A Roadmap for horizontal multistage EGS heating projects in Germany: assessing deployment potential and limiting factors

Nora Medgyesi[1]; Anastasia Sidorova[1]; Fabian Uth[1]; Thomas Hamacher[1]

[1] Technical University of Munich

Enhanced Geothermal Systems (EGS) using horizontal wells and multistage stimulation ("next-gen EGS"), represent a promising advancement in geothermal technology. Recent results from Fervo Energy's Cape Project, which achieved peak flow rates of 107 L/s, demonstrate that EGS can deliver outputs comparable to conventional hydrogeothermal systems. While international projects in the US and Switzerland primarily target baseload electricity generation, next-gen EGS could offer significant potential to address Germany's urgent need for renewable heat. Unlike electricity, heat must be produced locally, and short-term revenues in the heating market are typically lower than in the power sector. Consequently, site selection for heating projects depends not only on geological conditions but also on heat demand and land-use constraints. For next-gen EGS in Germany, these challenges are compounded by regulatory restrictions such as fracking bans in protected areas.

The Roadmap Next Generation Geothermal Project aims to identify and map key limiting factors for the development of next-gen EGS projects in Germany, providing a basis for a potential rollout strategy. The analysis is structured into four main categories: (1) Regulatory restrictions, including licensing complexity. (2) Heat demand analysis, including existing and planned district heating networks. (3) Stimulation potential, based on regional geology and evaluated through a decision tree that considers multiple factors: reservoir depth, tectonic stress field, and lithology with geomechanical, thermal and hydraulic properties. Additional criteria include proximity to fault zones and historical seismicity, as felt seismic events must be avoided during stimulation. (4) Local data density, quantified by the availability of borehole data, seismic, gravimetric, and aeromagnetic surveys, as well as scientific publications. Stimulation potential is not assessed qualitatively based on local data at this stage.

Each location is classified as a short-term, medium-term, long-term, or not feasible prospect for all four categories. These ratings are combined into a final score using a worst-case selection approach, ensuring that critical constraints cannot be offset by favorable conditions for other criteria. The resulting map guides public utilities and investors toward low-hanging fruits. By summarizing the key limiting factors for each area, it raises awareness of site-specific constraints and supports the accelerated deployment of projects where such limitations can be managed or mitigated. At the same time, the map highlights knowledge gaps, indicating where further research and exploration are required.

A Three-Dimensional Conceptual Model of the Yangyi Geothermal Reservoir Based on Integrated Data

Haizhen Zhai[1]; Olaf Kolditz[1]; Haibing Shao[1]

[1] UFZ Helmholtz Centre for Environmental Research

The Yangyi geothermal field in central Tibet represents a structurally controlled high-temperature geothermal system that has been extensively investigated through geological, geochemical and geophysical exploration, resulting in a substantial body of multi-source datasets. Despite this wealth of information, previous studies have predominantly addressed individual methods or limited spatial scales, and a unified framework for interpreting reservoir architecture, fluid migration pathways, and spatial heterogeneity has remained absent.

To address this limitation, this study integrates geological mapping, gravity and magnetotelluric surveys, borehole logging and well testing, together with short- and long-term tracer experiments, to construct a three-dimensional geological model of the Yangyi geothermal system within a consistent spatial framework. The model explicitly incorporates the major fault systems, deep and shallow stratifications constrained by the basement andesite layer, and the spatial distribution of low-resistivity zones. Productive geothermal wells, including ZK203, ZK208, and ZK403, are used to constrain the relationships between structural elements and observed hydraulic responses.

The results demonstrate that the spatial zonation of the Yangyi geothermal field is primarily governed by fault-controlled vertical structural differentiation. Shallow fracture networks spatially coincide with low-resistivity zones and constitute hydraulically efficient pathways that facilitate rapid tracer migration between wells. In contrast, the contribution of deep thermal fluids is mainly regulated by major fault structures and is progressively modified along structurally guided flow paths. Integrated geological, geophysical, and tracer evidence indicates that the parent geothermal fluid originates from deeply circulating meteoric water, ascending at depth predominantly along the F5 fault and migrating upward at shallower levels preferentially along the F3 fault. The development of low-resistivity zones reflects fracture enhancement and hydrothermal alteration within the shallow structural domain during this upflow process.

By integrating multi-source datasets within a three-dimensional geological modeling framework, this study provides a coherent structural interpretation for the coexistence of reservoir zonation and inter-well hydraulic connectivity in the Yangyi geothermal field, and offers robust structural constraints for identifying favorable reservoir configurations in fault-controlled geothermal systems.

Improvement and long-term sustainability of fracture permeability in crystalline basement rock

Harald Milsch[1]; Fiorenza Deon[1]; Ulrike Hoffert[1]; Lena Muhl[1]; Ingo Sass[1]

[1] GFZ Helmholtz Centre for Geosciences

Crystalline basement rocks hold a large geothermal potential but generally display a very low matrix permeability. Fluid flow through this type of rock therefore is determined by faults, fractures or fracture networks that often are sealed by hydrothermal precipitates. Qualifying crystalline rocks for geothermal energy usage therefore requires these structural units to be stimulated. Here, chemical stimulation that dissolves and removes the obstacles within the void space might be preferred as hydraulic stimulation techniques often carry the risk of induced seismicity yielding acceptability issues.

Moreover, once the reservoir has received successful hydraulic improvement, it is required that permeability is maintained over longer time spans, i.e., the economic lifetime of the geothermal system. Consequently, any process that may negatively affect permeability needs to be disclosed, understood and its impact evaluated. This process understanding can be generated by appropriately designed laboratory experiments at in situ reservoir conditions.

In this contribution we will outline (I) ongoing efforts at GFZ to test different stimulation fluids for their efficiency in improving permeability in crystalline rock at the same time having the minimum environmental impact and (II) experimental strategies and current investigations to predict the permeability evolution of fractures in this type of rock under mechano-chemical fluid-rock interaction processes with respect to flow of natural fluids during operation of the geothermal system.

Towards Digital Twins: Interpretable Physics-Based AI method for Near Real-Time Predictions

Denise Degen[1]; Yulia Gruzdeva[2]; Nicolas Hayek[2]; Marthe Faber[2]; Cristian Siegel[2]; Mauro Cacace[2]

[1] Technical University Darmstadt

[2] GFZ Helmholtz Centre for Geosciences

The development of digital twins for subsurface applications is important for the development of underground laboratories. At the same time, it faces several challenges, in this contribution we are focusing on the issue of providing near real-time predictions for numerical multi-physics applications described by partial differential equations. Even when fronted against state-of-the-art high-performance computing infrastructures, conventional multi-physics simulations are not real-time compatible because of their huge computational demand. At the same time, they are subject to uncertainties from, for instance, the geometry, material properties, and boundary conditions.

To address the computational demand, we introduce the usage of surrogate models. Surrogate models comprise data-driven and physics-based approaches. While data-driven techniques, such as neural-networks, well capture complex system responses, they typically lack interpretability, hindering the degree of reliability of the model outcomes. This, in turn, poses challenges for the integration into digital twins especially in applications where risks need to be assessed. In contrast, physics-based approaches are fully interpretable, but often limited to elliptic and parabolic partial differential equations. Hence, they cannot capture the full complexity of the systems dynamics. To overcome the limitations of both data-driven and physics-based techniques, we introduce a hybrid approach namely the non-intrusive reduced basis method within the class of projection-based model order reduction techniques.

In this contribution, we demonstrate for multi-physics applications how this interpretable physics-based AI method can be used to reliably and efficiently accelerate the high-fidelity numerical multi-physics simulations. Furthermore, we illustrate their integration into a Bayesian uncertainty quantification framework, including hierarchical approaches. At last, we discuss possibilities to extend the aforementioned approaches to allow for a continuous integration of observational data.

Thermal and microstructural controls on permeability evolution in the Tromm Granite (Odenwald, Germany): Experimental and microstructural insights

Angel Ramirez[1]; Leandra Weydt[1]; Luka Kiri[2]; Ingo Sass[2]

[1] Technical University Darmstadt

[2] GFZ Helmholtz Centre for Geosciences

Crystalline rocks are the hosts of several subsurface applications, including e.g., deep geological disposal of radioactive waste and enhanced geothermal systems (EGS), where the rocks are exposed to elevated pressures, temperatures, and high stress conditions. In these settings, stress-induced changes in permeability can significantly affect fluid circulation and heat transfer. Consequently, the temporal evolution of permeability under coupled thermo–hydro–mechanical (THM) conditions remains a key uncertainty for long-term performance and safety assessments of subsurface reservoirs.

The experimental program presented here was conducted within the AMPEDEK research project, which aims to characterize crystalline (igneous and metamorphic) rocks as potential host formations for the deep geological disposal of high-level radioactive nuclear waste. This study focuses on a granitic body located in the Tromm Massif (Odenwald, Germany), which has also been identified as a potential target for geothermal exploitation in hot crystalline rock as part of the GeoLaB project.

The permeability evolution and THM response of the Tromm Granite was investigated using long-term flow-through triaxial experiments. Cylindrical plugs were subjected to cyclic loading under triaxial stress conditions at temperatures of 30, 60, and 90°C. Permeability was continuously monitored during periods of 6 to 10 days, while axial and radial deformations were recorded throughout the experiments. Thin sections were prepared before and after the tests.

The experiments reveal a clear temperature dependence of permeability evolution. At lower temperatures (30°C), permeability exhibits minor and largely reversible fluctuations, indicating elastic opening and closure of microfractures. In contrast, at elevated temperatures (90°C), a pronounced and irreversible reduction in permeability occurs. These observations suggest a transition from predominantly elastic behavior to time-dependent and thermally activated deformation processes with increasing temperature.

Microstructural analyses revealed that fractures are dominantly transgranular and preferentially affect feldspars, while mafic minerals (mainly chloritized biotite) influence crack nucleation and propagation through elastic and mechanical anisotropy. Fracture geometries indicate the combined role of stress concentration at mineral boundaries, elastic and thermal expansion mismatches, and the presence of microstructurally weakened domains, particularly in altered feldspars. At higher temperatures, fracture apertures and geometries appear to be influenced by pre-existing microtextures, microporosity and fluid-rock interactions.

The results highlight that permeability in crystalline rocks is not only pressure-dependent but also evolves with time and temperature. In addition, fracture initiation and propagation are influenced by the mineralogical composition and textural characteristics of the rocks. These findings have direct implications for underground storage and geothermal applications: thermally induced permeability reduction may enhance containment in nuclear waste repositories while potentially limiting injectivity and productivity in geothermal reservoirs. Incorporating temperature- and time-dependent processes, as well as petrological features into THM models is therefore essential for reliable long-term predictions of subsurface system behavior.

Thermo-Hydraulic Modelling of Heat Extraction in Enhanced Geothermal Systems with Temperature-Sensitive Proppants

Saeed Mahmoodpour[1]; Michael Drews[1]

[1] Technical University of Munich

Enhanced Geothermal Systems (EGS) offer significant potential to increase the contribution of geothermal energy to the renewable energy portfolio. A common EGS configuration described in the literature consists of a pair of horizontal wellbores (a doublet) connected by hydraulically fractured pathways. Efficient design and implementation of such systems require accurate modelling of the hydraulic fracturing process to determine the geometry, shape, and aperture of the induced fractures. In addition, modelling proppant transport and placement is essential to ensure fracture openness throughout operation.

In the first stage of this study, the ResFrac simulation tool is used to model a multistage hydraulic fracturing operation, consisting of six fractures per stage, in a hypothetical doublet system using realistic input parameters. The resulting fracture geometries and apertures are then exported to the COMSOL Multiphysics® platform. In the second stage, high-resolution thermo-hydraulic (TH) models are developed in COMSOL based on one selected fracture stage.

