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RockBlockEx - A laboratory scale hydraulic fracturing experiment at differential stress of up to 20 MPa

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ABSTRACT

Understanding the relationship between fracture initiation and propagation, induced seismicity and fluid flow is crucial for geothermal reservoir engineering, as these processes are closely linked to the production of the reservoir. Previous experiments at the 10-1,000 m scale have revealed key concepts for managing induced seismicity and enhancing permeability (Schill et al., 2017; Zang et al., 2017). RockBlockEx, a new laboratory half-meter scale experiment, allows hydraulic fracturing experiments at realistic differential stress. This setup allows 3D localization of fracture-related processes through a dense distribution of sensors.

The apparatus consists of an exchangeable rock block integrated into a stainless-steel frame that applies differential confinement pressure from three directions through flat jacks. An injection well and up to four production wells can be drilled into the rock block. Sensors monitor pressure, temperature, acoustic emissions and self-potential (SP) signals. Additionally, fiber optic cables can be installed. Besides hydromechanical interaction, RockBlockEx is designed to investigate SP response to hydraulic fracturing. Previous studies have shown correlations of SP with pressure drop and SP during fracturing and circulation phases at lab scale (Hu et al., 2020), with induced seismicity during injection and during shut-in phases at reservoir scale (Marquis et al., 2002), as well as poroelastic response to hydraulic fracturing at underground laboratory scale (Haaf et al., subm.). RockBlockEx allows for investigating such effects under controlled laboratory conditions and repeatable.

1. INTRODUCTION

Hydraulic fracturing plays a pivotal role in enhancing geothermal reservoirs by increasing rock permeability and enabling fluid flow. Enhanced Geothermal Systems (EGS), particularly in crystalline rocks, rely on this technique to achieve the flow rates required for efficient geothermal energy production. However, optimizing hydraulic fracturing remains challenging due to the complex interactions between fracture propagation, induced seismicity, and fluid dynamics.

The RockBlockEx project addresses these challenges through a laboratory-scale experiment designed to simulate realistic reservoir conditions. The apparatus incorporates a modular design and advanced sensor technology to enable precise monitoring of fracture initiation and propagation. By bridging the gap between small-scale laboratory studies and field-scale applications, RockBlockEx contributes to a deeper understanding of hydraulic fracturing processes, ultimately improving the safety and efficiency of geothermal energy extraction.

A distinctive feature of RockBlockEx is its ability to investigate self-potential (SP) responses during hydraulic fracturing. Previous studies have shown correlations of SP with pressure drops during fracturing and circulation phases at the lab scale (Hu et al., 2020), with induced seismicity during injection and shut-in phases at the reservoir scale (Marquis et al., 2002), and with poroelastic responses at the underground laboratory scale (Haaf et al., subm.). RockBlockEx allows for investigating these effects under controlled, repeatable laboratory conditions, contributing valuable insights into fracture monitoring and risk mitigation.

The primary objectives of RockBlockEx are to analyze fracture initiation and propagation under realistic differential stress conditions, evaluate the correlation between acoustic emissions (AE), self-potential (SP) signals, and fracture growth, validate SP monitoring as a predictive tool for induced seismicity, and generate high-resolution datasets for calibrating numerical reservoir models. These objectives aim to enhance understanding of fracture dynamics and improve hydraulic fracturing protocols for geothermal applications.

2. METHODOLOGY AND EXPERIMENTAL DESIGN

The RockBlockEx project addresses the challenges of fracture initiation and propagation by developing an innovative laboratory-scale experimental framework. This setup enables controlled hydraulic fracturing of crystalline rock to systematically investigate the fundamental mechanisms governing fracture behavior. The findings from these experiments aim to pave the way for more efficient and environmentally sustainable geothermal resource utilization.

A distinctive feature of RockBlockEx is its ability to maintain fractures open after initiation, allowing long-term observation of fracture dynamics. The modular experimental frame incorporates an exchangeable rock block within a stainless-steel casing, which applies differential confinement pressures—up to 20 MPa—from three directions using flat jacks (see Fig. 2-1). This design replicates realistic subsurface stress conditions. The rock block can accommodate one injection borehole and up to four production boreholes, supporting diverse experimental configurations.

