The DEGREE Project: A Digital Laboratory for Geothermal Exploration in the Eifel Region

Matthias Volk[1], Jacob Alexander Frasunkiewicz[2], Patrick Laumann[1], Atefeh Rahimi[3]
✉: matthias.volk@gfz.de, jafrasun@uni-mainz.de, plaumann@gfz.de, atefeh.rahimi@eonerc.rwth-aachen.de
[1]GFZ Helmholtz Centre for Geosciences, Potsdam, Germany, [2]Johannes Gutenberg University Mainz, Geosciences, Mainz, Germany, [3]Computational Geoscience, Geothermics and Reservoir Geophysics (CG3), RWTH Aachen University, Aachen, Germany

Scientific background: the DEGREE project

In the DEGREE project we are working towards a **digital laboratory** for geothermal explorations. The goal is to develop methods and tools for data analysis, visualization, and decision making that can be used to plan exploration projects and increase their probability for success.

We will demonstrate the functionality of such a laboratory with data and underground models from the **East Eifel region**. This region has recently received increased interest due to the occurrence of low-frequency earthquakes, often interpreted as a sign of rising volatiles in the crust, and new tomographic models with low-velocity anomalies beneath the Laacher See volcano, possibly indicating fluid ascent.

In this poster we present the different data processing and modeling stages as well as a plan for how to combine and couple these in a virtual digital laboratory. We also give some background on a possible future application, a geothermal play fairway analysis.

Figure 1: Eifel region within Germany

Main challenges

Availability of data.

As part of this project, the local state office for geology (Landesamt für Geologie und Bergbau Rheinland-Pfalz) provides scans of borehole reports from the target region. However, as these date back many decades, they are not available in a machine-readable format. We are working on the automatic extraction of some information from these reports which would greatly improve the structural models and provide boundary conditions for the geophysical modeling.

Complex geological structures.

The subsurface in the East Eifel is affected by Variscan folding and faulting, and by laterally varying time-equivalent Devonian facies domains. This structural and stratigraphic complexity makes geological modelling and uncertainty propagation particularly challenging.

Large uncertainties.

Subsurface data is typically associated with large uncertainties that must be propagated through the entire modeling chain in order to obtain quantitative predictions that are useful for downstream analysis tasks (e.g. PFA).

Combination of workflows and models.

The different modeling stages build on top of each other and ideally should be run in one workflow. The individual software packages used in each stage have their own input and output formats that are not necessarily standardized. In this project we can couple these in an ad-hoc manner but further work would be needed for interoperability with similar goals.

Possible application: Play Fairway Analysis (PFA)

The PFA produces **two-dimensional maps** that indicate **prospective areas** (fairways) for further geothermal exploration, derived by a sequence of processing steps on raster and vector layers. Typical operations include interpolation, thresholding and weighing as well as combination of different layers.

The PFA needs **input by a domain expert**, both for model setup as well as for the assignment of parameters such as weights or thresholds. The laboratory should provide a graphical interface to control parameters and provide fast feedback to a user by executing a PFA workflow. This approach allows for interactive exploration of the parameter space and provides the basis for a statistical analysis.

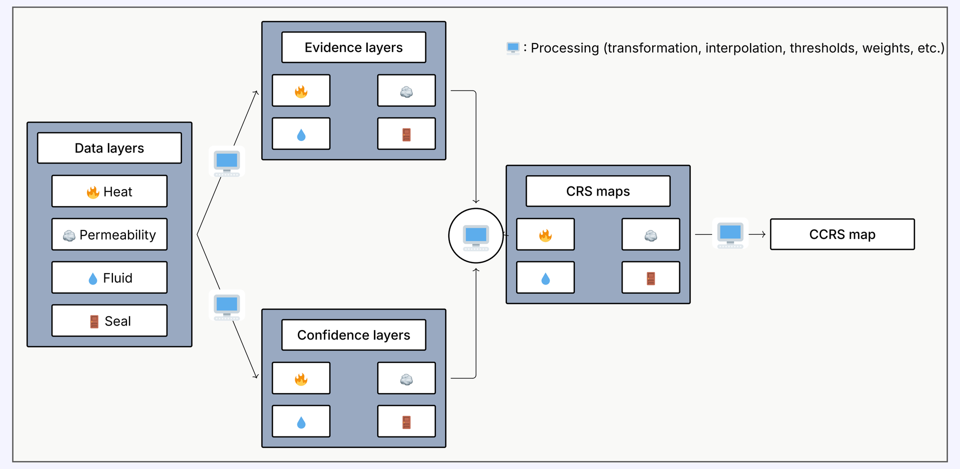

Figure 2: Schematic Geothermal PFA

Seismological Data (WP3)

Data.