Due to heterogeneity in the shape and aperture of the generated fractures, early thermal breakthrough is likely to occur in highly conductive fracture pathways. To mitigate this effect, temperature-sensitive proppants—previously introduced in the literature—are evaluated as a control mechanism. Multiple TH simulation scenarios are conducted to assess the impact of temperature-sensitive proppants on the performance of the designed doublet system.

The results demonstrate that temperature-sensitive proppants are an effective means of delaying thermal breakthrough and enhancing the total heat extraction capacity of EGS. Their effectiveness is strongly influenced by the degree of fracture aperture variability, with more heterogeneous fracture networks exhibiting greater performance improvement. Additionally, water loss is a critical concern in EGS operations, particularly when fractures intersect highly conductive formations. Temperature-sensitive proppants can reduce fracture conductivity in such zones, thereby mitigating fluid loss and improving overall system efficiency.

Overview of Downhole Logging measurements for GeoLaB drilling Project

Simona Pierdominici[1]; Jochem Kueck[1]

[1] GFZ Helmholtz Centre for Geosciences

Geophysical wireline logging of borehole GLB01 was conducted along the full open-hole section (161 mm nominal diameter) using slim-hole tools operated by the Operational Support Group (OSG) of the International Continental Scientific Drilling Program (ICDP) and Terratec Geophysical Services. The logging suite included caliper (CAL), natural and spectral gamma-ray (GR and SGR), magnetic susceptibility (MSUS), electrical resistivity (Rdeep and Rshallow), sonic (Vp and Vs), acoustic and electrical imaging (ABI43 and MRI), density (GGD), neutron porosity (NN), nuclear magnetic resonance (NMR), and optical televiewer (OPTV). Logging data reveal that GLB01 penetrates predominantly granite formation to approximately 410 m, followed by a 10 m cataclasite interval and gneiss-amphibolite rocks down to 500 m.

The downhole logging measurements show remarkable differences among the three lithological units. The GR and SGR logs exhibit a quasi-monotone pattern within the granite units, whereas a pronounced spike marks the presence of the 10 m cataclasite interval. In contrast, the GR and SGR responses in the gneiss-amphibolite units are more variable, suggesting the presence of multiple intercalated layers. A comparable pattern is observed in the magnetic susceptibility, which remains low throughout the granite, increases slightly within the cataclasite interval, and rises sharply below 462 m, consistent with a lithology enriched in ferromagnetic minerals such as magnetite and hematite.

The presence of borehole enlargements significantly affects the quality of sonic, neutron, density and resistivity logs, thereby increasing the uncertainty of log-based interpretations. Under these conditions, physical properties and elastic parameters were reliably estimated only within selected intervals characterized by a more regular borehole geometry, where it was possible to distinguish rigid or brittle rock formation. In contrast, borehole GLB02 is not affected by borehole enlargements and therefore exhibits significantly more reliable log measurements.

Particular emphasis was placed on the analysis of acoustic and optical televiewer logs, which provide critical measurements for identifying tectonic features determining their dip, dip direction, spatial distribution along the borehole. This analysis addresses one of the primary objectives of GeoLaB, namely to elucidate the role of fracture-controlled processes in crystalline rock formations. A total of over 1680 structures were identified in GLB01. These were classified as major, minor, and partially open joints, filled fractures, veins, and lithological contacts or bedding planes. For each feature, azimuth, dip, and aperture were measured. Fracture density decreases markedly below ca. 412 m, indicating that the gneiss-amphibolite units are considerably more compact and mechanically robust than the overlying granite. This is also reflected in fracture apertures, which exceed 40 mm primarily within the upper granite section. No borehole breakouts were observed.

The GLB01 wireline logging dataset provided an initial structural and mechanical overview of the crystalline basement, linking lithology, alteration, and fracture distribution to rock strength. The next steps will focus on further refining and detailing this framework by integrating GLB01 logging data with those from GLB02, as well as additional information, such as drill core sample analyses.

Hydraulic Fracturing by Supercritical CO2 Injection in the Presence of Rock Microstructure

Keita Yoshioka[1]; Weihong Yuan[1]; Tao You[1]

[1] Montanuniversität Leoben

Supercritical CO2 fracturing is expected to create more complex fracture networks than water-based counterparts, thereby improving the permeability and heat extraction in geothermal reservoirs. The underlying fracture mechanisms driven by this low-viscosity fluid may differ from conventional hydraulic fracturing. In this study, we develop a stabilized hydromechanical phase-field fracture model to simulate hydraulic fracturing in two- and three-dimensional polycrystalline microstructures. To address numerical instabilities caused by strong heterogeneity and operator splitting, we propose a novel spatial stabilization term for the monolithic solution of the coupled hydromechanical problem. We then conduct numerical simulations of hydraulic fracture evolution considering rock microstructure under water and supercritical CO2 injection. Our numerical results reproduce laboratory observations and demonstrate that the generation of complex fracture networks is controlled by both rock heterogeneity and fracturing fluid. Our findings further confirm that supercritical CO2 fracturing is more likely to trigger remote activation of heterogeneous interfaces, leading to more complex fracture morphologies.

Monitoring cementation and drilling processes in GeoLaB exploration wells with fiber optic sensing

Jérôme Azzola[1]; Simon Blaise[1]; Emmanuel Gaucher[1]

[1] Karlsruhe Institute of Technology (KIT)

As part of the initial phase of the GeoLaB project, two exploration wells - GeoLaB1 (vertical) and GeoLaB2 (deviated) - were drilled to characterize the geological setting, test advanced monitoring technologies, and prepare for future experiments. Following drilling, coring and logging of the 500-m vertical well GeoLaB1, a fiber-optic cable was clamped behind the casing in a U-loop configuration and permanently cemented. The cable contains multiple fibers, enabling simultaneous and complementary distributed fiber-optic sensing.

A first dataset was acquired during and after the cementation of GeoLaB1 using Distributed Temperature and Strain Sensing (DTSS) based on Brillouin Optical Time-Domain Reflectometry and Distributed Acoustic Sensing (DAS). These two methods provide complementary information: DTSS captures the quasi-static strain response associated with cement placement and hardening, while DAS records the dynamic seismic and vibrational signals generated during cement injection. Their combined use contributes to a comprehensive characterization of the thermo-mechanical and mechanical processes occurring along the wellbore during cementation. DAS strain-rate data recorded continuously during the drilling of the nearby deviated well GeoLaB2 constitute the second dataset.

After presenting the technical aspects of the measurement setup, we analyze the fiber-optic responses to the GeoLaB1 cement job using DAS and DTSS data supported by conventional well logging data, and present DAS observations of drilling operations at short offset. The results illustrate on the one hand how DAS and DTSS data complement the assessment of well integrity compared to standard approaches. On the other hand, they give insights into drilling-induced signals and near-wellbore processes with a high spatial resolution.

Shear Behavior of Natural Granite Joints from the GeoLaB Exploration Well: Implications for Underground Geothermal Research Laboratories

Kai Li[1]; Carola Buness[1]; Thomas Kohl[1]; Jens Christian Schneider[1]; Hans Henning Stutz[1]

[1] Karlsruhe Institute of Technology (KIT)

The mechanical behavior of natural rock joints critically controls the stability, permeability evolution, and stimulation efficiency of geothermal energy applications and geotechnical engineering considerations. Within the framework of the planned underground research laboratory in the GeoLaB project, this study investigates the shear behavior of natural granite joints recovered from different depths of the GeoLaB-1 exploration well drilled into the Tromm Massif (Odenwald, Germany).

Four joint samples containing pre-existing natural fractures were prepared for direct shear testing. Each specimen consisted of two rough joint halves, preserving natural surface morphology and lineation. Tests were conducted using a rock mechanic direct shear apparatus allowing normal loads up to 500 kN and shear displacements up to 90 mm. One multi-stage and three single-stage shear tests were carried out to explore joint behavior.

A multi-stage shear test was performed on one joint sample under progressively increasing normal forces of 10, 20, 40, 80, and 160 kN. All stages occurred within the shear-off regime, characterized by asperity degradation and a lack of a clearly identifiable transition from dilation-controlled to friction-controlled behavior. Progressive asperity destruction resulted in significant loss of surface integrity, producing a layer of crushed rock material that prevented post-shear surface morphology analysis.

To preserve joint surface characteristics for morphological investigation, single-stage shear tests at low normal force of 10 kN were conducted on three different samples. These tests revealed joint-specific shear and dilation responses governed by the combined effects of asperity geometry and intact rock strength. While single-stage tests provide limited constraints on full frictional behavior, they enable pre- and post-shear surface scanning and offer valuable input for correlating mechanical response with quantitative roughness descriptors such as Joint Roughness Coefficient (JRC) and Hurst exponent.

The results highlight the strong dependence of joint shear behavior on stress path and testing methodology, with important implications for the design of controlled stimulation experiments, and stability assessments in underground research laboratories. The observed low friction angles and rapid asperity degradation emphasize the need for realistic joint characterization in crystalline geothermal reservoirs. Ongoing work focuses on integrating high-resolution surface scans with mechanical data to improve constitutive descriptions of joint behavior for GeoLaB.

Towards a digital twin of the GeoLaB Tromm site

Karsten Rink[1]; Felix Raith[1]; Özgür Ozan Sen[1]; Fiorenza Deon[2]; Nadine Haaf[3]; Marcel Horovitz[4]; Thomas Kohl[3]; Stefan Lüth[2]; Edinsson Munoz[4]; Bastian Rudolph[3]; Ingo Sass[2]; Christoph Schüth[4]; Olaf Kolditz[1]

[1] UFZ Helmholtz Centre for Environmental Research

[2] GFZ Helmholtz Centre for Geosciences

[3] Karlsruhe Institute of Technology (KIT)

[4] Technical University of Darmstadt

GeoLaB is an underground research laboratory (URL) currently in the planning stage, focussing on geothermal energy production in crystalline rock. Accompanying the planning, a virtual geographic environment is being built and updated with datasets as they become available. The focus of this data integration process are currently the various exploration campaigns that ensure that the planned site in southern Hesse, Germany, is suitable for building the laboratory and conducting experiments. Over the past two years, multiple exploration campaigns have been funded to acquire detailed seismic, geophysical, magnetic, and hydrological datasets in the area around the Tromm mountain ridge. In addition, two exploration wells with a depth of 500 m have been drilled to ensure the selected site is suitable for the construction of an underground lab.

3D representations of acquired datasets have been created and are visualised in a unified geographic context in combination with datasets provided by state offices (such as fracture networks, geological maps, buildings and protection areas) as well as geological information to gain new and detailed insights about geotechnical and hydrogeological conditions in this region. In addition, a hydrogeological simulation already provides information on groundwater and saturation and a structural model will soon allow for a coupled THM simulation. With over 500 datasets already gathered in the scope of the project, data management is vitally important and workflows are being defined for preprocessing, conversion, modelling and visualization.

This contribution focusses on the combined 3D visualization of campaign data acquired during the site selection process and aims primarily at planning and stakeholder information. However, the long-term goal is building a functional digital twin of the URL and all experiments as well as the surrounding area.

Geophysical Characterization of Crystalline Rock Using Gravimetry, Magnetics, and DC Resistivity for the GeoLaB Project

Nadine Haaf[1]; Nicolas Neuwirth[1]; Dr. Bastian Rudolph[1]

[1] Karlsruhe Institute of Technology (KIT)

The GeoLaB project aims to develop a deep underground research infrastructure in crystalline rock to advance the understanding of processes relevant to Enhanced Geothermal Systems. A key requirement for site development is the reliable identification of fault and fracture zones that may control permeability and fluid flow. In this context, this contribution focuses on the application and interpretation of potential field methods—gravimetry and magnetics—supported by DC electrical resistivity, as tools for structural characterization during the GeoLaB exploration phase.

