Task 1.2

Task Title

Reservoir Modelling and Validation

Research Partners

Swiss Federal Institute of Technology in Zurich (ETHZ), École Polytechnique Fédérale de Lausanne (EPFL), University of Neuchâtel, University of Bern, Università della Svizzera Italiana, Paul Scherrer Institute (PSI), University of Applied Sciences Rapperswil (HSR), Swiss Seismological Service (SED)

Current Projects (presented on the following pages)

Hydraulic stimulation (collaboration with tasks 1.3 and 4.3)

Numerical Modeling of Fluid Injection Induced Shear Failure In Fractured Reservoirs
R. Deb, P. Jenny

High Performance Computing of Evolving Fracture Networks
B. Galvan, G. Jansen, S. A. Miller

Modern techniques in high performance computing for modeling the stimulation process of deep geothermal systems
G. Jansen, B. Galvan, S. A. Miller

Hydro-Mechanical Coupling in Heterogeneous Fractures
D. Vogler, F. Amann, P. Bayer

A coupled fluid flow–seismicity model for real-time assessment of induced seismic hazard and reservoir creation
V. Gischig, J. Doetsch, S. Wiemer

Long-term reservoir operation and optimization (collaboration with task 1.1 and 4.3)

Numerical simulations of fluid-rock interaction in enhanced geothermal and CO2 injection systems - implications for the utilization of deep reservoirs in Switzerland
P. Alt-Epping, L. W. Diamond

Numerical modeling of highly fractured media for Enhanced Geothermal Systems
J. Patterson, T. Driesner, R. Kraus

Geochemical effects on long-term permeability evolution and heat extraction
J. Mindel, T. Driesner

Impact of liquid and supercritical CO2 injection on host rock properties
R. Makhnenko, D. Mylnikov, L. Laloui

Mixed electrolyte solutions in geothermal systems: experimental and molecular dynamics insights
D. Zezin, T. Driesner

Exploration & Reservoir characterization

Numerical upscaling of seismic characteristics of fractured porous media
E. Caspari, M. Milani, J. G. Rubino, T. M. Müller, B. Quintal, K. Holliger

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Fault detection method to anticipate felt induced seismicity in geothermal and geologic carbon storage projects
V. Vilarrasa, G. Bustarret, L. Laloui

International collaborations on integrated geothermal systems characterization (COTHERM = SNF Sinergia project, ETHZ, PSI, University of Iceland)

Geologic controls on supercritical fluid resources above magmatic intrusions
S. Scott, T. Driesner, P. Weis

Fluid-Rock Interactions in Icelandic Hydrothermal Systems
B. Thien, G. Kosakowski, D. Kulik

Seismic Response to Fluid Effects in Fractured Geothermal Reservoirs
M. Grab, H. Maurer, S. Greenhalgh

Task Objectives

Task 1.2 focuses on reservoir modelling to address fundamental challenges in DGE:

- DGE roadmap workshops showed that our limited understanding of the fundamentals of hydro-mechanical processes during hydraulic stimulation is the biggest knowledge gap towards routinely engineering heat exchangers at depth. Task 1.2 works towards development of novel simulation codes that allow rigorous simulation and in-depth analysis of coupled hydro-mechanical processes
- The understanding of the long-term evolution and efficiency of reservoirs during operation is heavily underdeveloped due to a lack of projects that generated practical experience (e.g., how efficiently and sustainably can heat be produced from fractured reservoirs). Task 1.2 predicts and quantifies the long-term behaviour of deep geothermal and CO2 reservoirs
- Reservoir exploration and characterization requires interplay between field-based measurements and interpretation of results by numerical methods. Task 1.2, in close collaboration with Task 1.3 (see also poster there), works towards integration of these two approaches. This includes experimental work on different scales.

A number of partners is involved in international collaborations with “established” geothermal countries (US, Iceland, New Zealand) to test and optimize methods and to gain experience in applying them to actual, operating systems.

Interaction Between the Partners – Synthesis

- Two workshops in 2015 (May 12: Task 1.2 workshop at EPFL; May 4: Joint workshop of Tasks 1.2 and 4.3 at USI)
- NRP70 collaboration between ETHZ, UNiNE and USI: regular interactions and meetings
- Various interactions on meetings, workshops etc. held by related projects (GEOTHERM-2, NRP70, COTHERM)
- Mutual direct involvement of staff of different partners in various projects and across tasks (e.g., NRP70 project that involves UniBE, UniL, ETHZ and links across tasks 1.1 and 1.2; NRP70 project that involves ETHZ, UniNE, USI and links tasks 1.2 & 4.3, GEOTHERM-2 involves and links across tasks ETHZ, PSI, EPFL, UniBE, UniNE)
- Numerous bilateral and trilateral discussions regarding new simulation code developments

Highlights 2015

- First numerical simulations of supercritical geothermal reservoirs, published in Nature Communications (Sam Scott et al., ETHZ; open access: doi:10.1038/ncomms8837); this is an outcome of the international collaboration with Iceland within the COTHERM project (SNF Sinergia) that acts under the umbrellas of IPGT (International Partnership for Geothermal Technology)
- Victor Vilarrasa (EPFL) was awarded the Alfons Bayó Award to Young Researchers by the International Association of Hydrogeologists – Spanish Group
- Novel approaches to simulate fluid injection-induced shear failure in fractured reservoirs working in 2D (see poster by Deb&Jenny, ETHZ)
- Numerical methods for upscaling of seismic characteristics of fractured porous media, which may become an essential tool for Task 1.1 (see poster by Caspari et al.)
- Experimental evaluation (complemented by simulations) of hydromechanical couplings during shear on rough fractures (see poster by Vogler et al.)
- Prototype of 3D reactive transport code for modelling long-term permeability evolution and heat extraction in realistic fracture network representations nearly completed (see poster by Mindel et al.)

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Numerical Modeling of Fluid Injection Induced Shear Failure in Fractured Reservoirs

Rajdeep Deb, Patrick Jenny
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Introduction

Numerical studies of enhanced geothermal systems (EGS) require efficient modeling and simulation of the coupled solid and fluid mechanics in the reservoirs. Geothermal systems are natural heat exchangers and the heat exchange between fluid and rock depends strongly on fracture network properties and fluid flow paths. Rock mechanics plays a key role in forming and creating new flow paths, and therefore a first objective is to obtain a physically accurate numerical modeling strategy to describe the geo-mechanics. A number of properties such as fracture orientation with respect to the principal stress tensors, preferential fluid flow path, friction properties and fracture toughness etc. determine the different failure scenarios. Shear failure is one of the principal mean of achieving increased flow properties through the fracture network.

Methods

In order to properly describe the coupled fluid and solid mechanics problem in EGS systems, large fractures are generally represented as discrete manifolds embedded in the elastic domain, where the system cannot bear traction forces beyond a certain maximum limit. Failure occurs along the fracture manifolds, once the local shear force exceeds the local sustainable traction force. Then an irreversible rock displacement occurs along these manifolds, which is termed as slip. This slip is very important to determine the hydrodynamic flow radius in these fractures. Resolving the shear slip requires to have a domain discretization fully resolved around each fracture network while using traditional FEM or FVM approaches. But this is computationally expensive when the domain is filled with a lot of fractures. An alternative approach is to use special basis functions, which respect the discontinuity along the fractures. A method has been developed here, which resolves such discontinuities for any arbitrary fracture orientation in a finite volume discretization. The displacement solution is given by

$$\mathbf{u} = \sum_{i=1}^{N_e} \mathbf{u_i} N_i(\mathbf{x}) + \sum_{j=1}^{N_s} \mathbf{s_j} \left(\sum_{p=1}^{4} N_p(\mathbf{x}) H_p(f(\mathbf{x})) \right) \quad (1)$$

$$H_p(f(\mathbf{x})) = H(f(\mathbf{x})) - H(f(\mathbf{x_p})) \quad (2)$$

$$\int_\Omega (\nabla \cdot \tilde{\sigma} + \vec{f}) d\Omega = 0 \quad (3)$$

$$\int_{d\Omega} \tilde{\sigma} \cdot d\vec{A} + \int_\Omega \vec{f} d\Omega = 0 \quad (4)$$

$$\tau(s_x, s_y) = (S_0 + \mu_d \sigma_c(s_x, s_y)) \quad (5)$$

The equation (2) defines the discontinuity function, where f(**x**) is a signed distance function from the fracture line and H is the Heaviside function. The choice of such a discontinuity function in the equation (1) guarantees the continuity of the gradients of displacement and therefore guarantees the continuity of shear traction and compressive forces along the fracture lines. Here, equation (3) integrates the stress equilibrium equation over a finite volume segment and equation (4) represents the equilibrium between the stress forces on the domain boundary with the volume forces. Equation (5) restores shear traction force to the friction limit. In order to improve computational efficiency of the numerical linear solver, fast multigrid method is used along with a local Gauss-Seidal pre-conditioner around the failed fracture segments.

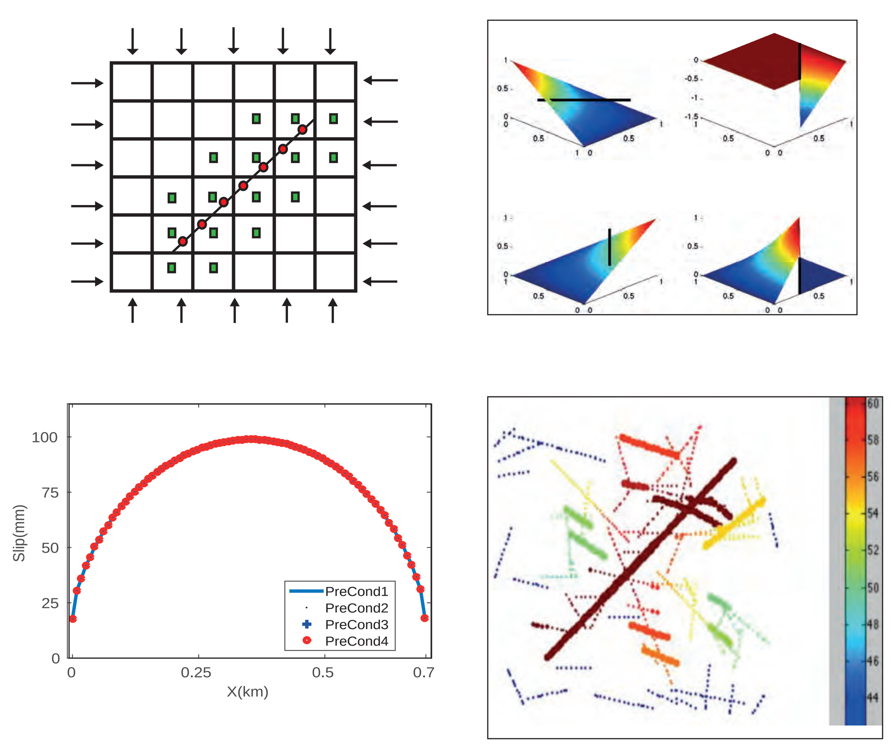


Figure 1. The figures respectively represent in clockwise order from top left, the discretization of the fractured domain, the discontinuity basis functions, the slip solution using different pre-conditioning for mechanical failure of large fractures and finally a snapshot of the pressure solution for a stochastic fracture network with thicker lines representing segments, which have already undergone shear failure and therefore have increased aperture.

The fluid injection into the fracture network and the surrounding matrix domain is solved using finite volume method in a hierarchical fracture network framework. The following equations describe the equations for fluid flow along fractures and the surrounding matrix :-

$$\frac{\partial E_f^i}{\partial t} - \nabla \cdot \left(\frac{b^i \boldsymbol{k^i}}{\mu} \cdot (\nabla p^i - \rho g) \right) + \Psi^{i \to d} = q^i,$$

$$\frac{\partial \phi^d}{\partial t} - \nabla \cdot \left(\frac{\boldsymbol{k^d}}{\mu} \cdot (\nabla p^d - \rho g) \right) + \Psi^{d \to i} = q^d$$

$$E^i = E_0 + \left(\frac{a}{1 + (9\sigma_n'/\sigma_{nref})} \right)$$

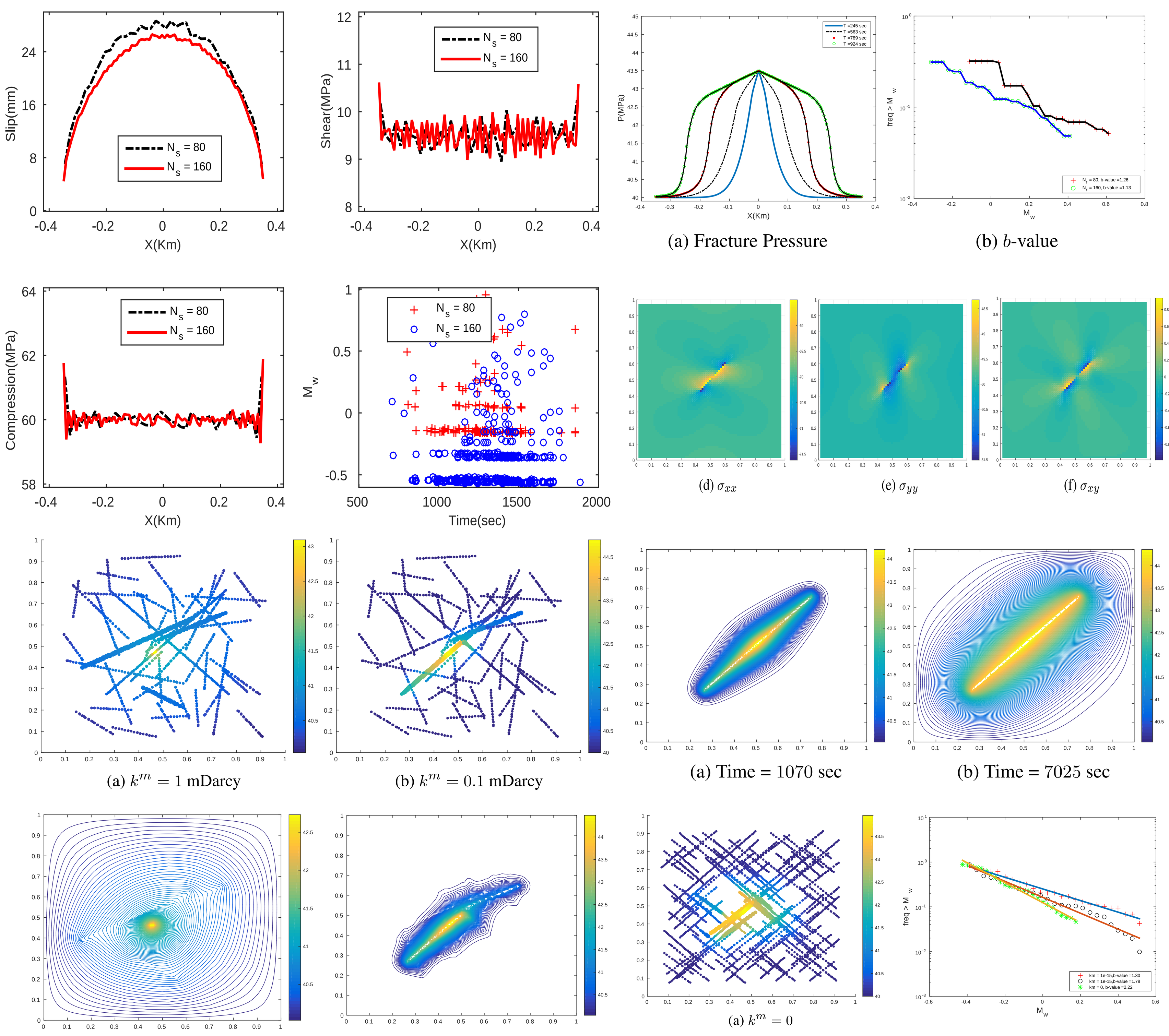
$$b^i = b_0^i + \beta_1 s_1 + \beta_2 s_2$$

Key Achievements of The Project

1. The modeling can resolve pressure injection induced seismicity for two dimensional problem with fracture manifolds.
2. Modeling also approximates the shear failure effect on increasing permeability.
3. The modeling resolves the shear failure of fractured domain without resolving grid near the fractures and therefore computationally efficient.

Future Project Goals

1. Improve the numerical efficiency using better pre-conditioner or numerical solver and parallelization of the code.
2. Extend the modeling strategy to include more accurate friction law such as Rate-State or Slip-Weakening law and extend to 3D problem.
3. Include tensile failure and fracture propagation for EGS systems.



Fig–2 The single fracture shear failure and pressure solution, the pressure contours of two different fracture networks with matrix permeability and pressure solution for a fracture network with impermeable matrix is presented. Further, the seismic moment magnitude is analyzed and semi logarithmic plot of frequency of moment magnitude are presented for different scenarios. Also the stress field solution for the single fracture is presented under shear failure.

Conclusions

A new finite volume based method is developed to model shear failure which includes special basis functions for discontinuity. The mechanical solver is coupled with a flow solver, which relies on hierarchical fracture network modeling approach, and it allows to compute flow induced shear failure along pre-existing fractures. The most expensive component of such computer simulations is due to large linear systems stemming from the matrix discretization. The linear solver is based on a combination of Gauss-Seidel and multigrid iterations.

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High Performance Computing of Evolving Fracture Networks

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Abstract

The Geothermics Group at the University of Neuchâtel recently acquired and installed the first stage of a High Performance Computing (HPC) system to simulate fracture growth coupled to hydro-mechanical and hydro-thermal processes. We are developing and implementing new algorithms designed and optimized for GPU/MIC hybrid clusters. We are aiming, with our current configuration, to achieve numerical resolution of 512x512x512, with the possibility to expand the system if we are successful.

1. Introduction

The most important aspect of Enhanced Geothermal Systems (EGS) is proper engineering of the fracture network created by fluid injection to optimize connectivity for sufficient flow rates while also minimizing seismic risk. Modelling the nucleation, growth, and coalescence of fractures and their hydro-mechanical and hydro-thermal coupling requires the development of new algorithms and High Performance Computing (HPC) to simulate these processes at sufficient resolution to aid in the design and implementation of injection scenarios. We focus on developing these algorithms for implementation on the state-of-the-art computational platforms based on Graphics Processing Unit- (GPU) and Many Integrated Core- (MIC) accelerator cards. Our recently installed first stage GPU/MIC cluster "Thor" (Figure 1) will be used to simulate 3D hydro-mechanical models with target resolution of 512x512x512

2. Approach

The first step was to demonstrate that generating numerical fractures (e.g. strain localization) can be accomplished entirely on a GPU-cluster platform in simulations of an elastic-plastic rheology with hardening/softening and damage. Figure 2 shows the results for an 8-card GPU cluster with a numerical resolution of 2048x2048, and demonstrates successful modeling of fracture nucleation, growth, interaction and coalescence; a milestone never before achieved on a GPU cluster. The results in Figure 2 were obtained using the finite difference approximation together with mass scaling, which we have found to be very sensitive in 3D to the mass scaling values chosen. To avoid *ad hoc* choices in mass-scaling that may lead to incorrect or misinterpreted results, we are pursuing alternative modeling schemes such as mesh-free and finite element methods to insure robustness in the 3D domain. Another approach that we are taking is to develop a pre-processing application for tangible devices that makes constructing the numerical domain as intuitive and simple as possible. The 2D version of this application was used to construct the numerical domain (Figure 3), showing how complex geometries (determined from either seismic data or other geophysical techniques) can be easily and quickly (about 1 hour) transformed into a numerical domain.
Our goal is a fully coupled Thermo-Hydro-Mechanical-Chemical (THMC) simulator optimized for the GPU/MIC high performance architecture with good scalability that can be explored to gain insight into complex coupled processes of THMC systems in general and enhanced geothermal systems in particular.

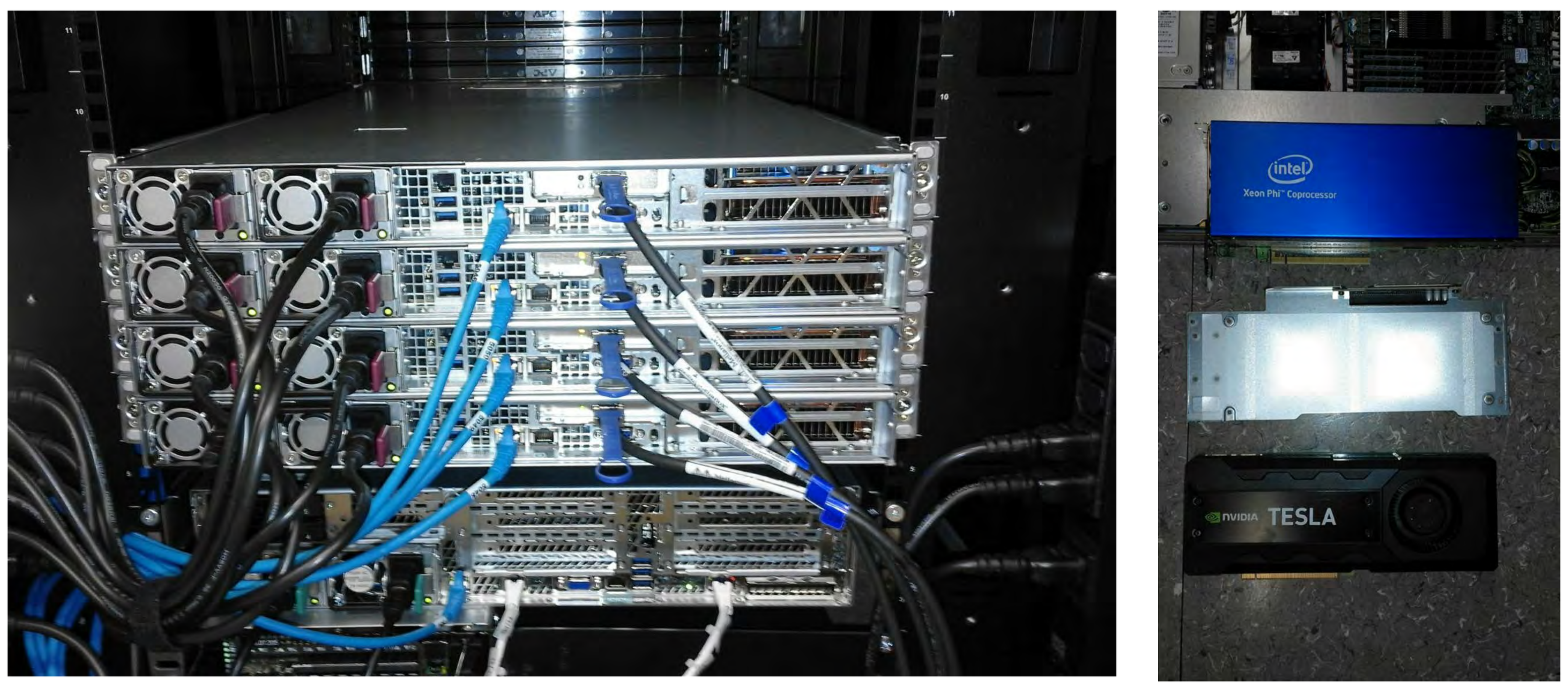


Figure 1: a) View of GPU/MIC cluster Thor recently installed at the University of Neuchâtel. The setup includes 4 computing nodes each equipped with two GPU Tesla 40K cards, one Intel Xeon Phi (MIC) coprocessor card, two 2 CPU 10 core Intel Xeon E5-2650, and Infiniband connection at 56 Gbits/s. The system includes about 1TB RAM and 20TB storage. This system, once proven, can be upgraded by adding additional nodes.

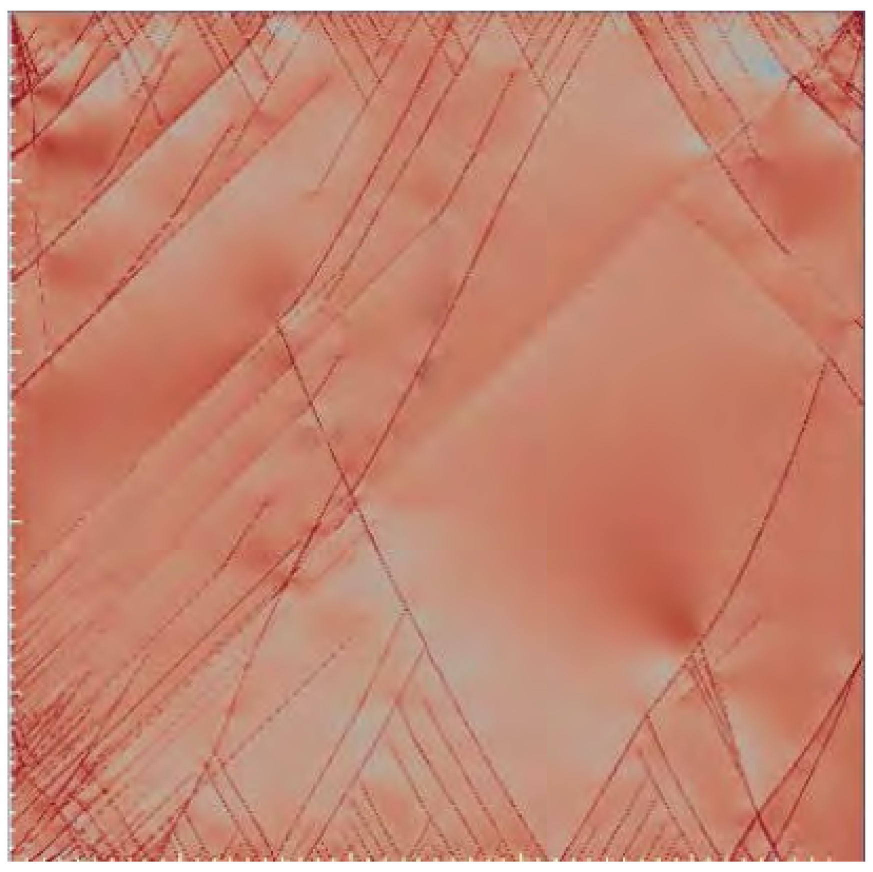


Figure 2: Fracture network simulated on an 8-card GPU cluster. This is the first time fracture evolution and growth has been simulated at high resolution using only GPU, a significant development for utilizing this accelerating platform.

3. Results

Figure 2 shows fracture evolution for a simple system with an initially heterogeneous distribution of material strength analogous to material defects. Fractures behave as expected, with new fractures terminating on interaction with previously formed fractures. Figure 3 shows GPU-cluster results for numerical fracture evolution in a more complex geologically system, demonstrating how insight can be gained by such models, and the output from our envisaged THMC model can be explored for statistical properties, flow properties, and ultimately the long-term viability of a geothermal resource.

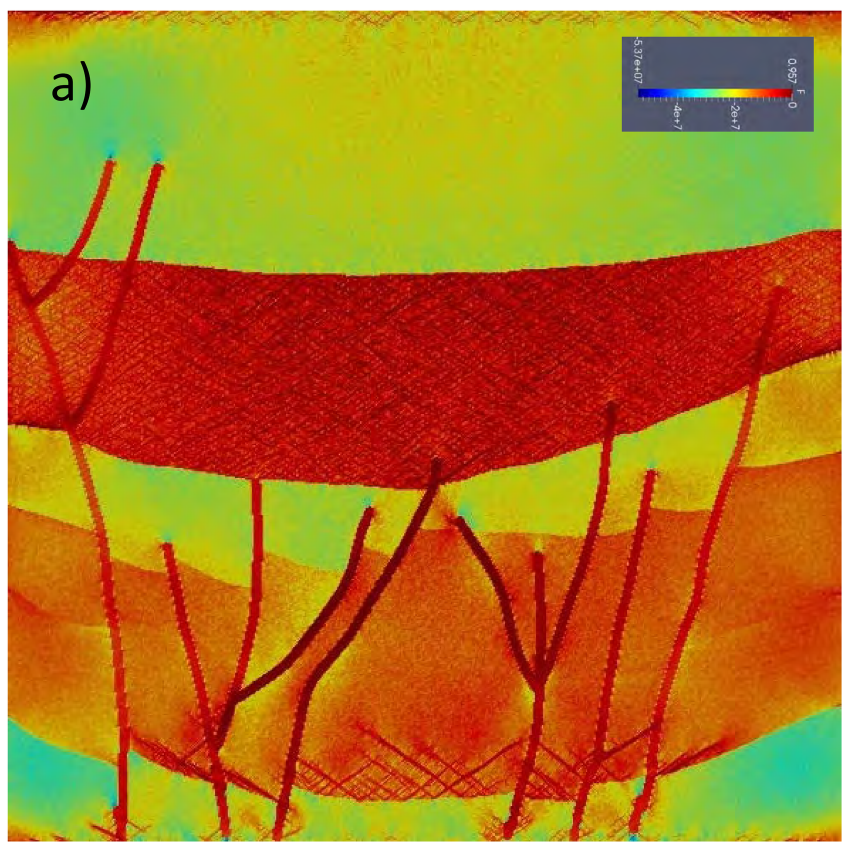
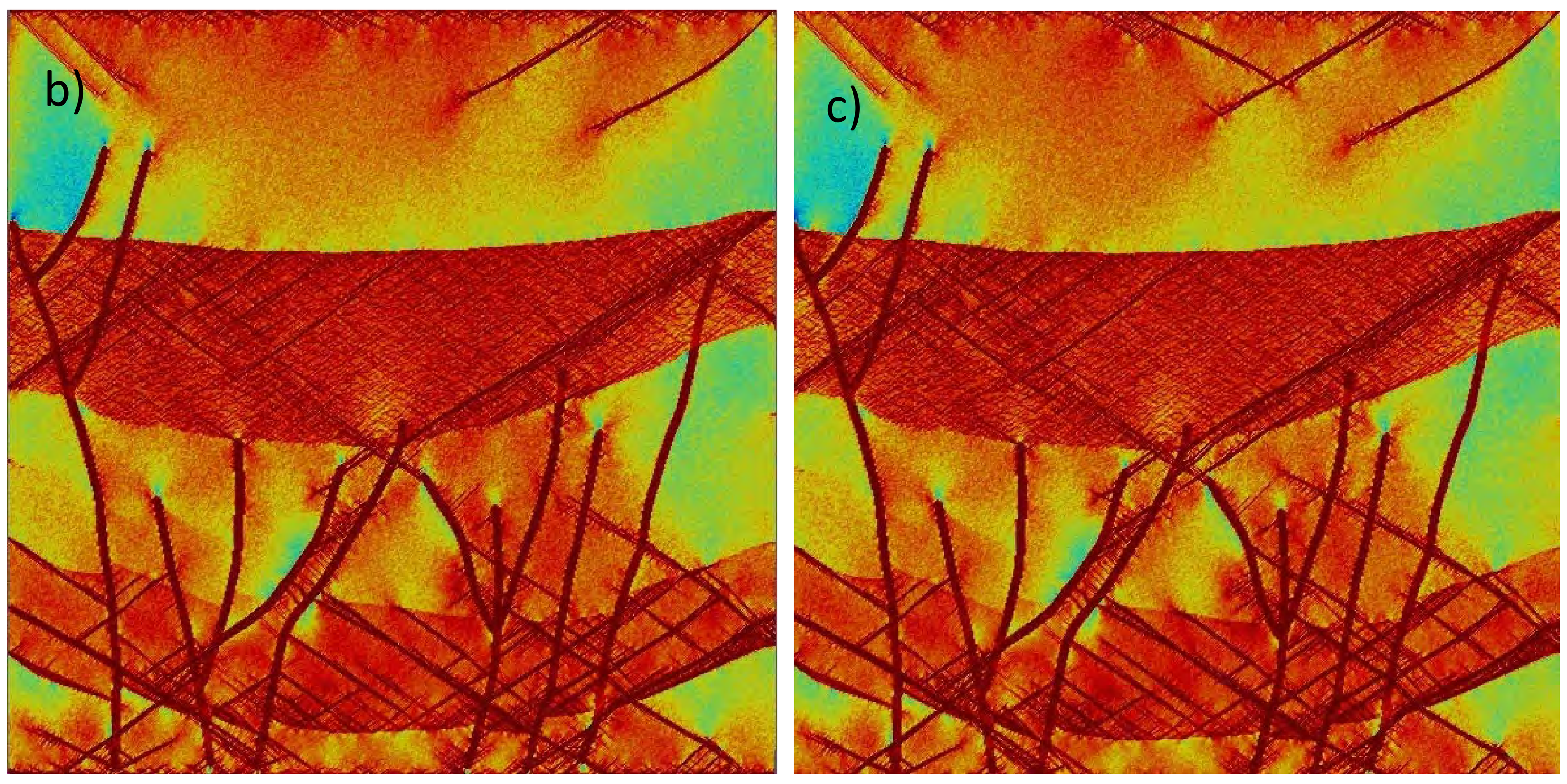


Figure 3: GPU cluster results demonstrating evolving numerical fractures in a geologically complex environment. The simulation shows how fractures interact and develop into complex patterns that would act as the dominant flow paths for fluid and advection of heat. We are currently evaluating the statistics of these fracture networks and developing flow and heat transport models to couple to these networks.