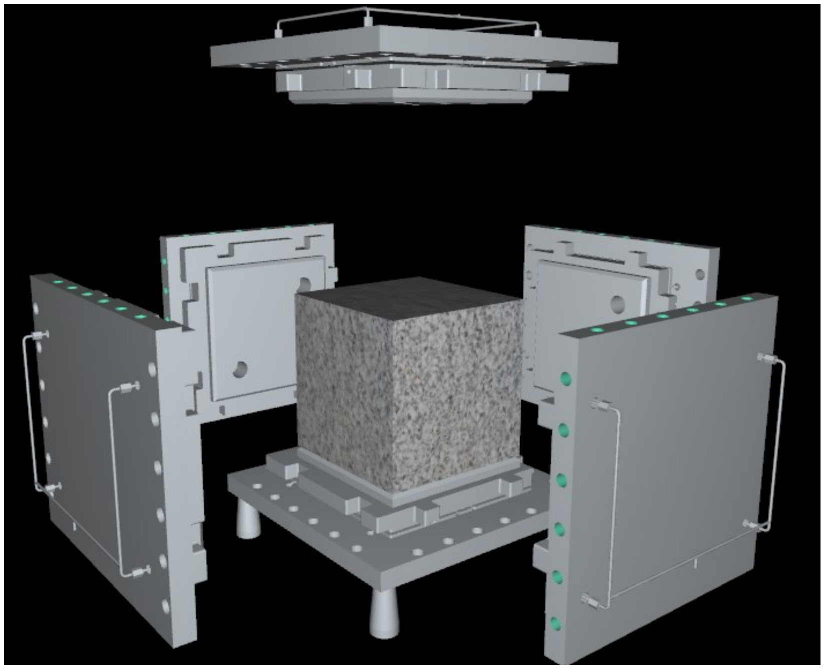

Figure 2-1: Schematic of the RockBlockEx setup, illustrating the modular stainless-steel frame and the flat jack system applying differential pressure to the exchangeable rock block.

Key features of RockBlockEx include:

- Injection and Production Wells: One injection well and up to four production wells drilled into the rock block for versatile testing scenarios.
- Acoustic Emissions (AE): The sensors are Nano30, 300 KHz mini sensor with one meter side cable with Tone burst preamplifier with 40 dB gain, 4-meter BNC/SMB Preamplifier Cable at a Eight Channel Acoustic Emission System Card from Physical Acoustic Corporation.
- Self-Potential (SP) Signals: The Ag/AgCl electrode consists of a thin Ag/AgCl semiconductor pellet with a silver thread attached to the back manufactured by GeoGurk.
- Pressure sensors: Manufactured by Keller.
- Temperature Sensors: Manufactured by Campbell Scientific.
- Syringe pump: The Teledyne ISCO 500D syringe pump offers flow rates from 1µl/min - 204 ml/min and pressures up to 259 bar.
- Additionally, fiber optic cables can be installed.

The integration of these advanced monitoring systems allows RockBlockEx to serve as a controlled environment for testing hypotheses and developing predictive models that can enhance geothermal reservoir management and reduce seismic risks. Fig. 2.2 shows the detailed installation of the sensors.