An integrated geophysical survey was carried out in the Tromm area (Hessian Odenwald), combining ground-based gravimetric measurements, magnetic profiling, and DC electrical resistivity tomography (ERT). Gravity data were processed using standard corrections and filtering approaches, while magnetic data were analyzed using derivative-based methods to enhance structural features. ERT profiles provided complementary information on subsurface resistivity variations along selected transects.

The results reveal several zones characterized by coinciding gravity lows, magnetic anomalies, and resistivity variations, showing consistent spatial patterns across the different methods. These zones are interpreted as structurally heterogeneous areas within the crystalline basement and form the basis for identifying target areas for further investigation within the GeoLaB project.

A Workflow for Integrating GIS Data into Implicit Geological Models within a Digital Twin Framework

Jian Yang[1]; Florian Wellmann[1]

[1] RWTH Aachen University

The GeoDT subproject of the GeoLab initiative requires a geological model that can serve as a stable geometric backbone for a digital twin while remaining adaptable to an evolving and heterogeneous data base. In this work, the focus is placed on establishing a workflow that links GIS-based data preparation with three-dimensional geological modeling, rather than on the geological model as a standalone result. Implicit geological modeling with GemPy is used to represent the subsurface structure, while a large part of the effort is dedicated to the systematic handling of GIS data such as geological maps, digital elevation models, and structural observations. These data sets originate from different sources, resolutions, and formats and therefore require coordinated preprocessing steps before they can be translated into geometric constraints for the model.

Spatial data processing and interpretation are carried out in QGIS, whereas GemGIS is used to connect the GIS environment with the geological modeling framework. Within the established workflow, GemGIS supports coordinate handling, data transformation, and the structured transfer of GIS-derived information into the implicit modeling domain. The resulting GemPy-based geological model is not restricted to a single representation but can be consistently transformed into different model discretizations, including voxel-based models and unstructured meshes, depending on the requirements of subsequent applications. This enables geological interpretations developed in a GIS context to be incorporated directly into the model in a transparent and reproducible way, while maintaining flexibility for downstream use in simulation and analysis. The geological model can therefore be updated consistently as new data become available and integrated as an active component of the GeoDT digital twin.

Reactive Flow-Through Experiments Investigating the Evolution of Transport Properties in Conventional and Supercritical EGS

Juliane Kummerow[1]; Gina Rüdiger[2]; Lena Muhl[1]; Erik Spangenberg[1]; Timm John[2]

[1] GFZ Helmholtz Centre for Geosciences

[2] Free University of Berlin

Enhanced Geothermal Systems (EGS) and emerging superhot geothermal concepts rely on sustained fluid circulation through deep, low-permeability crystalline rocks exposed to temperatures ranging from approximately 150 to 500?°C. Across this wide thermal spectrum, fluid–rock interactions exert a primary control on permeability evolution, fluid composition, and the long-term efficiency of heat extraction. However, the governing chemical processes differ fundamentally between conventional EGS stimulation conditions and supercritical geothermal environments, and experimental constraints remain limited. Petrophysical flow-through experiments provide a robust laboratory framework to investigate these processes under controlled yet dynamically evolving conditions.

This contribution presents a portfolio of high-temperature flow-through experiments designed to investigate fluid–rock interactions relevant to both conventional and superhot EGS reservoirs. At temperatures of 150 – 200?°C, experiments focus on chemically assisted stimulation under subcritical conditions. Reactive fluids, including modified mud acid and chelate-forming agents, are circulated through core-scale rock samples to quantify permeability enhancement by mineral dissolution, and the risk of secondary mineral precipitation during stimulation. Continuous monitoring of permeability and effluent fluid chemistry enables assessment of stimulation efficiency and short- to medium-term petrophysical evolution under representative injection conditions. At higher temperatures extending into the supercritical regime (> 374?°C, 25 MPa), the experimental emphasis shifts from applied stimulation strategies to fundamental investigations of the electrical properties of rocks and permeability, governed by reactive transport in supercritical aqueous fluids. These experiments aim to characterise how reactive transport and mineralogical changes affect both flow pathways and electrical signatures, providing critical insights for reservoir delineation and monitoring in superhot EGS environments.

Post-experimental microstructural and mineralogical analyses, including X-ray computed tomography (XCT), scanning electron microscopy (SEM), and electron microprobe analysis (EMPA), will link macroscopic changes in permeability and electrical properties to pore-scale alteration patterns and mineral changes. The resulting datasets provide essential constraints for reactive transport models and improve predictions of permeability evolution and geophysical behavior in both conventional and supercritical EGS reservoirs.

Effects of Rough Fracture Opening on Laminar Single-Fracture Flow

Carola M. Buness[1]; Fabian Nitschke[1]; Thomas Kohl[1]

[1] Karlsruhe Institute of Technology (KIT)

Accurately predicting fluid dynamics in crystalline rock remains fundamental to geothermal reservoir management. Near injection wells, high fluid pressures drive low effective normal stress conditions, often resulting in normal opening or shear displacement with minimal abrasion. This study investigates the relationship between granitic fracture surface roughness and the resulting hydraulic behavior under these specific conditions. While global surface statistics are frequently used to characterize fractures, our high-resolution topography measurements, among others of granite fracture samples from the Tromm Massif (Odenwald, Germany) and Soultz-Sous-Forêts (Rhine graben, France), reveal that local fluctuations in the surface roughness height gradient are a non-negligible factor in determining fracture void space. We demonstrate that during shear displacement, these local fluctuations dominate the evolution of the fracture aperture and the overall void geometry. The resulting fracture voids exhibit wider apertures than conventional models, leading to varying normalized local aperture distributions with shear. Using this adjusted void geometry, we analyzed the influence on laminar flow dynamics. Our results indicate that the interplay between local height gradient fluctuations and shear-induced opening significantly affects both hydraulic conductivity and flow non-uniformity (channeling). These findings suggest that conventional models relying solely on global roughness parameters may deviate from natural field conditions.

Structural modelling of the Tromm: Data preparation and integration

Markus Bleicher[1]; Fiorenza Deon[1]; Mrityunjay Singh[1]; Ingo Sass[1]; Hema Priya Rajangam[1]; Felix Raith[2]; Olaf Kolditz[2]

[1] GFZ Helmholtz Center for Geosciences

[2] UFZ Helmholtz Centre for Environmental Research

The exploration for the underground research Laboratory GeoLaB focused on the Tromm in the Odenwald crystalline complex (Germany). The first GeoLaB project, GeoDT, will support the laboratory in the future with a digital twin. This requires a structural model which is a geological framework of faults and lithological domains which can be versioned and is updateable. As such, it has major controls about placement of rock characteristics, experiment design, subsurface comprehension, construction decisions and the settings and boundaries to enable coupled simulations.

The GeoLaB consortium organized and conducted two seismic campaigns, potential geophysics, drilled two exploration wells, hydrogeological sampling and monitoring campaigns. A structural model imports profiles (e.g. seismic, resistivity) from which it infers lithological domains, key interfaces, lithological and structural domains. Additionally, in some cases, the data which compiled the profiles can be imported, which allows for a second perspective and, in case of uncertainties or data mismatches, for alternative interpretations.

The data required for a structural model, such as digital elevation models or profiles, needs to be collected from the entire dataset. Next up is visualizing the data with QGIS and Paraview. These tools support 3D integration of the data with quality control, harmonizing spatial reference frames, deriving structural constraints, assessing uncertainty, testing and comparing alternative interpretations. This allows for quick overview, judgement and, if necessary, processing of the data, as well as providing a differentiation between useable files and auxiliary files visible outside the software.

Hydraulic Characterization of a multi-stage Enhanced Geothermal System: A Workflow Integrating Pre- and Post-Stimulation Tests with Real-Time Microseismic Monitoring at the Bedretto Underground Laboratory (Switzerland)

Andres Alcolea[1]; Peter Meier[1]; Falko Bethmann[1]; Raymi Castilla[1]; Fabien Christe[1]; Ben Dyer[1]; Dimitris Karvounis[1]; Francisco Serbeto[1]

[1] Geo-Energie Suisse AG

This study presents an integrated workflow for the hydraulic and geometric characterization of multi-stage Enhanced Geothermal Systems (EGS), integrating hydraulic testing with real-time microseismic monitoring. The workflow was developed within the ZoDrEx (Zonal Isolation, Drilling, and Exploitation of EGS Projects) framework and applied at the Bedretto Underground Laboratory for Geosciences and Geoenergies (BULGG), Switzerland. The analysis focuses on the multi-stage stimulation of two boreholes, ST1 and ST2. A total of 78 hydraulic and seismic datasets (41 from ST1 across 9 isolated intervals, and 37 from ST2 across 6 intervals) were evaluated to characterize reservoir properties at three key stages: pre-stimulation, during stimulation (primarily through intermediate shut-in interpretation), and post-stimulation.

The interpretation is based on a one-dimensional, three-zone numerical model consisting of a borehole skin, a stimulated zone, and the intact crystalline host rock. Given the low injection volumes per stage (up to 5m3), mechanical and thermal effects were neglected to focus on hydraulic regime diagnostics. Key parameters evaluated include wellbore storage and the spatial extent and the transmissivity and storage coefficient of all 3 zones.

The results show that:

1. All tested intervals developed a highly transmissive skin surrounding the borehole.

2. The extent of both the skin and stimulated zones correlates well with the measured microseismic event cloud, which was used as prior information for parameter calibration.

3. In both boreholes, stimulation led to a significant and permanent increase in the transmissivity of the stimulated zone, by a factor of 50-100 relative to initial values.

4. The hydraulic regime, identified through slope analysis of the pressure derivative in diagnostic plots, typically initiates as linear flow (consistent with the pre-notching of the isolated intervals) and progressively evolves toward radial flow as the stimulated zone becomes pressurized. In some cases, spherical flow was identified, suggesting hydraulic connectivity of the stimulated fracture to surrounding fractures, consistent with observed increases in cross-flow toward upper intervals during stimulation.

Overall, the proposed workflow provides a robust and systematic approach for the hydraulic and geometric assessment of multi-stage EGS in crystalline basement rocks, demonstrating the value of integrating hydraulic diagnostics and modelling with real-time microseismic observations.

Experimental studies on chemical stimulation through reactive transport processes in Enhanced Geothermal Systems (EGS)

Gina Rüdiger[1]; Juliane Kummerow[2]; Laurenz Schröer[3]; Chandra Widyananda Winardhi[3]; Veerle Cnudde[3]; Timm John[1]

[1] Free University of Berlin

[2] GFZ Helmholtz Centre for Geosciences

[3] Ghent University

Reactive transport processes are of critical importance in various geological settings, governing rock alteration, ore deposit formation, CO2 sequestration and Enhanced Geothermal Systems (EGS). In EGS, these processes, initiated by chemical stimulation, result in dynamic changes in mineral composition and petrophysical properties. Porosity generation and permeability maintenance are essential for EGS, as they facilitate efficient fluid flow and, consequently, heat transport. However, the parameters controlling the efficiency of chemical stimulation of low-permeable rocks are incompletely understood and experimental studies are still sparse.

To simulate coupled reactive transport processes in low-permeable crystalline reservoirs, we performed hydrothermal closed-system experiments on the laboratory scale. Chemical stimulation of granite with modified regular mud acid (RMA) was conducted under geothermal reservoir conditions. Subsequently, post-flush experiments were carried out with the reacted granite to test the stability of newly-formed phases.