3) Future Developments

Future developments include development and implementation of 3D mesh-free rock mechanics simulators to run in GPU/MIC clusters in order to handle the geological complexities present in real world geothermal applications. We will also develop GPU/MIC-based finite element flow and heat transfer codes to couple to the rock mechanics simulator. Our main goal is to make use of new computing paradigm based on many core devices to develop new strategies for numerical geodynamical modeling of lithospheric processes.

Acknowledgments

We appreciate the financial support from UniNE for acquisition of the "Thor" cluster.

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Modern techniques in high performance computing for modeling the stimulation process of deep geothermal systems

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The NFP70 project "Modeling permeability and stimulation for deep heat mining" is a joint project of the ETH Zürich, Università della Svizzera italiana (USI), University of Neuchâtel (UniNe) and the Swiss National Supercomputing Centre (CSCS). Within the project the challenging task of understanding the permeability evolution in deep reservoirs is investigated by different approaches by the collaborators.

1. Introduction

Modern high performance computing techniques are required to meet the computational demands of state of the art multiphysics models as they have become increasingly demanding concerning hardware resources. In recent years however, the rate of processor performance gain by hardware improvements stagnates. Hybrid architectures based on traditional multicore processors and modern accelerators (e.g. the graphics processing unit GPU) have become more important.

Simulating the stimulation process of reservoirs for deep heat mining is numerically challenging. Classical approaches can not provide the desired level of detail in terms of resolution and model completeness both. Thus, modern techniques need to be utilized, especially in 3D simulations.

Objectives of study

- Utilize modern numeric techniques in the context of geothermal modeling.
- Use the power of supercomputers to allow high resolution 3D simulations
- Understand the permeability evolution during stimulation of deep reservoirs

2. Method

We employ the Finite Element Method to solve the equations for nonlinear fluid pressure diffusion and mechanical equilibrium from continuum mechanics.

$$\frac{\partial(\phi c_f p)}{\partial t} = -\nabla \cdot \left[\frac{k p_w}{\mu_w} \cdot (\nabla p_w - \rho_w \vec{g} \nabla z)\right] - q = 0$$

$$\nabla \cdot \sigma - \rho \vec{g} - \alpha \nabla p - \beta K \nabla T = 0$$

Material deformation is modeled through theory of plasticity and damage with shear (e.g. Mohr-Coulomb) and tensile criteria.

Discretized equations are assembled and solved in parallel. The problem geometry is distributed among the processors to reduce the memory footprint.

Highlighted features:

- Fully parallel
- Dimension independent
- Adaptive mesh refinement using *deal.II* [1]
- Distributed geometry using *p4est* [2]
- Sophisticated parallel nonlinear solvers using *PETSc* [3]

3. Adaptive Mesh Refinement (AMR)

Usually only in certain parts of the domain a high solution accuracy is required. Adaptive mesh refinement is used to perform refinement in current active parts of the domain while other parts are coarsened in based on a refinement criterion in order to maintain load balance.

3.1 Physics based refinement

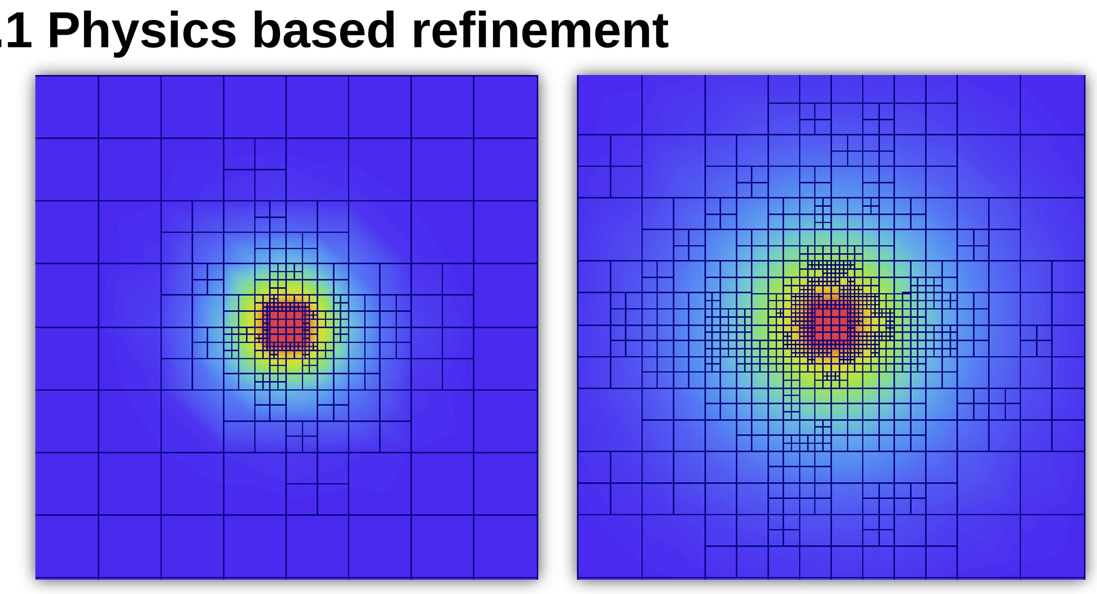

Fig 1. Adaptive mesh refinement for a diffusion process based on the gradient of the fluid pressure

3.2 Geometry based refinement

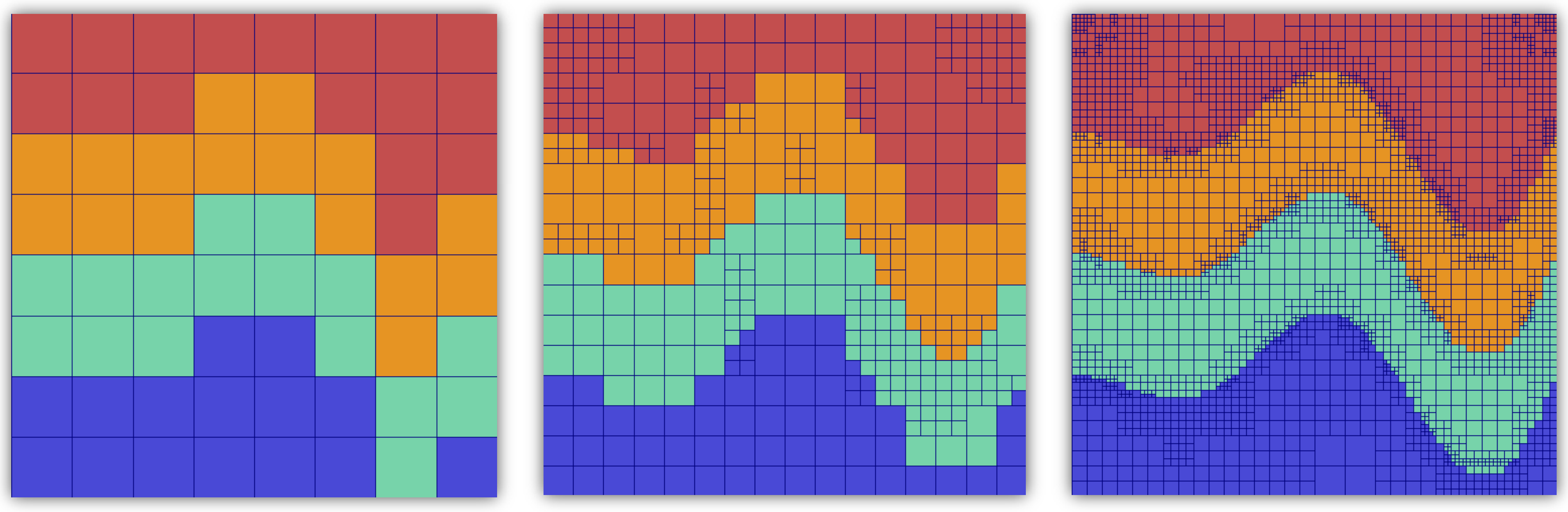

Fig 2. Adaptive mesh refinement based on the contrast of material properties of the geological setting.

4. Preliminary Study

Coupled hydro-mechanical simulation of a high pressure injection into a permeable structure. Injection fluid pressure is increased up to 20MPa and kept constant for the duration of the simulation.

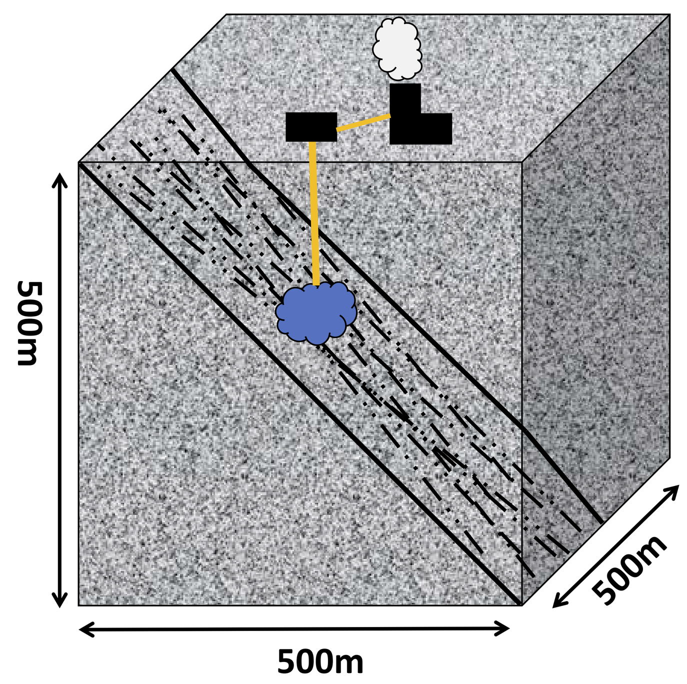

Fig 3. Model setup

Highlights in Figure 4:

- Fluid pressure front follows the permeable pathway
- Envelope of plastic deformation zone follows the 10MPa fluid pressure isosurface
- Plastic deformation follows material friction angle and not angle of permeable zone

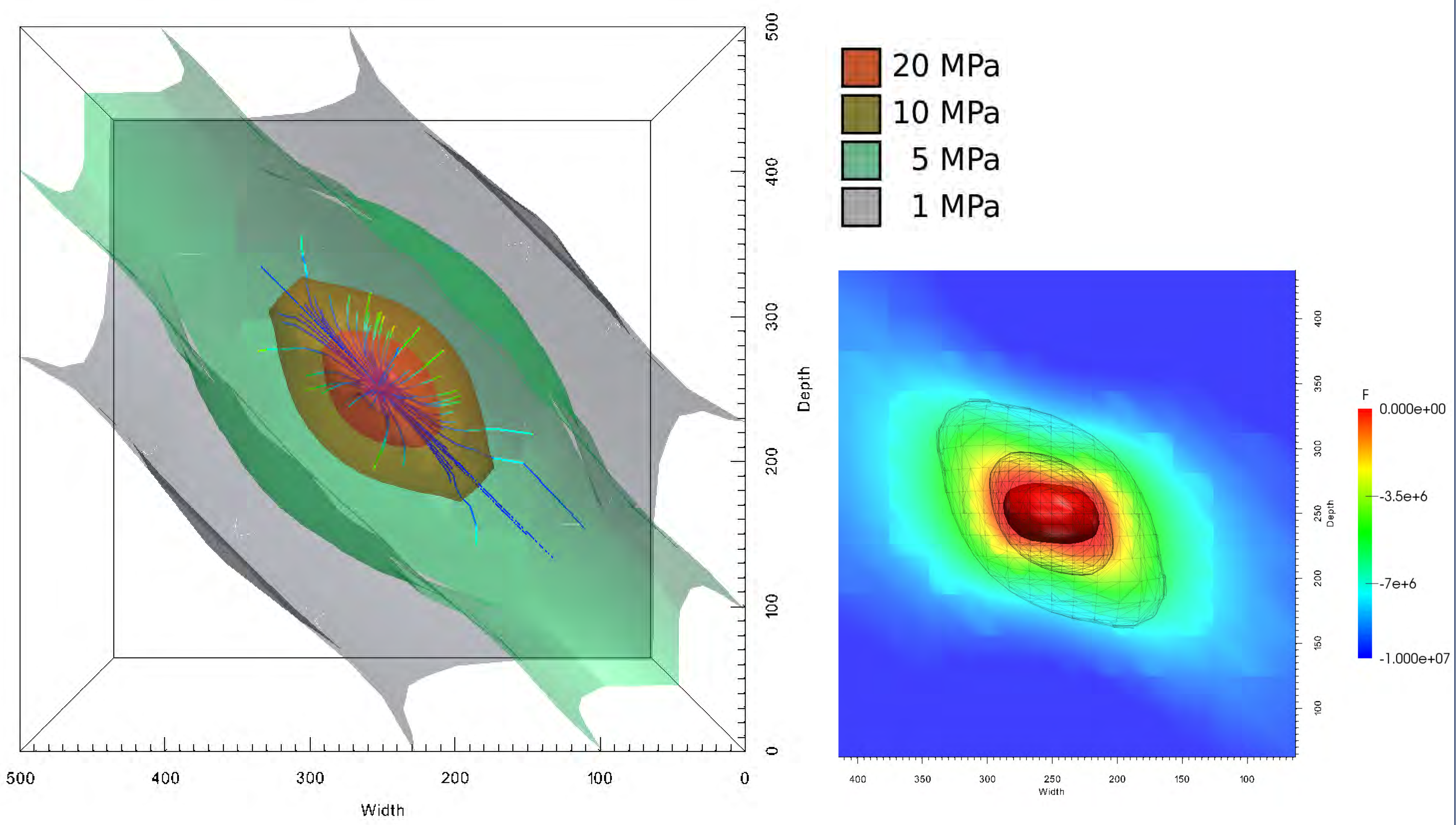

Fig 4. a) Fluid pressure isosurfaces and velocity streamlines for tracer particles inserted at the source. **b)** Plastic deformation zone envelope close to the 10MPa fluid pressure isosurface

6. Conclusions

Problems related to the stimulation process of deep geothermal reservoirs greatly benefit from modern computational techniques. Our preliminary studies suggest that especially adaptive mesh refinement is well suited to handle the complexity of geologic settings while limiting the computational demands within the realms of possibility.
In the future the anticipated performance gain will enable us to model the evolution of deep geothermal reservoirs based on fully coupled simulations with high resolution in three dimensions.

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2. C. Burstedde, L. Wilcox and O. Ghattas, *p4est: Scalable Algorithms for Parallel Adaptive Mesh Refinement on Forests of Octrees*. SIAM Journal on Scientific Computing 33 no. 3 (2011)
3. S. Balay et al., *PETSc Web page*, http://www.mcs.anl.gov/petsc (2015)

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Fluid Flow in Heterogeneous Fractures

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Introduction

- Enhanced Geothermal Systems (EGS) rely on sufficiently high production rates and are naturally low permeable.
- Hydro-Mechanically coupled processes in fractures are crucial to understand reservoir productivity and are typically modelled using the assumptions of a parallel plate model (cubic law) [Louis 1967].
- Cubic Law:

$$Q = -\frac{a_{hyd}^3 w}{12\mu} \nabla p \qquad (1)$$

- For Hydro-Mechanical coupling, application of the cubic law suggests changes in mechanical aperture a_{mech} to be equal to changes in hydraulic aperture a_{hyd}.

Hydro-Mechanically Coupled Laboratory Scale Experiments

- Normal loads up to 68 MPa (about 2600m overburden)
- 5 to 10 loading cycles
- Natural granite fractures
- Fractures are investigated mated and offset

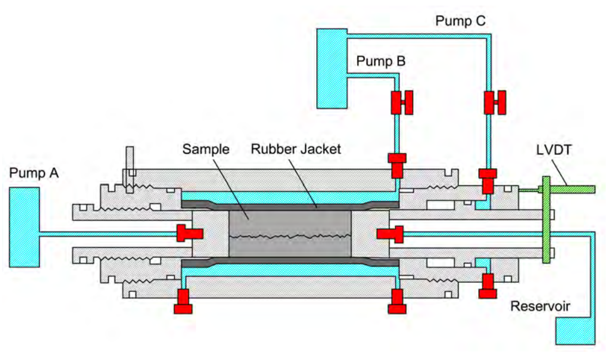
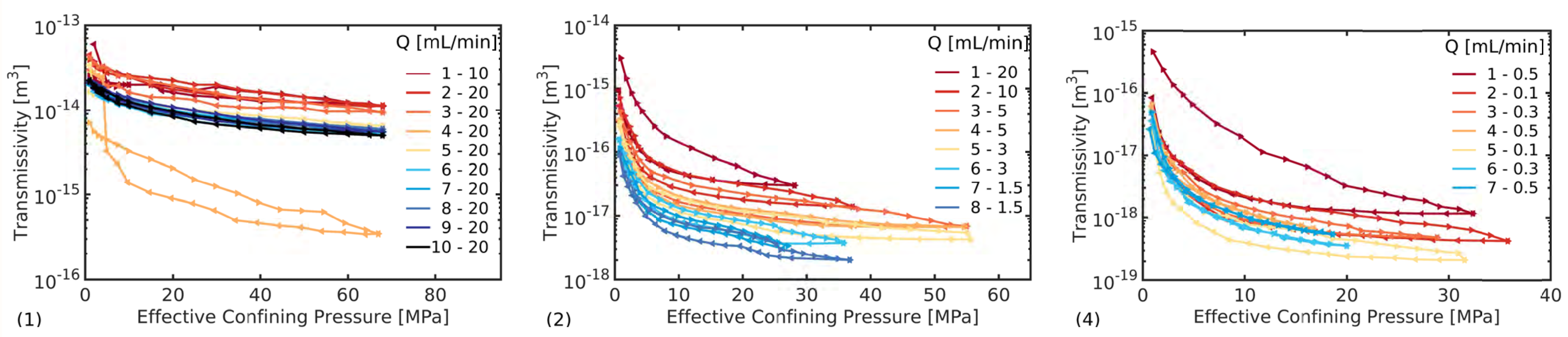
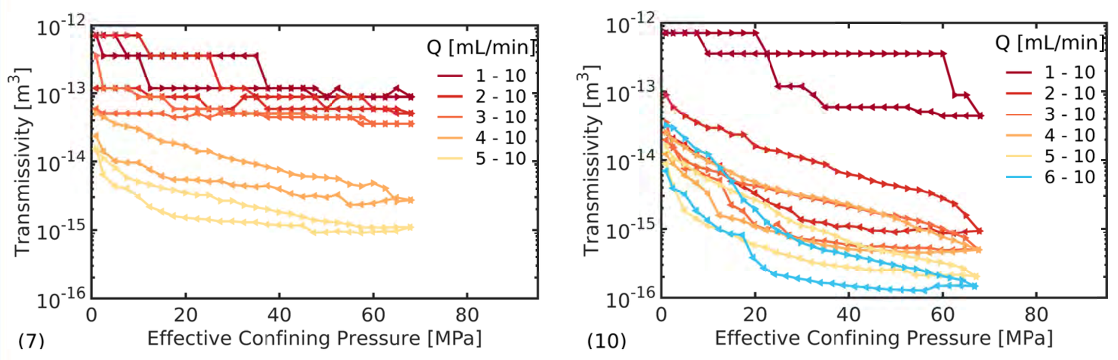


Figure : Experimental setup.

Results - Permeability Changes



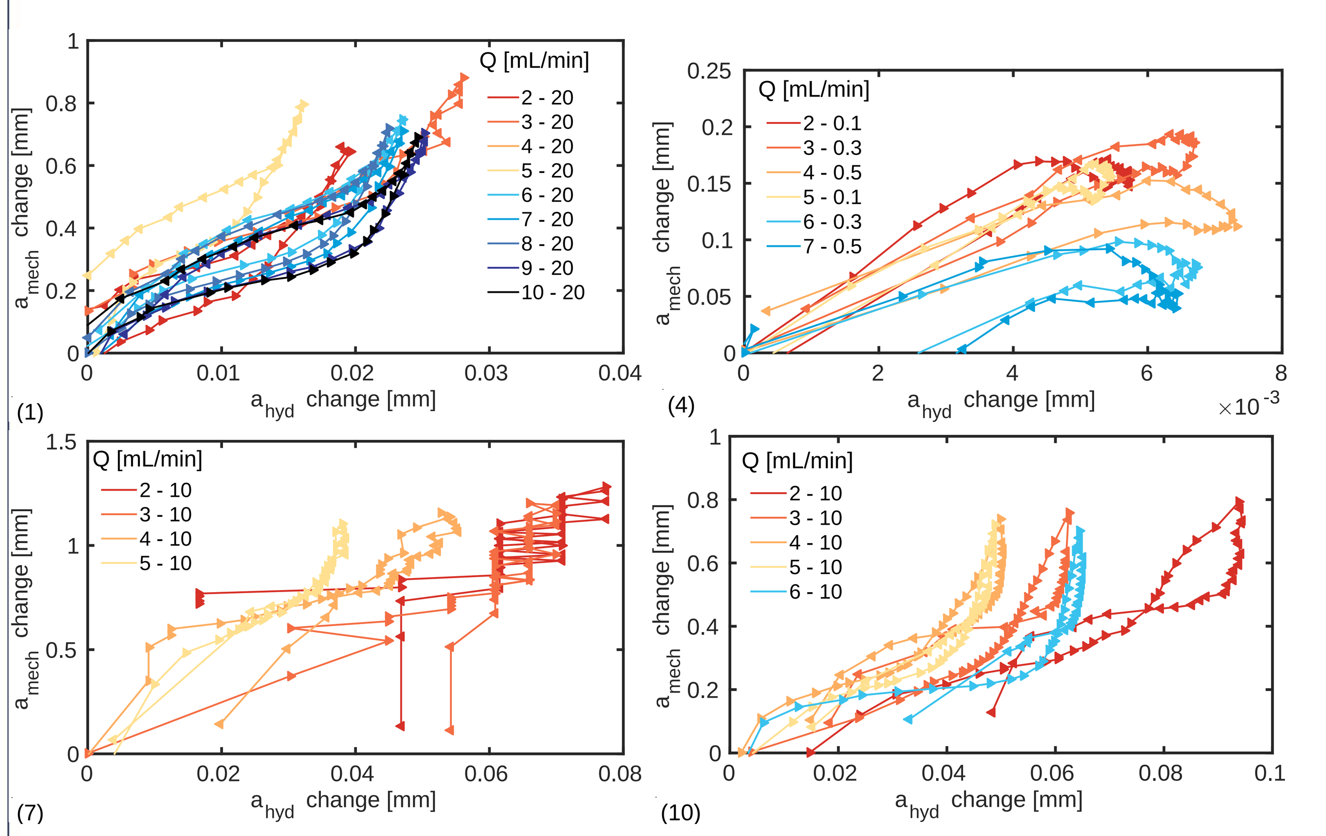


The plots show transmissivity

$$T = \frac{a^3}{12} = \frac{Q * \mu}{w * \nabla P} \qquad (2)$$

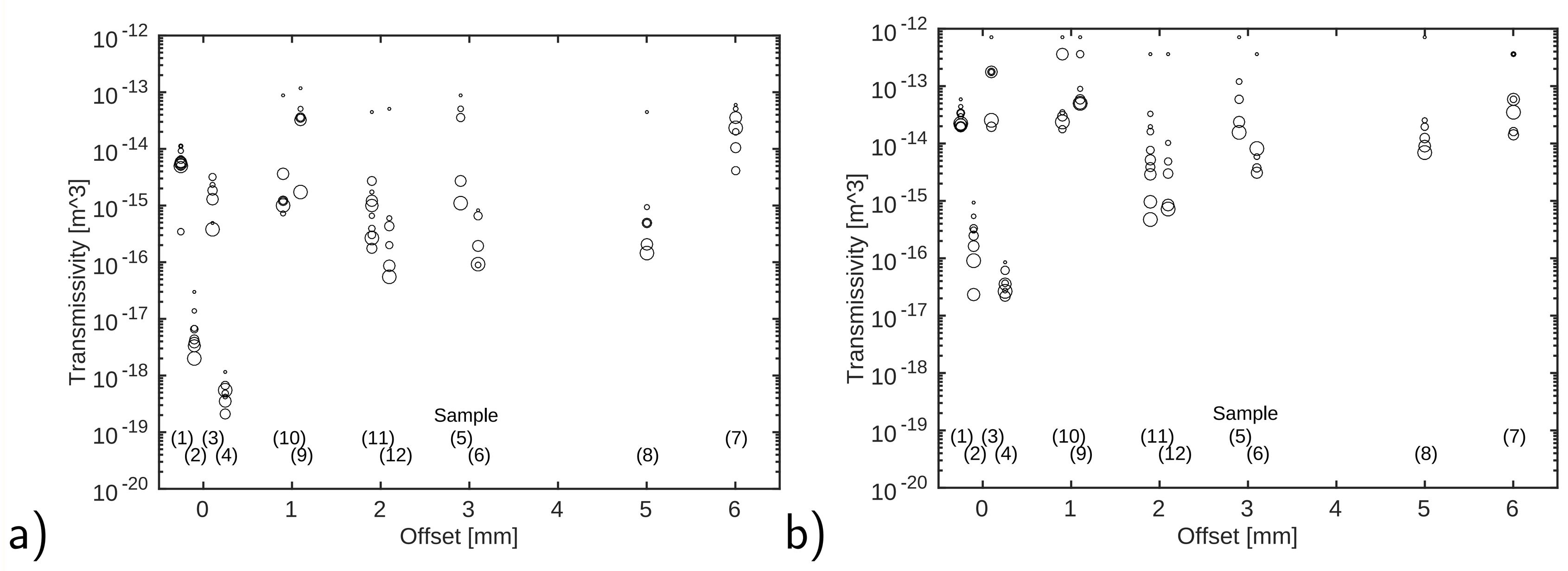
during confining stress changes from 1 MPa to maximum confining pressure (▷) and back to 1 MPa (◁) .