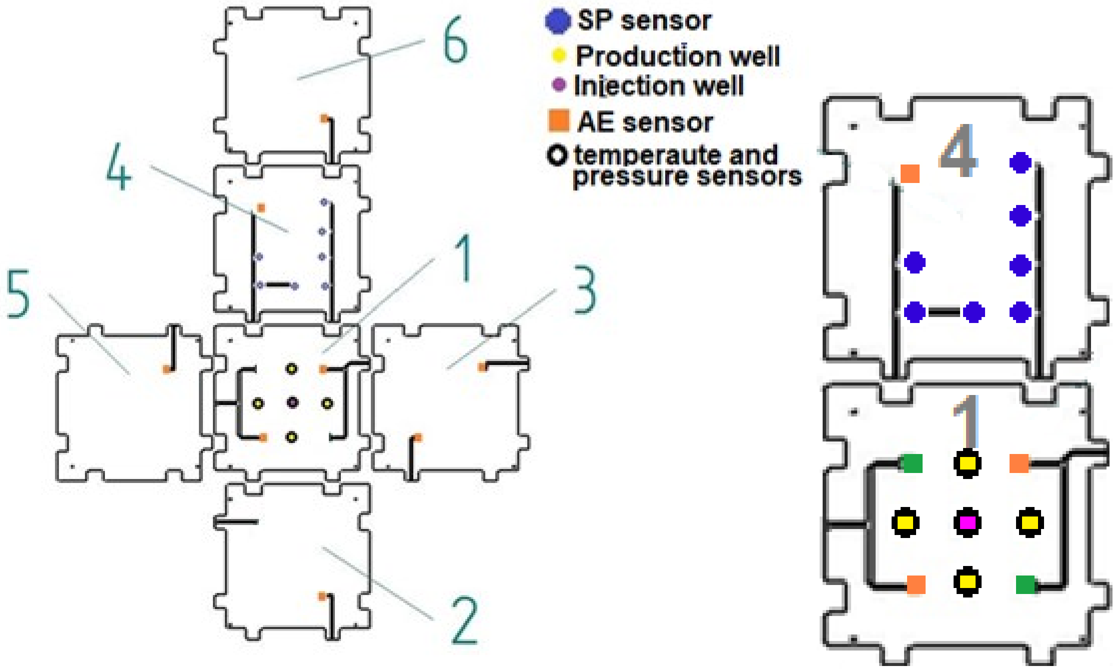

Figure 2-2: Detailed sensor layout showing the integration of acoustic emissions (AE), self-potential (SP) signals, pressure, and temperature sensors for comprehensive 4D monitoring.

3. INNOVATIVE FEATURES OF THE ROCKBLOCKEX SETUP

The RockBlockEx setup integrates a novel flat jack system designed to simulate realistic geothermal reservoir conditions. Pressure is applied to the rock sample from all six sides, closely replicating in-situ stress environments. Developed and provided by GGB GmbH, these flat jacks consist of hydraulic cushions welded between stainless steel plates. They can be filled with hydraulic fluid and operated at pressures up to 200 bar—double the capacity of previous experiments. This capability allows for the simulation of extreme stress conditions and enables detailed study of fracture initiation and propagation. In addition to replicating reservoir stress conditions, RockBlockEx enables detailed fluid flow experiments to study transport dynamics within fractured media. This dual functionality allows for a more comprehensive understanding of both mechanical fracturing and subsequent fluid circulation.

Beyond fracture formation, RockBlockEx supports fluid flow experiments, enabling investigation into fluid transport and circulation processes within fractured rock. This dual capability broadens the project's scope and provides critical insights into improving the efficiency and sustainability of geothermal energy extraction. To build on initial experimental results, RockBlockEx will expand its research by incorporating a variety of rock types that reflect realistic geothermal reservoir conditions.

Future experimental phases will focus on testing different rock types to represent diverse geothermal environments.

- Granite will be used in the initial experiments to replicate typical deep geothermal conditions.
- Basalt has been identified as a priority due to findings from the RN-15/IDDP-2 well, where magnetotelluric (MT) results revealed a shift to higher frequencies requiring further analysis.
- Porous sandstone will serve as a preliminary material for the DeepStor scientific infrastructure project at KIT.

Additionally, future experiments will be complemented by numerical modeling to interpret the mechanical, hydraulic, and hydro-mechanical contributions to observed signals. This integrated approach will help refine monitoring strategies and improve predictive models for managing induced seismicity and fracture behavior in geothermal reservoirs.

4. 3D SCAN GRANIT BLOCK

The granite block used for this experiment was scanned to detect and localize cracks that could affect the hydraulic fracturing process. The cube-shaped granite block, with a side length of 0.44 m, was subjected to non-destructive phased-array ultrasound testing. Initially, a high-frequency longitudinal wave phased-array system operating at 2.25 MHz was tested but was found ineffective due to insufficient wave penetration. Subsequently, the Proceq Pundit PD8000 system was employed, which operates with low-frequency (65 kHz) shear waves. This system allowed for deeper wave penetration and better visualization of cracks due to its longer wavelength.

The scanning process utilized eight-channel pulse-echo ultrasound data collection in a reduced Full Matrix Capture (FMC) mode. Each channel employed three transmitters and receivers to capture detailed acoustic data. To achieve high-resolution measurements, the scanning was performed in the near field with a step size of 2 cm. The data were processed using the Synthetic Aperture Focusing Technique (SAFT), which provided enhanced reconstruction by focusing on every point in the measurement area. This technique was further refined using the Pundit Vision software and Kassel Collection software, specifically tailored for cubic geometries.

Each of the five accessible sides (top. left, right, front and back) of the granite block was scanned in three overlapping stripes, resulting in detailed 3D reconstructions. These reconstructions were aligned according to the cube's geometry and combined to produce an integrated visualization of the cracks. The phased-array shear-wave ultrasound scans successfully localized surface and subsurface cracks within the granite block. Key findings include:

- **Top in red**: Cracks extending to neighboring sides left and right were detected.
- **right green**: A prominent surface crack was observed, along with subsurface extensions to the bottom side.
- **left blue**: Cracks were identified both on the surface and at the intersection with the back side.
- **front mint:**: Scans conducted at 25 kHz provided better depth penetration, revealing cracks at greater depths but with lower resolution.
- **back magenta**: Subsurface cracks were detected extending beneath the top side.