We characterized and quantified chemical, mineralogical, and microstructural changes of granite samples exposed to reactive fluids, partly in three dimensions, using X-ray powder diffraction (XRD), scanning electron microscopy (SEM), electron microprobe analyses (EMPA), Raman spectroscopy, optical profilometry, X-ray micro-computed tomography (μCT) through the EXCITE network at the Centre for X-ray Tomography at Ghent University, and fluid chemical analyses. Furthermore, fluid pathways and phase distribution, after the fluid-rock interaction, in the granite samples are detected, thereby providing insights into the reaction process and the influence of experimental parameters on the reactions.

Our experimental results demonstrate the efficiency of chemical stimulation of granite, accompanied by a substantial increase in interconnected porosity, driven by coupled mineral dissolution and the formation of denser phases replacing the original mineral assemblages.

Key findings emphasize the potential of reactive transport by laboratory chemical stimulation to affect significantly the petrophysical properties of granites under geothermal reservoir conditions.

Virtual Boreholes from Downhole Logging Data

Victor Haefner[1]

[1] Karlsruhe Institute of Technology (KIT)

This work presents a virtualization workflow for downhole logging and core data developed within the GeoDT project and based on GeoLaB data, integrating heterogeneous datasets into a coherent, geo-referenced subsurface model. The approach combines automated core image processing, downhole imaging, and log-based visualization to improve data consistency, usability, and accessibility while reducing manual effort.

Geological core samples were acquired and digitized on site using a line-scanner system. Although this enabled rapid acquisition, the resulting images exhibited inconsistencies in orientation, cropping, and annotation due to field conditions and manual edits. To address these issues, a lightweight, fully automated image-processing framework was designed. The pipeline detects and corrects scan orientation using scanner-specific boundary features, performs precise and uniform cropping, and determines the geological top and bottom of each core segment by analyzing color-coded reference marks applied during sampling. These steps ensured standardized, analysis-ready core imagery suitable for archiving and further interpretation. The framework also supports reading and writing scanner-generated DMT files, correction of segment lengths based on processed scans, and enrichment of metadata by integrating missing depth information from MDIS.

Processed core data were uploaded to centralized infrastructures, including Kadi and MDIS, enabling reproducible access and long-term storage. In parallel, a virtual geological model was established to contextualize the core and logging data spatially. A surface model of the Tromm area was generated using satellite imagery and 3D tiles, providing an up-to-date geographic reference for the GeoLaB drilling site. Borehole trajectories supplied by GFZ were integrated and exported for external use, forming the basis for subsurface visualization.

As additional boreholes and higher-resolution log datasets became available, scalability challenges emerged, including increased memory consumption and longer application startup times. To address this, a more efficient data management strategy was implemented. Two-dimensional downhole log data were segmented into one-meter intervals and stored as image tiles, enabling a level-of-detail mechanism that loads data on demand. This significantly reduced resource requirements and improved performance, while also supporting deployment as a web-based virtual model.

Advanced downhole imaging data, including RGB and ABI logs, were incorporated into the unified model. Image analysis methods were applied to correct device-related distortions, align data to magnetic north, and ensure spatial consistency along the borehole paths. The resulting integrated model enables joint visualization of core scans, RGB downhole imagery, dip and ABI logging data, supporting structural interpretation such as fracture analysis within a single, geo-referenced virtual environment.

Overall, the presented workflow demonstrates a robust and scalable approach to virtualizing downhole logging and core data, enhancing data quality, interoperability, and accessibility for geological analysis.

Towards a robust 3-D stress prediction for the Tromm region

Karsten Reiter[1]; Steffen Ahlers[1]; Moritz Ziegler[2]; Denise Degen[1]; Louison Laruelle[3]; Oliver Heidbach[3]; Andreas Henk[1]

[1] Technical University Darmstadt

[2] TU München, TUM School of Engineering and Design

[3] GFZ Helmholtz Centre for Geosciences

The present-day stress state is an important parameter for any use of the underground, regardless of whether it concerns wellbore drilling or underground mining activities. To assess the mechanical and hydraulic behaviour of the rock units, a 3-D description of the stress state (orientation and magnitudes) is essential. However, in the early stage of exploration, reliable knowledge of the 3-D geological structure, mechanical rock properties, and model calibration data is limited. Therefore, frequently 3-D geomechanical models are employed that allow for the prediction of the complete stress tensor in the model volume, even when only sparse and scattered information on rock properties and model calibration data is available.

The processes of model preparation, calibration, and uncertainty assessment have been further developed and improved over the last decade. This was mainly driven by a comprehensive investigation program in the framework of the search for a final nuclear waste repository in Switzerland and non-site-specific research projects in Germany, carried out in support of the national site selection process for nuclear waste disposal. The latter investigated the regional-scale spatial variability of the stress field and its impact on derived parameters, such as slip tendency. In the past, only a single best-fit model was possible to compute, as only average rock properties and limited numbers of reliable stress magnitude data were available. New approaches and tools now enable statistical uncertainty predictions of the complete stress tensor for each depth and each rock unit, based on geomechanical models calibrated on a wide range of different data types.

The first stress prediction efforts in the GeoLAB framework only allowed for generic approaches that investigate, e.g., the influence of topography or the Otzberg fault zone. As a result of the rigorous exploration efforts over the past two years, significantly more data is now available for the target region of the GeoLAB project, the Tromm pluton in the Odenwald. This enables us in the next years to provide much more reliable stress predictions using geomechanical modelling approaches for that region. The presentation will provide an overview of the up-to-date workflow for 3-D geomechanical modelling with a focus on model calibration options to provide the range of likely stress states. Furthermore, the impact of rock stiffness on the model results will be presented as the key contributor to the uncertainties of the predicted stress magnitudes.

Process Model Development for a Geothermal Digital Twin Framework

Yuxiao Wang[1]

[1] Kiel University

Digital twins are emerging as a key paradigm for integrating heterogeneous subsurface data and physics-based models to support the safe and efficient development of deep geothermal systems. As a digital twin should be able to mimic and predict the behaviour of the geothermal system, a process-based model needs to be incorporated. In this study, we develop a conceptual framework for the Geolab site (Odenwald, Germany) to integrate geological, hydraulic, and thermal datasets into a representative process model. This model serves as a blueprint to identify necessary data and model data workflows for integration into the digital twin framework. As an initial step, a two-dimensional thermo-hydraulic model is constructed as a baseline to investigate the influence of key hydraulic, thermal and geometric parameters on pressure and temperature distribution as well as groundwater and heat flow rates. A series of test cases are designed at a smaller scale using uniform boundary conditions, enabling systematic observation of temperature evolution and flow behavior under specific boundary conditions. The simulation results demonstrate that hydraulic permeability plays a critical role in controlling the temperature field, with high permeability enhancing advective heat transport and thus leading to lower subsurface temperatures. Embedded fractures can strongly disturb the flow field and modify heat transfer patterns. All models are implemented using the OpenGeoSys (OGS) platform. The developed workflow establishes a systematic implementation framework for automated simulations, providing a foundation for future real-time monitoring, data assimilation, and dynamic model updating within a digital twin environment.

Data-Driven Approaches to Subsurface Characterization with Implications for Geothermal Research

Saeid Sadeghnejad[1]; Thorsten Schäfer[1]

[1] Friedrich Schiller Universität Jena

The characterization of geothermal systems is challenging due to inherent natural subsurface heterogeneity, limited data availability, and the high computational cost of some coupled thermo-hydro-mechanical-chemical simulations. Recent advances in artificial intelligence (AI) and machine learning (ML) provide complementary approaches to conventional physics-based modelling and data characterization. This contribution summarizes a set of recent studies from our research group that apply AI and ML to complex subsurface problems and discusses how these methodologies can be extended to geothermal reservoir characterization.

These works include data-driven approaches for analysing heterogeneity at the pore scale, extracting features from imaging datasets, and constructing surrogate models for computationally expensive numerical simulations. Although these studies were not originally developed for geothermal applications, the underlying concepts address geothermal project challenges, such as subsurface heterogeneity and the efficient approximation of coupled multi-physics processes. In particular, shallow and deep learning techniques enable automated pattern recognition from high-dimensional datasets and support uncertainty analysis at reduced computational cost.

Representative examples include the application of convolutional neural networks for automated feature detection and classification (e.g., rock lithology and fracture/stylolite localization) in whole-core imaging datasets, the use of ML models to construct pore network models of heterogeneous rocks across multiple scales, the development of shallow and deep surrogate models to approximate numerically expensive simulations from the pore to the field scale (e.g., colloidal particle migration and deposition in the subsurface), and ML-assisted digital rock physics workflows combining X-ray CT imaging to quantify transport processes in fractured subsurface systems.

By translating these AI-based strategies across subsurface research domains, this work illustrates how ML can complement existing characterization workflows in geothermal research. The presented perspective emphasizes methodological transferability and cross-domain learning, highlighting how advances developed in related subsurface studies can inform future research directions in geothermal science.

Hydro(geo)logical monitoring and integrated hydrological modelling of groundwater systems at the GeoLaB Tromm site

Edinsson Muñoz-Vega[1]; Marcel Horovitz[1]; Stephan Schulz[1]; Nils Michelsen[1]; Christoph Schüth[1]

[1] Technical University Darmstadt

One of the key questions to be addressed during the exploratory phase of GeoLaB concerns the dynamics of the groundwater systems in the Tromm area in terms of quality and quantity. However, the geological setting is complex and comprises plutonic, metamorphic, and sedimentary rocks, all affected by varying degrees of fracturing and intersected by regional fault systems. These units, particularly the crystalline rocks, are difficult to investigate directly, resulting in a general lack of subsurface information in the study area. In addition, alluvial and colluvial deposits, soils developed under grasslands and forests, as well as weathered zones and associated saprolites, are expected to exert significant control on groundwater flow and on recharge and discharge processes. This combination of factors makes hydrological and hydrogeological assessments particularly challenging.

To investigate the influence of the different hydrogeological units on groundwater and surface water dynamics, we follow two complementary approaches. First, we conduct a monitoring and sampling campaign, initiated in November 2025, focusing on springs, streams, and subcatchment outlets in the vicinity of the Tromm exploration site, as well as drinking water wells operated by local water suppliers. Water samples are analyzed for various parameters, including major ions, trace elements, and stable water isotopes. In addition, the installation of automated soil water content sensors, discharge stations, and monitoring wells is planned.

The second approach consists of integrated hydrologic modelling using ParFlow–CLM over a domain larger than the Tromm area to allow for more realistic boundary conditions. The modelling focuses on testing alternative assumptions regarding the hydraulic properties and geometries of shallow deposits and weathered horizons, which are expected to strongly control groundwater flow and surface water dynamics. As a first step, a suite of steady-state simulations is used to assess groundwater table depths and drainage networks under different conceptual models. Subsequently, transient simulations will be conducted for the most plausible scenarios and compared with observations of discharge, groundwater levels, and soil moisture profiles obtained from the monitoring program. Preliminary results highlight the strong sensitivity of groundwater table depths to the conceptualization of shallow and weathered units.

The aim of this work is to present the current state of the monitoring and modelling activities and to illustrate the potential of this integrated approach to constrain hydrogeological conditions in the GeoLaB area. Overall, this will provide a first hydro(geo)logical assessment of the GeoLaB site and outlines a monitoring and modelling framework that can be progressively refined to support future exploration activities and the design of the underground laboratory.

GLB1 well: can a comparison between mineralogic and downhole logging investigation play a role on the GeoLaB construction plan?