Results - Mechanical and Hydraulic Aperture Changes



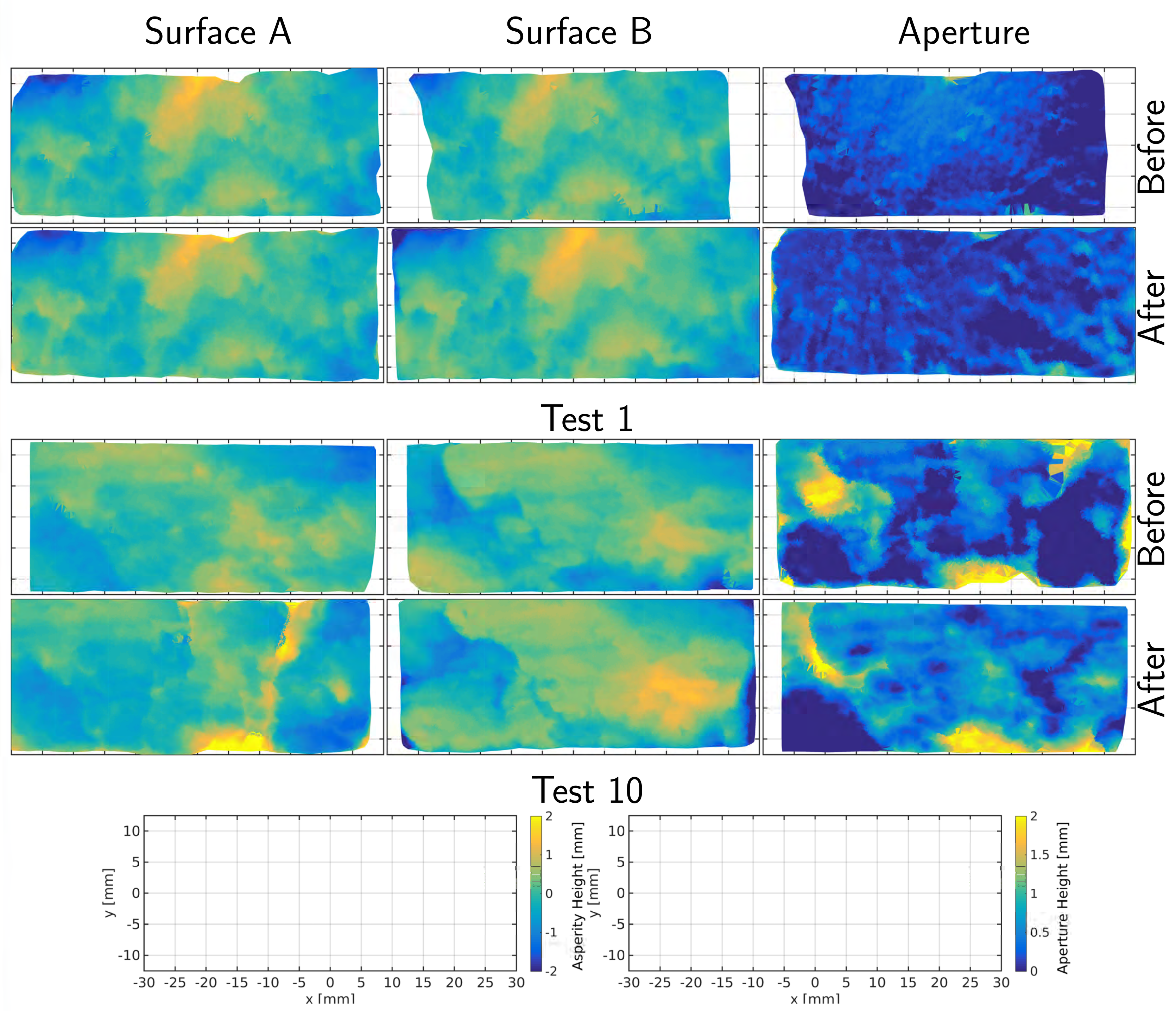
Changes of a_{mech} vs a_{hyd} are calculated by comparison to the initial values at 1 MPa. Changes in a_{mech} are always more pronounced than in a_{hyd}. Maximum changes in a_{mech} tend to be constant for $P_{conf,max}$, while changes in a_{hyd} converge.

Results - Transmissivity evolution for different shear offsets



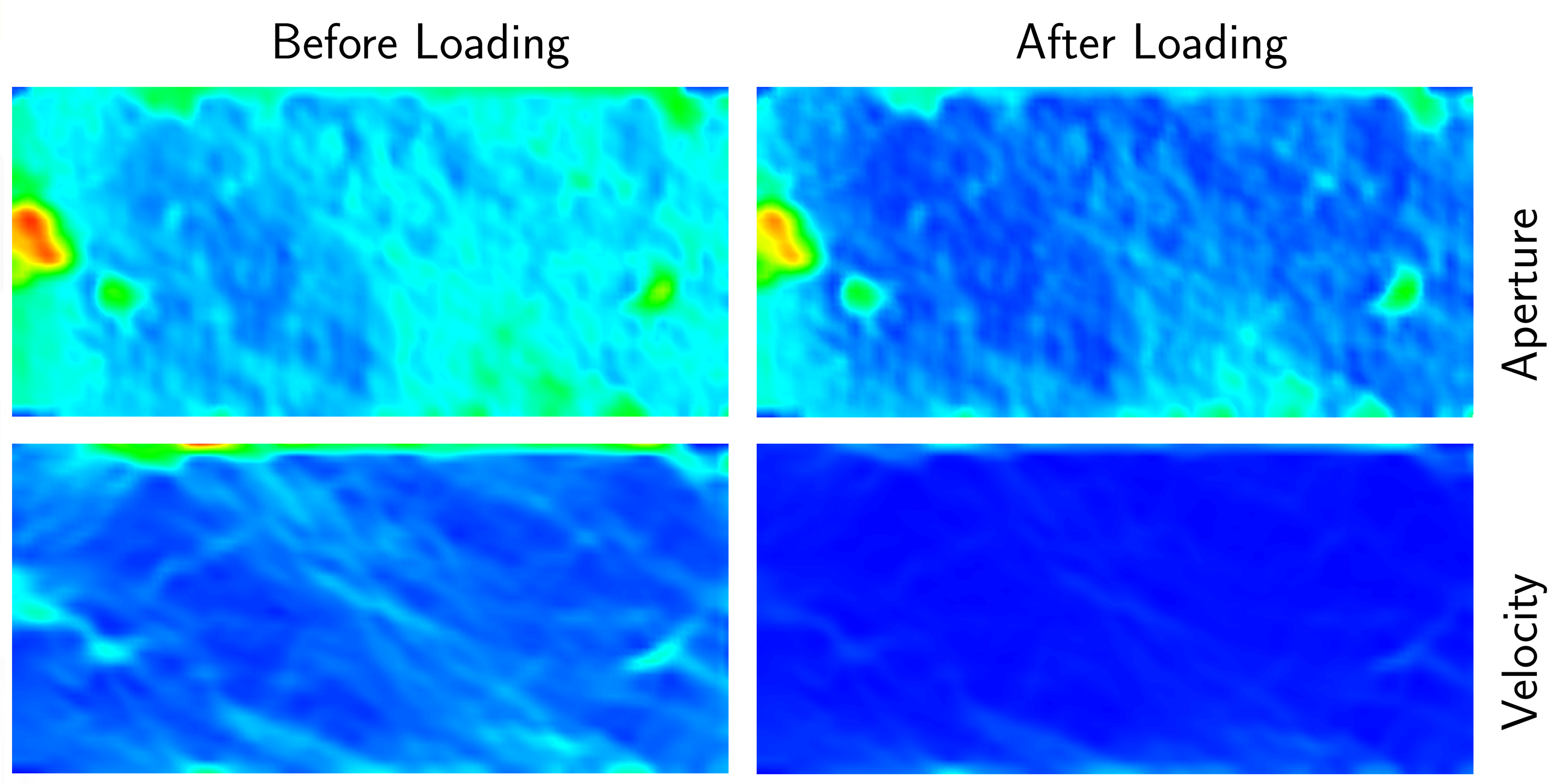
Transmissivity values at maximum confining pressure (a) and 1 MPa confining pressure after each cycle (b) for all normal loads vs sample offset for all samples. Cyclic loading progresses from the first cycle (smallest circle) to the last cycle (largest circle).

Fracture Surfaces Before and After Testing



Photogrammeteric scans of fracture surfaces before (top) and after (bottom) testing allow investigation of roughness, damage and strength between surfaces and apertures.

Hydro-Mechanically Coupled Flow in Fractures



Hydro-Mechanically coupled fluid flow during normal loading in the experiments is simulated with the GEOS framework developed at LLNL.

Conclusions

- Permeability generally decreased with ongoing loading cycles, pointing to non-elastic deformation of the fracture surfaces.
- Surface damage and increased gauge material in the fracture permanently decreased permeability.
- Gauge material is only flushed out of the fracture during decreasing normal loads, which can contribute to the observed hysteretic permeability behavior
- Mechanical aperture changes are significantly larger than hydraulic aperture changes
- Hydraulic apertures do not change for large confining stresses when fluid flow is restricted to channeling
- Experiments can be simulated in Hydro-Mechanically coupled model

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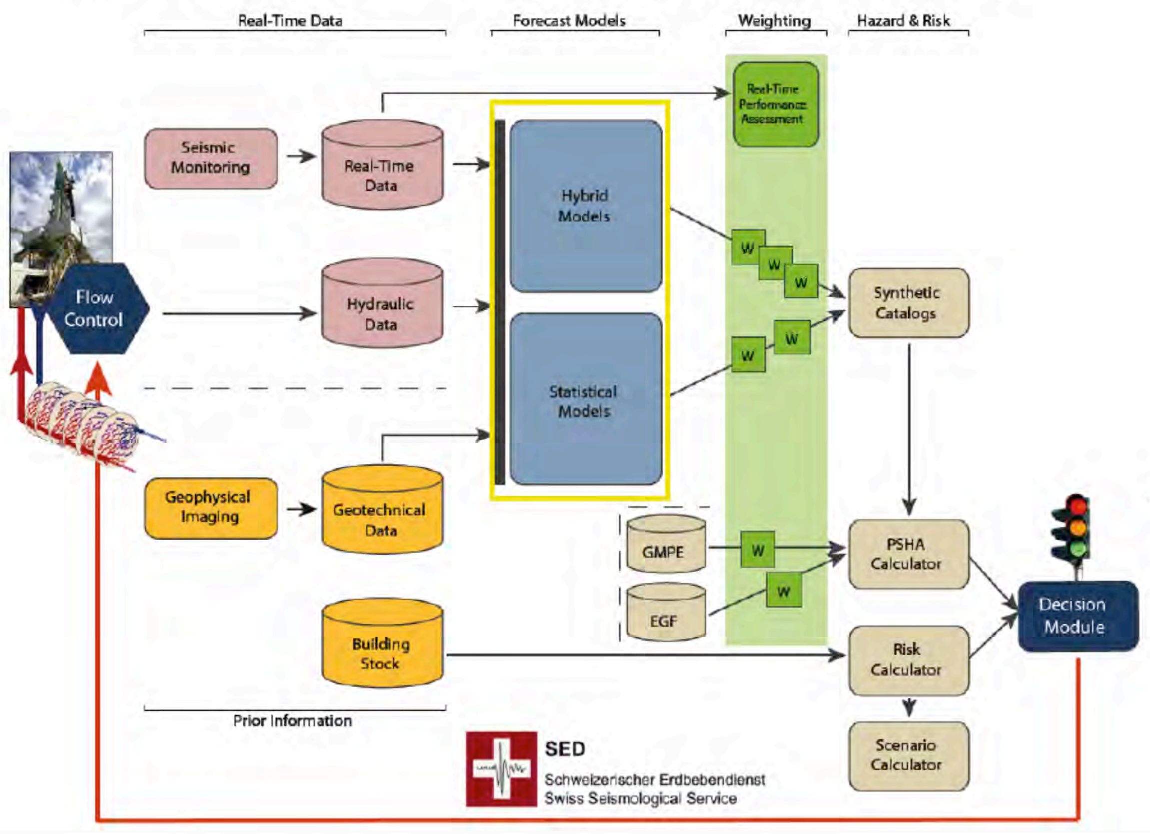
A coupled fluid flow–seismicity model for real-time assessment of induced seismic hazard and reservoir creation

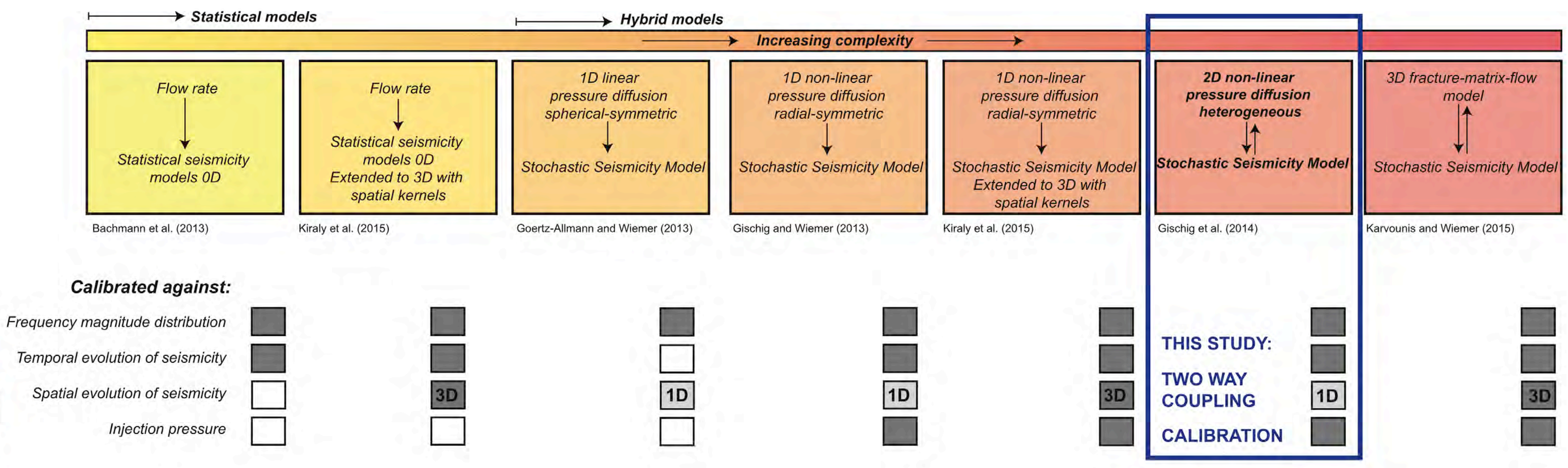
Valentin Gischig (ETH Zurich), Joseph Doetsch, Stefan Wiemer

Abstract: *New induced seismicity forecast models are currently being built and calibrated to become part of a real-time hazard assessment tool – the Advanced Traffic Light System ATLS. The models that currently are able to reproduce event numbers and statistics of observed induced seismicity sequences range from basic statistical models to so-called hybrid approaches. In the latter, seismicity is triggered by transient pressure changes modelled by linear or non-linear pressure diffusion models. A severe limitation of the current hybrid models is their loose coupling between seismicity and fluid flow, i.e. they include only one-way coupling from pressure to seismicity, but ignore the feedback of seismicity on the permeability field. We propose a new equivalent continuum fluid flow approach, in which seismicity is triggered by pressure diffusion on potential earthquake hypocenters randomly distributed in space. In addition, two-way coupling is enabled by enhancing permeability in the mesh cells intersected by the source area of the triggered earthquakes. Upon triggering the induced events are assigned a magnitude randomly drawn from Gutenberg-Richter distribution with a pre-defined b-value. The earthquake catalogues thus produced by a stochastic process exhibit a realistic statistical distribution. By enhancing permeability in dependence of slip that is estimated from magnitude and standard earthquake scaling laws, the model yields not only estimates of seismic hazard, but also of the degree of reservoir permeability enhancement obtained by the spent seismic hazard. In the framework of a real-time traffic light system, such a model would not only inform on the current seismic hazard, but also if the required reservoir properties have been achieved. The traffic light system could then be operated with two stop criteria: one based on seismic hazard, the other on based on reservoir size and properties. Here, we present the model procedure along with first results from joint calibration against induced seismicity data as well as wellhead pressure and flow rate as observed during the stimulation at the Basel EGS project in 2006.*

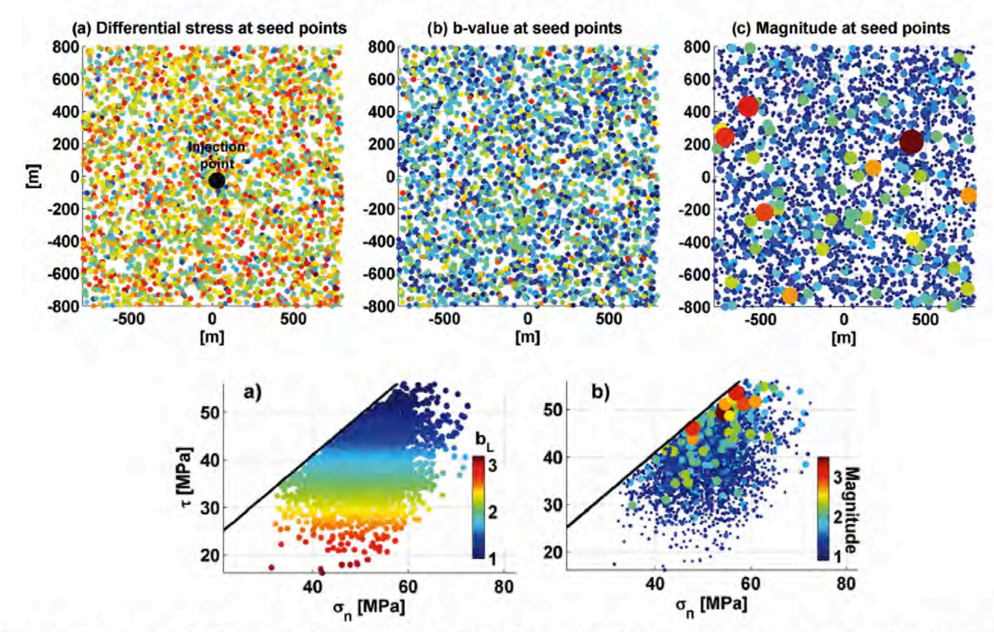
Real-time hazard assessment
The Advanced Traffic Light System (ATLAS)



Forecast Models:



Stochastic seismicity model



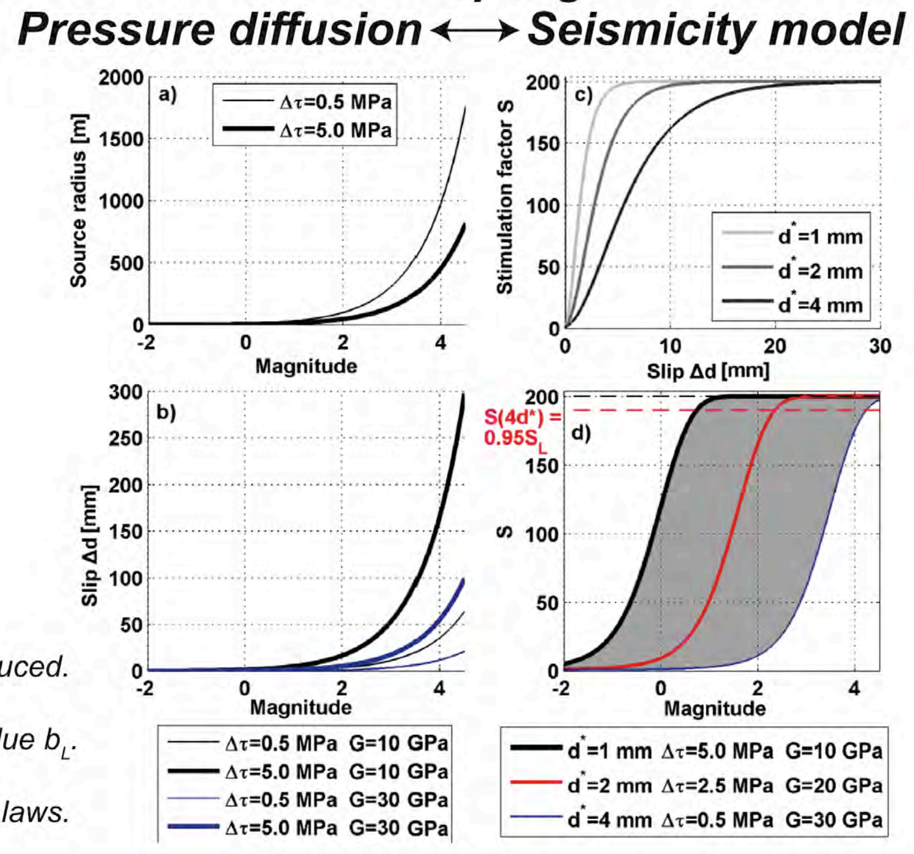
1 If fluid pressure is higher than Mohr-Coulomn failure pressure an earthquake is induced.

2 Magnitude is randomly drawn from a Gutenberg-Richter distribution with local b-value b_L.

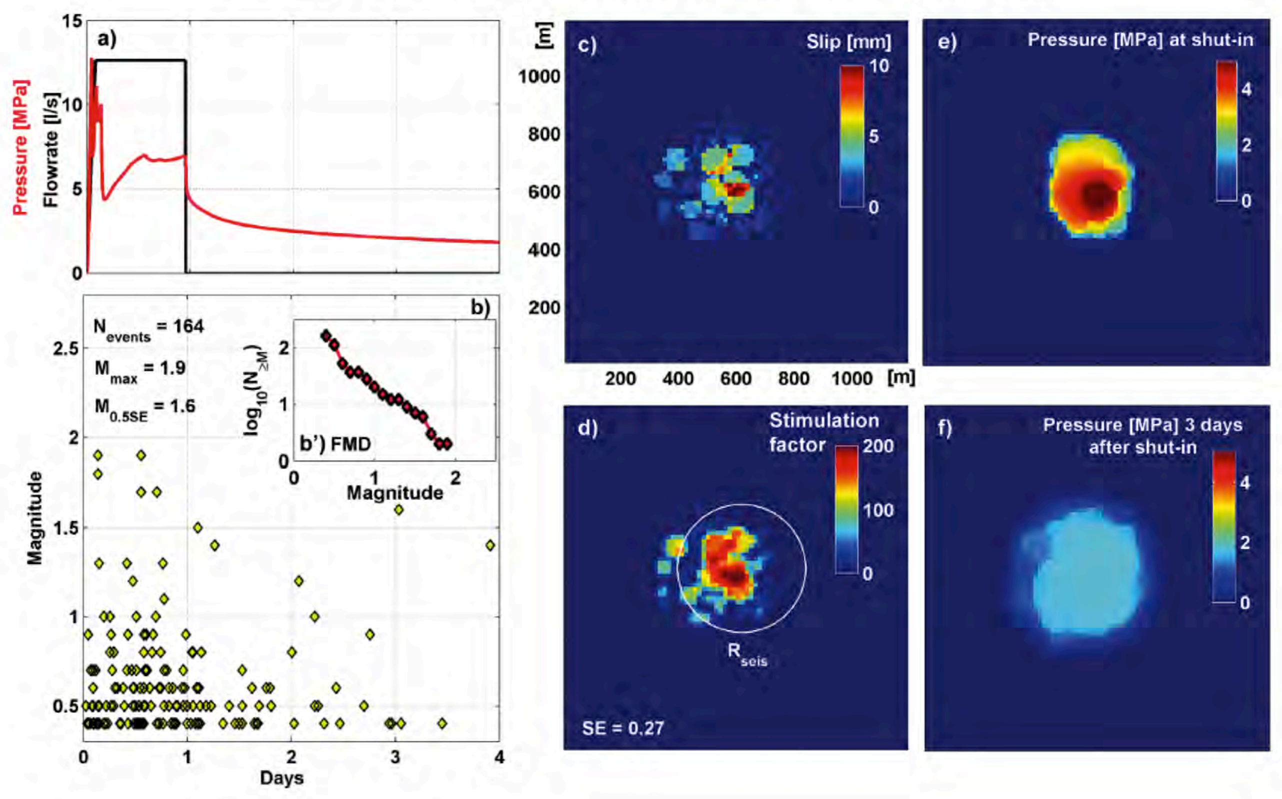
3 Source parameters (source radius, slip distance) are derived from standart scaling laws.

4 Within the source area permeability is increased as a function of slip.

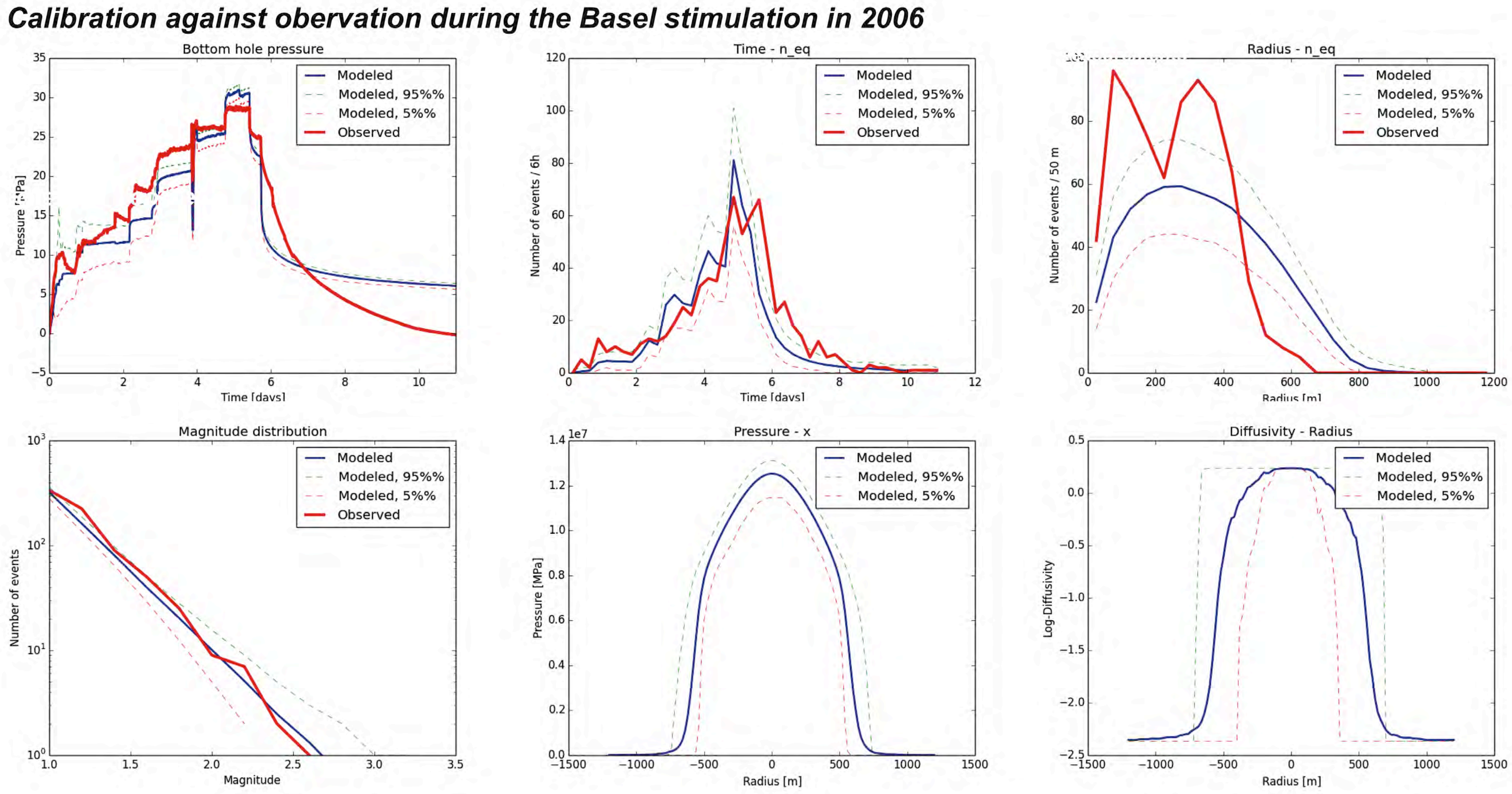
Coupling
Pressure diffusion ⟷ Seismicity model



A single model realization as example



Calibration against obervation during the Basel stimulation in 2006



Two-way coupled simulation implemented in Python using the FiPy software package for the non-linear difdussion simulation and MPI4Py for parallelisation. With the MPI parallelisation, the simulation scales perfectly up to 1000 CPUs (number of forward runs).

All model forecasts (injection pressure, spatial and temporal seismicity evolution, frequency-magnitude-distribution) comes as distribution based on >1000 realizations.

Strongest model sensitivity observed for maximum permeability increase S_L, and M_{min} the smallest magnitude modelled, and the seed density. M_{min} and seed density are strongly correlated and need to be varied in pairs. We find that it is important to model small earthquakes (0.0 < M < 0.9) that are below the magnitude of completeness, even if the number of earthquakes cannot be compared to the observed catalog.

Required computational resources:

- *One forward model (= 12 days of stimulation): computation time 10 min.*
- *For 1000 realizations: computation time using 48 cores is 3:20 hours on ETH Cluster EULER.*
- *Monte-Carlo calibration against learning period of 1 stimulation days estimated to be 6 hours on 1000 cores (360,000 forward runs).*

Conclusions

- *2D two-way coupled seismicity-fluid flow model can be calibrated against real observations (e.g. in Basel).*
- *Near-real-time performance is possible through massive upscaling*
- *Many application beyond real-time seismic hazard forecasting: e.g. scenario modeling, reservoir design tool.*
- *Design tool: it may be possible to estimate the heat exchanger properties that can be obtained at a predefined level of seismic hazard considered allowable for a project site.*
- *Scenarion models:*

  - It was shown that less than 10 magnitudes M ≥ 1.5 may contribute as much to permeability enhancement as more than 100 smaller ones.

  - At a given site, the achievable permeability enhancement is strongly tied to seismic hazard. Site specific conditions have a much larger impact on seismic hazard than injection strategy.

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Numerical simulations of fluid-rock interaction in enhanced geothermal and CO_2 injection systems - implications for the utilization of deep reservoirs in Switzerland

Peter Alt-Epping & Larryn W. Diamond
Rock-Water Interaction, Institute of Geological Sciences, University of Bern

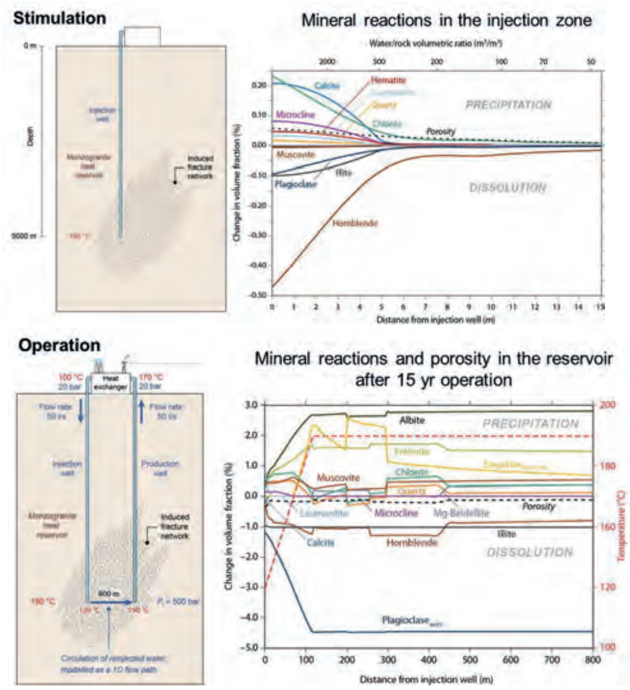
Abstract

Geothermal exploitation or the injection of CO_2 into a subsurface reservoir constitutes a perturbation of the physico-chemical conditions in the reservoir that may have been undisturbed for millions of years. This perturbation will invariably introduce disequilibrium, setting in motion a chain of processes which will alter the conditions in the reservoir and affect the safety and the sustainability of the operation. For instance, mechanical disequilibrium may trigger earthquakes, geochemical disequilibrium will initiate fluid-rock reactions leading to permeability changes in the reservoir, scaling or corrosion of wells or pipes, and/or the contamination of groundwater. Coupled numerical models are an important tool for elucidating and predicting the implications of subsurface utilization, for assessing what-if scenarios and for helping design monitoring or, in case of failure, remediation strategies.