Iso-surfaces generated from the combined scans highlighted reflective features corresponding to cracks and material discontinuities. The method revealed that the cracks often contained abrasive materials, leading to reduced resolution in some regions. Nonetheless, the integrated 3D visualization provided a comprehensive understanding of the crack network within the granite block as shown in Fig. 4.1

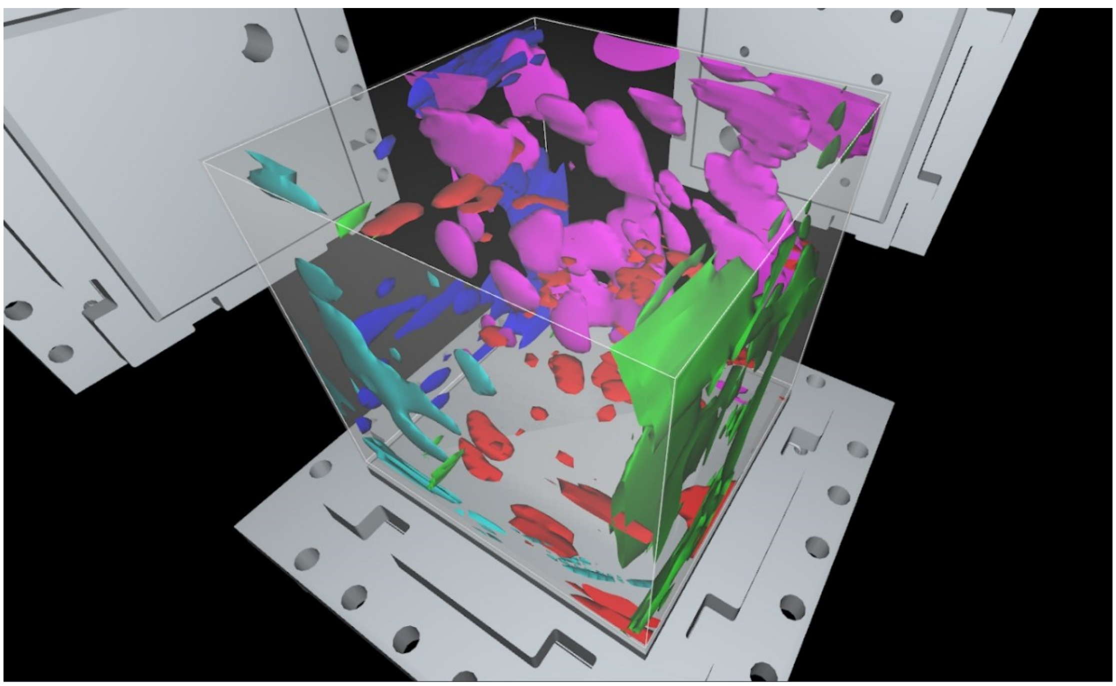

Figure 4-1: 3D reconstruction of crack networks within the granite block, showing localized surface and subsurface fractures as identified through phased-array shear-wave ultrasound and SAFT processing.

The large iso-surfaces at the edge represent the backwall echo of the corresponding studied side of the granite. Figure 4.2 gives a detailed overview of the front, back and top view scans.