Fiorenza Deon[1]; Simona Pierdominici[1]; Ben Norden[1]; Johannes Preisendanz[2]; Luca Kiri[1]; Ulrike Hoffert[1]; Harald Milsch[1]; Ingo Sass[1]; Thomas Kohl[2]

[1] GFZ Helmholtz Centre for Geosciences

[2] Karlsruhe Institute of Technology (KIT)

The recent investigation on the GLB1 wellbore and the recovered cores made considerable progresses.

Downhole logging interpretation, non-destructive Multi-Sensor Core Logger (MSCL) measurements and destructive measurements including mineralogic and petrologic analyses now provide a more detailed characterization of both the borehole and core material.

A first set of selected XRD measurements on core samples, XRF whole rock geochemical analyses, geochemical analyses on thin sections by means of EMP were conducted in order to classify the different lithologies, including granitic and metamorphic units characterizing the wellbore. On top of the petrographic characterization, on-going work aims to correlate downhole logging measurements with the mineral composition of the cores, particularly focusing on the occurrence of Fe-bearing minerals and alteration.

These findings will help to better plan the geomechanical experiments and the designed flow-cell experiments with the core material.

A precise determination of the alteration on fractured and intact cores will improve the understanding of the rock properties, which are fundamental for the construction design of the GeoLaB underground laboratory.

The state of seismic exploration of the GeoLaB Tromm site – lessons learned so far

Stefan Lüth[1]; Fiorenza Deon[1]; Rüdiger Giese [1]; Katrin Jaksch[1]; Rüdiger Misiek[2]; Nicolas Neuwirth[3]; Bastian Rudolph[3]; Ingo Sass[1]; Amr Talaat Tolba[3]

[1] GFZ Helmholtz Centre for Geosciences

[2] DMT GmbH & Co. KG

[3] Karlsruhe Institute of Technology (KIT)

As part of the geoscientific exploration, the GeoLaB Tromm site has been investigated by two seismic surveying campaigns, complementing the so far available structural and geophysical information from surface mapping, gravity and magnetic surveying, electrical resistivity tomography (ERT), and other methods. The contribution of the seismic exploration is expected to provide data for a structural characterization of the underground down to the depth range of a potential underground laboratory, and below, i.e., from the earth's surface down to approximately 1 km below ground level.

Seismic imaging projects in mountainous areas, such as the Odenwald around the Tromm site, face various challenges, such as limited accessibility for placing seismic source and receiver locations according to the needed spatial resolution, or receiving a complex reflected/backscattered wave field due to a complex underground structure, violating common assumptions made in classical seismic exploration approaches. Therefore, an initial pilot seismic survey, consisting of 2 perpendicular profiles ("Pilot Seismic Tromm 2024") was acquired in September 2024. A major task of this survey was to assess the feasibility of structural imaging of the Tromm Granite and surrounding structures and to provide initial geophysical parameters important for a more detailed planning of a full-scale 3D exploration (e.g., the distribution of seismic velocities).

One year later, after the exploratory boreholes have been completed, this pilot seismic survey was complemented by the "VSP and 2D Seismic Tromm 2025" (VSP: Vertical Seismic Profiling). This survey consisted, on the one hand, in a Zero-Offset-VSP acquisition along the GeoLaB-1 borehole, providing high-resolution seismic data for a precise velocity-depth profile along that borehole, and for imaging small-scale reflective features along the borehole. On the other hand, the seismic vibro source was operated along the two profiles acquired in 2024, while recording the signals in the GeoLaB-1 borehole, and along the vibro-profiles. The downhole-recording of the vibro source operations along the lines will provide imaging data focusing around the track of the borehole and may contribute to identifying small-scale fault zones around the borehole.

The data acquired by the Pilot Seismic Tromm 2024 was processed and imaged in the time and depth domains by a contractor, and depth-migrated sections are available along the two vibro lines. The main feature, identified on both sections, is, in the area of the Tromm Granite, rather weak and diffuse reflectivity in the first 400 m below ground level, followed by a clear unconformity at 400 m depth, below which complex structural patterns are observed. For further discussion of the sections, please refer to Tolba et al. (this vol.).

The currently available seismic results have shown that the densely spaced acquisition of vibro-seismic lines in this mountainous region is able to identify major unconformities in the underground and to indicate potential fault zones. These observations, and the knowledge gained on the distribution of seismic velocities, support the conceptual design of further seismic 3D imaging of the Tromm site, once the decision has been made to build an underground laboratory there.

DESMEX - Semi-airborne electromagnetic exploration with UAV-towed magnetometers

Raphael Rochlitz[1]; Pritam Yogeshwar[1]; Philipp Kotowski[2]; Barbara Blanco-Arrue[1]; Wiebke Mörbe[1]; Mathias Ronczka[1]; Thomas Günther[3]

[1] LIAG Institute for Applied Geophysics

[2] University of Münster

[3] Freiberg University of Mining and Technology

Modern geophysical exploration methods increasingly make use of unmanned aerial vehicles (UAVs) to carry scientific instruments. In general, UAVs help to accelerate data acquisition and reduce the need for ground access. For semi-airborne electromagnetics (sAEM), as developed within the Deep Electromagnetic Sounding for Mineral Exploration (DESMEX) projects, UAVs offer an effective alternative for local scale investigations. UAV-based sAEM surveying offers significant and unique potential for targeted exploration of earth resources, including mineral deposits at as well as groundwater systems various spatial scales. Here, we address related instrumental developments, processing, modeling, and inversion workflows, as well as the interpretation of results based on selected representative case studies.

Of particular interest is the combined application of two different receiver instruments: a scalar (MagArrow) and a vector (SHFT-02e) magnetometer. The scalar magnetometer is not affected by motion-induced electromagnetic noise and is sensitive to lower frequencies. The processed transfer functions provide high-quality data below 200 Hz, whereas the vector magnetometer covers the frequency range above approximately 10 Hz. Accordingly, the scalar sensor is generally more sensitive to deeper electrically conductive structures, while the vector magnetometer is better suited to resolving shallower features. A combination of both sensor types improves the resolution of subsurface structures and also supports quality control of the individual recordings.

The drone-based sAEM method was primarily applied to explore massive sulfide deposits at the Hope and Poderosa demonstration sites, as well as a graphite deposit at the Kropfmühl graphite mine. In a transfer-oriented application, the method was used to investigate saltwater intrusion in northern Germany within the BlueTransition project. In the framework of the SeeKaquA project, we surveyed the Cuvelai–Etosha Basin in Namibia to characterize a deep aquifer system. For the interpretation of the resulting conductivity models, we compare our results with existing geological information, other geophysical data, and borehole logs.

Regarding methodological advances, we highlight the influence of different magnetometer suspension systems. Extensions of the open-source inversion framework custEM/pyGIMLi enable the combined inversion of scalar and vector data, as well as semi-airborne and ground-based controlled-source or natural-source EM data. This approach not only improves resolution capabilities but also supports the evaluation of data consistency, misfit behavior, and resolution characteristics.

A Hydromechanical Phase-Field Model for Predicting Hydraulic Fracturing in Brittle Rocks

Davood Yazdani Cherati[1]; Antal Csuka[1]; Stefan Vogt[1]; Roberto Cudmani[1]

[1] Technical University of Munich

Enhanced Geothermal Systems (EGS) represent a promising renewable energy technology with the potential to provide reliable, low-carbon baseload power by enhancing the permeability of deep, low-permeability rock formations. This paper proposes a hydromechanical phase-field model for simulating hydraulic fracturing in EGS. The porous medium is modeled using classical Biot poroelasticity, while fracture behavior is governed by a phase-field formulation. Fracture propagation is driven by elastic energy, with the phase field serving as an interpolation function that smoothly transfers fluid properties from the intact medium to the fully fractured state. A segregated (staggered) numerical scheme is employed and implemented in COMSOL Multiphysics. The capability of the proposed approach is demonstrated through a two-dimensional example in which water injection into a natural fracture leads to fracture propagation.

A GIS-Based Screening Framework for Geothermal–CRM Co-Production: From Global Data Integration to Site Selection

Fatemeh Hosseinpour[1]; Glenda Taddia[1]; Martina Gizzi[1]

[1] Politechnico Torino

Critical raw materials (CRMs) such as lithium are essential for the energy transition, yet their supply remains exposed to geopolitical and environmental risks due to strong geographic concentration. Geothermal systems, especially those producing hot, saline brines, offer a potential dual benefit: provision of renewable heat and power and co-production of dissolved CRMs. Recent studies and pilot projects in the Upper Rhine Graben and other high-enthalpy environments have demonstrated the technical feasibility of integrating direct lithium extraction (DLE) into geothermal operations, while also drawing attention to open questions associated with the "return" of chemically and thermally modified brine to the reservoir.

This study focuses on the screening and data integration required to address these questions in a structured way. A GIS database has been assembled that links geothermal plants, hard-rock critical mineral occurrences and, where available, fluid chemistry information. Five major open datasets were combined in a single GIS framework, using the same coordinate system and field structure, so that technology types, geological context and available fluid data can be mapped in a consistent way. Within this framework, representative geothermal settings where co-production is conceptually attractive can be identified, compared and ranked. The database enables cross-comparison of global plant inventories, qualitative assessment of plant–mineralization proximity (including potential scaling environments), and the identification of regions where geothermal infrastructure, metallogenic background and fluid data overlap, as well as areas where one or more of these elements are missing.

As an outlook, this spatial screening framework can be used to define candidate sites and boundary conditions for site-scale thermo-hydraulic simulations in FEFLOW, with the aim of exploring, in simplified form, how different "returned brine" scenarios may influence flow, heat extraction and pressure evolution. The emphasis of this contribution, however, is on the construction and use of the harmonized database as a transparent, reproducible basis for preliminary assessment of geothermal–CRM co-production potential and for formulating hypotheses to be tested in future numerical and experimental studies.

In the context of underground research laboratories such as GeoLaB, the screening work presented here mainly provides regional context and a way to identify representative geothermal settings for co-production. The database helps highlight where geothermal infrastructure, favorable geological background and available fluid data coincide, and where important gaps remain. This information can be used as a first step towards defining realistic scenarios and boundary conditions for future experiments and numerical models.

Imaging Granite–Metamorphic Unconformities and Structural Variability Using PSDM Seismic and Borehole Data: Implications from the Tromm Area, Germany

Amr Talaat Tolba[1]; Jens Carsten Grimmer[1]; Stefan Lüth[2]; Bastian Rudolph[1]; Fiorenza Deon[2]; Simona Pierdominici[2]; Thomas Kohl[1]; Ingo Sass[2]

[1] Karlsruhe Institute of Technology (KIT)

[2] GFZ Helmholtz Centre for Geosciences

An initial geological model for the Tromm area is constructed through the integration of wireline log data from the GeoLaB-01 and GeoLaB-02 wells with two orthogonally oriented 2D seismic profiles (E–W and N–S), acquired in 2024, and processed and imaged in both time and depth domains. The interpretation of the pre-stack depth-migrated (PSDM) seismic data, constrained by borehole information, enables delineation of the principal lithological framework and key bounding surfaces. A major regional unconformity separating upper granitic from lower metamorphic units is consistently imaged on both seismic profiles as a laterally continuous, high-amplitude reflector associated with a strong acoustic impedance contrast. This surface correlates closely with wireline log responses from both wells, characterized by an abrupt increase in gamma-ray values and P-wave velocity, and is independently confirmed by core descriptions from the GeoLaB-01 well, validating the granite–metamorphic contact.