The Eifel Large-N experiment generated over 5 TB of seismic data. In total, 495 seismic stations were deployed and recorded from September 2022 to September 2023 with a sampling frequency of 100 Hz. Additionally, a 60 km long Distributed Acoustic Sensing (DAS) cable was utilized for data acquisition.

Processing.

The collected seismic data are used for a variety of methods, including moment tensor inversion (Laumann et al., 2025), surface wave tomography, and full waveform tomography.

Interpretation.

These data will provide further insight into subsurface processes and properties in the Eifel region. They will help to better understand fluid-related processes as well as the tectonic and geological structure of the region.

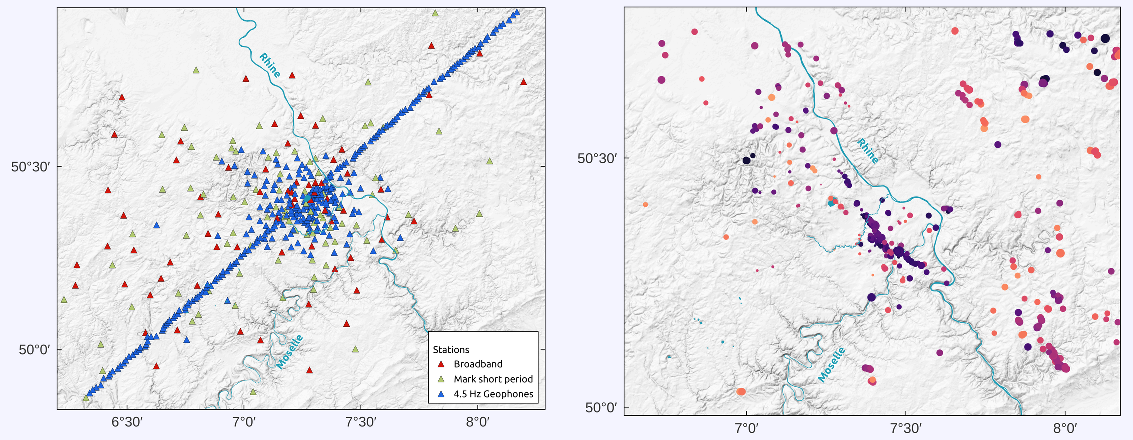

Figure 3: Large-N Network with Broadband stations, Mark short period stations and 4.5 Hz Geophone stations on the left and Map of seismicity distribution, detected with those data on the right.

Geophysical modeling (WP2b)

- The structural models from WP2a are converted into a **LaMEM.jl** thermo-mechanical simulation via **GeophysicalModelGenerator.jl**, assigning material properties per stratigraphic unit.
- Forward simulations produce thermal and mechanical fields that can be compared against surface observations from WP3.
- Adjoint-based sensitivity analysis will identify which parameters and regions require updating, closing the loop between model, data, and decision support in WP1.
- Long-term goal: a living model that assimilates new data as they become available, supporting iterative exploration planning within the virtual laboratory.