1. Introduction

With the decision to abandon nuclear energy production in Switzerland, alternative sources for energy have to be found. One of these potential sources is geothermal energy from high enthalpy systems. Owing to moderate geothermal gradients in Switzerland, these systems have to be installed at depths of at least 5 km, that is in the crystalline basement. As the basement rock exhibits low primary permeability, hydraulic stimulation is required to create pathways for the circulating fluid.
To avoid energy shortages during the transition to a nuclear free energy production, an option is to build gas fuelled power plants in which case solutions have to be found to extract and store the CO_2 which would be released as a byproduct. One possible solution is the sequestration of CO_2 in deep saline aquifers in the Swiss Molasse, such as the Trigonodus Dolomite of the Upper Muschelkalk formation.
We present results from numerical simulations which address 1) the chemical implications of operating an enhanced geothermal system (EGS) in the crystalline basement in Switzerland patterned after the abandoned project in Basel and 2) the implications and the feasibility of storing CO_2 in the Trigonodus Dolomite.

2. Geochemical implications of an EGS operation in the crystalline basement

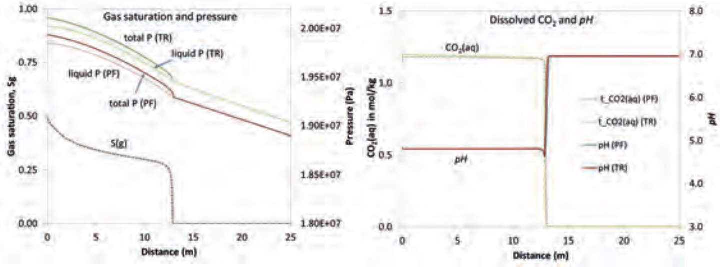


Carbonate precipitation, ferric alteration, feldspar hydrolysis and albitization are the main alteration processes during stimulation and operation, respectively. Porosity/permeability changes during stimulation and operation are negligible.

3. Geochemical implications and feasibility of CO_2 sequestration in the Upper Muschelkalk

Benchmarking PFLOTRAN

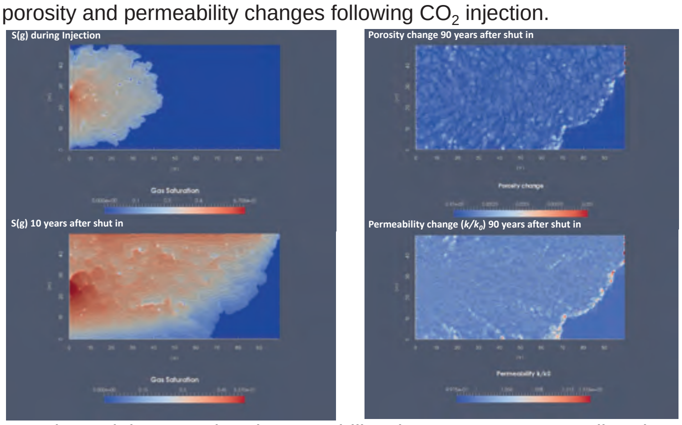
We use the reactive transport code PFLOTRAN (www.pflotran.org) to simulate scenarios of CO_2 injection into a carbonate aquifer patterned after the Upper Muschelkalk aquifer in N-Switzerland. As PFLOTRAN is a recent and ongoing code development project, we benchmark it against the well tested and widely used code ToughReact.



PFLOTRAN uses a somewhat simpler implementation of the CO_2-H_2O-NaCl system, introducing minor error. However, the better computational performance and less numerical dispersion makes it our code of choice.

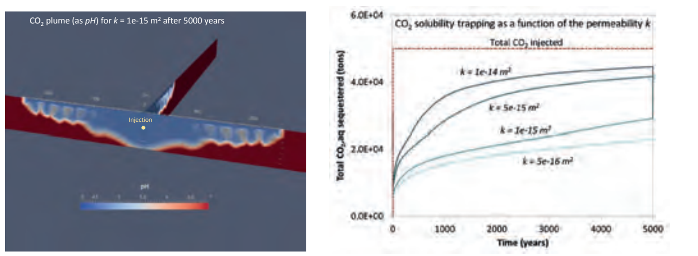
Injecting CO_2 into a carbonate rock - the effect on permeability

The Trigonodus dolomite of the Upper Muschelkalk is composed of dolomite and minor calcite and anhydrite. We implement a normally distributed porosity, permeability and mineral composition to assess the porosity and permeability changes following CO_2 injection.



Porosity and the associated permeability changes are very small and are not likely to affect injectivity or plume migration.

Chemical CO_2 trapping capacity in a carbonate hosted aquifer



CO_2,sc dissolution is the only effective mechanism of chemical trapping. Its efficiency is among other things strongly dependent on the permeability and permeability distribution in the aquifer.

4. Conclusions

We us reactive transport simulations to gain insight into chemical processes in geothermal or CO_2 injection systems. Simulations help assess potential risks (e.g. pore clogging, scaling, corrosion, mobilization of toxic components), enhance performance by assessing optimal conditions and develop monitoring or remediation strategies.

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CSMP++ 3D reservoir simulator for modeling permeability and stimulation for deep heat mining

James Patterson, Thomas Driesner, Rolf Kraus

Background: Enhanced Geothermal Systems (EGS)

A typical geothermal project extracts the hot fluid initially present in a porous, permeable, and usually sedimentary reservoir. The hot fluid is brought to the surface, used for either electricity generation (if possible) or space heating, and reinjected to the reservoir to replace the fluid extracted. In EGS, the reservoir is composed of fractured, crystalline bedrock, such as granite. The rock matrix in these reservoirs has negligible porosity and permeability, thus the circulating fluid must propagate through fractures in the subsurface and extract the heat from the hot, dry rock (HDR). Even in naturally fractured rock, there is no guarantee that well-to-well fracture connectivity exists or that an adequate amount of water throughput is possible. Therefore, the reservoirs must be enhanced through hydraulic stimulation known as "hydro-shearing," in which water is injected at elevated pressures that allow pre-existing fractures to shear under in-situ reservoir stresses. Ideally, these slip events increase the overall reservoir transmissibility.

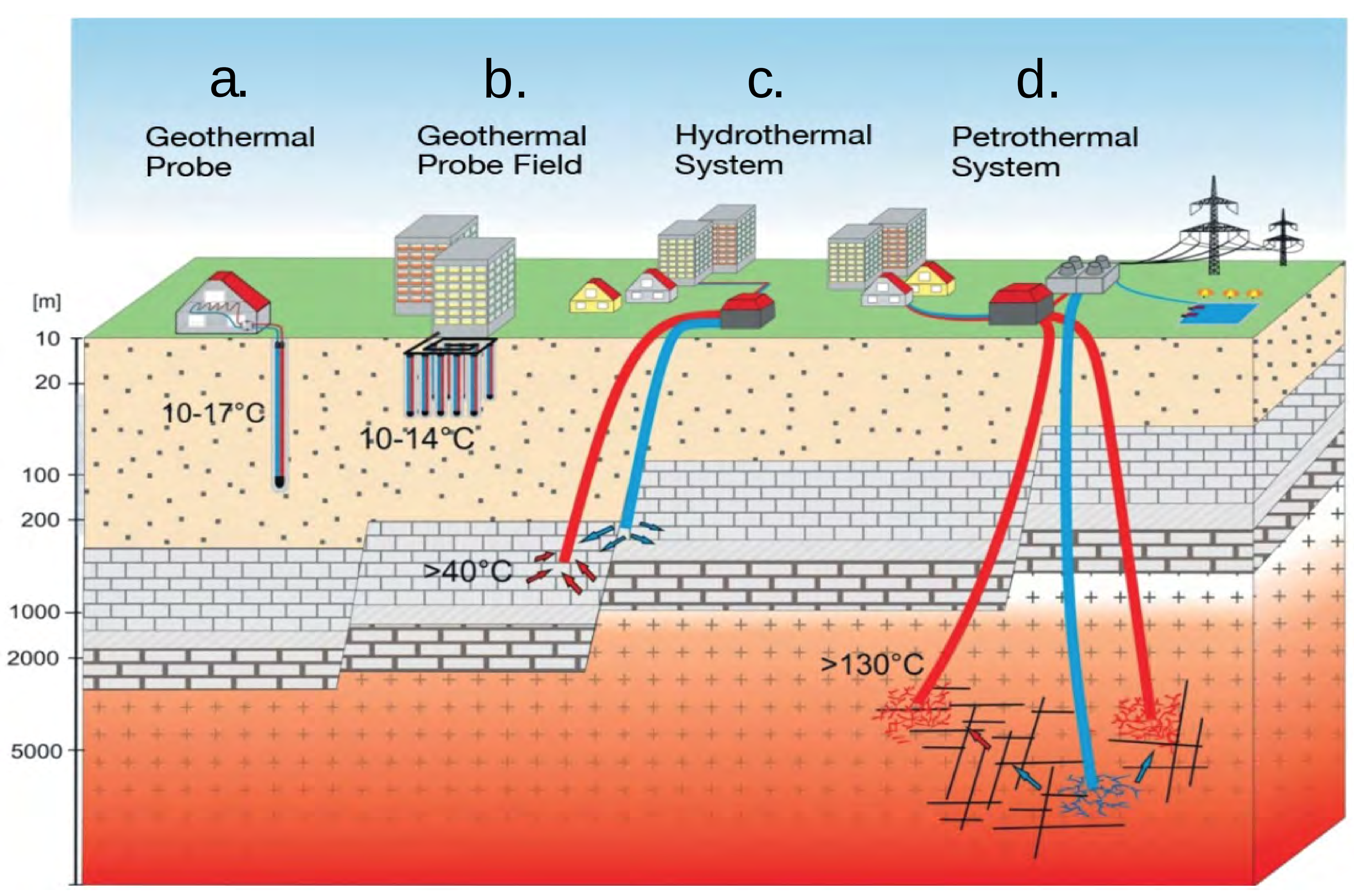

Fig. 1. *Traditional geothermal techniques are shown in (a.), (b.), and (c.), while an EGS project is shown in (d.).* [1]

Objective: Accurately Simulate Fluid Flow and Breakthrough

Substantial fracture connectivity and transmissibility still does not guarantee success in EGS. The heterogeneity of fracture orientation, distribution, and size could cause fluid to bypass a significant portion of the reservoir, resulting in decreased extracted water temperature. Simulating these effects leads to more realistic prediction of expected energy output.

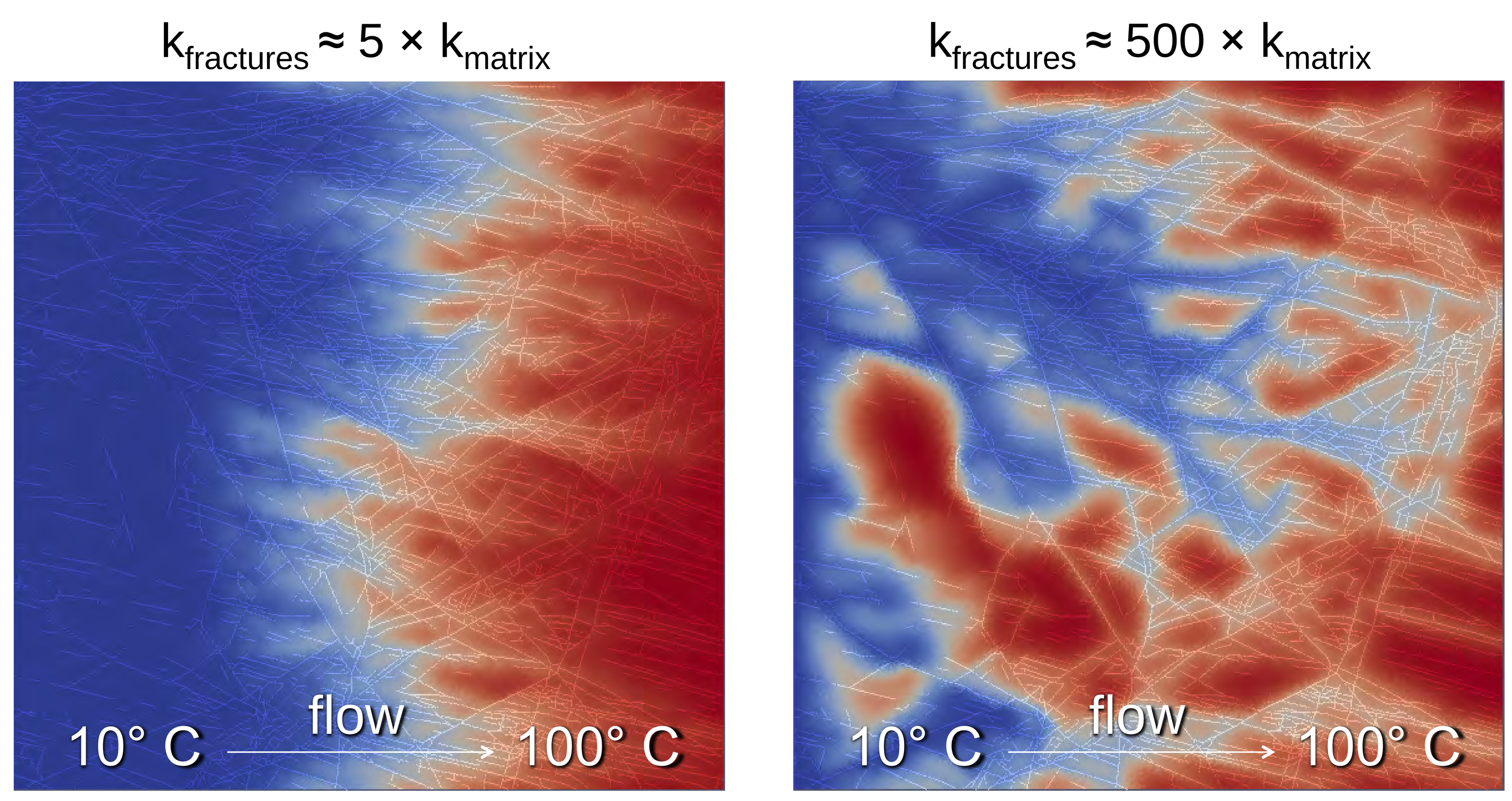

Fig. 2. *Cold (10°C) water injection into a hot (100°C) fractured reservoir. Fracture permeability on the right figure is 100 times larger than the left (using CSMP++ with altered parameters from [2]).*

Impact of Fracture Heterogeneity

Each fracture has it's own heterogeneous aperture distribution that will cause fluid to channel along preferential flow paths. In 3D, fluid flow through a fracture network already has poor reservoir sweep, due to the fluid flowing in 2D plane fractures. With the effect of individual fracture heterogeneity, the flow is further concentrated into 1D tube-like channels, leaving large portions of the thermal reservoir untouched. Future work will consider how this effect impacts the overall heat extraction efficiency of EGS projects.

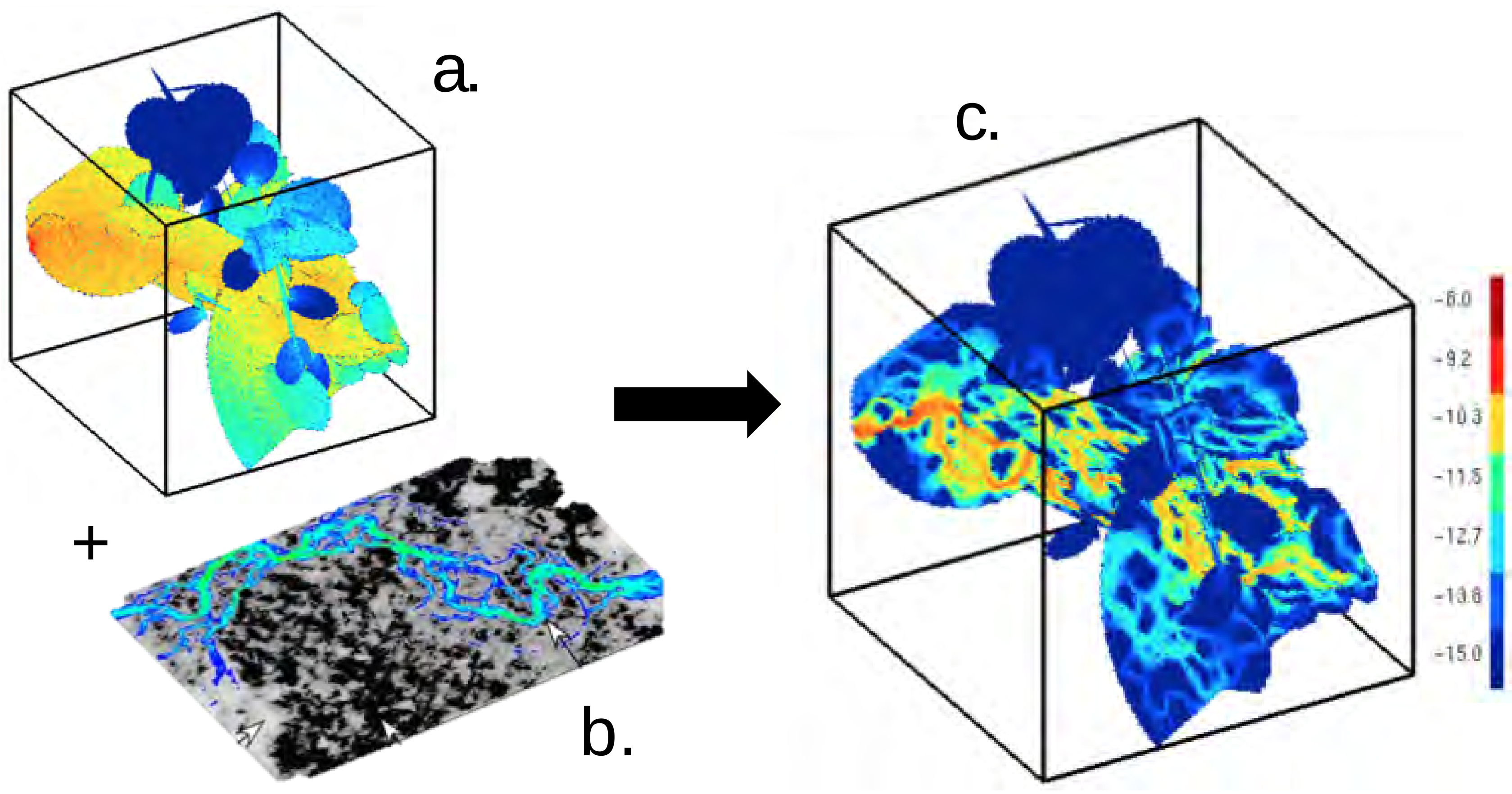

Fig. 3. *The combination of flow in a fracture network (a.)*[3] *and flow in a heterogeneous fracture (b.)* [4] *results in a highly channelized flow (c.)*[3] *with poor reservoir sweep efficiency. Scale on right displays logarithm of mean flow value*

THMC Modeling

The permeability and connectivity of the fracture networks in EGS reservoirs is a key component in determining the flow rate and temperature of the extracted water, and therefore the project's success. These fracture properties are dynamic, changing in response to rock temperature (T – thermo), fluid pressure (H – hydrologic), stress-state (M – mechanical), and precipitation/dissolution (C – chemical). While THM processes begin to affect the fractures quickly, chemical alteration generally occurs later in the life of the EGS field4. Future work will attempt to accurately simulate THM (and C, if possible) processes on geologically realistic geometries using the Complex Systems Modeling Platform (CSMP++), developed at ETH Zurich.

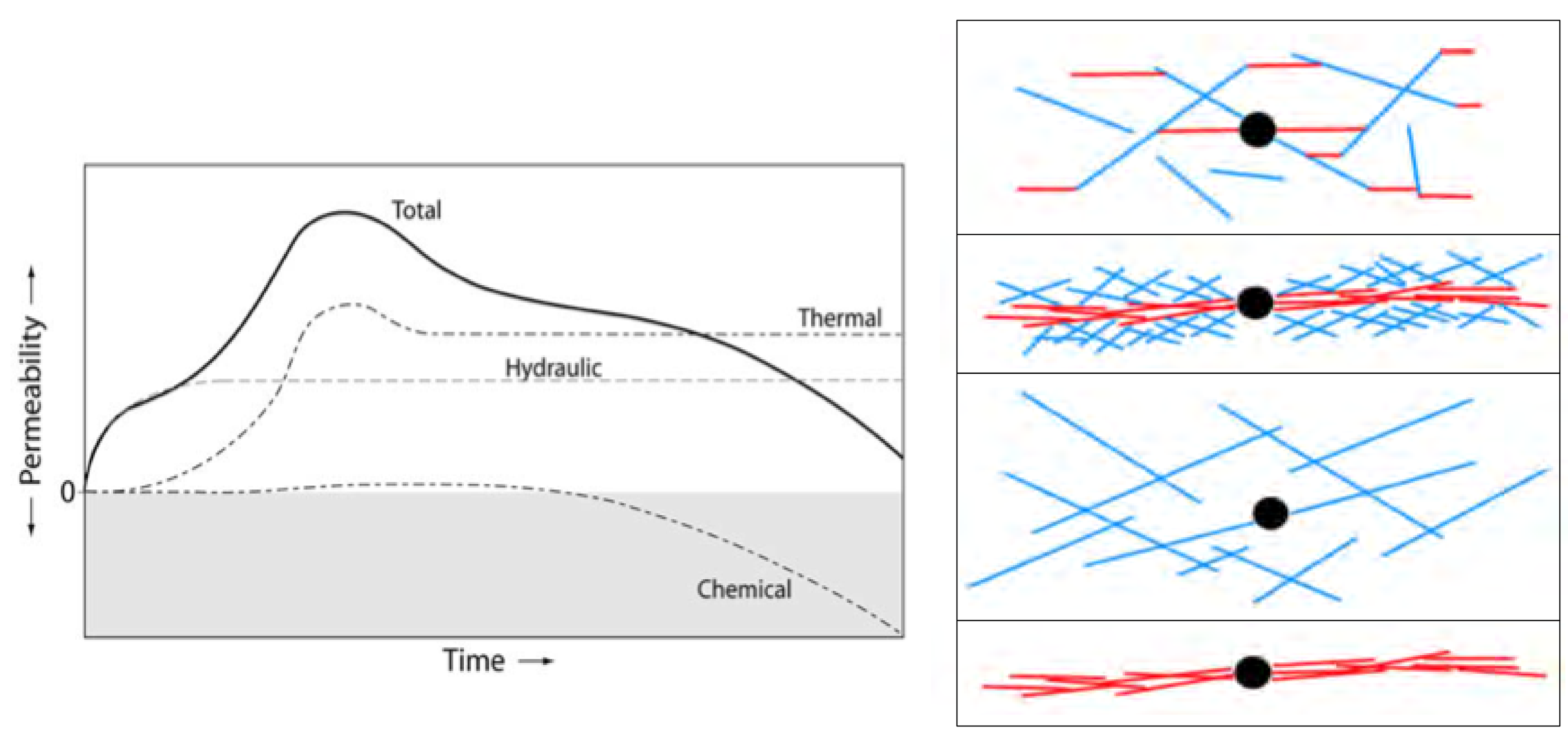

Fig. 3. (left) *Relative time scales of the processes e ects on fracture permeability throughout reservoir's life.* [5]
(right) *Various geomechanical possibilities of fracture network growth around a well during stimulation.* [6] *Red lines represent new fractures due to tensile failure; blue lines represent preexisting fractures enlarged due to shear slippage.*

[1] Schwarz, K., Rauch, T. (2014), Deep Geothermy #1: Energy from the Earth's crust. Retrieved from http://explore-house.eu/en/2014/02/12/deep-geothermy/
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Geochemical effects on long-term permeability evolution and heat extraction

Julian Mindel and Thomas Driesner, Institute of Geochemistry and Petrology, ETH Zurich

Abstract / Background

Reactive transport through irregularly fractured rock masses is a key phenomenon in ore-forming hydrothermal systems, geothermal systems, and many other geological processes and will affect the mechanical properties and hydraulic apertures of fractures.

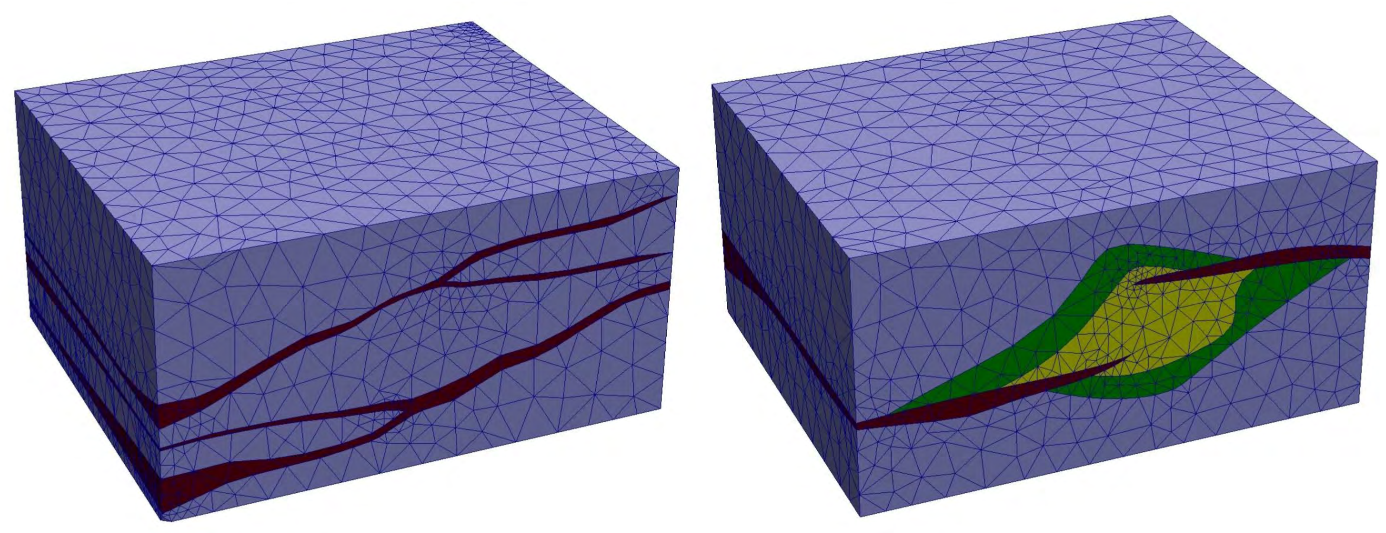
Realistic representations of such systems have so far been hampered by technical limitations of most hydrothermal reactive transport codes, namely the ability to represent discrete fracture networks in a porous rock matrix.

This poster is a progress report on our work on coupling a combined finite element – finite volume scheme of the revised CSMP++ flow simulation platform [1] with the GEMS3K [2] chemical equilibration code.

We show two synthetic geometries in which fracture zones are represented as thin, porous zones of higher permeability but with non-uniform shapes. This work is a further step towards modeling reactive transport with realistic representations of discrete networks of thin fractures in large porous rock masses. Understanding the interaction of coupled processes such as mineral precipitation and dissolution, fluid flow, thermal effects, buoyancy, and mechanics is key for risk assessment and planning of Enhanced Geothermal Systems (EGS).

Methododology

Honoring the governing equations for compressible porous media flow and chemical transport in our simulator, we designed two synthetic geometries to study the propagation of a dolomitization front using the chemical conditions of the benchmark by Engesgaard and Kipp [3].



Conditions chosen in that benchmark minimize feedbacks resulting from porosity changes, etc.. The left side of the simulation boxes is applied a Dirichlet boundary condition for aqueous Mg and a left to right pressure gradient is applied to induce flow.

In the model setup, calcite is considered to form a thin coating on pore walls and reacts to dolomite with the incoming aqueous Mg chloride solution.

Outlook

We are currently working towards adopting the CSMP++ "split node" approach [4] for reactive transport. In this approach, nodes at material boundaries are duplicated to allow an accurate calculation of fluid flow transport (although likely applicable to other processes as well) across material interfaces, in particular between fractures and matrix rock.

Simultaneously, we are working on improving the current THMC couplings in the code. The main new implementation is the inclusion of temperature effects.

As a further improvement, and given that chemical calculations within the simulator are expensive CPU-wise, we are currently working on the parallelization of that part of the process. Both OpenMP (for simulations in shared memory systems) and MPI (for distributed memory systems) are under construction and testing.

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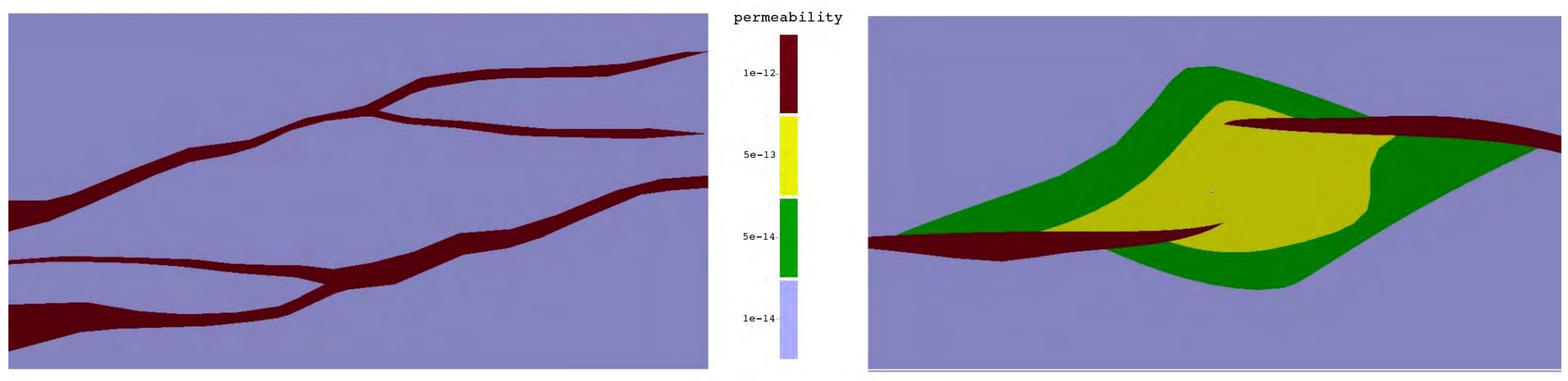

Figure 1: Geometry 1 (left cross-section) is aimed at showing the propagation of the dolomitization front through a porous matrix with two fracture zones of higher permeability. Geometry 2 (right cross-section) mimics a fault stepover with damaged matrix in the stepover zone. Both geometrical cross-sections vary slightly across the third dimension in an attempt to trigger non-uniform advancing chemical fronts.

