaB or geothermal energy, respectively. If GeoLaB is mentioned in the article, it is the main topic in two thirds of cases. Among the positive aspects, the suitability of the Tromm, safety through monitoring and the great potential of crystalline rock for the energy transition are mentioned particularly frequently. Conversely, the most frequently cited negative aspects pertain to water pollution, perceived lack of information, numerous uncertainties, impact on nature and, most significantly, BGE participation. The tenor of the articles with a direct reference to GeoLaB is mostly neutral (~80%) and negative in less than 10% during the survey period. Scientists, the KIT as coordinator, Helmholtz and citizens are mentioned as actors in over 50% of the articles with direct GeoLaB reference.

Email Newsletter

The newsletter serves to share key information, give a snapshot of ongoing activities, and invite readers to upcoming events. The first edition was sent out on December 1, 2024 (Figure 9-7). For future reference and for those not subscribed to the newsletter, all issues are also available on the GeoLaB website.

Social Media

Social media accounts on Facebook (Figure 9-8) and Instagram (Figure 9-9) were set up to reach a wider audience, including the younger generation. Great care has been taken to create an appealing layout. The posts aim to inform, enhance understanding, share impressions, and spark curiosity about GeoLaB.

Figure 9-7: Newsletter. The first email newsletter was sent out on December 1, 2024, providing an overview of GeoLaB and the dialogue events from the previous months.

Figure 9-8: Facebook presence with basic information and facts about GeoLaB and news on current events.

Figure 9-9: Instagram presence showing the example of information on the exploration drilling.

9.2 KEY FINDINGS AND CONCLUSIONS

Pro-active communication efforts have proven to be important. Outreach activities paid off, and GeoLaB received attention in the press, mostly in neutral terms. Not surprisingly, the subject of BGE involvement is one that necessitates continuous clarification.

It is crucial to ensure that the website is easily understandable for citizens. Consequently, enhancements were implemented at this juncture. While a more scientific approach can be adopted for sub-pages at a later stage, it is not the primary focus of the current project phase.

A permanent dialogue and addressing stakeholders personally at an early stage pays off. Informing citizens early and in detail is also essential and is almost always very well received. Intensive dialogue efforts could not prevent extensive opinion-forming against GeoLaB, especially in one district.

The planned information measures should be closely aligned with the different stages of the project. Evening events alone do not appeal to a large group of citizens, so variety is key. Focusing on formats that encourage dialogue in small groups and one-on-one conversations is also valued by stakeholders.

9.3 NEXT STEPS

In 2025, further exploration steps such as geophysical and hydrogeological measurements, the drilling of exploratory wells with logging and testing and a further seismic campaign will be carried out. These activities will be intensively flanked and supported by targeted communication measures. Once the results of current and future scientific measurement campaigns are available, they will be prepared for the various stakeholders in a targeted manner.

We will continue to use a multi-layered approach, offering information, promoting dialogue, and offer excursion-type events with tangible experiences. These efforts will include updating the website, conducting drone flyovers, producing an informational film about GeoLaB, engaging in media work including TV appearances, and offering guided tours of the drilling site with experts in science and drilling technology. We also place great importance on providing stimulating activities and educational offers for children and young people.

10 APPENDIX

10.1 GOVERNANCE

10.1.1 Involved Institutions

Karlsruhe Institute of Technology

The project team at KIT coordinates the GeoLaB project and contributes to geothermal research in GeoLaB with its interdisciplinary competence portfolio.

German Research Centre for Geosciences

The GFZ specialises in research into the solid Earth. GFZ scientists contribute their knowledge of geosciences and drilling technology to GeoLaB.

Helmholtz Centre for Environmental Research

The involved scientists of the UFZ are experts in environmental informatics. They are developing the 'Virtual GeoLaB', a comprehensive digital twin of the real research laboratory in the virtual world.

Darmstadt University of Technology

TU Darmstadt contributes to GeoLaB with regional geoscientific knowledge. The scientists involved are primarily concerned with geological and hydrogeological topics.

Federal Company for Final Storage

In the context of the GeoLaB project, the Federal Company for Final Disposal (BGE) is interested in understanding the challenges associated with the construction of underground facilities and the potential role of innovative technical solutions in addressing these challenges. BGE's involvement in GeoLaB will end with the commissioning of the research laboratory. No repository will be built at the actual GeoLaB site. The legally regulated selection process for a repository is independent of BGE's GeoLaB acitivites.

10.1.2 Persons

Prof. Dr. Thomas Kohl
KIT – Coordinator

Dr. Bastian Rudolph
KIT – Project leader

Prof. Dr. Ingo Sass
GFZ – Spokesperson “Science”

Prof. Dr. Olaf Kolditz
UFZ – Digital GeoLaB;
UFZ representative

Dr. Katharina Schätzler
KIT – Spokesperson “Communication”

Dr. Karsten Rink
UFZ – Spokesperson „Digital GeoLaB“

Prof. Dr. Christoph Schüth
TU Darmstadt – Hydrogeology;
Spokesperson „Planning”

Charlotte Horstmann
KIT – Spokesperson „Technics“

Dr. Jérôme Azzola
KIT – Geophysics

BGE GeoLaB team with PD Dr. Wolfram Rühaak, Otto Christopeit, Dr. Melissa Perner (until 2024), Dagmar Dehmer, Prof. Dr-Ing. Jürgen-Heinz Schamp, Thora Schubert.