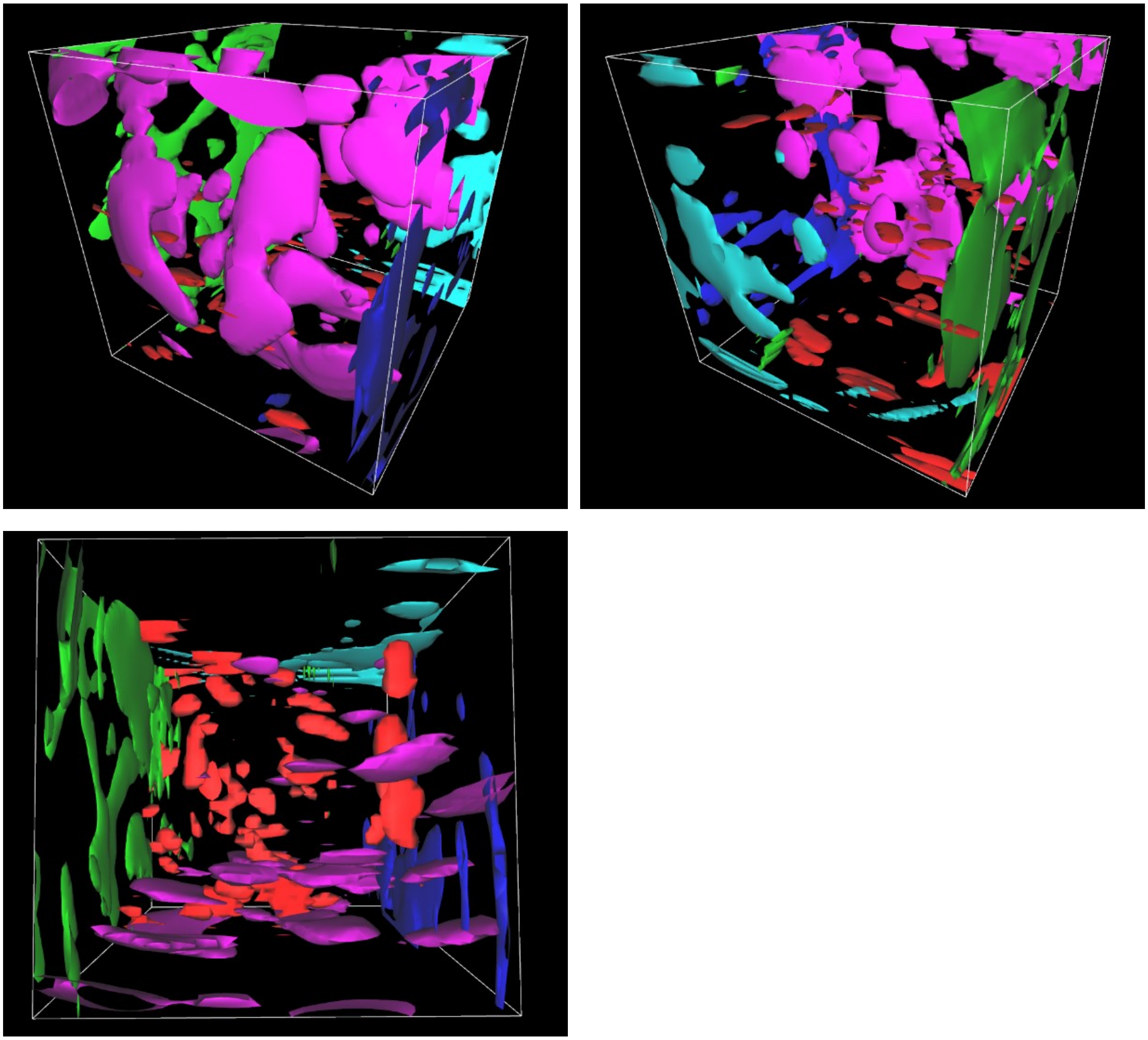

Figure 4-2: Detailed overview of the scans with a front, a back and a top view.

5. VISUALIZATION

The goals of the visualization are first to virtualize the entire experimental setup, hardware, sensors, systems and measurements, and then to serve as a basis for monitoring the experiment while it is running. The system should also provide feedback for efficient real-time control of the experiment. In short, the goal is to be able to see the fracking process, understand its behavior when the control parameters are changed, control the fracking process, and ultimately gain a complete understanding of the fracking experiment. In order to monitor the fracking process, it is necessary to provide real-time online visualization based on sensor data to give direct feedback on any changes in the rock. The data stream is realized using UDP to avoid network communication delays. An additional TCP communication runs in parallel to avoid any data loss, this is important to ensure that all events are recorded and stored as the rock deformations are not reversible and therefore the process is not easily repeatable as it would require a new rock block, therefore each measurement must be recorded without loss to maximize the return on investment.