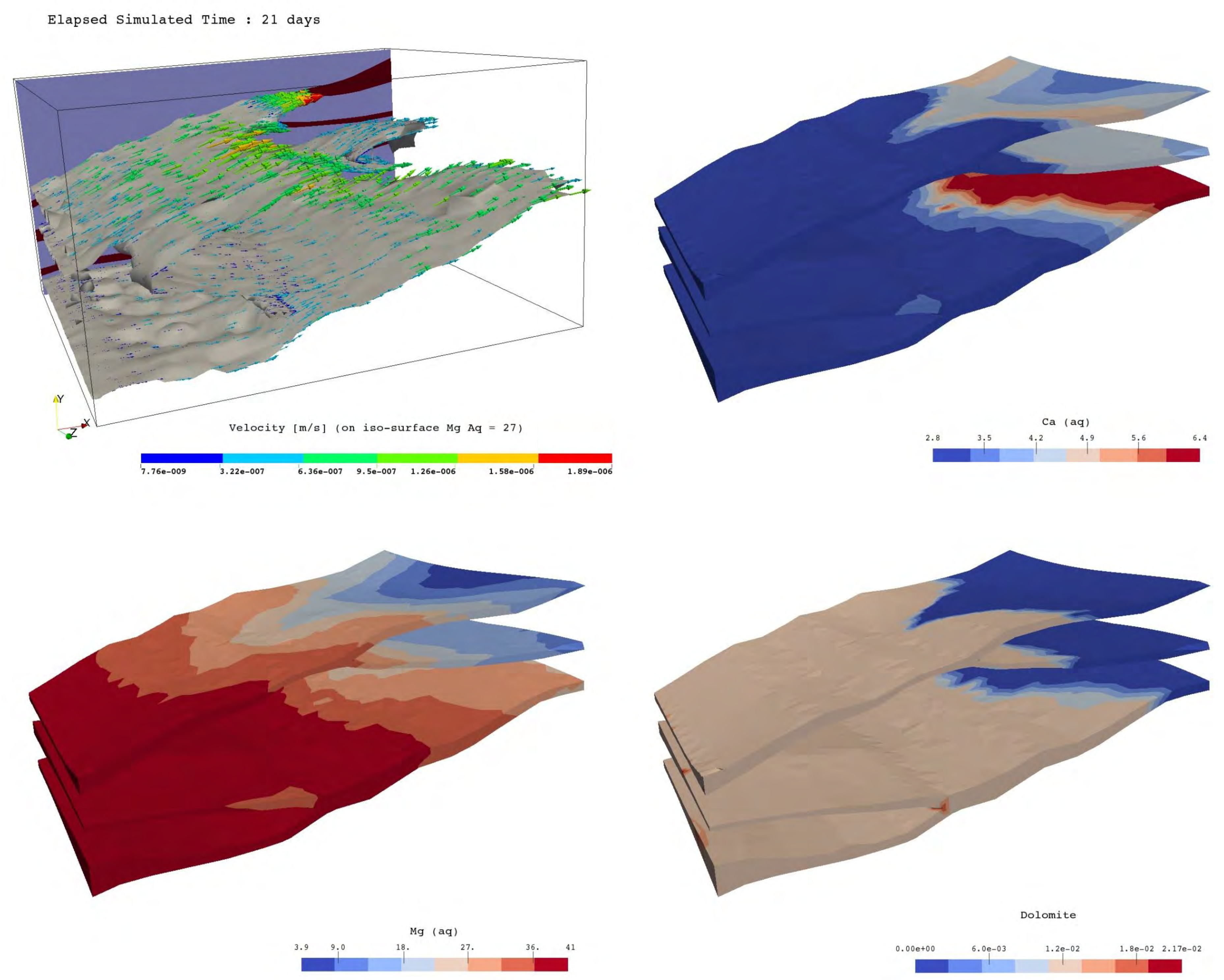

Figure 2: Due to thickness variations inside the fracture zones, their orientation in the fluid pressure field, and the effects of branching on fluid pressure gradients, the chemical front advances heterogeneously.

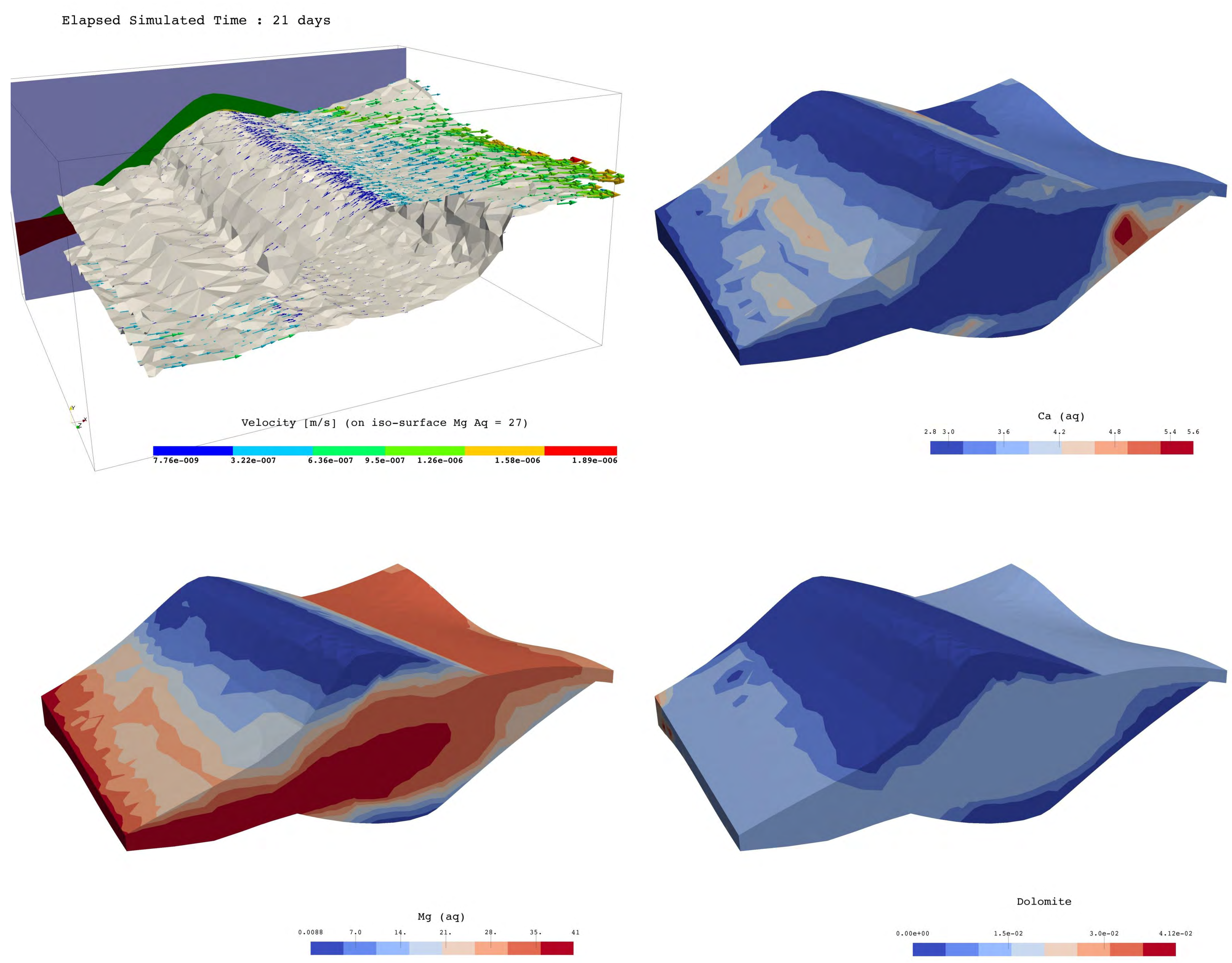

Figure 3: Also here, non-uniformity of the geometry leads to heterogeneous advancement of the chemical front.

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Impact of liquid and supercritical CO_2 injection on host rock properties

Roman Makhnenko, Danila Mylnikov, and Lyesse Laloui

Soil Mechanics Laboratory – chair «Gaz Naturel» Petrosvibri, École Polytechnique Fédérale de Lausanne

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1. Introduction

Research of the chair "Gaz Naturel" – Petrosvibri at the EPFL contributes to SCCER-SoE task 1.2: "Reservoir modelling and validation". Both numerical modeling and experimental investigation of geomechanical processes involved in deep geological storage of CO_2 are performed in cooperation with government agencies: SFOE and Swisstopo. Proper assessment of carbon dioxide storage procedure allows to significantly reduce its concentration in the atmosphere and thus directly contributes to Swiss energy strategy 2050.

Deep saline aquifers have the greatest potential for geological storage of carbon dioxide and due to their worldwide occurrence can play a major role in reduction of carbon dioxide emissions. Injected CO_2 changes the local effective stresses and temperatures and thus can significantly deform the aquifer and the surrounding media. Sandstone reservoirs, which mostly are high-permeable single-porosity systems, are usually considered as a host rock material. The ongoing experimental investigations involve conventional triaxial and oedometric tests, where carbon dioxide is injected in water-saturated host rock material at different temperatures and pressures. This poster presents the current findings on CO_2 saturation and flow in sandstone.

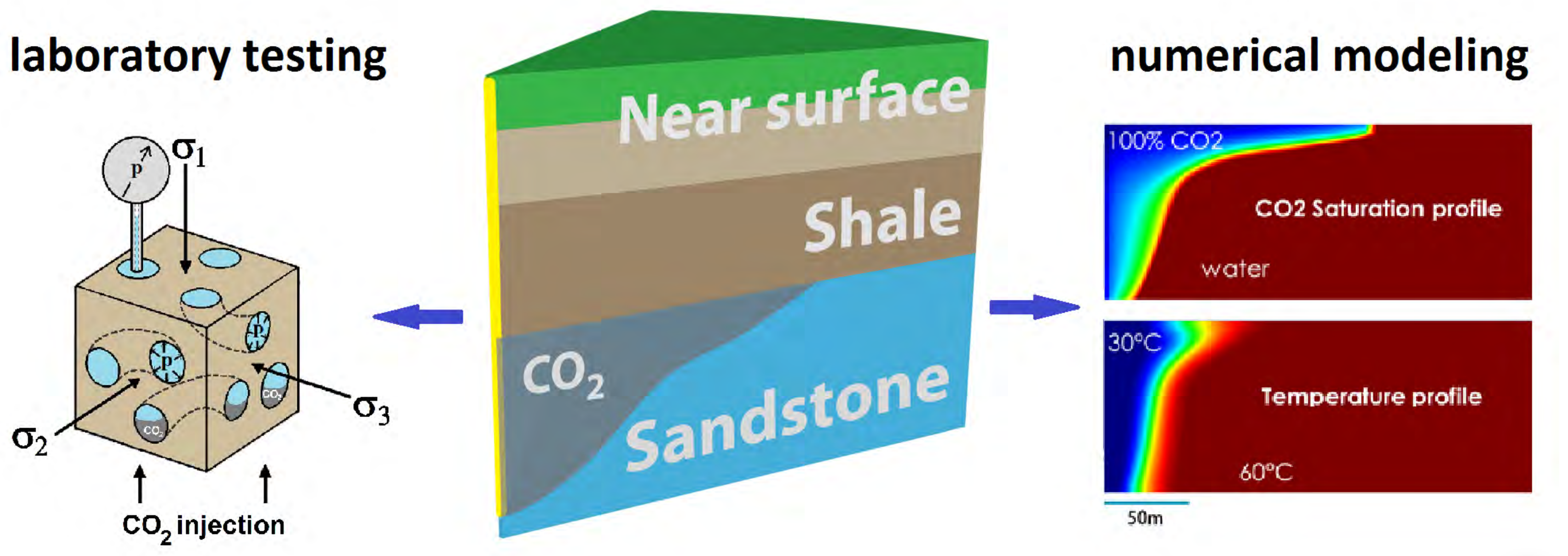

Fig. 1: Sketch of the research activities on geologic CO_2 sequestration.

2. Background and methods

CO_2 is usually injected in liquid state and, in sedimentary basins at depths below 800 meters, it changes its phase to supercritical fluid ($scCO_2$), which means that its temperature and pressure are above 31.1° C and 7.4 MPa. Carbon dioxide then can dissolve in the *in-situ* fluids and be trapped stratigraphically under the low permeable cap rock and in pore space of the storage formation, as well as by reacting with minerals that form it.

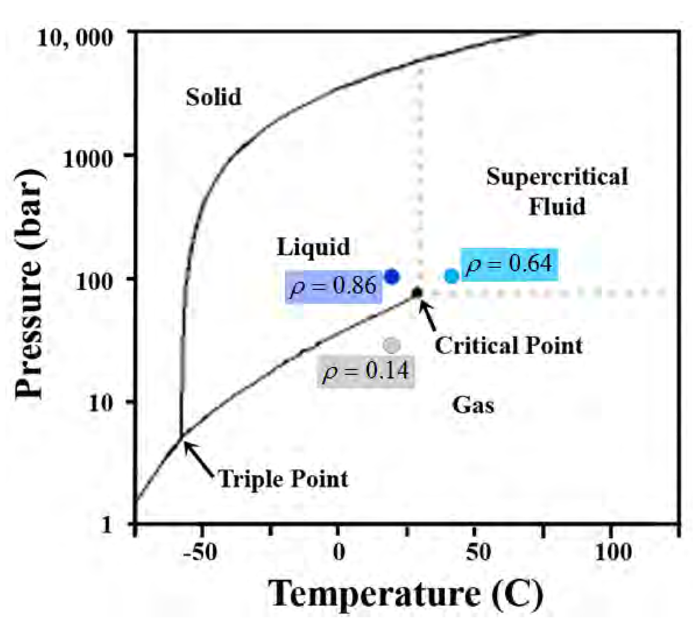

Fig. 2: CO_2 phase diagram.

CO_2 and CO_2-rich water injection tests were performed on cylindrical specimens (height h = 12.5 mm diameter D = 35 mm) loaded in oedometric cell (zero lateral strain). Liquid (20°C) and supercritical CO_2 (39°C) were injected at pressure p_f = 10 MPa and effective mean stress P' = 6 MPa. The effective permeability for i-th phase was calculated from knowledge of fluids viscosity μ_i and measurements of volume outflow ΔV_i per time Δt:

$$k_i^{eff} = \frac{4 \cdot \Delta V_i \cdot \mu_i \cdot h}{\pi \cdot \Delta t \cdot D^2 \cdot \Delta p_f}$$

The relative permeability for i-th phase is

$$k_i^{rel} = \frac{k_i^{eff}}{k_{abs}},$$

where k_{abs} is the absolute kinematic permeability of rock.

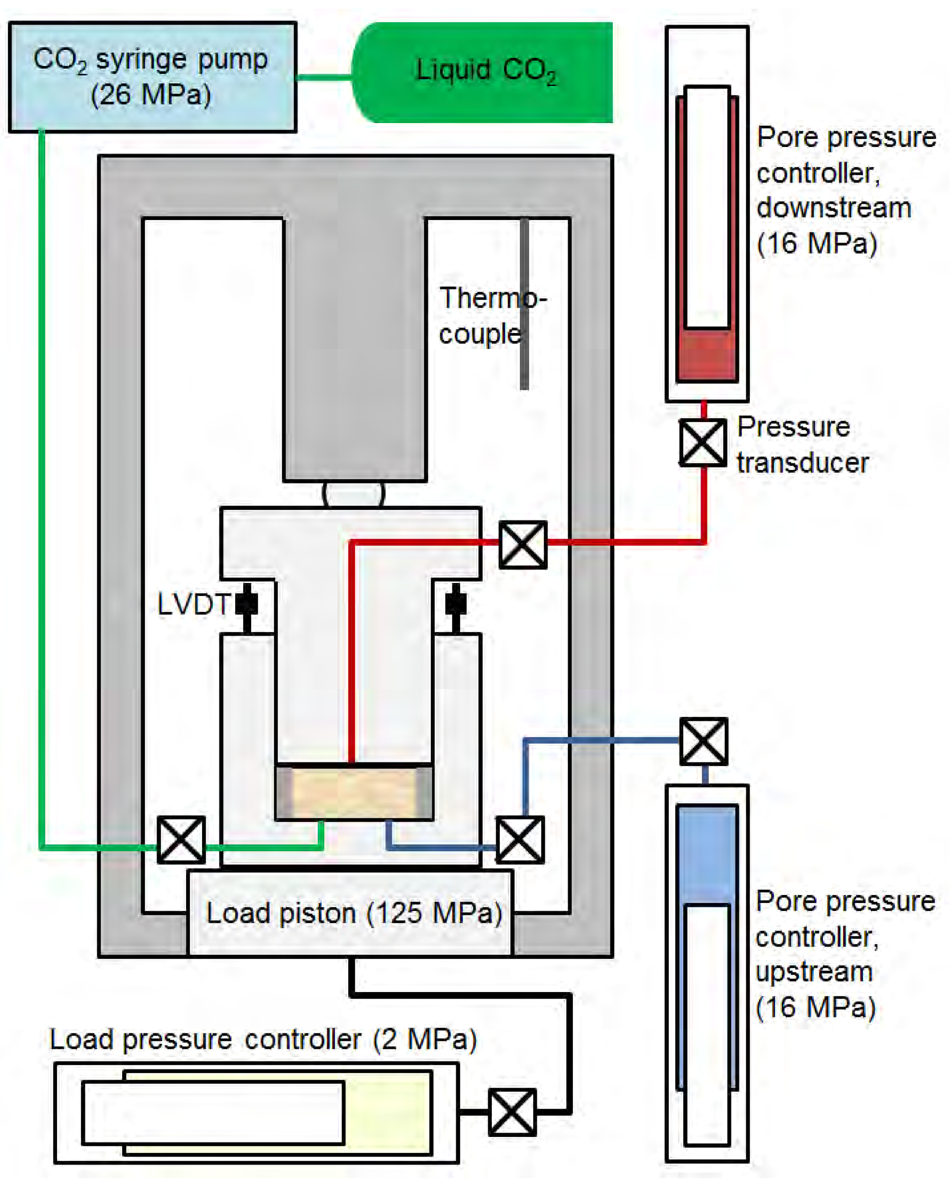

Fig. 3: Experimental setup: oedometric cell.

3. Results and Discussion

Berea sandstone is quartz-rich rock with 23% porosity, 60 mD permeability, and 20 mm dominant pore diameter. The rock was fully saturated with water at p_f = 10 MPa and its poroelastic parameters (Makhnenko and Labuz, 2015) and permeability at different temperatures (Figure 5) were measured.

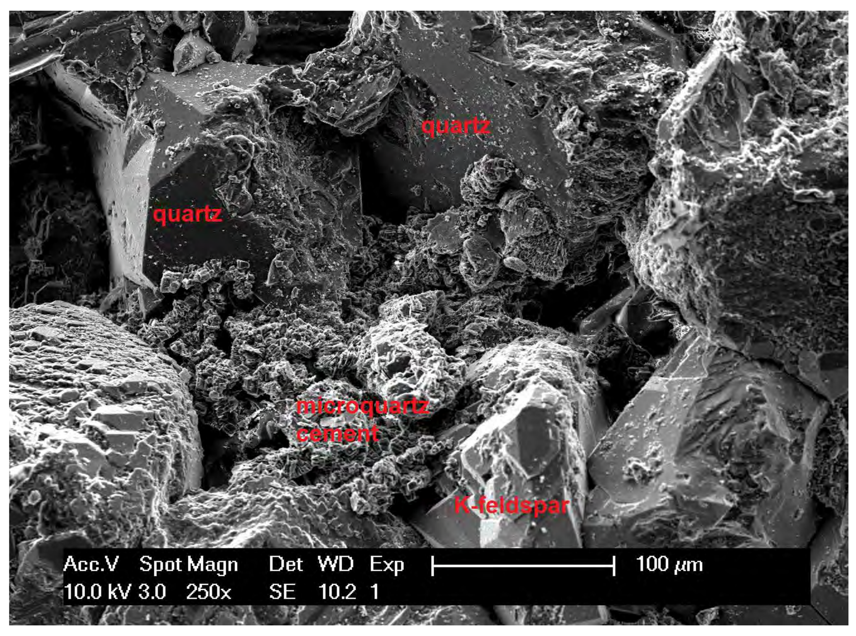

Fig. 4: Microphotograph of Berea sandstone.

Then CO_2 and CO_2-rich water were injected and residual water saturation after CO_2 flow reached the steady-state condition was evaluated from measurements of Skempton's B coefficient, which reflects the compressibility of pore fluid. Relative permeability of liquid CO_2 was found to be 20% larger than the one at supercritical state and both of them are within the reported trends for high-permeable rocks. Slightly different curves were obtained for relative permeability of water at different temperatures and the results are fitted with two different models.

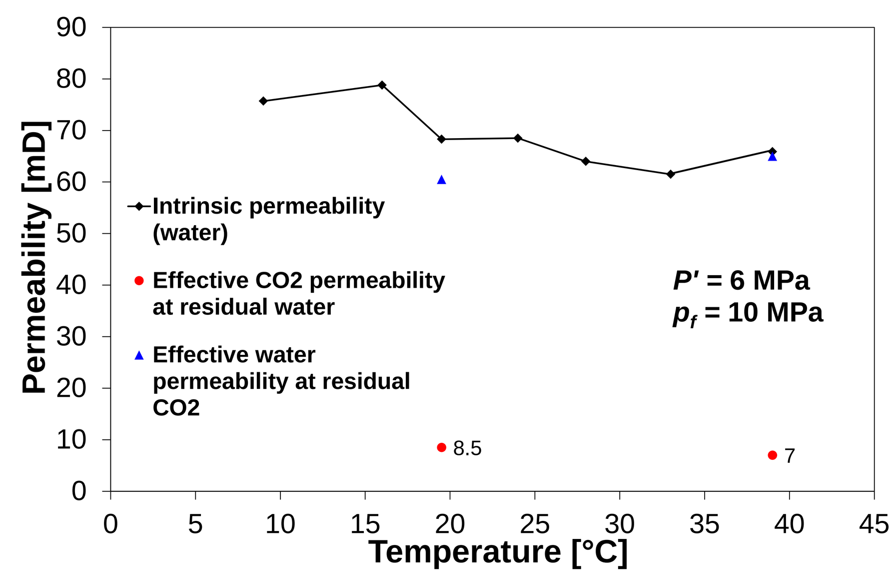

Fig. 5: Water and CO_2 permeability of water-saturated sandstone at different temperatures.

Brooks and Corey (1964) predict:

$$k_w^{rel} = \left(S_w^*\right)^{N_w}$$

where saturation parameter S_w*:

$$S_w^* = \frac{S_w - S_w^{res}}{1 - S_w^{res}}$$

Van Genuchten (1980) assumes:

$$k_w^{rel} = \sqrt{S_w^*}\left\{1 - \left(1 - \left[S_w^*\right]^{1/m}\right)^m\right\}^2$$

Parameter N_w was calculated to be 2.7 at 39°C and 4.2 at 20°C. Van Genuchten m-parameter gives the best fit for m = 0.80 at 39°C and m = 0.78 at 20°C. Both models do not capture observed local increase in relative water permeability at S_{H_2O} = 0.6, so it has to be explored further.

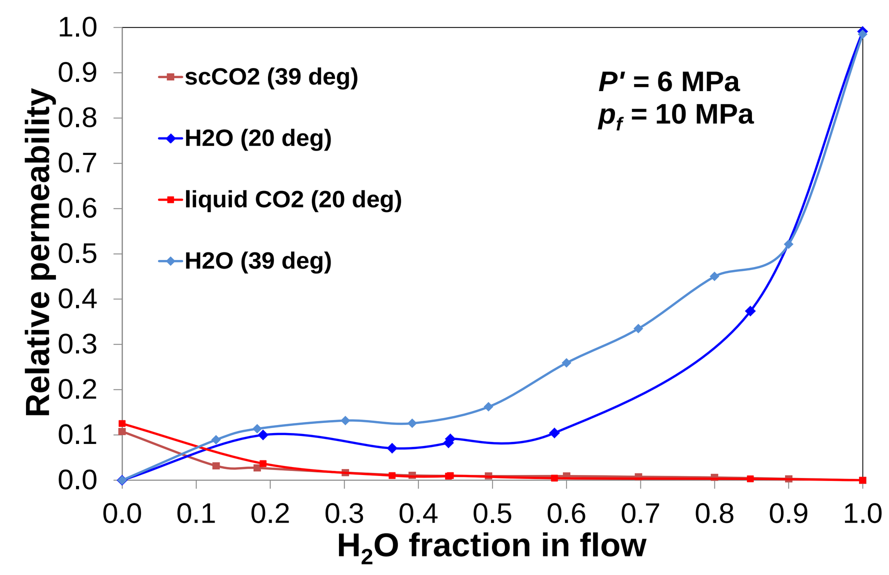

Fig. 6: Relative permeability of H_2O and CO_2 at 20˚C and 39˚C vs H_2O fraction in flow.

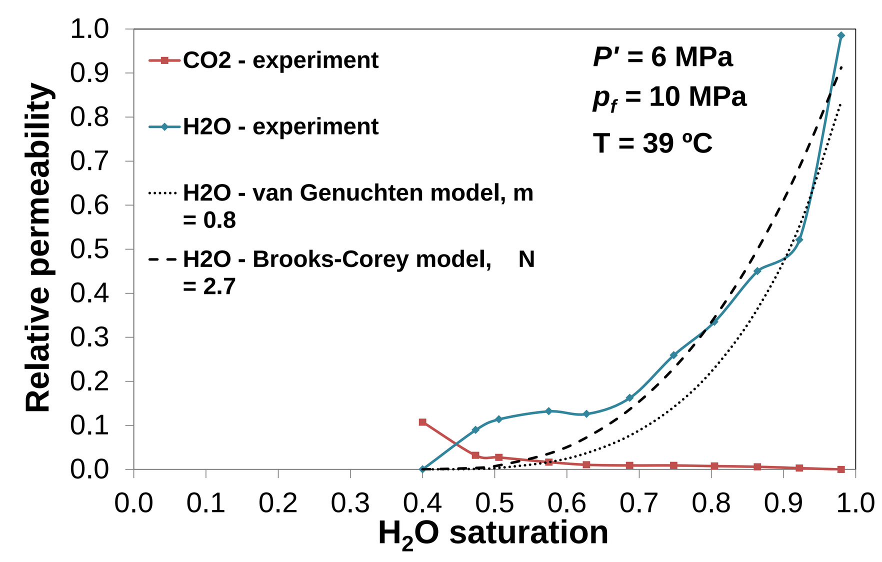

Fig. 7: Relative permeability of H_2O and $scCO_2$ and fitting with different models.

4. Conclusions

In order to study the host rock behavior during deep geological carbon dioxide storage, CO_2 and CO_2-rich water were pressurized to 10 Mpa and injected in water-saturated sandstone at 20°C and 39°C. Relative permeability of liquid CO_2 (20°C) was found to be 20% larger than the one at supercritical state (39°C) and both of them are within the reported trends for high-permeable rocks. Changes in mechanical properties of rock due to CO_2 injection are currently under consideration.

Acknowledgements

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Mixed electrolyte solutions in geothermal systems: experimental and molecular dynamics insights

Denis Zezin, Thomas Driesner

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Introduction

Aqueous fluids containing electrolytes are the essential components of geothermal systems. These solutions may contain tens % of dissolved salts (Na, K, Ca, Mg; Cl, SO_4) and can be under high *T* (up to 250 °C and above) and high *P*. Such saline aqueous fluids can be a primary medium of heat extraction from geothermal reservoirs or control the efficiency of CO_2 sequestration in deep aquifers. The thermodynamic properties of fluids and *PVTx* relations for aqueous mixtures of electrolytes must be known for evaluation of dissolution/precipitation of minerals and porosity/permeability changes.
In order to better understand the effects of mixing of electrolyte solutions and find meaningful mathematical expressions describing these effects, we employed a dual approach coupling experiments and MD simulations.

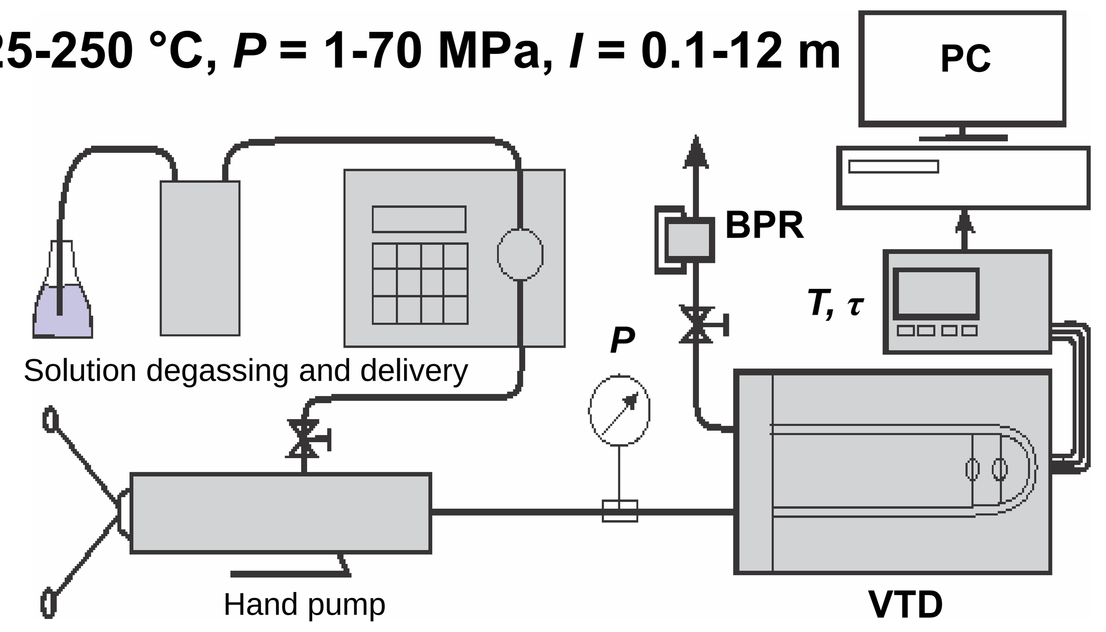
Experimental approach

Density measurements for mixed electrolyte solutions were done using vibrating tube densitometer (VTD).

