Task 1.3

Title

Hydrothermal heat exploitation and storage

Projects (presented on the following pages)

Geoelectrical methods: new insights for geothermal energy prospection and exploration
Aurore Carrier, Matteo Lupi, Carole Nawratil de Bono, Federico Fischanger, Gianfranco Morelli, Julien Gance

Numerical Modelling of the Geneva Basin: from reservoir to geothermal simulations
Marine Collignon, Marion Alcanié, Øystein Klemetsdal, Olav Møyner, Halvard Nilsen, Knut-Andreas Lie, Antonio Rinaldi, Matteo Lupi

Modelling two-phase flow with boiling and gas partitioning
Alina Yapparova, Dmitrii Kulik, George-Dan Miron, Thomas Driesner

Thermo-hydraulic testing of fractured rock mass for heat storage projects
Reza Sohrabi, Benoît Valley

Investigating mineral reactions during high-temperature aquifer thermal energy storage (HT-ATES) in the Swiss Molasse Basin
DB van den Heuvel, C Wanner, U Mäder, LW Diamond

HEATSTORE
Luca Guglielmetti, Andrea Moscariello, Thomas Driesner, Martin Saar, Benoit Valley, Reza Sohrabi, Larryn Diamond, Daniela van den Heuvel, Christoph Wanner, Carole Nawratil de Bono, Michel Meyer, Francois Martin, David Dupuy, PierVittorio Radogna, Energie Wasser Bern

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Geoelectrical methods : new insights for geothermal energy prospection and exploration

Aurore Carrier, Matteo Lupi, Federico Fischanger, Gianfranco Morelli, Julien Gance

Motivation

-Energetic transition -> developing geothermal energy use
-Previous geological, petrophysical and geophysical studies highlight high geothermal potential of Great Geneva Basin
-To evaluate in situ parameters drillings could be made but are very expansive and do not provide 3D information
-Deep ERT = cheaper alternative

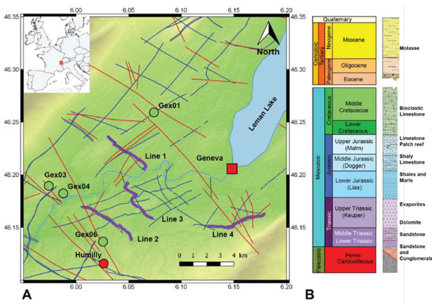
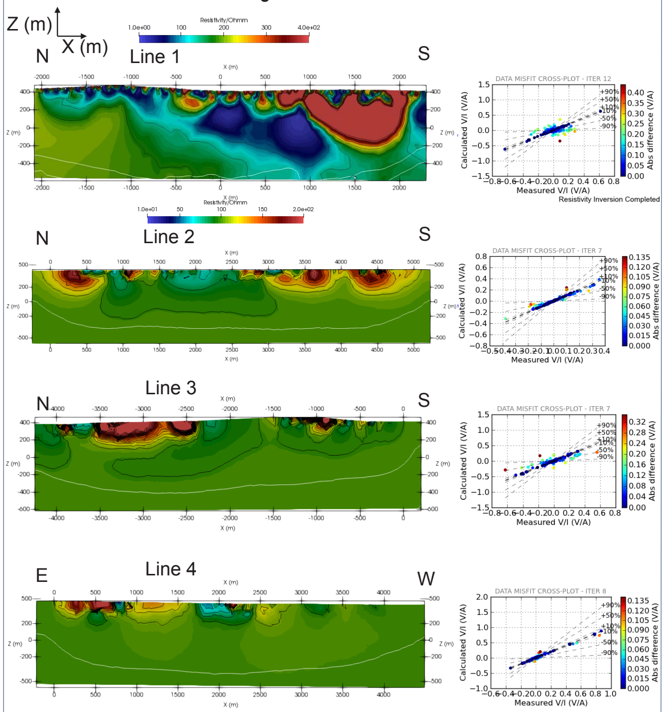


Figure 1: A) Topography of the investigated area and available data. Blue lines : previous active seismic lines, red lines: interpreted faults (GeoMol project), circle points: wells reaching top mesozoic unit, the color corresponds to the lithological unit reached (lithostratigraphic column in panel B). Purple lines: deep ERT profiles performed for this study.

Results

Obtained data are processed and inverted using FullWave Viewer and ERTLab softwares provided by IRIS instruments and GeoStudy Astier.