In addition to this well-constrained boundary, the seismic data indicate possibly a second, deeper interface at the base of the metamorphic unit, separating well-imaged and relatively coherent reflector bundles on top from less coherent and partly isolated seismic reflectors below. As this boundary was not intersected by the existing wells, it needs to be considered as unconfirmed and introduces additional uncertainty to the deeper geological model (>750 m). Seismic interpretation further indicates lateral variations in the apparent thickness of the metamorphic unit, with relatively lower thickness in the northern part of the study area that increases towards the south.

Structural interpretation highlights localized seismic responses on the E–W profile suggestive of faults or ductile shear zones within the metamorphic unit, expressed by subtle reflector offsets and west-dipping reflectors. The W-dipping reflector is apparently limited to the metamorphic rocks and unlikely to continue into the granites and hence unlikely to be mapped at the surface. The absence of comparable small-scale fault responses on the N–S profile suggests a predominant N–S fault strike, rendering these structures more readily detectable on the E–W-oriented seismic line while remaining poorly resolved or invisible on the N–S section. Together, these results define an initial geological model that integrates seismic, wireline, and core data, while clearly identifying both confirmed features and key uncertainties requiring further investigation.

Long-term geophysical monitoring of fault-heating and fluid-injection processes in shale rocks at the Tournemire URL, Southern France

Rüdiger Giese[1]; Audrey Bonnelye[2]; Carolin Boese[1]; Christian Cunow[1]; Pierre Dick[3]; Roman Esefelder[4]; Tobias Förster[1]; Sven Fuchs[1]; Katrin Jaksch[1]; Grzegorz Kwiatek[4]; Stefan Lueth[1]; Ben Norden[1]; Katrin Plenkers[6]; Ingo Sass[1]; Sebastian v. Specht[1]; Arno Zang[1]; Günter Zimmermann[1]

[1] GFZ Helmholtz Centre for Geosciences

[2] Université de Lorraine

[3] Authority for Nuclear Safety and Radiation Protection (ASNR)

[4] Friedrich-Schiller-Universität Jena

[5] Free University Berlin

[6] GMuG Gesellschaft für Material-prüfung und Geophysik

The international research program CHENILLE (Coupled beHavior undErstaNdIng of faulLts: from the Laboratory to the fiEld) addresses key questions on the impact of elevated temperatures on shear zones and fault reactivation processes in shale formations. Here, we report results from a thermally controlled in situ fluid-injection experiment conducted on a strike-slip fault zone at the Tournemire Underground Research Laboratory (URL), southern France (formerly operated by IRSN). The research aims to understand the mechanical, hydraulic, structural and thermal evolution of a fault zone under coupled thermal and hydraulic loading. Key observations are derived from multiple geophysical monitoring methods, including Acoustic Emission (AE), active seismic surveys, thermal diffusion, and Distributed Temperature Sensing (DTS), to capture in situ temperature evolution and structural changes within the fault core and damage zone.

The Tournemire URL is located on the western margin of the Mesozoic Causses Basin in southwestern France. It transects an approximately 250 m thick Toarcian shale formation, bounded above and below by aquiferous limestone units. The URL is intersected by several strike-slip fault zones that played a significant role in the tectonic evolution of the Causses Basin. One of these structures is the F2 fault, where the CHENILLE experiment is being conducted. It is a well-exposed, sub-vertical strike-slip fault cutting through the Toarcian shale and has been extensively studied due to its structural and hydrogeological properties. The fault zone comprises a fault core and a fault damage zone, with a total thickness of approximately 5 to 10 m, including a clay-rich fault core up to 1.2 m thick.

The CHENILLE experiment relies on borehole-supported observation methods. DTS installed in four boreholes, 12 AE sensors are deployed in four wells, 18 boreholes host 3C-geophone receivers for active seismic recording; and two wells are equipped with 3 m long heater units. Fluid injection is performed using a double-packer probe, enabling separate stimulation of two intervals: 1.85 m within the fault core and 3.1 m within the damage zone.

Heating started in November 2023 and ended in June 2024. Temperature did not exceed more than 40°C at a distance of about 1.5 m. Three series of injection tests with gas (nitrogen and argon) and water have been carried out in June/July 2024, October/November 2024, and June/July 2025, targeting both the core and damage zone. Injection test periods were characterized by a significant increase in AE activity, with up to 1000 events per day in the fault damage zone. Persistent AE activity is also observed throughout the monitoring period in the southwest of the AE network, coinciding with a low P-wave velocity zone. Seismic tomography surveys were conducted before and after heating and the 2024 gas injection campaign. In the region extending from the injection interval to the gallery, a P wave velocity decrease of 0.1 to 0.3 km/s was observed after stimulation. Ongoing analyses will further integrate geophysical monitoring data acquired during thermal decay and in the 2025 injection tests.

A portfolio of services and developments ranging from applications in shallow to deep geothermal reservoirs extending from science to industry

Nathan Dutler[1]

[1] Solexperts AG

In this article, I provide a brief overview of projects in which Solexperts has been involved. These include design, construction, laboratory testing, on-site installation, testing and monitoring, analysis, and reporting.

In order to gain better insights into the thermo-hydro-mechanical (THM) coupling at borehole walls where breakouts can occur, a project funded by the Swiss National Science Foundation (SNSF) called "Thermally Induced Borehole Breakout Experiments" (TIBEX) was developed in collaboration with the University of Neuchâtel. The probe was successfully tested in the underground laboratory for Geosciences and Geoenergies in Bedretto (BedrettoLab) (Bröker et al. (2025)).

Also at BedrettoLab, a 14-fold multi packer system with sliding sleeves was installed in an inclined borehole to investigate the seismo-hydro-mechanical couplings and scale up the findings from the "In-Situ Stimulation and Circulation" project (Amman et al. (2018) at the Grimsel Test Site.

One development with a focus on industrial scale is Micro Turbine Drilling (MTD Geissler et al. (2023)). This method makes it possible to drill cost-effectively a few meters long small caliber deviated boreholes from an existing cased/uncased borehole in rock formations to increase permeability in cases of insufficient productivity. This is particularly useful for minimizing exploration risk. It also includes the development of a new mechanical double packer system, a shut-in tool, and a probe for real-time data acquisition, which enable hydraulic testing and/or stimulation in a single pass.

For HT-ATES Bern Forsthaus (GeoEnergieSuisse), we supplied an injection and monitoring system in a well doublet and were involved in on-site monitoring, performing various types of tests, e.g., slug tests, jacking tests, long-term injections including chemical analyses, and CO2 brine injections for acidification including water recovery and water sample analysis (Meier et al. 2025).

Last year, a deep geothermal well was successfully tested in Jura, Switzerland. This included data acquisition and monitoring of pressure and hydraulic data for hydraulic well tests before and after stimulation, as well as test stimulations.

Further developments of in-situ gas sampling probes (i.e., for dissolved H2, He, Ne, CO2, CH4, etc.) were successfully tested and implemented in a field campaign in Lorraine. Further projects may lead to the testing of shallow and deep geothermal wells to gain more insight into partial pressures of dissolved gases and saturations in natural environments and under production conditions.

Amann et al. (2018): The seismo-hydromechanical behavior during deep geothermal reservoir stimulations: open questions tackled in a decameter-scale in situ stimulation experiment. Solid Earth 9(1):115–137. https:// doi. org/ 10. 5194/se-9-115-2018

Bröker, Valley, Dutler & Steiner (2025): A novel in-situ heating probe for borehole breakout studies: First results from controlled borehole heating experiments, 23rd swiss geoscience meeting, 06.12.2025, Bern.

Geissler, Garsche, di Mare & Bracke (2023): Overview and comprehensive performance description of a new Micro Turbine Drilling – MTD technology for drilling laterlas into hard reservoir rock, IJRMMS 161: 105253.

Meier et al. (2025): An innovative approach to improve flow between wells in the heat storage project of Bern Forsthaus, Bern, European Geothermal Congress 6.-10.10.2025, Zurich

DESMEX - Evolution of semi-airborne controlled-source electromagnetics for mineral exploration and beyond

Pritam Yogeshwar[1] on behalf of the DESMEX Consortium

[1] LIAG Institute for Applied Geophysics

DESMEX (Deep Electromagnetic Sounding for Mineral Exploration) is a multidisciplinary research initiative bringing together a consortium of universities, research institutions, governmental organizations, geophysical service providers, and industrial partners. Building on more than a decade of continuous methodological and technical development, as well as various applications, DESMEX aims to bridge the gap between ground-based and fully airborne electromagnetic (EM) systems. This is achieved by combining the flexibility, resolution, and depth sensitivity of controlled-source EM techniques with the efficiency and spatial coverage of airborne surveys. Here, we present an overview of the evolution of semi-airborne controlled-source EM methods for mineral exploration and related subsurface applications, covering the complete chain from instrumentation and data acquisition to advanced processing, inversion, and real-world case studies.

In the early phases of the DESMEX project, the primary focus was on the development of novel transmitter and receiver concepts for semi-airborne EM acquisition. This included helicopter-towed receiver systems and, in subsequent stages, UAV-towed receiver platforms. These configurations enable adaptable survey geometries and allow EM measurements to be optimized for different target depths and a wide range of geological settings. Significant effort was devoted to reducing system- and motion-related noise, improving timing accuracy, and enhancing overall data quality under challenging field conditions. In parallel, natural-source methods such as audio-frequency magnetotellurics (AFMAG) were integrated to extend the depth of investigation and to support joint interpretation with controlled-source EM data.

A central component of DESMEX is the development of robust processing and numerical workflows for semi-airborne EM data. This includes advanced processing strategies and dedicated noise suppression techniques for large-scale and motion-affected datasets. Forward modeling and inversion capabilities were expanded toward realistic three-dimensional scenarios and large survey areas. More recent developments include joint inversion approaches that combine controlled-source EM, AFMAG, and complementary geophysical data sets. Together, these advances enable improved imaging and interpretation of complex, exploration-relevant subsurface targets.

In later project phases, the applicability of the DESMEX concept was demonstrated through a series of case studies conducted in Germany, across Europe, in Namibia, and at other international test sites. These examples include mineral exploration in structurally complex terrains, detailed imaging of fault and fracture systems, investigations of deep groundwater systems, and investigations of deeper targets that are difficult to resolve using conventional airborne EM methods alone. The results demonstrate the strengths of semi-airborne EM in terms of depth penetration, spatial resolution, and survey efficiency.

Overall, DESMEX establishes semi-airborne controlled-source electromagnetics as a versatile and scalable exploration technology. By combining innovative hardware concepts with advanced processing and inversion strategies, the project demonstrates clear added value for mineral exploration and provides a transferable methodological framework for related applications, including groundwater exploration, geothermal systems, and environmental investigations.

Sequential Chemo-Mechanical Phase-Field Modeling of Corrosion-Induced Cracking in Geothermal Pipes

Akash Kumar[1]; Nishant Prajapati[1]; Martin Reder[1]; Ravi Kumar Jeela[1]; Daniel Schneider[1]; Britta Nestler[1]

[1] Karlsruhe Institute of Technology (KIT)

Geothermal piping systems operate in chemically aggressive environments that promote corrosion-driven material degradation and subsequent mechanical failure. Corrosion-induced loss of structural integrity can significantly reduce the pressure-bearing capacity of geothermal pipes, posing risks to operational safety and long-term system reliability. Capturing the interaction between chemical degradation and mechanical fracture is therefore essential for predictive integrity assessment of subsurface energy infrastructure.