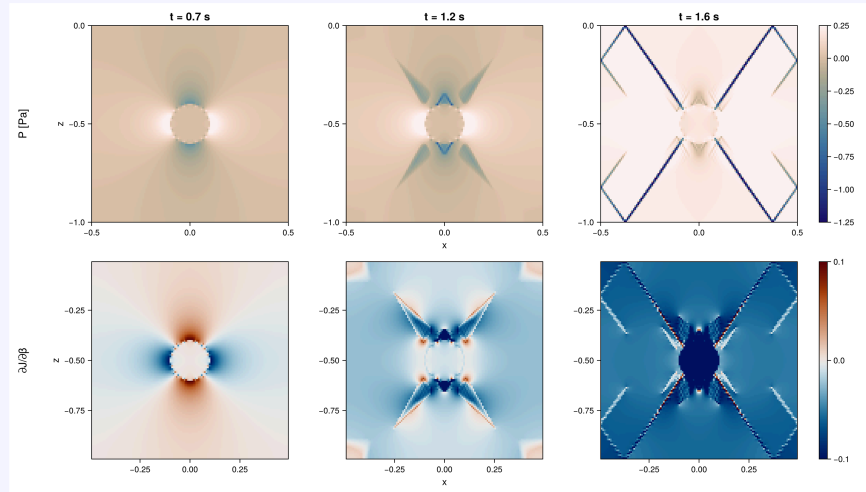

Figure 4: Adjoint sensitivity kernels of pressure within a weak inclusion w.r.t. compressibility.

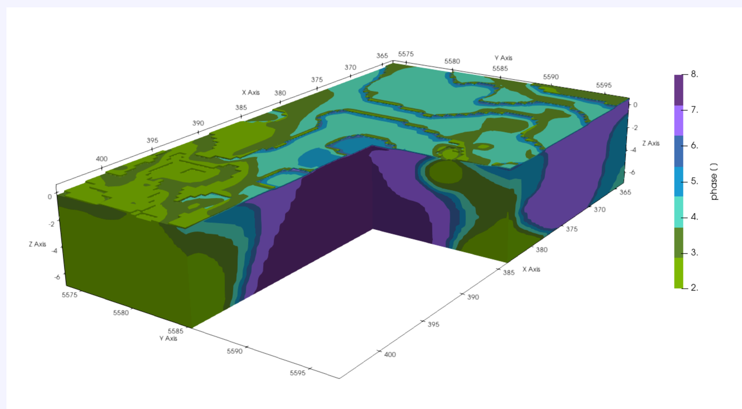

Figure 5: Geological input for *LaMEM.jl*.

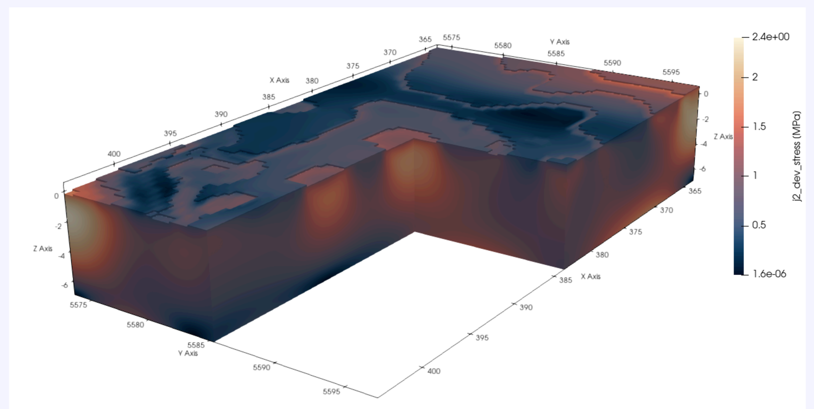

Figure 6: Computed stress field.

Geological modeling (WP2a)

Uncertainty-aware structural modeling with GemPy.

WP2a develops a **GemPy-based** workflow for reproducible **3D geological modeling** of the Eifel region using available geological, geophysical and hydrogeological datasets. The model is constructed stepwise with limited structural constraints, allowing updates as new project data become available. Uncertain input parameters are sampled to generate ensembles of plausible models and quantify spatial geometric uncertainty, providing input for simulations, digital-lab visualization and future Play Fairway Analysis.

1. Input geological constraints.

Geological map contacts, fault traces, cross-section interpretations and orientation data are converted into GemPy interface and orientation constraints.

2. Stepwise model building.

The model starts from a simplified stratigraphic framework and gradually extended with geological complexity.

3. Uncertainty propagation.

Instead of using only one deterministic model, we assign uncertainty to geological input parameters such as contact positions and orientation data. These uncertainties are then sampled with a **Monte Carlo approach** to generate an ensemble of plausible structural models.

4. Uncertainty products & workflow connection.

Probability and **entropy maps** summarize spatial geological uncertainty and the resulting model ensembles support simulations, digital-lab visualization and future Play Fairway Analysis.