Sensors that measure the electrical self-potential in the rock between one electrode and the reference electrode each provide a scalar value. Seven of these electrodes provide such an electrical self-potential on one side of the rock block. These values are visualized in real time to analyses the effects of fracking on the electrical self-potential. In particular, the flow rate and electrochemical properties of the injected fluid are expected to have an effect. The output of the acoustic sensors is a time series, around 300 kHz. The streams must be segmented to detect acoustic events. These are mapped over the different streams to obtain a 3D position for each event using triangulation. The result is a sparse 3D point cloud. The segmented events are processed in real time to create a more intuitive visualization of the changes in the rock. Spatial structures such as voxels and octrees are used to integrate the data and then generate a triangular mesh. The most recent events are highlighted and visually faded out over time, and a persistent model is continuously generated based on all recorded events to hopefully create a model that indicates the extent of the fracture in the rock. This will allow the fracture to be monitored in real time, showing where in the rock the fracture is active as pressure, flow rate or temperature changes. In addition to the acoustic signals, temperature and pressure are measured in each borehole. These are also visualized in real time to provide feedback on the effects of varying pressure and temperature at the pump. All these measurements should contribute to a more complete model of the seismic events, real-time deformation and permanent changes in geometry and topology within the rock.

The visualization of the sensor streams is realized in an interactive real-time 3D system. This allows the visualization to be tuned to optimize the overall understanding of the dynamic changes in the rock. The underlying system of the visualization is an open-source 3D engine called PolyVR, designed for virtual engineering applications. Its strengths are its great flexibility and ease of use to quickly develop 3D interactive and immersive applications ("GitHub - Victor-Haefner/polyvr," n.d.). Especially important are the built-in modules and methods for visualization, simulation and interfaces for data exchange, as well as network communication. Figure 5-1 shows a diagram of the system architecture.

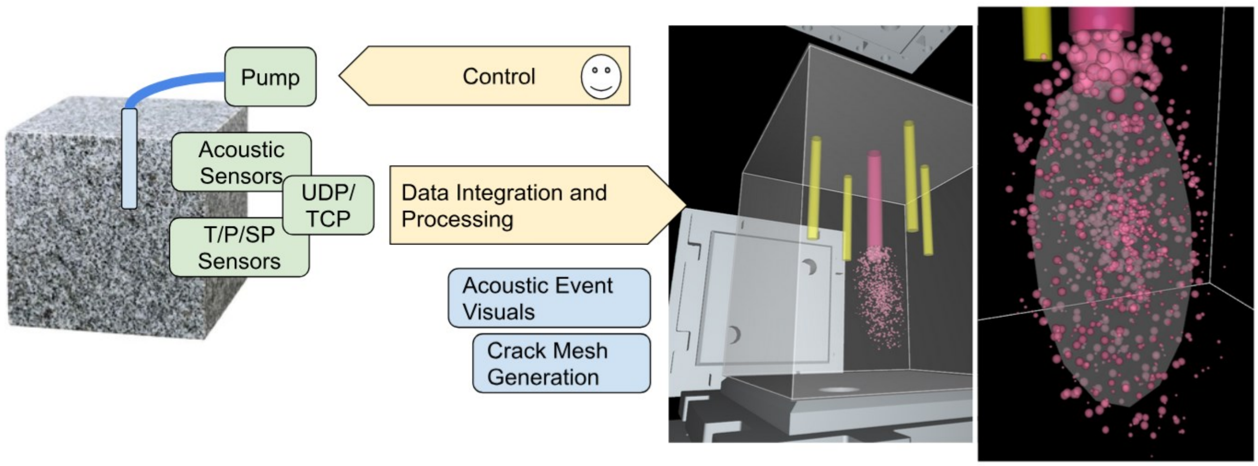

Figure 5-1: Diagram of the system architecture.

6. CONCLUSION

The RockBlockEx project represents a significant advancement in the study of hydraulic fracturing processes, offering a unique combination of modularity, scalability, and cutting-edge sensor technologies. Its innovative flat jack system, capable of applying differential pressures up to 200 bar, enables realistic simulation of geothermal reservoir conditions. This allows for comprehensive investigations of fracture initiation, propagation, and fluid transport under controlled and repeatable laboratory conditions.

By integrating real-time monitoring through acoustic emissions and self-potential signals, RockBlockEx provides critical insights into fracture mechanics and induced seismicity. The ability to test various rock types, including granite, basalt, and porous sandstone, broadens the experimental scope and supports the development of more efficient and safer hydraulic fracturing protocols for EGS.

Beyond geothermal energy, the data and methodologies developed through RockBlockEx will contribute to innovations in reservoir engineering, environmental risk assessment, and seismic risk mitigation. Planned modeling efforts and the analysis of SP responses will further deepen the understanding of hydro-mechanical interactions in fractured rock systems.

As global energy systems transition toward sustainable sources, tools like RockBlockEx will be indispensable for addressing technical, environmental, and societal challenges. This project not only advances our understanding of geomechanical processes but also exemplifies how integrated, high-precision technologies can drive progress in renewable energy solutions.

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