- The density difference $\Delta\rho$ between an experimental aqueous solution and reference fluid (pure solvent) can be evaluated from the measured periods of vibration of the tube using the equation:

$$\Delta\rho = \rho - \rho_r = K(\tau^2 - \tau_r^2)$$

T = 25-250 °C, P = 1-70 MPa, I = 0.1-12 m



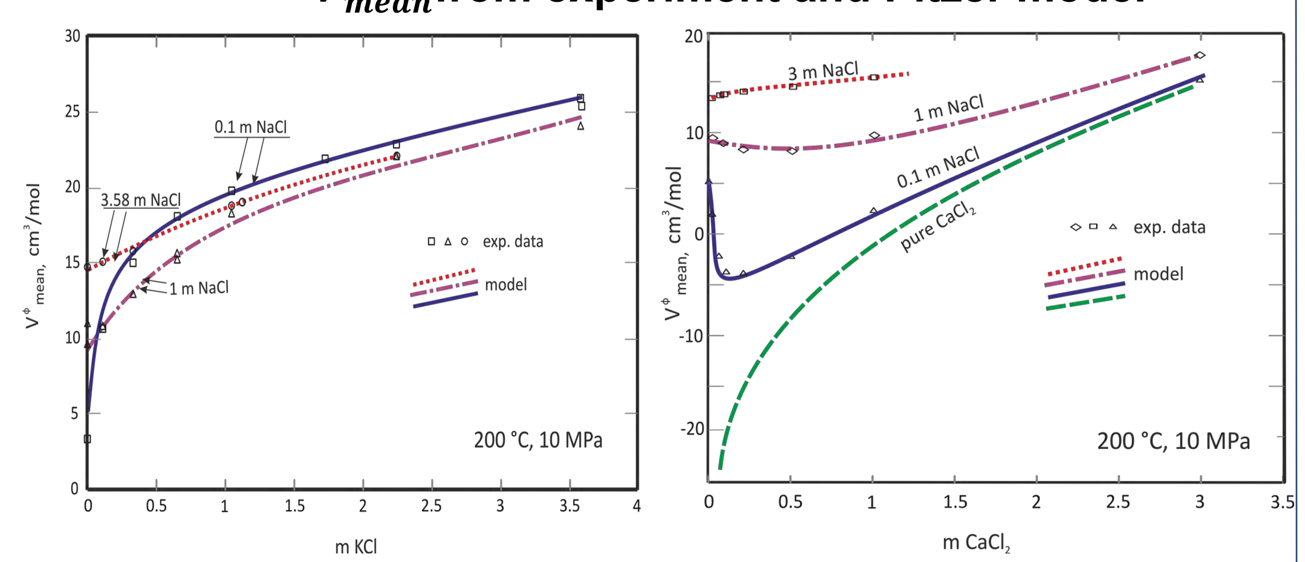
- Mean apparent molar volume V^ϕ of aqueous mixtures calculated:

$$V^{\phi}_{mean} = \frac{1000(\rho_0 - \rho)}{\sum_j m_j \cdot \rho \cdot \rho_0} + \frac{\sum_j m_j \cdot M_j}{\sum_j m_j \cdot \rho}$$

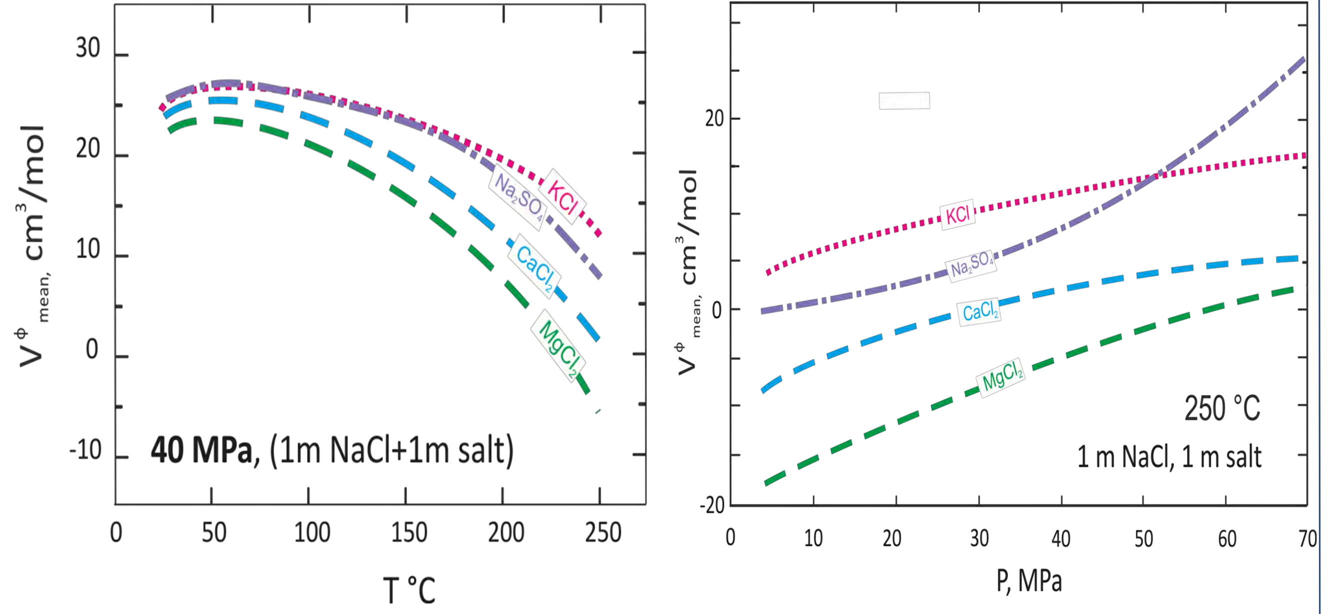
- Fit of V^{ϕ}_{mean} to the Pitzer equation

- Evaluation of partial molar volume of components and the volume of mixing: $V_{mix} = V^{soln} - V^{id\ mix}$

V^{ϕ}_{mean} from experiment and Pitzer model



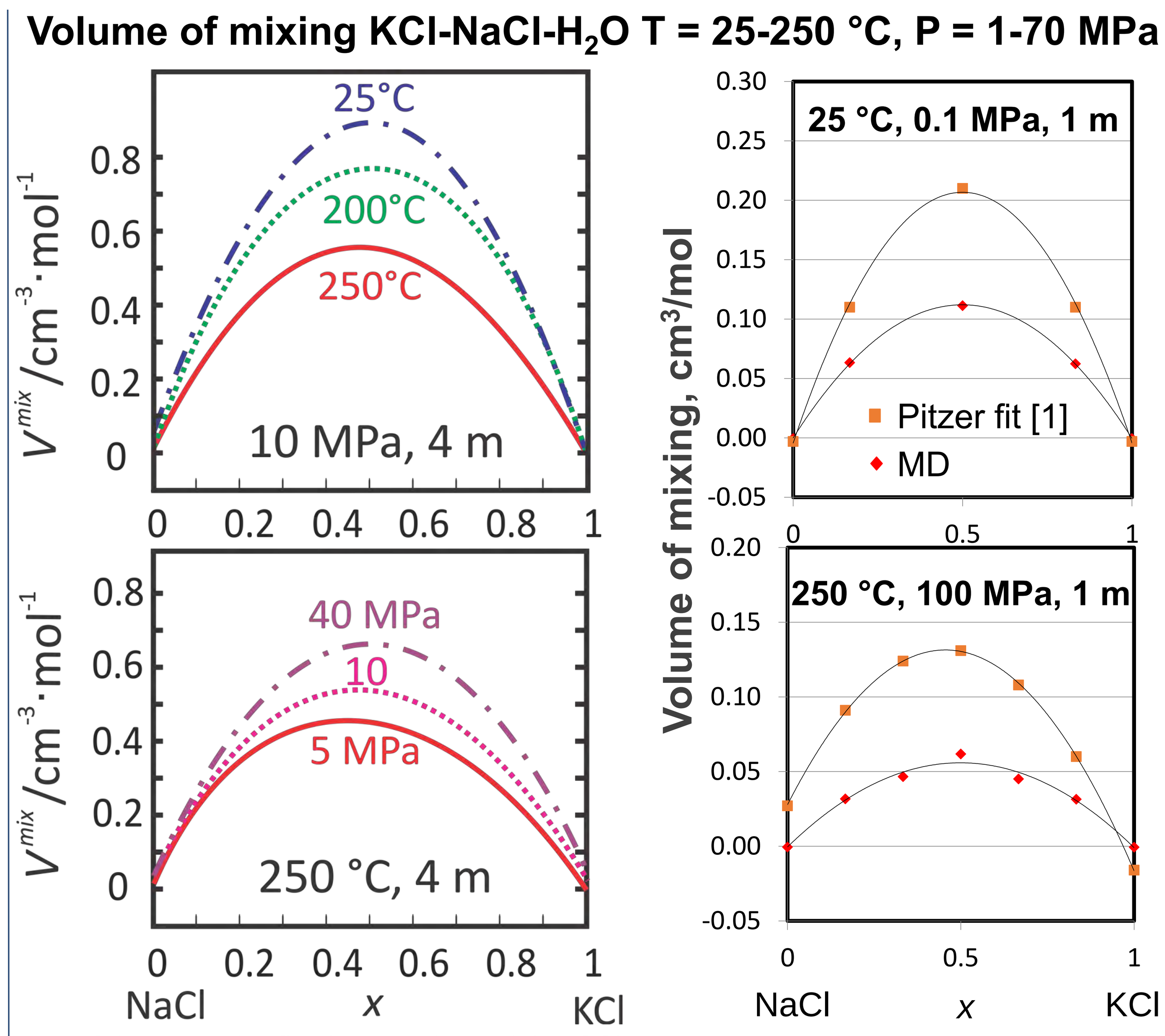
T- and P- dependencies of V^{ϕ}_{mean}



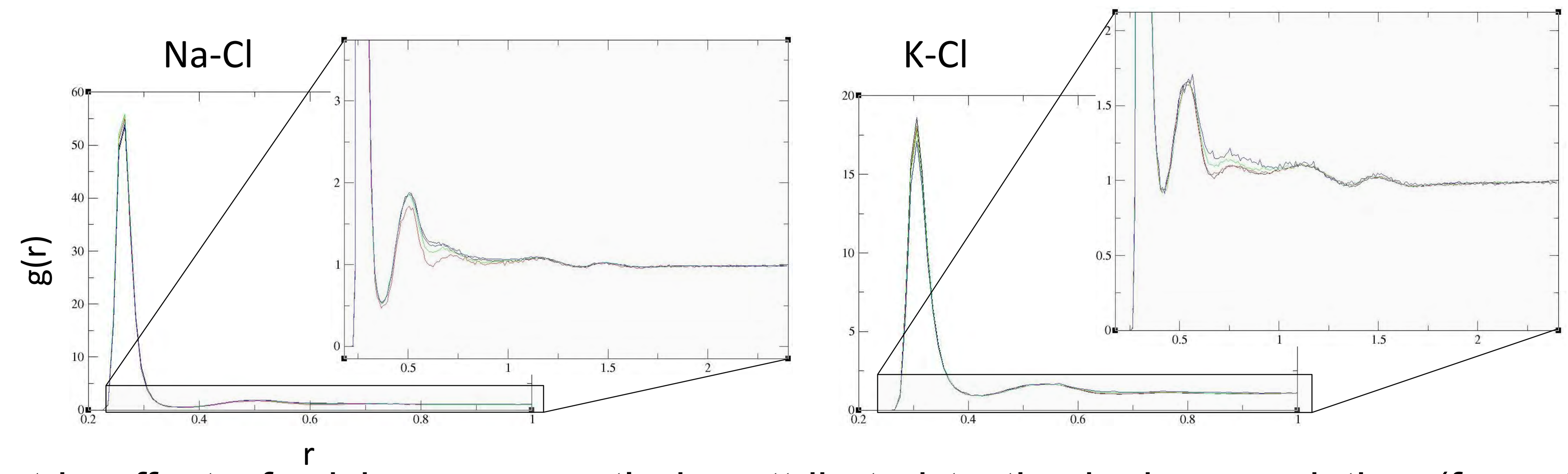
It is possible to qualitatively reproduce the volumetric effects of mixing of electrolyte solutions (KCl+NaCl) using MD simulations. Thus, we have tried to explain the non-ideal behavior of macroscopic physical properties of aqueous solutions via observed molecular level interactions.

Results

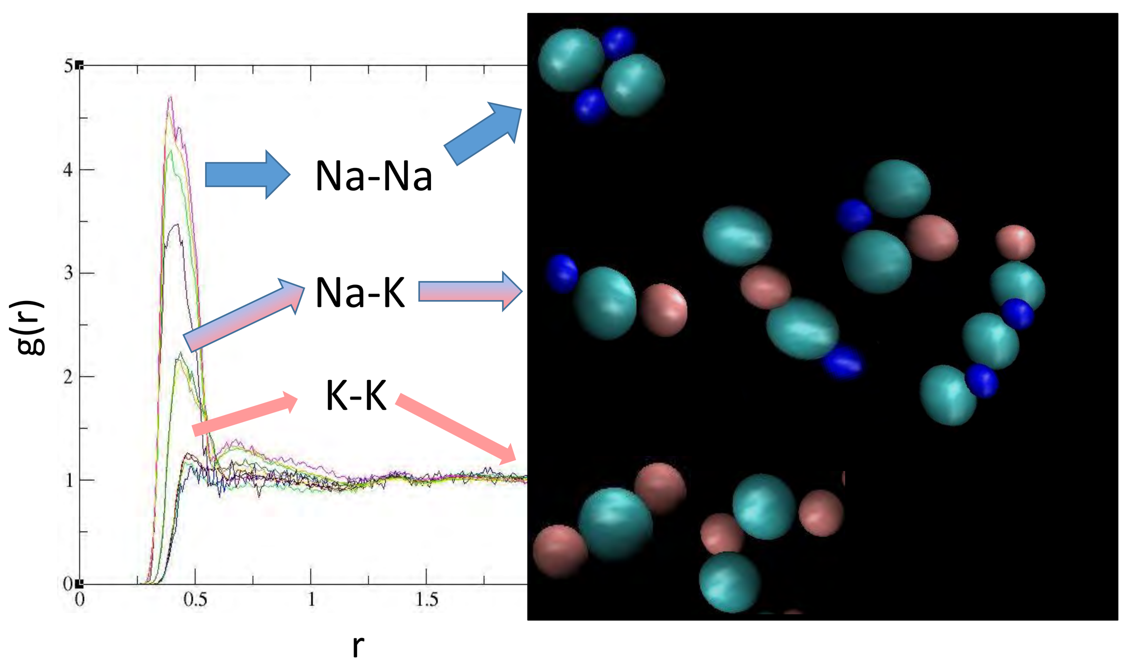
Volume of mixing KCl-NaCl-H_2O T = 25-250 °C, P = 1-70 MPa



(Pitzer equation fitted to experimental data [1])

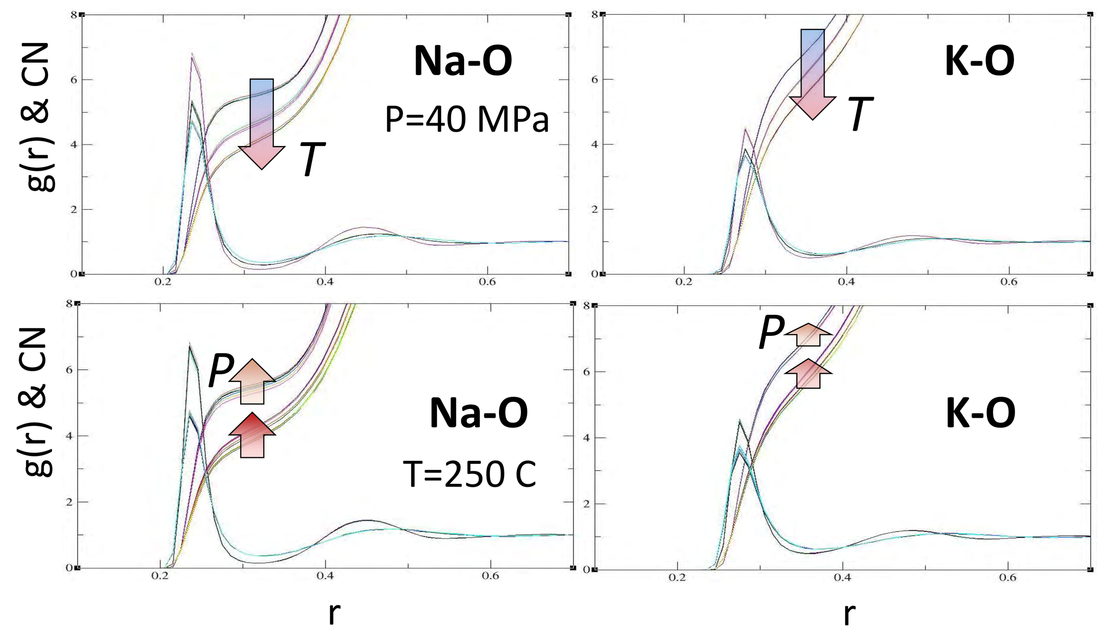


Volumetric effect of mixing can mostly be attributed to the ionic association (formation of clusters) with consequent changes in hydration structure around solute ions.



	pairs			complex clusters		
@ 250 °C	P, MPa			P, MPa		
xNaCl	10	40	100	10	40	100
0	0.27	0.28	0.28	0.19	0.17	0.17
0.2	0.28	0.28	0.24	0.22	0.18	0.16
0.5	0.26	0.26	0.26	0.32	0.28	0.21
0.8	0.22	0.24	0.25	0.40	0.35	0.28
1	0.25	0.22	0.27	0.40	0.37	0.29

@ 40 MPa	T, °C		
xNaCl	25	150	250
0	0.02	0.11	0.17
0.2	0.01	0.12	0.18
0.5	0.05	0.13	0.28
0.8	0.02	0.22	0.35
1	0.05	0.14	0.37



Increasing *T* :
- CN decreases
- association of solute ions grows
- V decreases

Increasing *P*:
- CN increase,
- association of solute ions is less
- V increases

- Quantitative evaluation of the solute-solvent and solute-solute interactions can provide a basis for mixing rules used in thermodynamic models for multicomponent aqueous solutions.
- The association of ions and perturbations in hydration shell affect *PTVx* properties of a solution, as well as activities of all components, thus disturbing thermodynamic equilibrium.

Molecular dynamics

Molecular simulations for mixed electrolyte solutions performed for *NPT* ensemble using SPC/E model for water, periodic boundary conditions for a box having volume ~140 nm³ and containing 17-432 solute ions (Na, K, Ca, Cl) and 4000 water solvent molecules, i.e. for concentration of electrolytes 0.1-3 m. GROMOS software [4] with modified 54A8 forcefield [5] was used for calculations.

All changes in volumetric properties of electrolyte solutions can be explained in terms of solute-solvent and solute-solute interactions.

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Numerical upscaling of seismic characteristics in fractured porous media

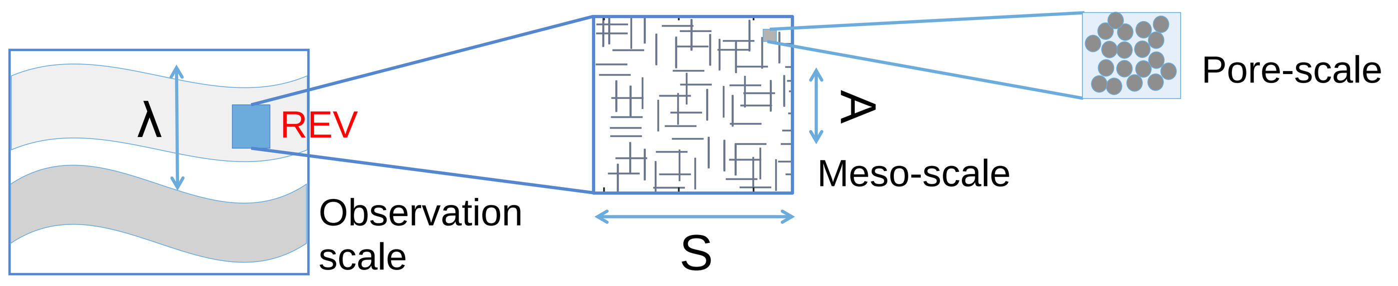
Eva Caspari, Marco Milani, J. Germán Rubino, Tobias M. Müller, Beatriz Quintal, and Klaus Holliger

Summary

The seismic and hydraulic characterization of fractured rocks has a number of important applications, such as, for example, the sustainable use of groundwater, the optimized production of geothermal energy and hydrocarbons, and the safe storage of nuclear waste. Recent studies have shown that attenuation and velocity dispersion of seismic waves are sensitive to the elastic and hydraulic properties and thus may provide critical insights into fracture characteristics. While fractures tend to control these properties they can in general not be resolved directly, which makes it challenging to relate measured seismic attributes to the characteristics of the medium. Analytical theories linking the effects of fractures to seismic attributes tend to be limited to simple geometries. One way to overcome this inherent limitation of analytical approaches is through numerical upscaling. Here, we apply a upscaling approach based on the theory of quasi-static poroelasticity to fluid saturated porous media containing randomly distributed horizontal and vertical fractures. The inferred frequency-dependent moduli represent the effective behaviour of the underlying fractured medium, if the considered sub-volume has at least the size of a representative elementary volume (REV). We adapt a combined statistical and numerical approach originally proposed for elastic composites to explore whether the overall statistical properties of simple fracture networks can be captured by computationally feasible domain sizes. Our results indicate that, for the considered scenarios, this is indeed possible and thus represent an important first step towards the estimation of seismic characteristics of realistic fracture networks.

1. Numerical upscaling in poroelasticity

- Fluid pressure diffusion at mesoscopic scales: fractures are larger than the pore size but smaller than the dominant wavelength λ

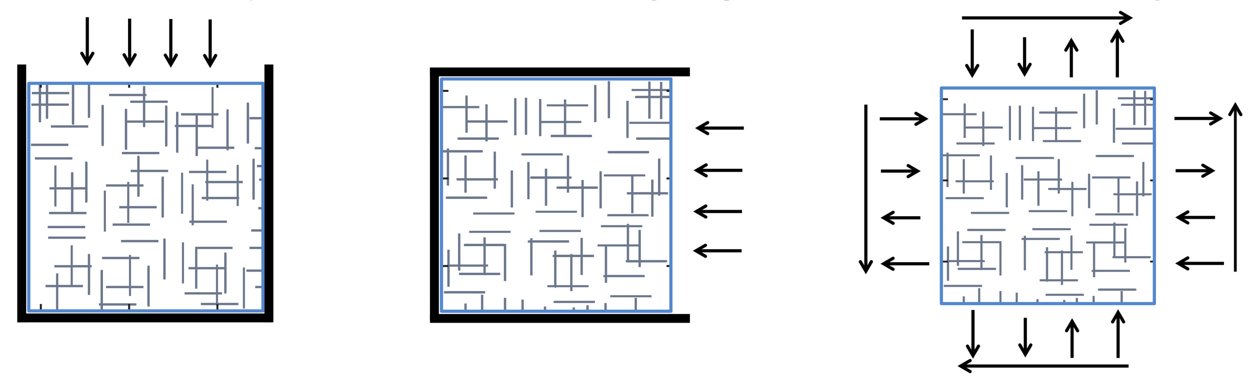


- Biot's (1941) quasi-static poroelastic equations:

$$\nabla \cdot \bar{\sigma} = 0, \quad \text{Stress equilibrium equation}$$

$$i\omega \frac{\eta}{k} \vec{w} = -\nabla p_f \quad \text{Darcy flow}$$

- 3 oscillatory relaxation tests (displacement boundary condition):



(Rubino et al., 2009)

- Spatial averaging of the resulting stress and strain fields over the sample domain *S* provide equivalent frequency-dependent moduli
- REV: upscaled moduli $C_{ij}(S)$ represent the effective behaviour of the underlying fractured medium, if (Hill, 1965):
  1. The inferred seismic properties are independent of the applied boundary conditions
  2. Sample is structurally representative of the entire medium
- Statistical analysis (Kanit et al., 2003):
  1. Variance of the upscaled moduli tends to zero: $Var\{Cij(S)\} \rightarrow 0$
  2. Estimation of the REV size from simulations of several realizations and domain sizes of the random medium by fitting the scaling law: $Var\{Cij(S)\} = \sigma^2 \frac{A}{S}$

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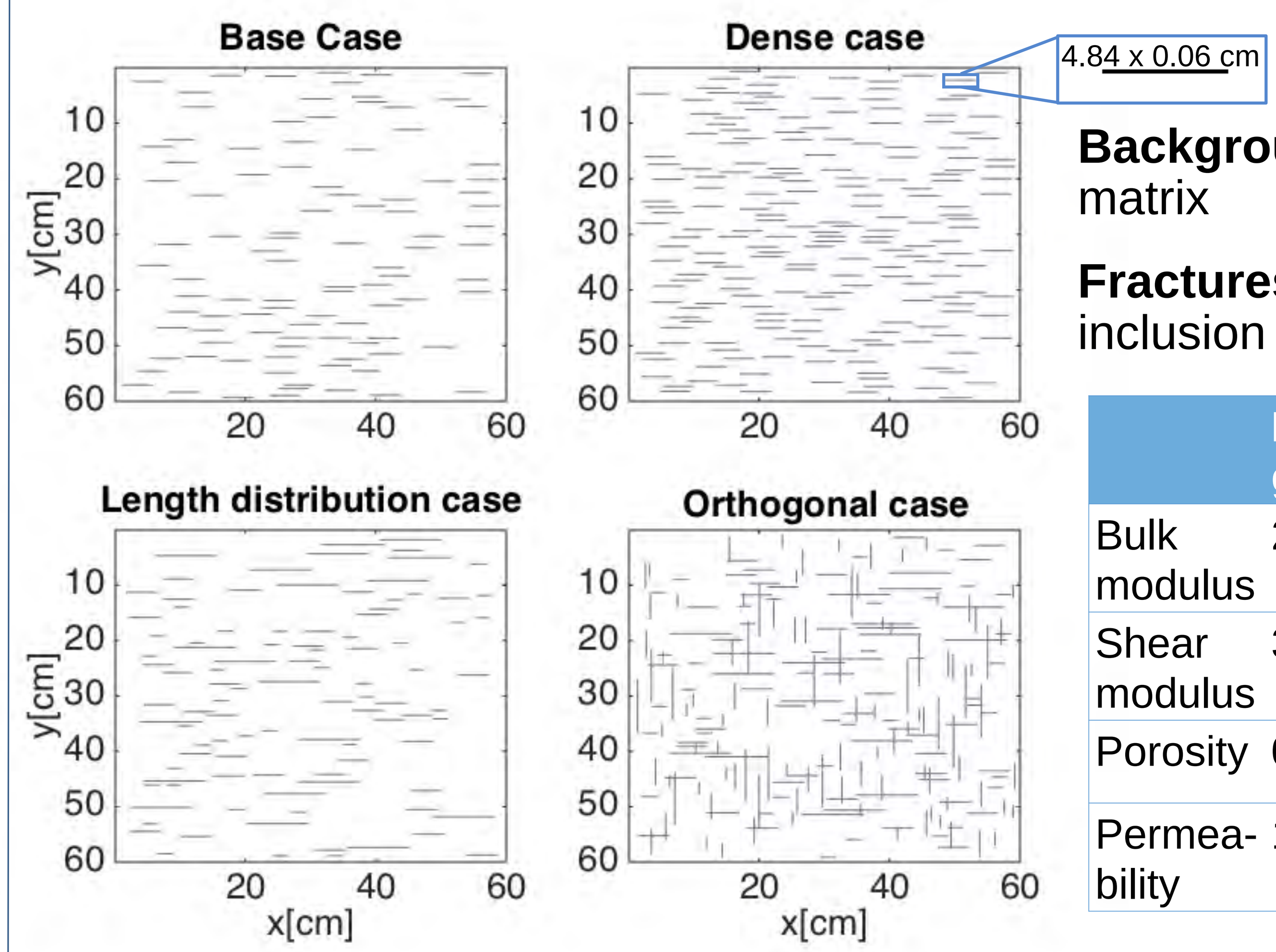
Rubino, J., C. Ravazzoli, and J. Santos, 2009, Equivalent viscoelastic solids for heterogeneous fluid saturated porous rocks: Geophysics, 74, N1–N13.