In this work, we present a sequential chemo-mechanical modeling framework for simulating corrosion-induced cracking in geothermal pipes. Chemical corrosion is first modeled using a grand-potential-based phase-field formulation that captures the evolution of metal–electrolyte interfaces and localized material dissolution. At selected representative stages of corrosion progression, the degraded pipe geometry is transferred to a mechanical phase-field fracture model. Internal pressure loading is then applied using a diffuse-interface approach to simulate crack initiation and propagation within the corrosion-weakened structure. All simulations are conducted at the mesoscale, enabling explicit resolution of corrosion morphology and its impact on pressure-driven fracture initiation.

The model captures key degradation mechanisms, including pitting-induced stress concentration, reduction of load-bearing capacity due to material loss, and pressure-driven crack growth originating from corrosion-damaged regions. Numerical examples demonstrate how corrosion depth and pit morphology strongly influence critical failure pressures and crack paths.

The present framework focuses on the dominant chemo-mechanical mechanisms governing corrosion-assisted failure in geothermal piping systems, providing a robust and computationally efficient tool for integrity assessment. The modular structure of the approach further enables straightforward extension toward thermal and hydraulic coupling in future multi-physics developments.

Structural and geological constraints on the subsurface geology of the Tromm area

Jens Carsten Grimmer[1]; Amr Talaat Tolba[1]; Ali Dashti[1]; Simona Pierdominici[2]; Thomas Kohl[1]

[1] Karlsruhe Institute of Technology (KIT)

[2] GFZ Helmholtz Centre for Geosciences

The two exploration boreholes GLB-01 and GLB-02 intersected a subhorizontal interface occurring between 405 m and 415 m below surface, separating an upper unit of granitic rocks in the hanging wall and a lower unit of metamorphic rocks in the footwall. This interface constitutes a seismic reflector documented in two orthogonally oriented 2D-seismic lines. Within the upper unit granites, at 238±6 m below surface a distinct shallowly N-ward dipping, c. 12 m thick mylonitic-cataclastic shear zone is present with a c. 1.6 m thick (ultra?) mylonitic core zone topped by cataclastic breccia and an apparent gradual transition into breccias below. This shear zone is not yet readily documented as seismic reflector. Quartz ribbons and relic rotated feldspar ?-clasts with distinct recrystallization tails, intensively sericitised, within a fine-grained mica-rich matrix indicate a subsolidus intra-granite ductile shearzone and syn- to post-kinematic fluid-rock interaction.

The interface at 405-415 m outlines a c. 10 m thick subhorizontal mylonitic-cataclastic foliation and coincides with the seismic reflector observed in both, the E-W and N-S trending 2D-seismic lines corroborating its generally planar geometry. Subhorizontal to shallow foliations are documented in OPTV data from both boreholes. The drilled metamorphic rocks are interpreted to represent part of the Weinheim–Waldmichelbach Unit (formerly: 'Schollenagglomerat'), exposed >2 km SSW of the drill site. The intersected subhorizontal interface is in marked contrast to variably dipping foliations in the boreholes beneath the interface and the metamorphic rocks in the area. While these rocks crop out at elevations of 300–400 m above sea level, c. 2 km SSW of the boreholes, the top of the metamorphic complex was intersected at c. 150 m above sea level. This marked contrast strongly indicates either a c. 15° structural plunge towards NNE or a fault-controlled, stepwise downthrow of the metamorphic rocks beneath the Tromm pluton, highlighting the complex subsurface architecture of the region.

Discrete Fracture Network Modeling Based on Borehole Image Log: Case Study of the GeoLaB

Rahim Habibi[1]; Ali Dashti[1]; Jens Carsten Grimmer[1]; Simona Pierdominici[2]; Thomas Kohl[1]

[1] Karlsruhe Institute of Technology (KIT)

[2] GFZ Helmholtz Centre for Geosciences

Discrete Fracture Network (DFN) modeling has become a crucial tool for characterizing fluid flow and transport in fractured geothermal reservoirs, where fractures often dominate hydraulic behavior, while the rock matrix plays a secondary role. Reliable DFN models require both robust statistical descriptions of fracture properties and direct constraints from field observations. In this contribution, we present a DFN-based hydraulic modeling study developed within the framework of the GeoLaB project, focusing on the GLB01 borehole located in the Odenwald region of southwest Germany.

The GeoLaB project aims to improve the understanding of fracture-controlled processes in crystalline rock formations through the integration of geological, geophysical, and hydraulic data. In this study, borehole image log data from the Acoustic Borehole Imager (ABI) acquired in the GLB01 well are used to derive key fracture characteristics, including orientation, spacing, and aperture-related indicators. These fracture features are first explicitly represented along the wellbore, ensuring that the DFN model is directly conditioned to observed subsurface data.

To extend the fracture information from the borehole into the surrounding rock volume, a stochastic DFN generation approach is employed. The spatial distribution of fractures is governed by a Fisher distribution, which preserves the dominant fracture orientations observed in the ABI logs while allowing for natural variability at the reservoir scale. This approach enables the construction of a three-dimensional DFN that is statistically consistent with borehole observations and representative of the fractured crystalline system.

The hydraulic response of the resulting DFN model is investigated through numerical fluid injection simulations. The results demonstrate that fluid flow is strongly controlled by fracture connectivity, orientation, and density, leading to pronounced channeling effects and heterogeneous pressure propagation. The simulations highlight the critical role of fracture networks in governing reservoir-scale hydraulic behavior and emphasize the importance of data-constrained DFN models for geothermal reservoir characterization and stimulation planning. This study illustrates how borehole log data can be effectively integrated into DFN modeling workflows to improve predictions of fluid flow in fractured geothermal systems.

Phase-Field Modeling of Hydro-Thermal Processes in Geothermal Fractures

Fabian Epp[1]; Nishant Prajapati[1]; Martin Reder[1]; Akash Kumar[1]; Britta Nestler[1]

[1] Karlsruhe Institute of Technology (KIT)

Geothermal technologies are gaining importance as dependable, carbon-neutral energy solutions that support both climate protection and the stability of energy supply. To evaluate reservoir behavior, it is crucial to perform accurate continuum-scale and multiphysics numerical simulations of interacting fluid flow and heat transfer in fractured systems. The phase-field based diffuse interface method offers a strong alternative to conventional sharp interface formulations. Since it avoids the need for explicit interface tracking, it enables efficient numerical treatment of topological changes and simplifies the coupling of physical processes, making it especially well suited for the numerical analysis of geothermal reservoirs.

In this study, we examine laminar fluid flow and heat transfer in a parallel plate channel configuration at millimeter-scale to account for surface roughness effects. The fluid is represented as Newtonian, and momentum transport is governed by the incompressible Navier-Stokes equations, while heat transport is described by a convection-diffusion equation. With constant material properties, the coupling between flow and thermal transport is one-way. Within the diffuse interface approach, two corrections are proposed to increase the physical consistency of fluid flow and heat transfer at interfaces. In the flow formulation, a dissipative contribution is incorporated into the momentum equations to ensure no-slip behavior at fluid-solid interfaces. In the thermal model, a heat flux formulation that depends on the local interface orientation is introduced to consistently enforce thermal jump conditions across diffuse interfaces.

These methodological developments were implemented in the in-house finite-difference solver Pace3D, and both approaches were quantitatively validated against analytical solutions. In both validation cases, typical errors remain below 1%, demonstrating the robustness and accuracy of the methods. The modeling approach is further applied to realistic fracture geometries generated via a spectral synthesis method, demonstrating the diffuse interface model's ability to capture complex flow and thermal behavior. These results highlight its potential for application in geothermal reservoirs under diverse conditions and provide a solid foundation for future studies of coupled subsurface processes.

Geothermal Energy as a Strategic Domestic Resource for Germany and the Enabling Role of Enhanced Geothermal Systems (EGS)

Fabian Uth[1]

[1] Technical University of Munich

In the context of increasing geopolitical tensions, volatile energy markets, and the urgency of achieving climate targets, the secure and sustainable supply of energy has become a matter of strategic importance. Germany remains highly dependent on energy imports, exposing its economy and infrastructure to external risks while simultaneously pursuing ambitious climate neutrality goals. Strengthening domestic energy resources is therefore essential for enhancing resilience, reducing dependencies, and ensuring energy security.

Geothermal energy offers a combination of advantages among renewable energy sources, it is locally available, weather-independent, land-efficient, and capable of providing continuous heat and power. In Germany conventional hydrothermal resources are geographically limited, with most existing projects concentrated in specific regions such as the Bavarian Molasse Basin and Upper Rhine Graben. As a result, many cities currently lack access to geothermal energy despite substantial heat demand and suitable subsurface temperatures at depth.

Enhanced Geothermal Systems (EGS) have the potential to change this situation. By enabling the extraction of heat from low-permeability formations through advanced drilling, stimulation, and reservoir engineering techniques, EGS can expand the accessible geothermal resource beyond naturally permeable reservoirs. This opens the possibility of producing geothermal energy in regions previously considered unsuitable, thereby transforming geothermal energy from a regional option into a nationwide strategic resource.

The contribution highlights the importance of underground research infrastructures, pilot projects, and technological innovation in reducing uncertainties, improving performance, and enabling scalable deployment. In view of Germany's high heat demand, the need to decarbonize energy supply, limited hydrothermal resources, and continued reliance on energy imports, accelerating the development of geothermal energy, particularly Enhanced Geothermal Systems is becoming increasingly important for enabling a resilient energy supply based on domestic resources.

Integrated structure-based inversion of geophysical data for improved site characterization

Andrea Balza Morales[1]; Florian Wellmann[1]; Florian M. Wagner[1]

[1] RWTH Aachen University

Underground research laboratories are essential for advancing safe and robust subsurface technologies, as they enable controlled investigation of coupled processes where accurate structural characterization is critical due to the strong influence of geological heterogeneity on fluid flow and mechanical stability. Long-term radioactive waste storage requires a well constrained and geologically consistent characterization of the host formation. The Mont Terri Underground Research Laboratory (MTRL) in Switzerland represents one of the most comprehensively instrumented facilities worldwide for this purpose. Located within the Opalinus Clay, MTRL serves as a test site for repository-relevant investigations in a low-permeability formation. Within the Carbon Sequestration series D and E (CS-D and CS-E) experiments, a borehole network combined with time-lapse geophysical monitoring was deployed to assess the integrity of a structurally complex zone embedded within the host rock. This site provides an illustrative example of how geophysical methods can be used not only for monitoring, but also for detailed structural characterization in underground laboratory environments.

To address structural uncertainty in such contexts, we present a joint structure-based inversion framework in which multiple geophysical data sets simultaneously update a shared structural geologic model (geomodel). Structure-based inversion with implicit geological modelling directly updates subsurface interfaces, producing sharper and more geologically consistent images than voxel-based approaches, reducing uncertainty at boundaries, and simultaneously recovering the physical property contrasts within the defined geometric bodies. In the joint approach, complementary geophysical data sets such as seismic travel-time tomography and electrical resistivity tomography refines geological boundaries toward a structurally consistent solution. After each geometry update, region-wise homogeneous property inversions preserve method-specific contrasts. A final heterogeneous inversion resolves spatial property variations once the geometry converges.

The workflow was evaluated using a synthetic case study that reproduces the experimental configuration of two boreholes intersecting a faulted clay sequence. Starting from a simplified initial geometry, the inversion attempts to reconstruct the structural configuration and thereby assesses whether the acquisition layout provides sufficient sensitivity for reliable geometric recovery. Results indicate that joint structural updating improves geometric consistency and convergence behavior compared to independent inversions.

A defining feature of this approach is its implementation within open-source scientific software, enabling flexible coupling between implicit geological modelling tools and modular geophysical inversion frameworks. This ensures transparency, reproducibility, and adaptability to site-specific conditions without reliance on proprietary constraints. Although demonstrated at MTRL as an example in a clay-rich repository context, the methodology is transferable to crystalline basement investigations and geothermal research infrastructures. By enabling structurally consistent modelling, and uncertainty-aware interpretation, the framework provides a robust basis for informing the planning and experimental design of future underground laboratories, including GeoLaB.