Figure 3: Resistivity (Ohm.m) profiles obtained for lines 1 to 4 (c.f. location figure 1). Data misfit crossplots are shown on the right of each cross section. Lower coverage areas are below white lines.



-Data are obtained up to 1km depth
-Resistivity values are consistent with local geology and range between 10 to 600 Ohm.m.
-Observed resistivity variations within layers are consistent with previously observed faults

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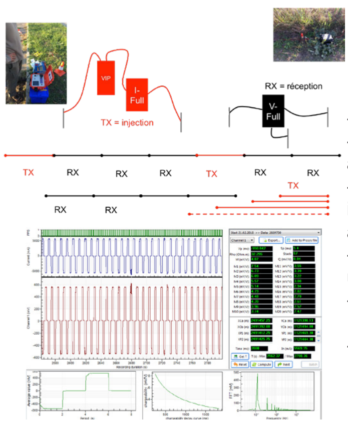
Material



- Lighter Cableless
- Freedom of geometry of acquisition
-Independent receivers and injection units enable to adapat to field constrains
- VIP 5000 to generate current up to 5 Amps
- 50 meters spacing between electrodes
- Continous acquisition (handle electrical noise)

Figure 2: A) Schematic representation of acquisition dispositif for ERT acquisition using FullWavers. Both injection and receivers units record continuously the current. All units are independant and are synchronized in time via GPS data.
B) Raw data obtained for one injection (B1-A2 electrodes of injection) at receiver position 1 for the first channel. Signal amplitude on RX1 is the order of 500 mV and chargeability curves can be obtained.

Discussion and Perspectives

-Well data : Molasse 10 to 50 Ohm.m and Cretaceous limestones 100 to 150 Ohm.m, drinkable water 10 to 20 Ohm.m
-Low resistivity body correlated with high porosity/low density rocks
-**Improve acquisition geometry** to increase sensitivity would need more time on the field
-**3D** experiment with more receiver units
-Bring key information **for fluid flow modelling**
-Refine inversion using prior information

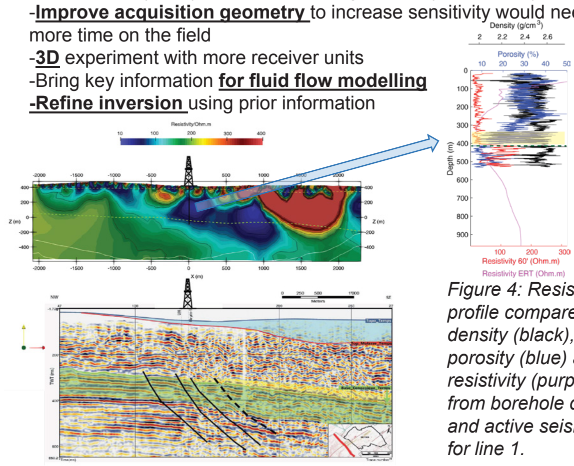


Figure 4: Resistivity profile compares to density (black), porosity (blue) and resistivity (purple) from borehole data and active seismics for line 1.

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Clerc, N., Rusillon, E., Moscariello, A., Renard, P., Paolacci, S., & Meyer, M. (2015). Detailed structural and reservoir rock typing characterisation of the Greater Geneva Basin, Switzerland, for geothermal resource assessment.
Chelle-Michou, C., Do Couto, D., Moscariello, A., Renard, P., Rusillon, E., 630 2017. Geothermal state of the deep western alpine molasse basin, franceswitzerland. Geothermics.
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Morelli G., Fischanger F., Gualerzi D., Occhi M., Ranieri G., Santarato G., 2010. 3D Cross-hole Electrical Resistivity Tomography to Control the Injection of Expanding Resins: A Case History in Venice (Italy). *Proceedings of 16th European Meeting of Environmental Engineering Geophysics (Near Surface Geophysics), Zurich (CH), September 6-8, 2010.*

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Numerical modelling of the Geneva Basin: From reservoir to geothermal simulations

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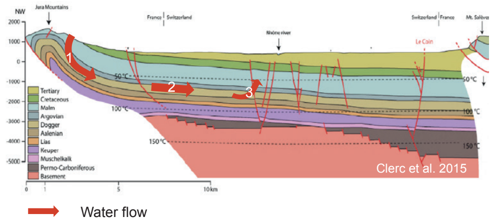
1. Introduction

The rapid economic development has triggered a constantly rising demand for energy. However, the limited amount of natural resources, as well as the global warming and pollution caused by industrial gas emissions and wastes urge to the development and production of renewable and sustainable energy. In addition to production, energy conservation and storage became equally crucial to make use of excess energy and waste in future times of high energy demand.