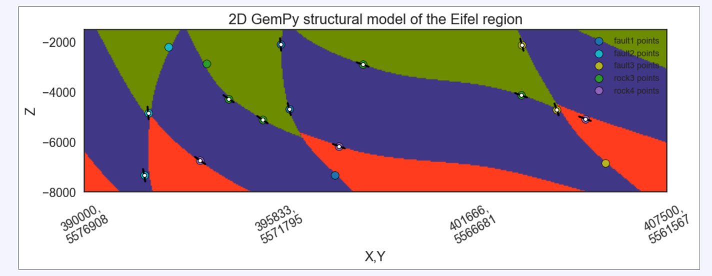

Figure 7: NW–SE section of the GemPy structural model of the Eifel region, with input interface and fault points. Geological boundaries are reconstructed by implicit interpolation.

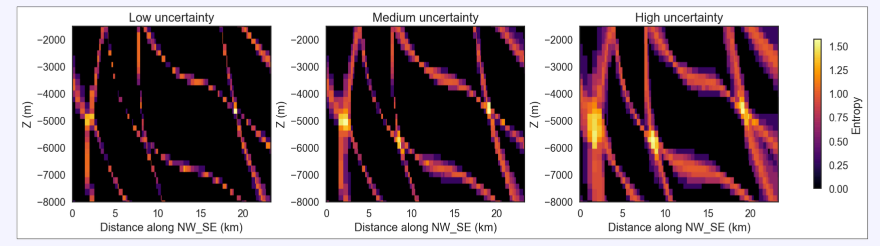

Figure 8: NW–SE section-based entropy maps illustrating the spatial distribution of model uncertainty under Low, Medium, and High uncertainty scenarios. Entropy highlights boundary zones and fault-related discontinuities, with higher and more laterally extensive values observed for increasing uncertainty levels.

Virtual Laboratory (WP1)

The virtual laboratory should fulfill a number of functional requirements (see below) but also integrate well into existing research infrastructures and procedures. From a technical point of view, we have identified three categories:

Data and metadata.

- Storage of **heterogeneous datasets** in an object store
- Association with **flexible metadata templates**
- Access via **API** and **browser interface**
- **Access management**, permission system, integration of identity providers

Interactive tools / visualization.

- Access without installation of specialized software
- Visualization of different types of data:
  - **3D raster** data
  - Structured and unstructured **meshes**
  - 2D Raster and vector **map layers**
- Interactive tools:
  - Standard **GIS features**
  - Extraction 2D from 3D data, e.g. **slices** or **contour surfaces**
  - Graphical **setup of workflows** and computations
  - Interactive **parameter input** (e.g. for thresholds or weights)

Workflows.

- Description of reusable workflow steps (e.g. **CWL**)
- Execution **engine** with connection to **HPC infrastructure**
- Graphical workflow **editor**

Prototype.

To demonstrate the functionality we plan to use **kadi4mat** as a data platform. Additionally, we are representing workflows and visualization tools in a **custom JupyterLab** which provides the right environment for both Python and Julia. The prototype can also be deployed on existing infrastructure (e.g. Jupyter4NFDI) or included into the Galaxy data science platform.

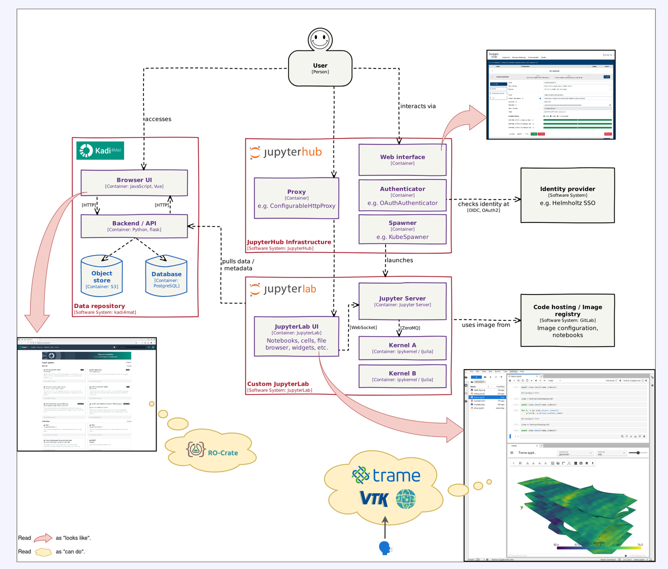

Figure 9: Components of the virtual laboratory prototype

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