Effects of preexisting fractures on earthquake precursory behavior

Taka Kanaya[1]

[1] Technical University of Darmstadt

The physics underlying earthquake precursory phenomena remains poorly constrained, particularly in crustal materials and reservoir rocks containing long preexisting fractures. We conduct axial compression experiments on pre-heated Fontainebleau sandstone with acoustic emission (AE) monitoring under confining and pore pressures of 30 and 5 MPa, respectively. Preliminary results show no systematic differences in precursory AE behavior between pre-heated and as-is samples. All samples exhibit b values between 0 and 1, with a wide range of overall b-value evolution toward failure, including both increasing and decreasing trends. Despite this variability, many samples show a local decrease in b value immediately before and during failure, preceded by a local increase near peak stress. These local b-value variations likely reflect distinct microfracturing processes in porous granular rocks, contrasting with the more monotonic b-value decrease commonly reported for crystalline rocks. Our results suggest that subtle differences in initial granular microstructure promote diverse precursory behavior under otherwise identical experimental conditions. Such variability may contribute to the range of precursory behavior observed in tectonic earthquakes, where many large events are not preceded by a decrease in b value. To investigate the role of aseismic deformation in fault nucleation, we are currently quantifying the evolution of microfracture distributions in deformed samples. These experiments constrain the evolution of seismic and aseismic precursory signals toward large earthquakes in highly fractured crust. In parallel, we are investigating precursory AE behavior in samples deformed under constant axial (tectonic) stress, but with increasing pore pressure. The latter experiments are aimed to understand the physics underlining the evolution of induced seismicity sequences in geothermal settings.

Mechanical Stiffness and Permeability of a Reservoir-Scale Rough Fracture During Closure

Jean Schmittbuhl[1], Qingling Deng[1], Mauro Cacace[3] and Guido Blöcher[3]

[1] University of Strasbourg
[2] Chongqing University
[3] GFZ Helmholtz Centre for Geosciences

Natural or artificial fluid flow in deep fractured reservoirs, such as enhanced geothermal systems (EGS), is primarily controlled by open fractures and faults, and is considered a key element for hydraulic performance. On the one hand, flow along these fractures is strongly affected by channeling between fracture asperities and fracture sealing along the open fracture space. On the other hand, fracture asperities and fracture seals also impact the mechanical behavior of fractures, especially their mechanical stiffness. Here, we study how the stiffness and the permeability of a realistic rough fracture at the field scale are linked and evolve during its closure. We show that the mechanical stiffness is exponentially increasing when the fracture permeability is decreasing. Moreover, this stiffness-permeability law is unique both during the mechanical and the chemical closure, being strongly related to the effective contact area along the fracture. The results have implications for large scale assessment of hydraulic properties of fractures and fractured reservoir stimulation.

Normal stress pulse during fluid-driven seismicity migration

Kamal Ahmadov[1], Jean Schmittbuhl[1], Thibault Candela[2]

[1] University of Strasbourg
[2] TNO, Geological Survey of the Netherlands

Fluid-injection–induced seismic swarms commonly migrate following a power-law relationship in time. While classical models predict square-root-of-time migration consistent with fluid diffusion, recent field observations show time exponents that deviate from 1/2 at several injection sites, suggesting additional controlling mechanisms.

Fractures play a central role in fluid flow and seismicity migration during injection operations. Here, we investigate fluid-driven reopening of a preexisting fracture when significant fracture deformation occurs, a process with important implications for the initiation and propagation of induced seismicity. We compare semi-analytical solutions for pressure propagation in a deformable fracture with numerical simulations using the Distinct Element Method (DEM) implemented in 3DEC (ITASCA). We examine the influence of injection conditions, including constant-pressure and constant-rate scenarios.

For low fracture stiffness, a sharp pressure front attached to a tensional stress pulse emerges. Under constant-pressure injection, this pulse propagates with square-root-of-time scaling, mimicking a pseudo-diffusive process, with slower migration as stiffness decreases. In contrast, constantrate injection produces tensile stress peak migration with time exponents greater than 1/2. Increasing the injection rate further raises the exponent, approaching quasi-linear propagation.

These results provide a mechanical explanation for the non-diffusive migration patterns observed at several fluid-injection sites and highlight the critical role of fracture deformability and injection protocol in controlling induced seismicity migration.

Water-glass-based injection materials for the application in crystalline rock environments

Philipp Herold[1], Holger Schmidt[1], Andreas Keller[1], Ulrich Kelka[1], Elzbieta Schmeidel[1], Hannes Räuschel[1]
[1] BGE TECHNOLOGY GmbH

The project PRECODE (Investigation of the effects of deep underground mining activities on the integrity of crystalline rock in the context of the disposal of high-level radioactive waste) is funded by BGE mbH and carried out by RWTH Aachen University (Chair of Engineering Geology and Hydrogeology) and BGE TECHNOLOGY GmbH in cooperation with the Bedretto Underground Laboratory in Switzerland. The project has three main research objectives related to assessing the suitability of crystalline rock as a host rock for the disposal of high-level radioactive waste. First, it aims to develop an improved understanding of the formation and evolution of excavation-induced damage zones. Second, methods are being tested to create natural-like fracture fillings through fluid injections in order to reduce rock permeability. Third, numerical methods are being developed to quantify the dilatancy and fluid-pressure criteria in crystalline host rock. This contribution focuses on the objective concerning the testing of injection methods.

In addition to the classic fields of applying injections in mining and tunneling, there are more specific use cases in nuclear waste repositories, such as the stabilization of excavation-damaged rock zones around sealing structures. The injection agents used must meet a set of different requirements. Chemical and mechanical stability over very long periods is of particular importance. The use of water-glass-based mixtures offers a significant advantage over cement-based injection materials or polyurethane resins and their derivatives. Suitable media for application in rock salt have already been patented by BGE TECHNOLOGY GmbH. Injection technology is routinely applied, but it must be adapted to the characteristics of other rock types, such as crystalline rock. For this purpose, a range of injection materials for use in crystalline formations was developed and tested. These materials include particle-free and particle-supported water-glass-based formulations as well as geopolymers. The evaluation of laboratory, pilot-scale, and in-situ tests shows that the injection materials are, in principle, suitable for application in the considered host rock.

Based on the laboratory program, six reference mixtures (three particle-free and three particle-supported) were identified and further tested. For the in-situ test, three injection materials were selected: a particle-free soft gel and two particle-supported formulations containing silica slurry and fly ash. As part of the in-situ experiments, six injection phases were carried out in two boreholes. In each case, a hydraulic path developed within the rock. Continuous recording of pressure and flow data, as well as analysis of pressure-drop phases, allowed robust hydraulic parameters to be determined. The injectivity index varied depending on the formulation used and provided valuable insights into the dynamic absorption capacity of the rock. It was demonstrated that the developed process chain, consisting of material development, technical implementation, and assessment procedures, can be applied in practice and enables homogeneous, dense filling of fractures under realistic boundary conditions.

The developed injection materials can be used for various applications. The primary goal is the local improvement of rock zones. At the same time, the materials can also be used for borehole sealing or for positioning sensors (e.g., for monitoring in a repository or long-term observation of experiments).

How Does High-Quality Multi-Level Communication for the GeoLaB Underground Laboratory matter?

Alessa Auerswald[1], Regina Schwald[1], Judith Bremer[1]

[1] Karlsruhe Institute of Technology (KIT)

GeoLaB is a planned underground laboratory that is currently in the exploration phase. Its framework conditions are complex and involve a wide range of stakeholders, making the project highly interdisciplinary. Natural- and engineering sciences intersect with the social sciences and humanities (SSH): while technology development is driven primarily by the former, infrastructure planning directly impacts local communities and the wider public. Consequently, the involvement of SSH is essential to assess societal implications and to guide stakeholder engagement.

This contribution (1) clarifies the role of SSH in GeoLaB, (2) argues that comprehensive, high-quality communication is a cornerstone of public acceptability and responsible research, and (3) presents how the GeoLaB Communications Group operationalizes these principles in practice.

Drawing on our experiences in the exploration phase, I will discuss the challenges that arise when developing a complex research infrastructure that affects the public. These challenges highlight the indispensable role of SSH.

To explore why communication is utterly important in complex research projects such as GeoLaB, I will first argue that communication is decisive for public acceptability of geothermal research and technology and is therefore essential for the success of the project. Beyond fostering social acceptance, structured and reflexive communication practices also contribute to responsible research by integrating societal concerns and promoting dialogue-oriented engagement.

Finally, I will outline how the GeoLaB Communications Group defines its role within the project and implements a comprehensive communication strategy. In order to achieve public acceptability and contribute to responsible research practices, we focus on a multi-level information campaign, including different social media platforms, analogue measures such as informational flyers and most importantly the direct engagement with affected citizens at markets and similar events. Additionally, future participatory research formats are currently being developed and will play a key role in the communication concept as well as within the broader GeoLaB research design. Through these measures, communication becomes a structural component of responsible research practice rather than a merely supportive function.

The TOUGH Project: Decameter-Scale In-Situ Experiment on THMC-Coupled Processes in Fractured Geothermal Reservoirs at the Grimsel Test Site

Timo Seemann[1], Mohammadreza Jalali[1], Mostafa Hajzaman[1], Shadi Fathi[1], Grzegorz Kwiatek[2], Florian Amann[1,3]

[1] RWTH Aachen University
[2] Gesellschaft für Materialprüfung und Geophysik mbH, Bad Nauheim
[3] Fraunhofer Research Institution for Energy Infrastructures and Geothermal Systems IEG, Aachen

In this contribution, we present an overview of the "TOUGH" project, which investigates coupled thermo–hydro–mechanical–chemical (THMC) processes during non-isothermal fluid circulation in deep geothermal reservoirs hosted in naturally fractured crystalline rock.

TOUGH integrates high-resolution in situ experimentation with coupled THMC numerical modelling to quantify dominant processes and upscale them toward predictive reservoir-scale behavior. Centered on controlled non-isothermal circulation, the project addresses key research questions related to the sustainable use of geothermal resources. These include: (i) the role of poro- and thermoelastic stress transfer in controlling the spatial and temporal distribution of induced seismicity in the near and far field; (ii) the transient impact of non-isothermal fluid circulation on flow channelization, hydraulic short-circuiting, swept reservoir volume, and early thermal breakthrough; and (iii) the effectiveness of intervention strategies to mitigate progressive reservoir cooling and sustain long-term energy yield.

The in-situ experiment will be conducted at the Grimsel Test Site (Switzerland), within a natural, well-characterized fracture zone in the "BK niche", where two years of non-isothermal fluid circulation are planned. The experimental design aims to bridge the scale gap between laboratory investigations and black box field-scale reservoir operations by enabling high-resolution monitoring over a straight-line circulation distance of approximately 35 m. The fracture zone hosts 19 instrumented boreholes forming a dense monitoring network comprising: (i) distributed fiber-optic sensing for continuous temperature and strain measurements (11 boreholes); (ii) an active seismic monitoring system with 16 acoustic emission sensors and a transmitter (5 boreholes); and (iii) a hydro-chemical monitoring network (8 boreholes) enabling hydraulic and thermo-tracer testing.

By combining controlled in-situ experimentation with process-based numerical modelling, TOUGH aims to provide a framework to quantitatively resolve coupled THMC processes and reduce uncertainties in the prediction and management of geothermal reservoirs.