Over the last two decades, several geological and geophysical studies were conducted in the Geneva Basin to investigate its geothermal potential for energy production. A large data set is now available, including exploration wells, active seismic, gravity and geoelectrical data. If the production of electricity might be challenging due to the low geothermal gradient, the shallower horizons (within the first 2 km) are now investigated for seasonal heat storage or direct heat production for modern buildings whose heating systems do not require high temperature (> 80ºC). However, if a static model of the Geneva Basin has already been proposed based on existing data, no flow modelling model exists. The Geneva Basin is located between two mountain ranges (the Alps and the Jura Moutains) and is drained by the Rhone River which takes its course in the Leman Lake. We here aim at developing a realistic large scale fluid flow model of the Geneva Basin that integrates the influence of the regional geology (i.e. infiltration from the Jura, lake, topography, faults, etc).



Water flow model

1: Rain infiltration
2: Percolation
3: Resurgence

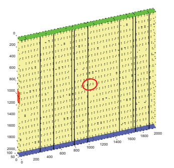
2. Numerical Model

We are currently developping a Matlab-based geothermal module to investigate the geothermal potential and heat storage strategies in the Geneva Basin. This module is based on MRST (Matlab Reservoir Simulation Toolbox), which is an open source Matlab toolbox, developed by the Department of Applied Mathematics at Sintef, Oslo, Norway (Lie et al., 2016). MRST was initially developed for oil and gas simulations but no thermal equations were implemented in the toolbox. Furthermore, an adequate formulation of the p,T-dependent parameters (i.e. density, viscosity, heat capacity, etc), required to produce realistic models for geothermal applications, is still lacking in MRST.

Geothermal module (implemented)
- single phase model (fully saturated)
- two-immiscible phase model
- p,T - dependent density equation for brine (Spivey et al., 2004).

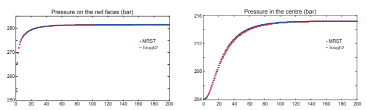
Benchmark

Comparison between MRST and Tough2.
Same initial setup and boundary conditions.



Physical domain: 2000x100x2000
Mesh: 20x1x20
Z_{top} = 1000 m
Z_{bot} = 3000 m
P_{init} = P_{hyd}
T_{init} = 283 K

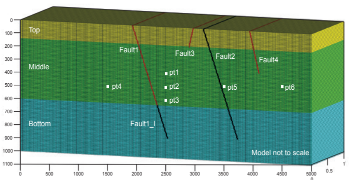
BCs: top: P_{top}, bot: P_{bot} (hydro).
face left side, P: 300 bar
no flux for T.



3. "Satigny" type Model

The model of Satigny is loosely based on the preliminary results of the ERT (electric resistivity tomography) done by Carrier et al. (cf. poster). The model dimensions are 5000x1x1000 m (2.5D) with a cell resolution of 10x1x10 m (i.e. 500x1x100 cells). The layers have a dip of ~6º, which is consistent with the regional formation dipping in the Geneva Basin. We considered a model with three layers that represent the quaternary, the molasse and the upper Jurassic.

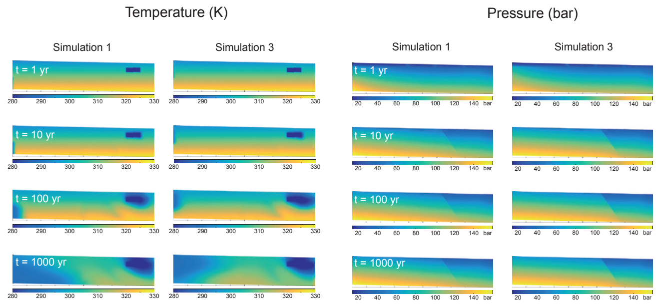
To mimic the lateral inflow of water from the Jura Mountains, a pressure and associated temperature conditions were applied on the left side of the domain. We considered successively the case where the water is infiltrating in outcropping Jurassic units (simu 1,2) and the case where infitration takes place in the outcropping molasse (simu 3,4).