Navid Bahrami Dashtaki
KIT – Drilling

Dr. Judith Bremer
KIT – GeoLaB communication;
Interface POF

Dr. Fiorenza Deon
GFZ – Exploration

Dr. Jens Grimmer
KIT – Geology

Dr. Nadine Haaf
KIT – Geophysical exploration

Prof. Dr. Shervin Haghsheno
KIT – Integrated Project Delivery

Said Kamrani-Mehni
GFZ – Exploration drilling management

Wolfgang Köbe
BGE - Drilling

Dr. Stefan Lüth
GFZ – Geophysics

Karine Marchand
KIT – Project administration

Henri Meinaß
TU Darmstadt – Geology

Nicolas Neuwirth
KIT – Project office

Angela Spalek
GFZ - Communication

…and many more.

10.1.3 Organigram

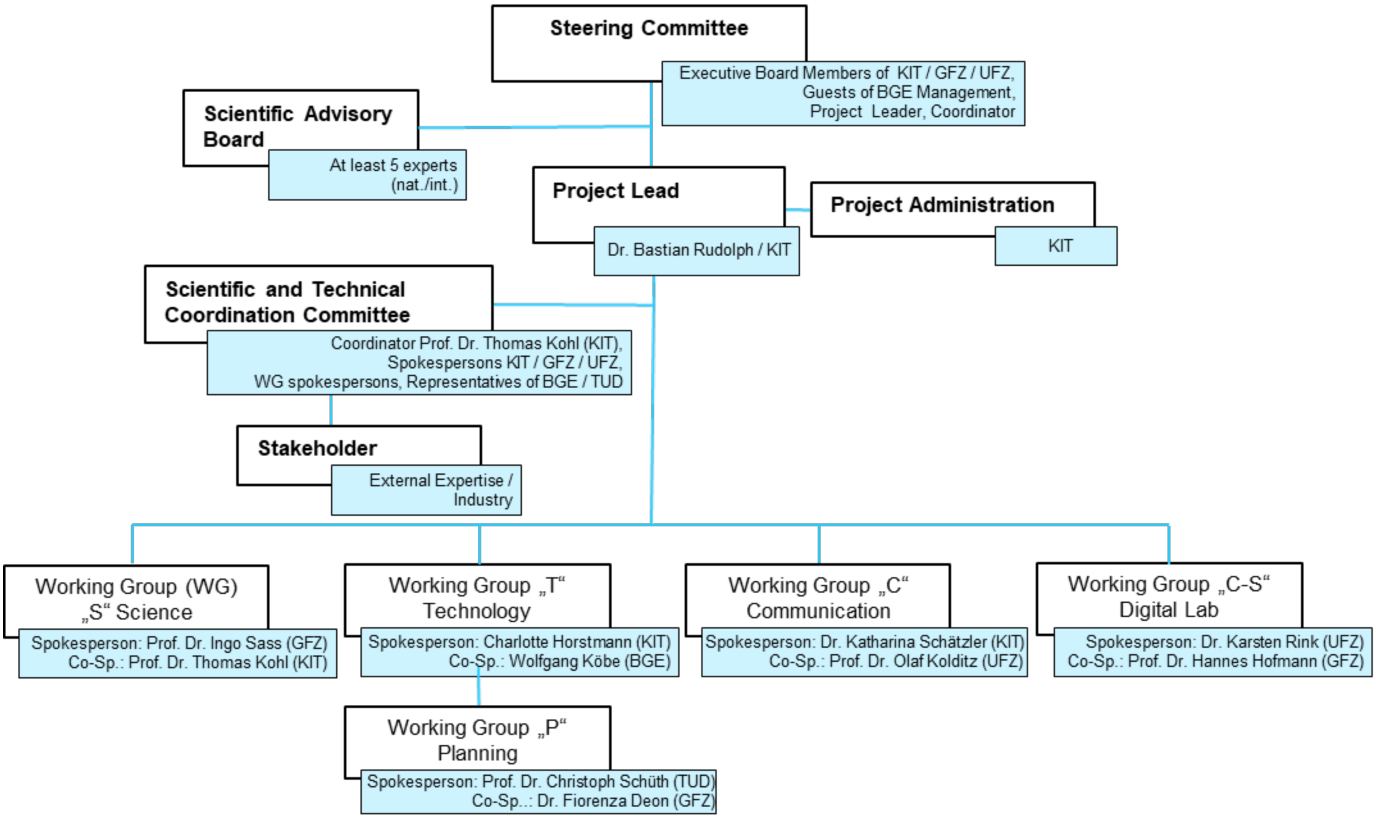


Figure 10-1: Organigram of the overall GeoLaB project

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