2. Fractured rocks modelled as poroelastic medium

2D numerical models of water-saturated tight sandstone containing uniformly random distributed horizontal and vertical fractures:



Background: stiff porous matrix

Fractures: compliant inclusion

	Back-ground	Fracture
Bulk modulus	26 GPa	0.03 GPa
Shear modulus	31 GPa	0.02 GPa
Porosity	0.1	0.8
Permea-bility	1 mD	100 D

Number of random medium realizations for 3 domain sizes:

Fractures/Area [m ²]	25/0.09	100/0.36	400/1.44	Fracture density
Base case	40	20	5	0.16
Dense case	40	30	5	0.32
Fractures/Area [m ²]	**50/0.09**	**200/0.36**	**800/1.44**	**Fracture density**
Length distribution case	60	30	5	0.208
Orthogonal case	40	20	5	0.416

3. Upscaled properties and estimation of the REV sizes

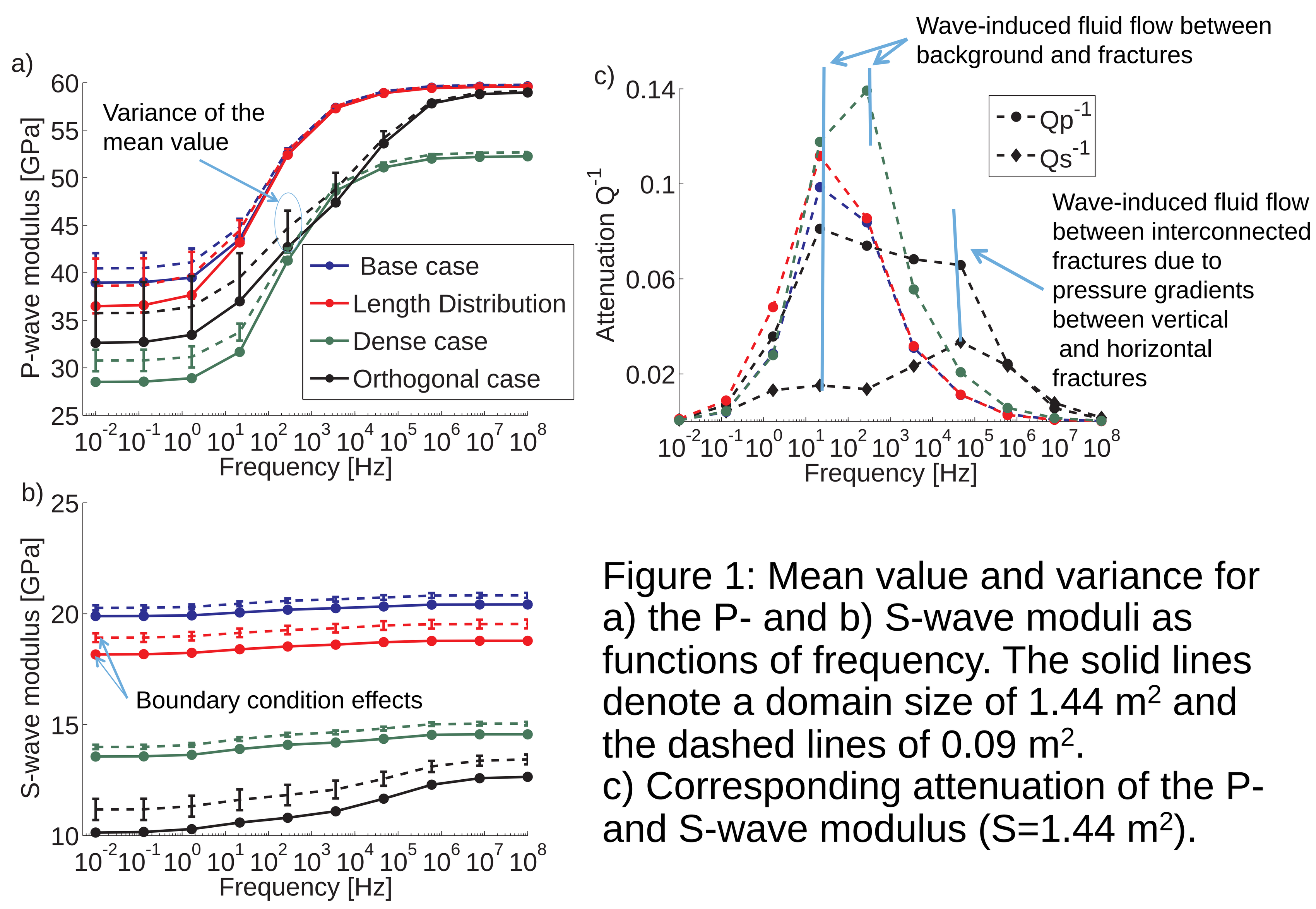


Figure 1: Mean value and variance for a) the P- and b) S-wave moduli as functions of frequency. The solid lines denote a domain size of 1.44 m² and the dashed lines of 0.09 m². c) Corresponding attenuation of the P- and S-wave modulus (S=1.44 m²).

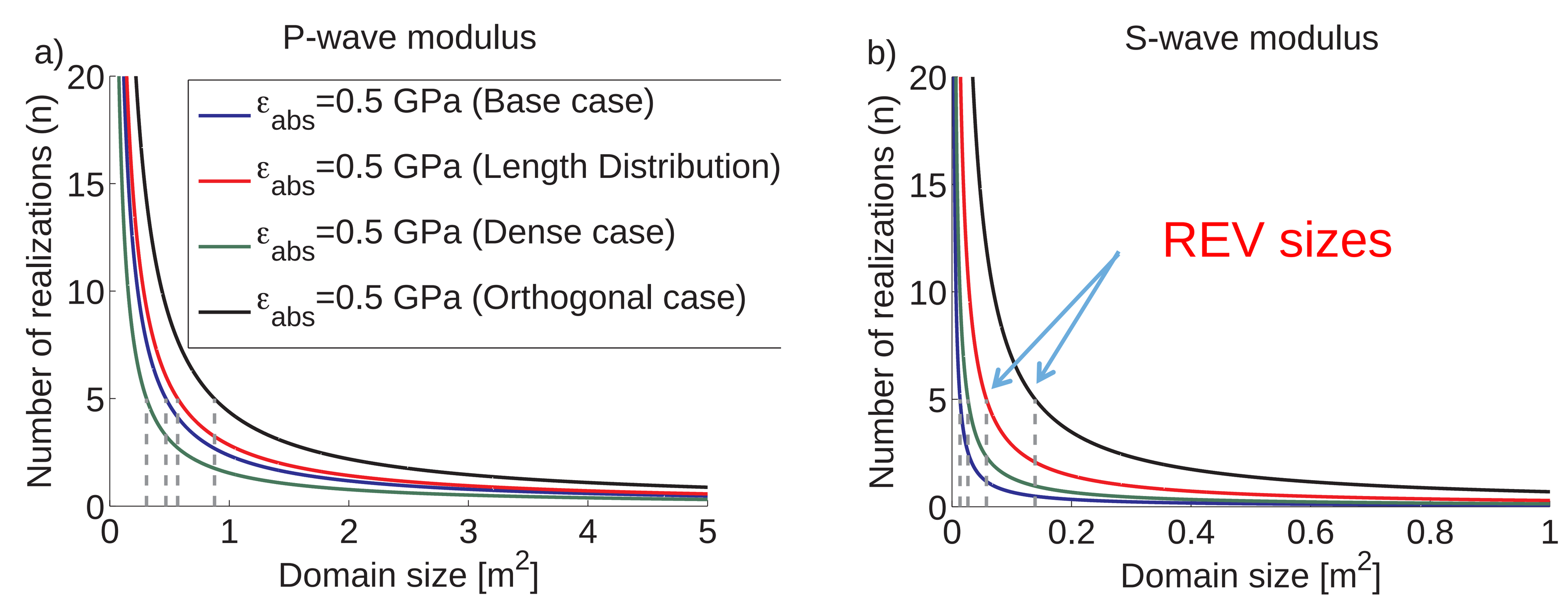


Figure 2: Number of realizations for an absolute error of 0.5 GPa of the upscaled a) P- and b) S-wave moduli as functions of the domain size at the lowest frequency. The dashed grey lines indicate the size of the REV for 5 realizations.

Outlook

- Can we define finite-size REVs for more complex fracture networks?
- Can we relate the attenuation caused by wave-induced fluid flow in such fracture networks to their effective hydraulic conductivity?

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Fault detection method to anticipate felt induced seismicity in geothermal and geologic carbon storage projects

Victor Vilarrasa, Gil Bustarret and Lyesse Laloui
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Abstract

The need to reduce carbon dioxide (CO_2) emissions to the atmosphere has motivated a significant increase of fluid injection in the subsurface in the last years. Fluid injection causes a pore pressure increase that may yield shear failure, inducing seismic events. If the induced seismicity is felt at the ground surface, public acceptance would be negatively affected and may end up with the halt of injection activities. Thus, anticipating felt induced earthquakes is crucial for the success of geothermal and geologic carbon storage projects. Our objective is to define a methodology to detect and locate low permeability undetected faults that may induce seismicity. We use diagnostic plots to identify the divergence time between pressure measurements and the overpressure that would correspond to a homogeneous aquifer with no faults. Simulation results show that this methodology can be successfully applied for water and CO_2 injection. The proposed methodology is general and can be easily applied to complex geometries, including several faults and leaky caprocks.

1. Introduction

The ongoing numerical investigations involve understanding the processes that could jeopardize the caprock and faults stability related to fluid injection in deep saline formations. This poster presents a methodology to detect and locate low permeability faults that cannot be detected with geophysical methods from the surface due to their small offset. A prompt identification of low permeability faults permits applying mitigation measures before an additional overpressure is generated, which could cause fault instability and induced seismicity.

Research of the chair "Gaz Naturel" – Petrosvibri at the EPFL contributes to SCCER-SoE task 1.2: "Reservoir modelling and validation". Both numerical modelling and experimental investigation of geomechanical processes involved in deep geological storage of CO_2 are performed in cooperation with government agencies: SFOE and Swisstopo. Proper assessment of CO_2 storage procedure will allow to significantly reduce its emissions to the atmosphere and thus directly contributes to Swiss energy strategy 2050.

2. The concept

Diagnostic plots (Fig. 1) are useful tools for well-test analysis to highlight changes in the evolution of fluid pressure evolution and to identify the most appropriate conceptual geological model. Diagnostic plots show pressure change and its logarithmic derivative evolution with time caused by injection, in log-log plots. The aim of using these plots here is to identify if pressure at a monitoring well diverges from the expected evolution if the aquifer was homogeneous and to identify the divergence time.

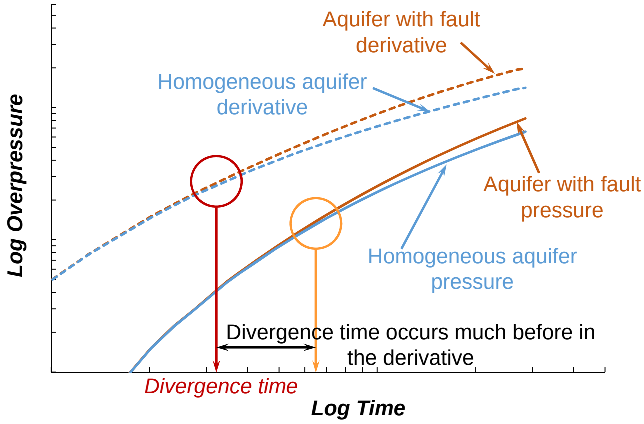

Figure 1. Diagnostic plots are a useful tool to anticipate to additional overpressure induced by the presence of undetected low permeability faults

3. Methods

The large extension (40km) of the numerical model in Fig. 2 intends to simulate an infinite aquifer (the pressure perturbation cone does not reach the boundaries of the model for the simulated injection time). A hydrostatic condition is imposed at the edges of the model. The no flow boundary conditions at the top and bottom boundaries simulate low permeability cap and base rock. We consider both water and CO_2 injection for a homogeneous aquifer and for an aquifer with a fault placed 2.5 km away from the injection well.

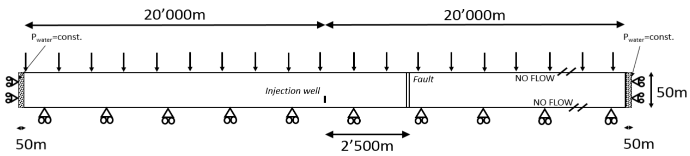

Figure 2. Schematic representation of the model geometry

4. Results

To observe an effect on overpressure evolution, faults should be at least three orders of magnitude less permeable than the aquifer (Fig. 3). From the divergence time in the derivative, the location of the fault can be determined. When injecting CO_2, the CO2 plume shape is also affected by the overpressure caused by the fault (Fig. 4). This asymmetry in the CO_2 plume shape may give additional information for fault detection and localization.

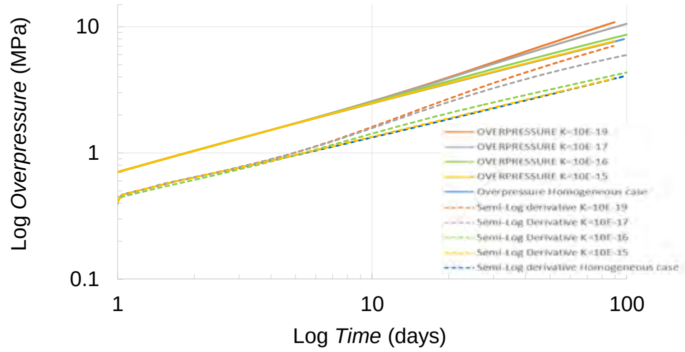

Figure 3. Sensitivity of overpressure to the permeability of the fault, measured at a distance from the injection well equal to two times the aquifer thickness (towards the fault)

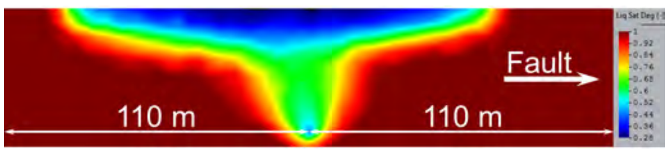

Figure 4. CO_2 plume shape affected by a low permeability fault

6. Conclusions

We propose a methodology to detect and locate low permeability faults that allows applying pressure mitigation actions with enough anticipation to avoid inducing an overpressure that could jeopardize fault stability and induce seismicity. Simulation results illustrate that faults affect overpressure evolution if the permeability contrast between the aquifer and the fault is of at least three orders of magnitude. This methodology to detect and locate low permeability faults can be applied to every injection site, including applications to geothermal energy and geologic carbon storage.

Acknowledgements

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COTHERM: Geologic controls on supercritical fluid resources above magmatic intrusions

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Heat transfer from a magmatic intrusion to groundwater occurs below drilled geothermal reservoirs. Temperatures in the immediate vicinity of magmatic intrusions exceed the critical temperature of water (374 °C), implying the possible occurrence of geothermal water as a single-phase, supercritical fluid. Thermodynamic considerations indicate that supercritical geothermal resources may be very favourable for power production (Fig. 1). In 2009-2012, an exploratory well drilled by the Iceland Deep Drilling Project (IDDP) penetrated a magma body at 2.1 km depth in the Krafla volcanic system[1] and tapped a reservoir of supercritical water capable of generating 35 MW electricity from a single well (Fig. 2), roughly 5-10 times the field average. The thermo-hydraulic nature of the reservoir at Krafla has remained enigmatic and the occurrence of comparable supercritical reservoirs in other magma-driven geothermal systems is unclear. Exploration has been limited by a lack of understanding of the primary geologic factors that control the occurrence, depth, size and thermo-hydraulic properties of target reservoirs.

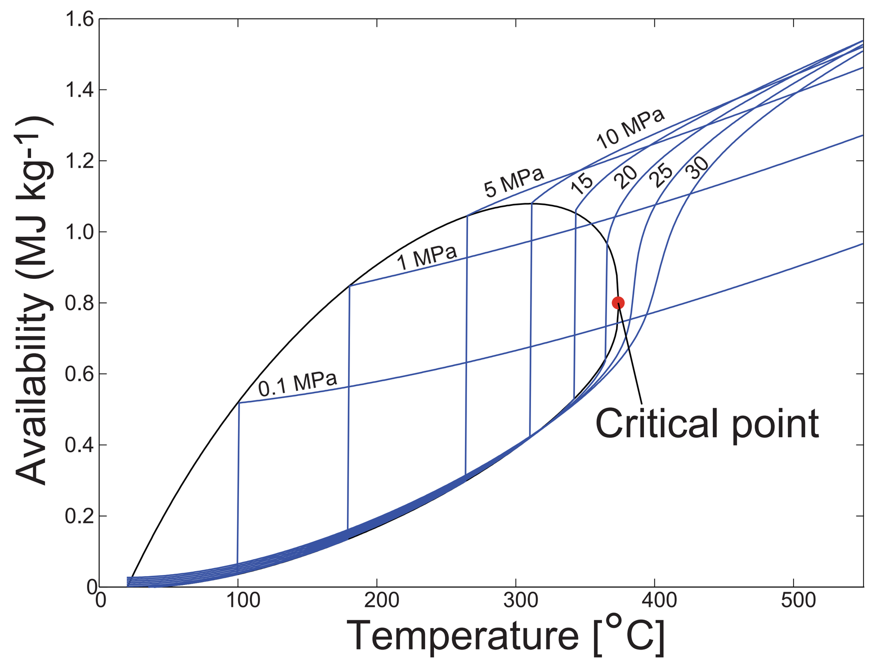

Fig. 1 (left): Availability (exergy) diagram for water, showing maximum energy extractable after cooling a kg of fluid from a given T, p to a dead state (25 °C, 0.1 MPa).

Availability = h – T_0S

Fig. 2 (right): Flow test of the IDDP-1 well, the world's first magma-enhanced geothermal system. The measured reservoir conditions were 450 °C and 3.2 MJ kg-1 (ref. 2). Credit: Kristján Einarsson

Formation of supercritical resources depends on host rock permeability and brittle-ductile transition temperature

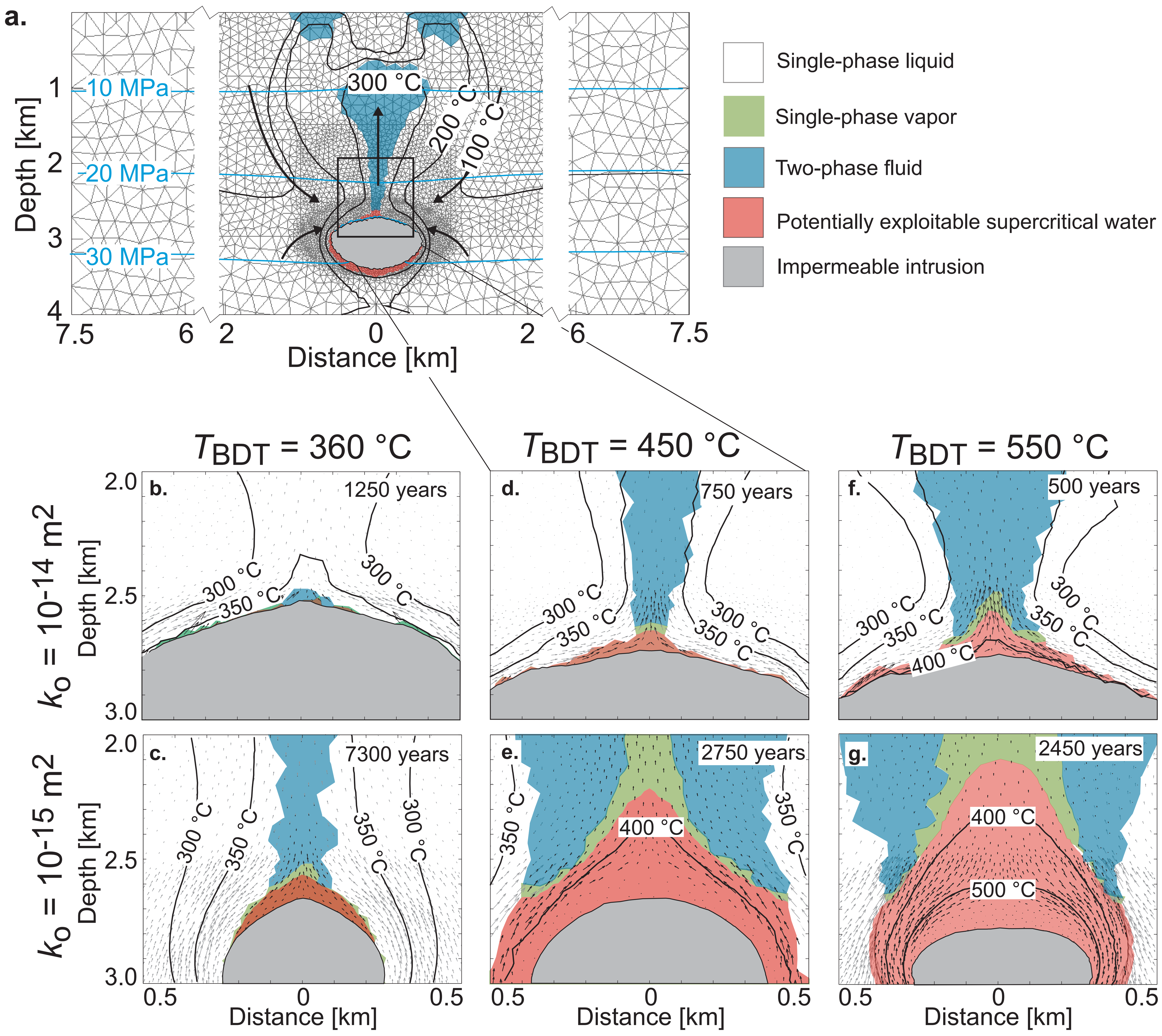

Fig. 3: a. Typical large-scale thermal structure of a simulated geothermal system b-g. Snapshots of the area near the top of the intrusion (black box in a.), under different conditions of host rock permeability (k_0) and brittle-ductile transition temperature (T_{BDT}).

- The key control on the formation of supercritical resources is the brittle-ductile transition temperature. Extensive supercritical water resources can develop if T_{BDT} is at least 450 °C (Fig. 3)

- The extent and temperature of supercritical resources strongly depend on host rock permeability. Supercritical resources in intermediate permeability systems are hotter (Fig. 3e, g). In such settings, supercritical resources can extend up to 700 m above the impermeable intrusion.

- By tracing the flow of water from the supercritical resource, we find that conventional high enthalpy geothermal resources form above supercritical resources as it ascends and progressively mixes with surrounding cooler water (Fig. 4).

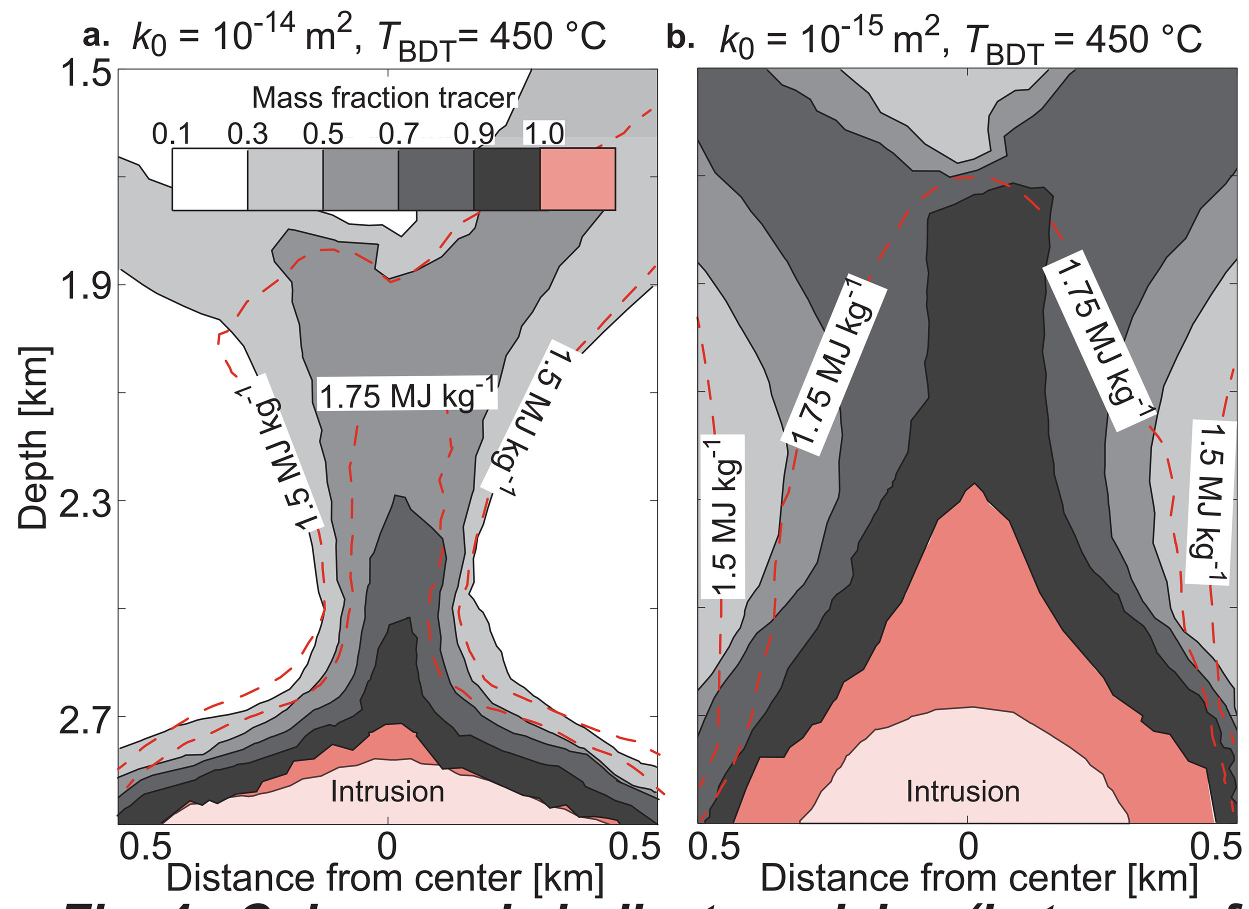

Fig. 4: Colour scale indicates mixing (in terms of mass fraction) of fluid ascending out of the supercritical reservoir (mass fraction 1, red) and cooler liquid and/or vapour (grey tones).

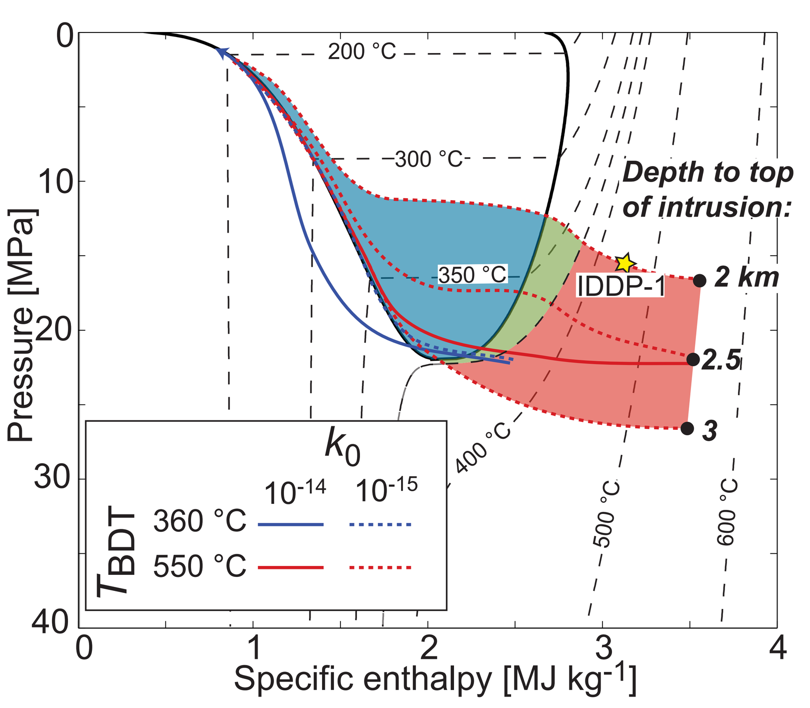

Fig. 5 (left): The thermal structure of high-enthalpy geothermal systems. Pressure-enthalpy ascent paths are superimposed onto a phase diagram of water. The areas of potentially exploitable supercritical fluid, single-phase vapour, and two-phase fluid are shown in red, green, and blue, respectively. The measured reservoir temperature and enthalpy for the IDDP-1 well is shown with a yellow star.

- The transition from supercritical to boiling conditions occurs over a small pressure range in high permeability systems and more gradually in intermediate permeability systems, reflecting the mixing dynamics (Fig. 5).

- Our models reproduce the conditions of the IDDP-1 well when the geologic controls are set to appropriate values (intrusion depth 2 km, T_{BDT} = 550 °C, $k_0 = 10^{-15}$ m2)

- Our models suggest that geologic conditions in most high-enthalpy geothermal fields allow the formation of potentially lucrative target resources.

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Reference list
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COTHERM SP2: Fluid-Rock Interactions in Icelandic Hydrothermal Systems

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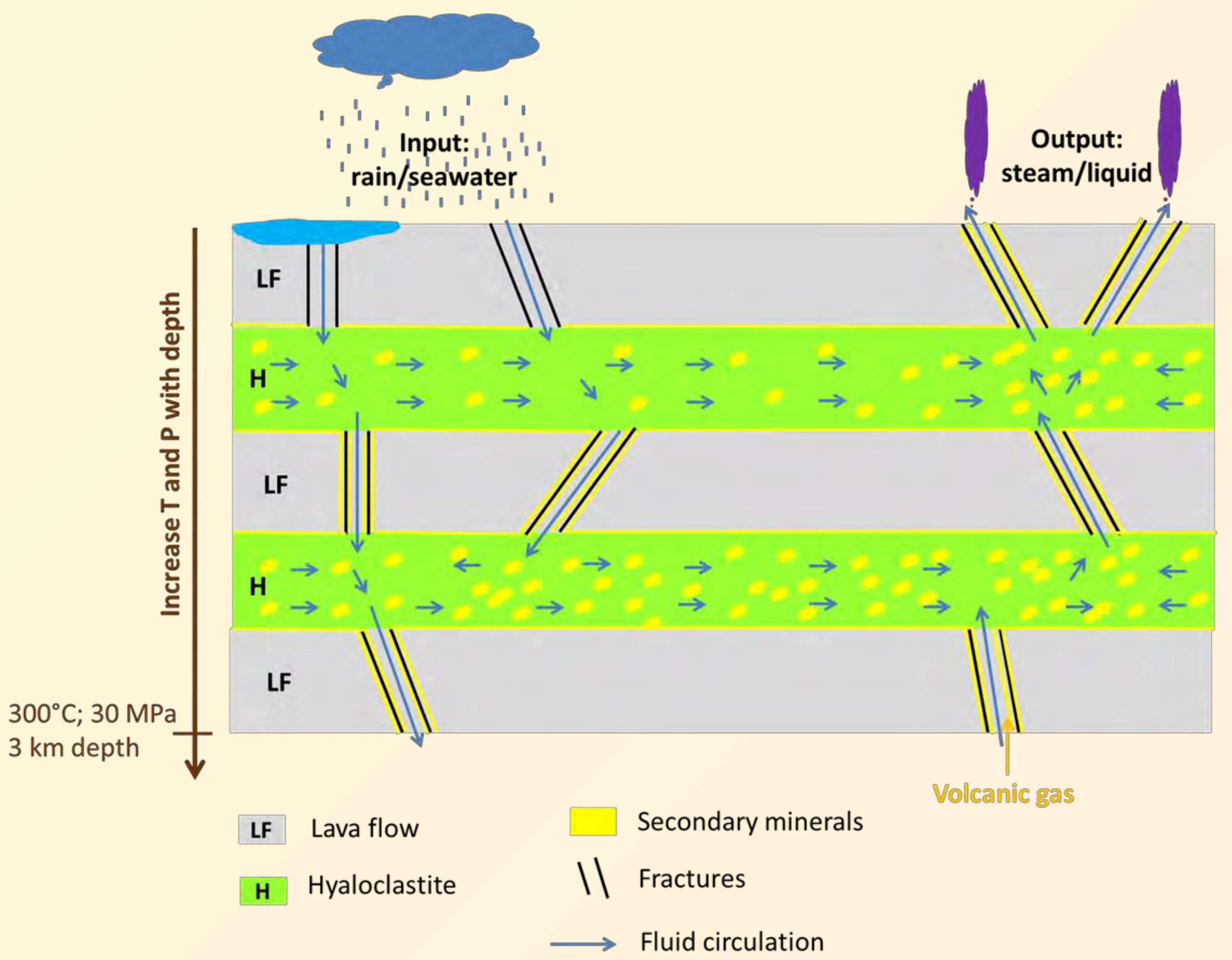
Introduction

Aim of this study: Understand the hydrothermal alteration of Icelandic geothermal systems. What is the influence of rock type, porosity, permeability, fluid composition, temperature, and kinetics?