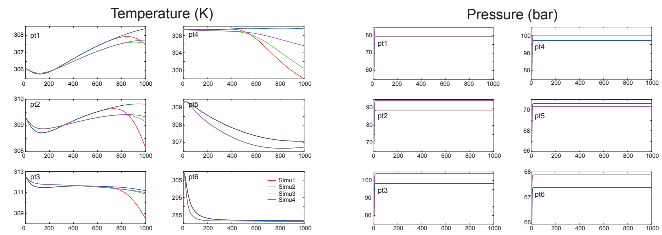


We setup for the initial pressure conditions a casi-hydrostatic pressure (the density was kept constant to compute the initial pressure) and for the initial temperature conditions a thermal gradient of 32º/km and a surface temperature of 293 k. The infiltrated fluid has either a fixed temperature of 290 K or depth-dependent temperature, with a lower thermal gradient. In the second case we considered that the fluid already warm up since its infiltration in the Jura mountains.

	Simu1	Simu2	Simu3	Simu4
Top	no flux P,T	no flux P,T	no flux P,T	no flux P,T
Bottom	no flux P,T	no flux P,T	no flux P,T	no flux P,T
Left	bottom only, fixed P,T P: Phyd + 10 bar. T: 290K	bottom only, fixed P,T P: Phyd + 10 bar. T: dT-5	middle only, fixed P,T P: Phyd + 10 bar. T: 290K	middle only, fixed P,T P: Phyd + 10 bar. T: dT-5
Right	fixed P,T P: Phyd. T: dT	fixed P,T P: Phyd. T: dT	fixed P,T P: Phyd. T: dT	fixed P,T P: Phyd. T: dT
Front	no flux P,T	no flux P,T	no flux P,T	no flux P,T
Back (lake)	few cells, fixed P,T P: Phyd + 10 bar. T: 280K	few cells, fixed P,T P: Phyd + 10 bar. T: 280K	few cells, fixed P,T P: Phyd + 10 bar. T: 280K	few cells, fixed P,T P: Phyd + 10 bar. T: 280K

	Permeability (mD)	Porosity (-)
Top	0.0035	0.05
Middle	5 (simu 1,2) - 10 (simu 3,4)	0.1
Bottom	5 (simu 3,4) - 10 (simu 1,2)	0.1
Fault1	10	0.1
Fault1_l	0.0001	0.01
Fault2	0.0001	0.01
Fault3	10	0.1
Fault4	10	0.1

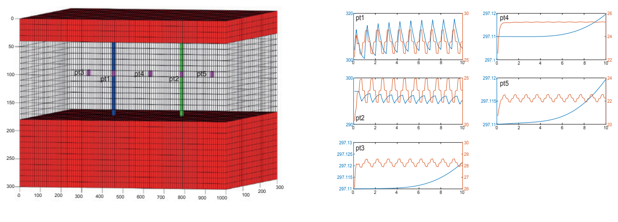


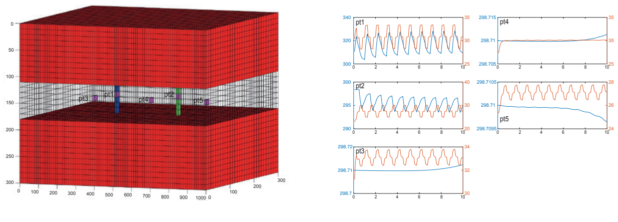


4. Heat Storage

For the heat storage simulations, we considered a simple 3D bloc of 1000*300*300 m with a cell resolution of 10*10*10 m and three layers of different thickness. We impose a pressure and temperature conditions on the left and right faces of the model while all other faces have a no flux condition. A casi hydrostatic pressure and a thermal gradient of 32º/km, with a surface temperature of 293K are prescribed as initial conditions. To the left we applied a fixed pressure P = P_{hyd} + 10 bars and a fixed temperature T = dT (initial temperature gradient). To the right we applied a fixed pressure P = P_{hydr} and a fixed temperature T = dT. The aquifer has a permeability of 5 mD and a porosity of 0.1. The top and bottom layers have a permeability of 0.001 mD and a porosity of 0.05.