- The underground is composed of hyaloclastites/volcanoclastites and lavaflows.
- In hydrothermal systems the protolith is altered to very different degrees by circulating fluid.
- Mineralogical changes resulting from alteration are likely to modify porosity and permeability and influence fluid circulation.
- Volcanoclastites are glassy fragments of basalt. They show high porosity and high permeability; and commonly high alteration.
- Lavaflows are dense basalts with low porosity and low permeability. They commonly show low alteration.



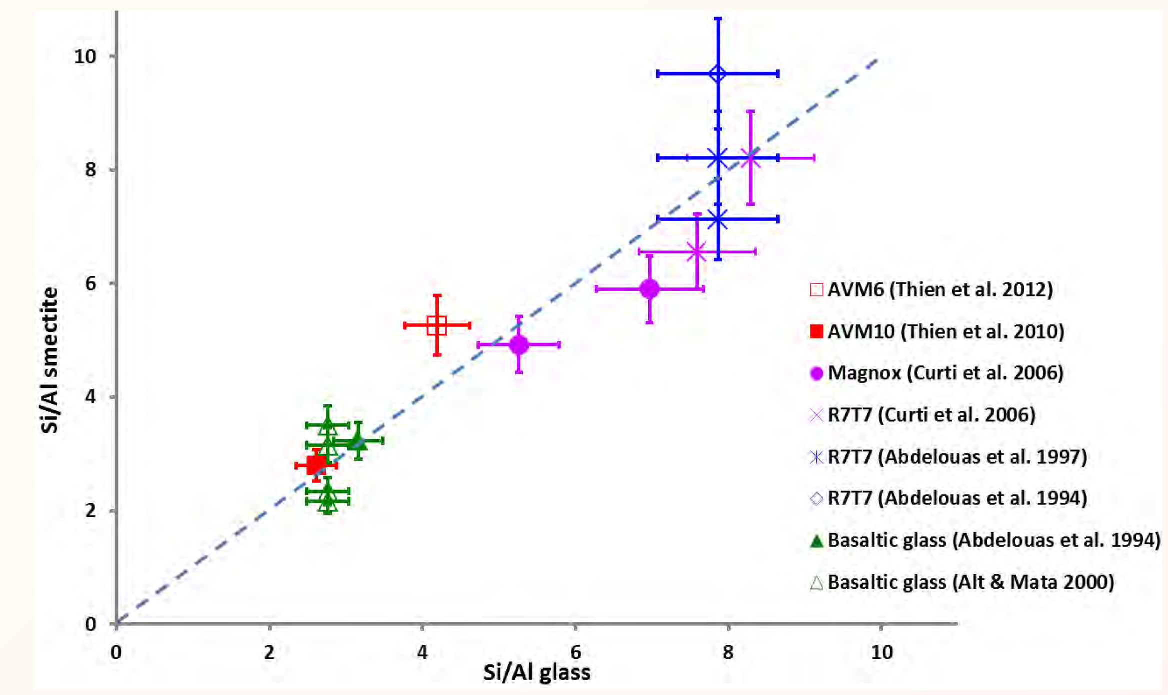
Thien et al. 2015, Geothermal Energy 3

Methods

- The geochemical system (composition of protolith and secondary minerals, fluid composition, thermodynamic and kinetic data) was setup with help of literature data and geochemical modeling, and was supported by collected field data which was investigated by macroscopic observation, XRD and thin sections measurements.
- Equilibrium calculations were done with GEM-Selektor v.3 (http://gems.web.psi.ch ; thermodynamic parameters mainly from SUPCRT98 database) to setup the system and to perform batch calculations.
- Reactive transport calculations with OpenGeoSys-GEM code were performed to account for dissolution/precipitation kinetics and diffusive transport.

First results

- Smectites are the most important minerals below 200ºC, but their composition was not well constrained in the literature. We found a correlation between secondary smectite composition and protolith composition:



Thien 2014, Applied Geochemistry 42

- With batch calculations, we demonstrated that the initial rock porosity determines the evolution of the system (*Thien et al. 2015, Geothermal Energy 3*). The transformation of protolith into secondary minerals increases the total mineral volume and therefore decreases the pore space (i.e. the volume available for water). The less the initial porosity is, the more the porosity is reduced during alteration and the volume available for water is reduced. Alteration consumes water. If water is no longer available, the alteration stops.

The high alteration of volcanoclastites

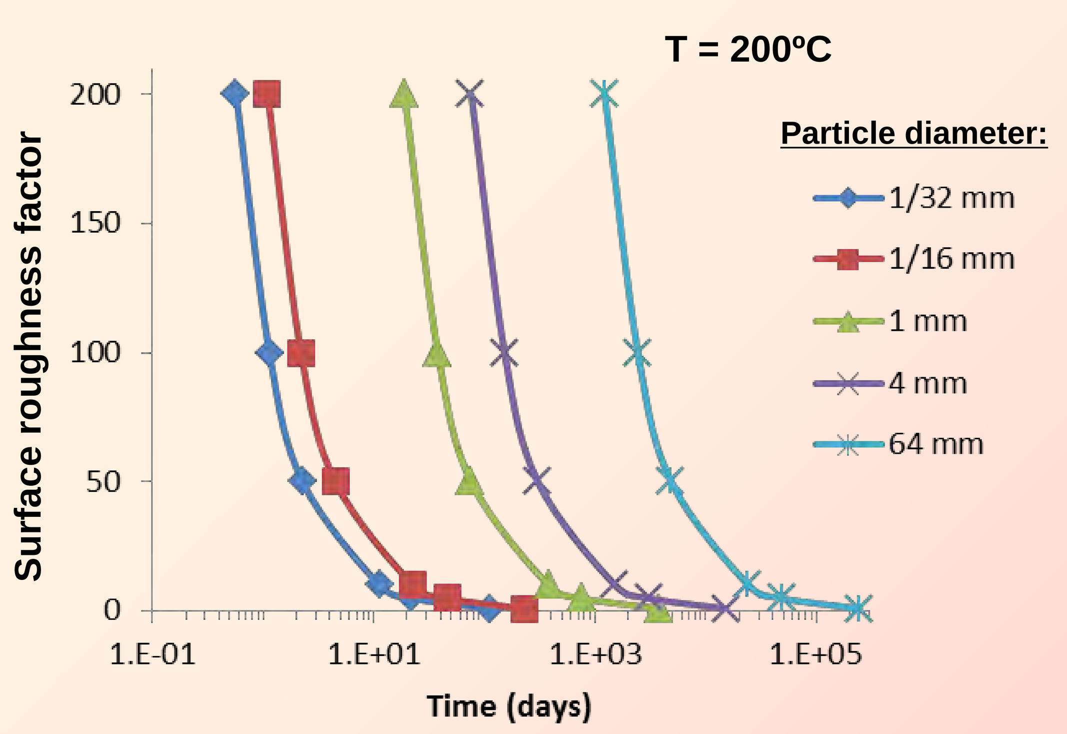
Observation:

Volcanoclastites are usually completely altered.

Explanation:

The high initial porosity is not significantly reduced during the alteration: the alteration can be completely achieved due to unlimited availability of water.

Calculation of the time necessary to completely alter volcanoclastites:



Potential effect of specific surface area: up to 6 orders of magnitude!

Thien et al. 2015, Geothermal Energy 3

Large reactive surfaces (due to small and rough particles) and high temperatures: very fast alteration (few hours to few years).

The limited alteration of lavaflows

Observation: Alteration rim around the fractures and vesicles filled with secondary minerals; the matrix is practically not altered.

Explanation:

- The pore space is poorly connected in intact basalt. It limits the availability of water in the matrix. The water consumed in the pores and the vesicles is not replaced.
- The fluid flow occurs in the large fractures. Solute diffusion occurs perpendicularly to fractures.

On-going work:

- To calculate how much tine is necessary to form observed alteration rims, by using the reactive transport code OpenGeoSys-GEM.
- To investigate which parameters influence the alteration: fluid composition, primary mineral reactive surface areas.

Acknowledgements

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COTHERM: Seismic Response due to Fluid Effects in Fractured Geothermal Reservoirs

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1. Introduction

Project **COTHERM** - **CO**mbined hydrological, geochemical, and geophysical modeling of geo**THERM**al systems – combines four subprojects and has the aim to advance the knowledge of Icelandic systems and to improve geochemical and geophysical exploration techniques.

In the geophysical subproject, we incorporate key parameters of the other disciplines in our geophysical models. This requires the study of the hydromechanical processes and their influence on seismic velocities and attenuation.

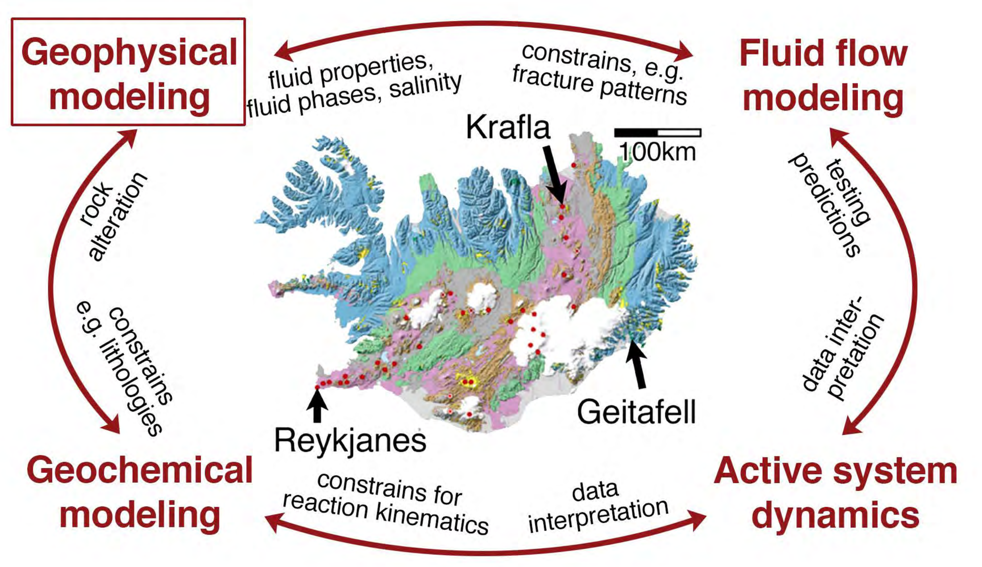

Fig 1: Geophysical modeling in the content of COTHERM. Geology map copied from Franzson (2011).

2. Geophysical properties of Icelandic systems:

There is only very limited petrophyisical information available form borehole cores and borehole logs of active systems. Therefore we combine laboratory- and field-scale experiments and modeling techniques to seismically parameterize Icelandic geothermal systems (Fig. 2).

Ambient temperature measurements include shallow seismic refraction tomography at the field scale and pulse transmission through small rock cores at the lab scale in order to characterize the seismic velocity structure of the fossilized and eroded system in Geitafell (Grab et al., 2015). Next, we perform laboratory experiments at in-situ conditions and a numerical modeling study to analyze the seismic response of fractured rock (work in progress).

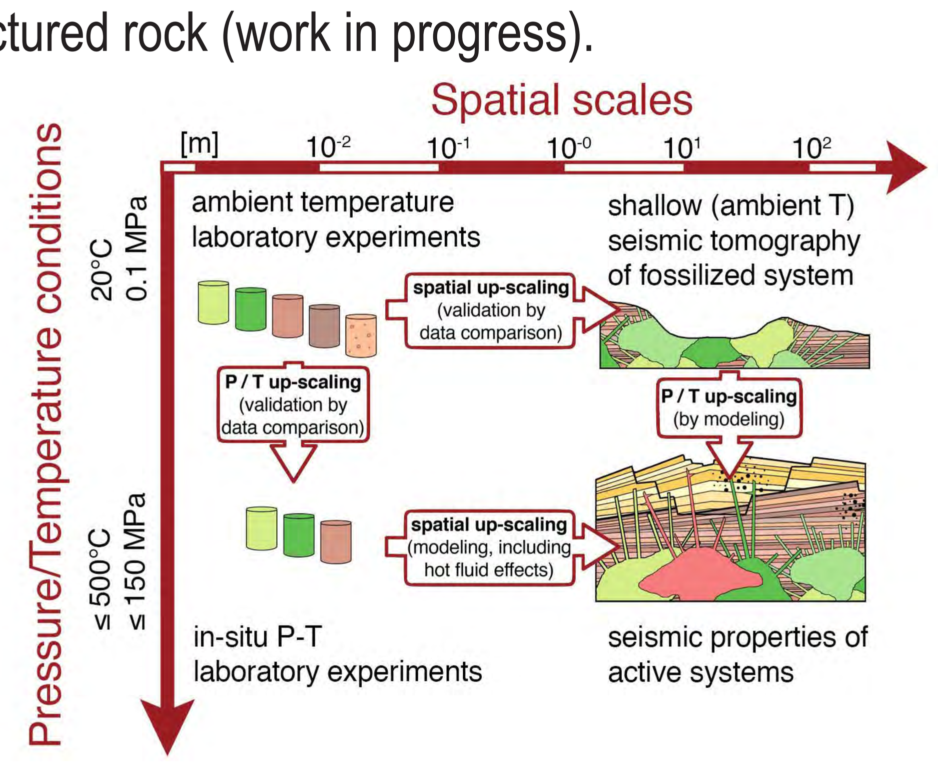

Fig 2: Approach for characterizing the seismic properties of active systems.

3. Ambient temperature laboratory and field results:

Our first results show the heterogeneity of the host rock in terms of V_P and V_S. Including all lithologies, both velocities vary over a wide range of up to 1500 m/s (Fig 3).

The comparison with the magnitudes of V_P anomalies due to hydrothermal upwelling, (estimated to be around 700 m/s by Ito et al. 1979, Jaya et al. 2010), highlights that exploring hot fluids with seismics is a challenging task, because the anomalies may be masked by natural variability.

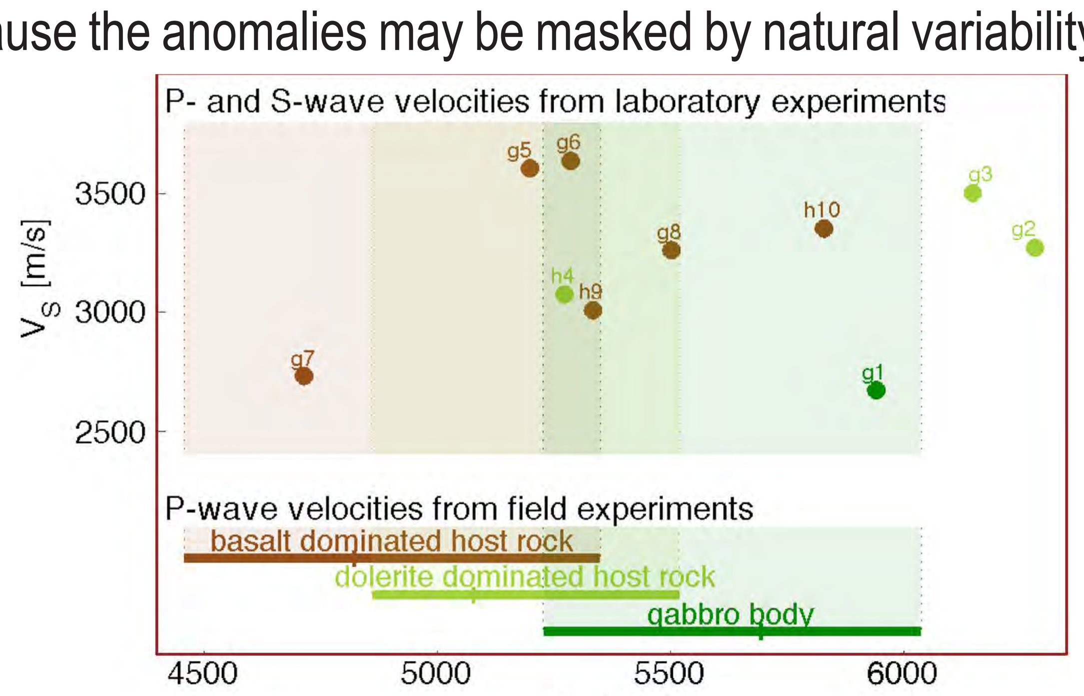

Fig 3: Seismic velocities of typical rocks. For more details see Grab et al. (2015).

4. Fluid Transport in Magmatic Systems - The Fractured Reservoir:

The Icelandic crust at depth consists of igneous rocks with low permeabilities. At shallower depths, basaltic lava flows and hyaloclastites with higher permeabilities are present. But they are often sealed by precipitation of secondary minerals. Thus, most fluid flow is expected to take place in fracture networks of variable type. Because the high-temperature geothermal systems are located on the on-land extension of the mid-Atlantic spreading ridge, there are various structures which potentially contain fracture networks as shown in Fig (4).

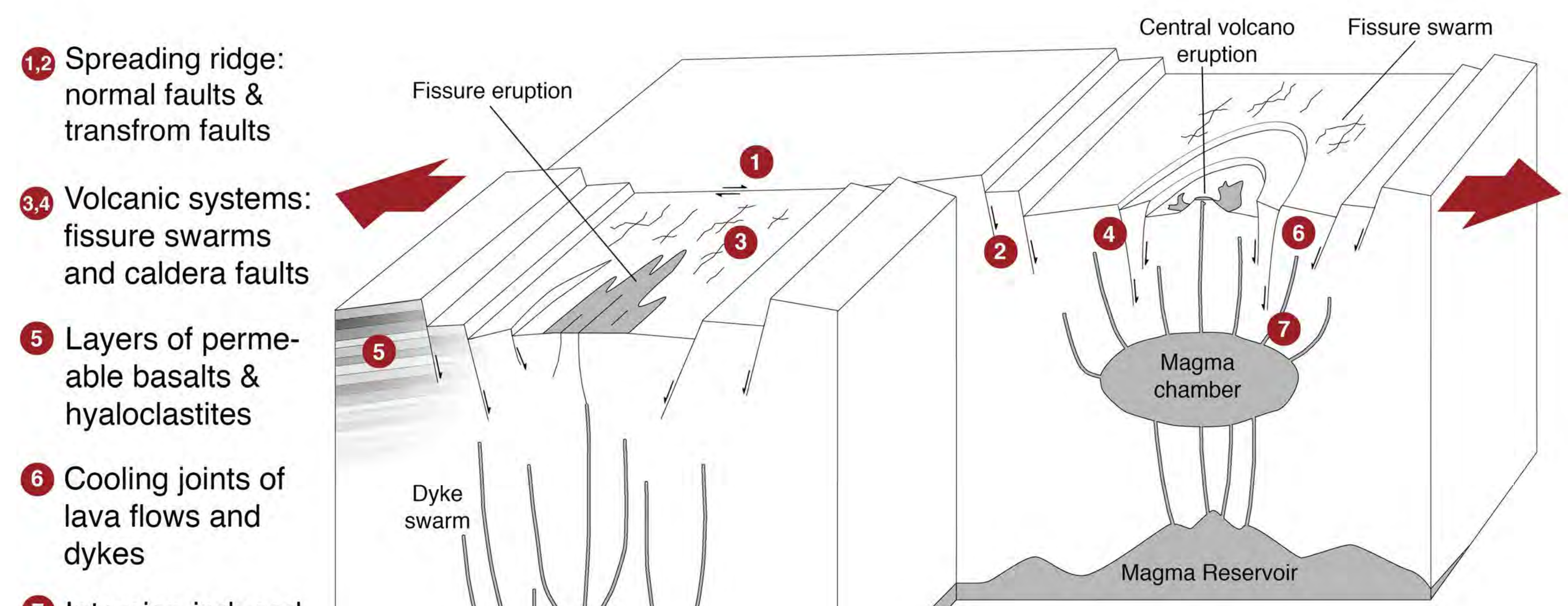

Fig 4: Typical features which build part of the fracture networks in Icelandic geothermal systems.

5. Oscillatory Compression and Shear Tests

Our numerical modeling study was done in cooperation with the Institute of Earth Sciences at the University of Lausanne.

An example work flow is presented in Fig (5). Input parameters require detailed knowledge of the geology, hydrology, rock mechanics and fluid physics. Output parameters are the P- and S-wave moduli M and G, and the quality factors Q_P and Q_S, which describe the P- and S-wave attenuation.

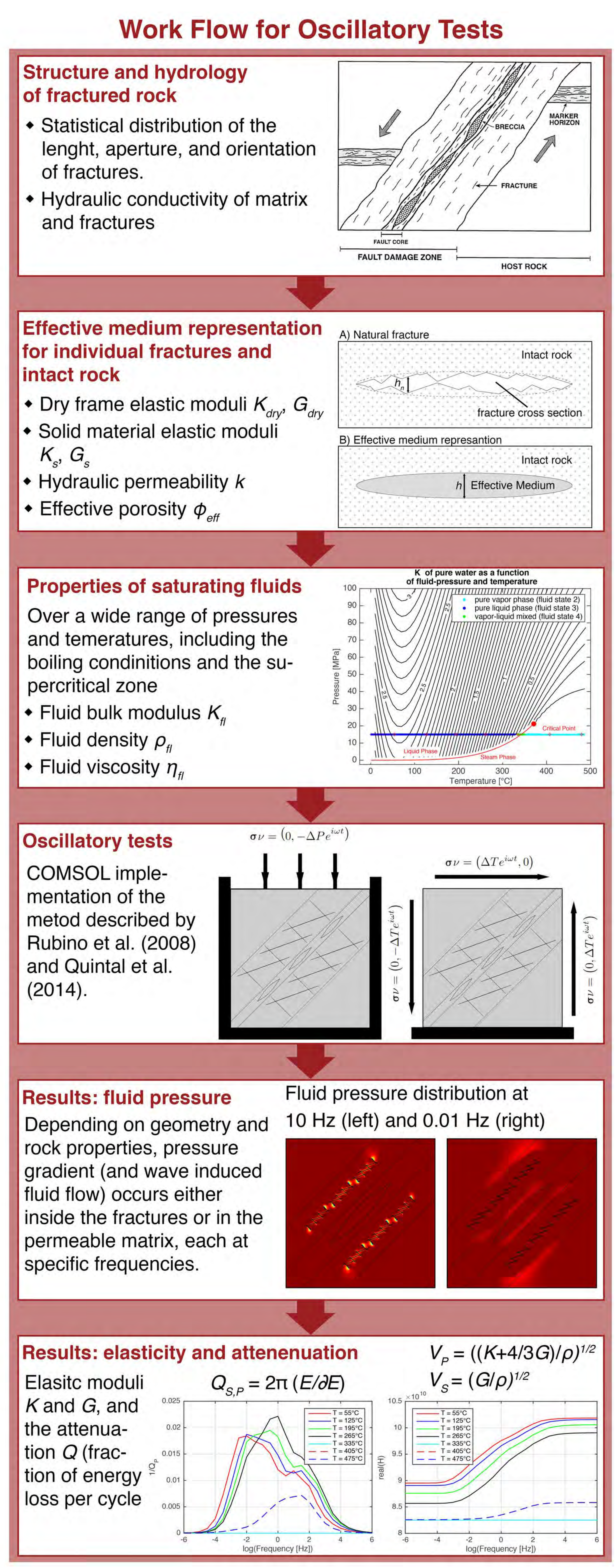

Fig 5: Work flow for oscillatory compressibility and shear modeling.

6. Preliminary Results

We performed oscillatory tests for a fracture network as it occurs in the damage zone of normal faults. The geometry of the fracture network was derived from a detailed study (Gudmundsson, 2001) of an outcropping fault in northern Iceland. In Fig 6, the statistical distribution is presented of the aperture, orientation, and length of the fractures forming the fracture network.

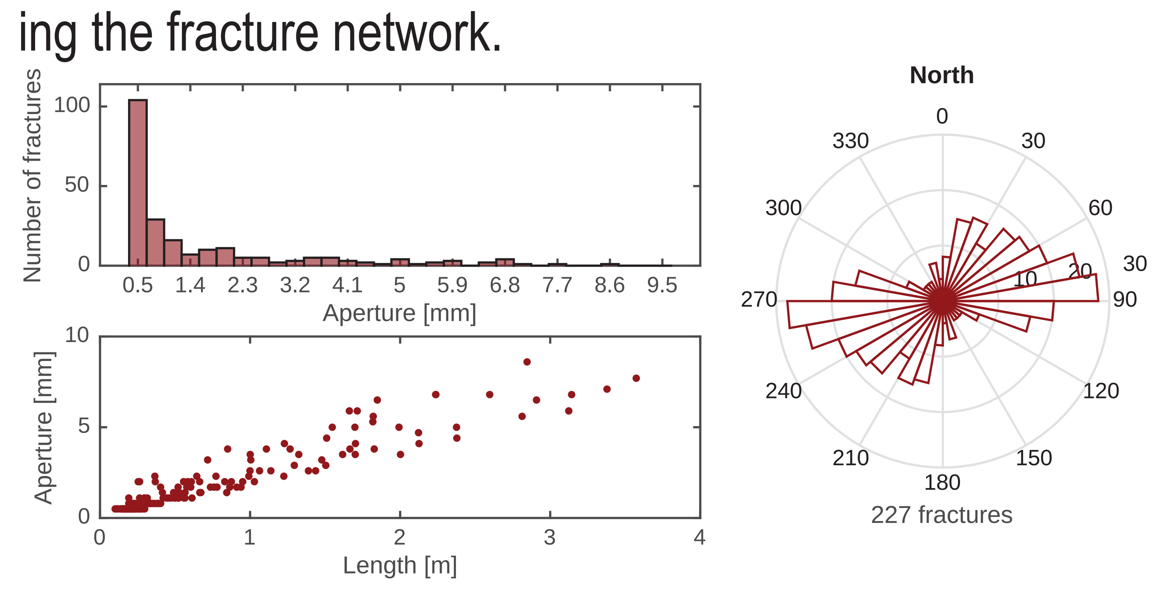

Fig 6: Distribution of aperture (top left), orientation (right), and length (bottom left) of the fractures shown in the model in Fig (7, left).

The fractured rock model is shown in Fig (7, left). In Fig (7, right), the resulting P-wave modulus M is presented. It shows the typical behavior of high H values at the high frequency limit and low H values at the low frequency limit. This is a preliminary result. For a quantitative interpretation, first the effective medium representation of the fractures needs to be specified more carefully.

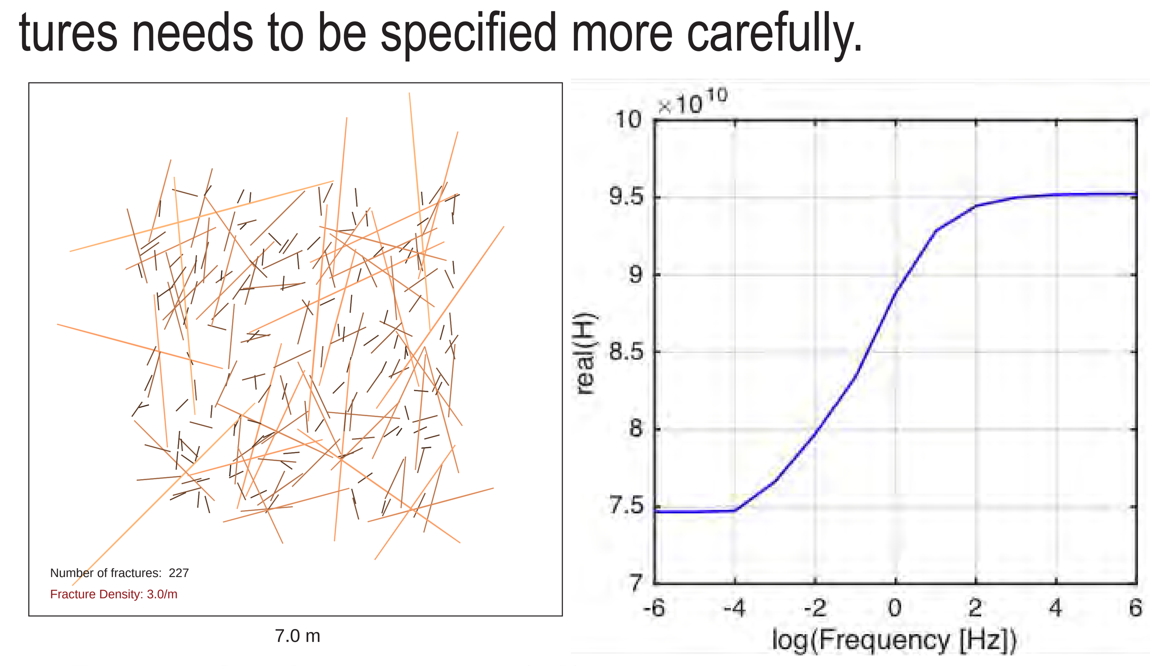

Fig 7: Model of the fracture network (left) and the corresponding P-wace modulus H resulting from the oscillatory compressibility test (right).

7. Acknowledgments

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