We considered a cycle of 10 years. From July to September, we inject hot water at a rate of 10^{-4} m^3s^{-1} and a temperature of 350K in Well 1 (blue well), while we pump cold water from the reservoir at the same rate in well 2 (green well). October to December is a period of rest, where nothing is injected nor pumped. From January to March, the water is extracted from the reservoir in well 1, while cold water (290 K) is injected in well 2. Finally, April to June is a period of rest. In these two simulations, we investigated the effect of the aquifer thickness on the dissipation of heat in the aquifer. We monitor the temperature and pressure in 6 different points in the reservoir.





5. Further development

Several implementations are still required in the **Geothermal Module**:

- **2 phase miscible model** to account for phase transitions (in high-enthalpy systems) or exsolution of gas in water.
- **salt transport** to account for convection cells that may develop in the aquifer during heat storage.
- p,T - dependent formulations of the parameters such as density, viscosity, heat capacity.

Additional modules of MRST (some still under development) could be later coupled to the Geothermal Module to build up more realistic but complicated models that take into account the rock-fluid interaction, the dual porosity, or the geomechanics.

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Clerc N., Rusillon E., Moscariello A., Renard P., Paolacci S. and Meyer M., 2015, "Detailed Structural and Reservoir Rock Typing Characterization of the Greater Geneva Basin, Switzerland for Geothermal Resource Assessment", World Geothermal Congress 2015.

Lie K.-A., 2016, "An introduction to reservoir simulation using MATLAB: User guide for the Matlab Reservoir Simulation Toolbox (MRST)". SINTEF ICT, http://www.sintef.no/projectweb/mrst/.

Acknowledgment:

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Modelling two-phase flow with boiling and gas partitioning

A. Yapparova (ETH Zurich), D.A. Kulik (PSI), G.D. Miron (PSI), T. Driesner (ETH Zurich)

Motivation: Geothermal systems

Magma-driven, high enthalpy geothermal systems are currently the only type of geothermal reservoirs that is routinely utilized for electrical power generation. The transient evolution of geochemical processes in the subsurface of these systems has remained elusive because direct observation is hampered by the extreme conditions in the boiling reservoir.

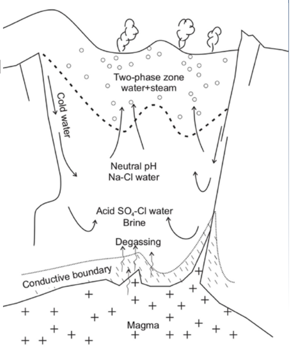

Fig. 1. Schematic section of a volcanic geothermal system depicting the origin, interaction, and possible evolution of fluids. (Arnorsson et al., 2007).

Methods

The CSMP++GEM reactive transport code:

- Control volume finite element method (CVFEM) to solve PDEs for two-phase flow and heat transport in terms of pressure, enthalpy and salinity on unstructured grids (Weis et al., 2014).
- Accurate thermodynamic representation of fluid properties – Equation of state for a H_2O-NaCl system (Driesner&Heinrich, 2007; Driesner, 2007).
- Chemical equilibrium calculations using the Gibbs energy minimisation method (GEM), implemented within the GEMS3K code (Kulik et al.,2013).
- Sequential Non-Iterative Approach (SNIA) for transport-chemistry coupling for fast reactive transport calculations (compared to SIA and fully implicit methods).

1D Model Setup

Hot low-salinity vapour at 300°C, 61 bar is injected from the left into the warm 5 wt% NaCl liquid at 200°C, 30 bar. Initial fluid composition is representative of a natural hydrothermal fluid.
A boiling/condensation zone develops in the middle part of the model, volatiles partition between the liquid and vapour phases.

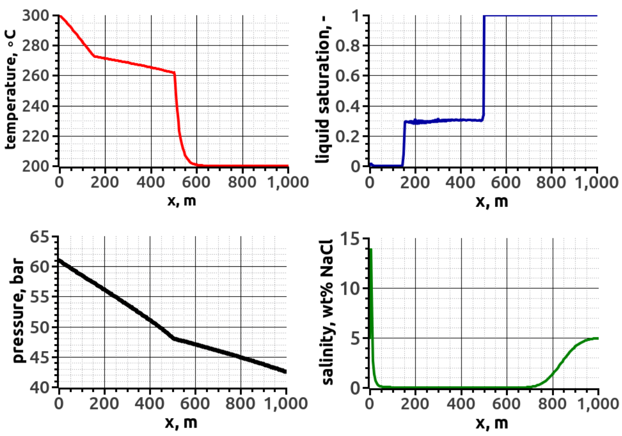

Fig. 2. Temperature, pressure, liquid saturation and aqueous fluid salinity after 300 years of the RTM simulation

Results and Discussion

Volatile species (CO_2, H_2S, CH_4, H_2) preferentially partition into the vapour phase. An increase of CO_2 concentration ahead of the two-phase zone has a major effect on the pH of a boiling solution.
The simulation predicts a narrow highly acidic zone that may develop at the border between the vapour-dominated and boiling/condensation zones, due to the specifics of HCl partitioning.

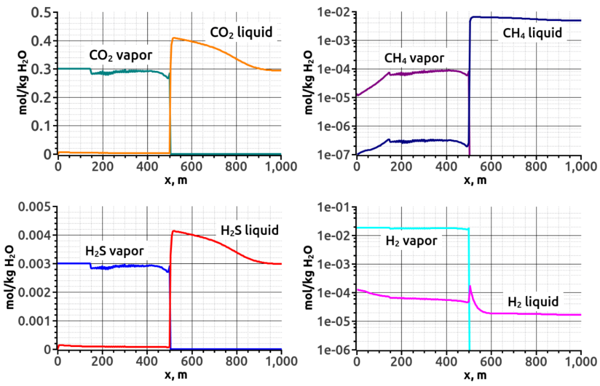

Fig. 3. Molality concentrations of CO_2, H_2S, CH_4 and H_2 in vapour and liquid phases after 300 years of the RTM simulation. Note the logarithmic scale on the right.

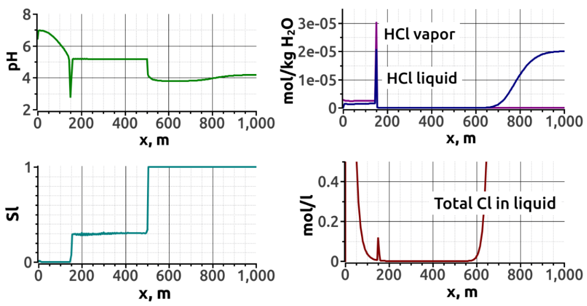

Fig. 4. Solution pH, liquid saturation, molality of HCl in vapour and liquid phases, and total chlorine molarity in liquid after 300 years of the RTM simulation.

Conclusion

The CSMP++GEM reactive transport modelling code represents a powerful tool for studying complex natural systems, having access to state of the art heat flow and chemical models, and allows us to explore the interplay of chemical reactions and two-phase transport in ore forming and high-enthalpy hydrothermal systems.

References

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2) Driesner, T., 2007. The system H2O-NaCl. Part II: Correlations for molar volume, enthalpy, and isobaric heat capacity from 0 to 1000C, 1 to 5000bar, and 0 to 1 XNaCl. Geochimica et Cosmochimica Acta 71 (20), 4902–4919.
3) Driesner, T., Heinrich, C. A., 2007. The system H2O NaCl . Part I : Correlation formulae for phase relations in temperature pressure composition space from 0 to 1000C , 0 to 5000 bar , and 0 to 1 XNaCl. Geochimica et Cosmochimica Acta 71, 4880–4901.
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Thermo-Hydraulic Testing of Fractured Rock Mass for Heat Storage Projects

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Motivation and objectives

Space heating demand is **highly seasonal** while heat production from industrial processes is regular throughout the year. It would be efficient to store excess heat in summer and recover it during the cold season (Figure 1). Medium depth aquifers that are not exploited for drinking water are a **target for heat storage**. It requires however a knowledge of characteristics of the aquifers that cannot be derived from standard well tests. The objectives of this research is to provide **well testing protocols that are adapted for heat storage** projects in fractured aquifers at early project stage, i.e. when a single well is available.

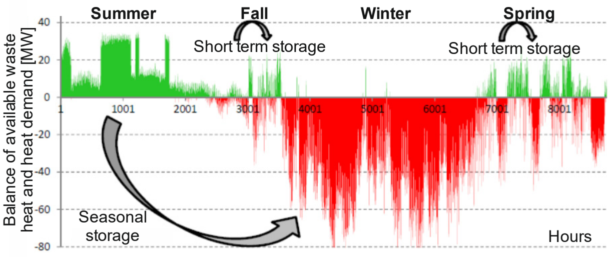

Figure 1: Opportunity for waste heat storage illustrate by heat availability and demand balance in Geneva, after Quiquerez et al. 2015.

Approach

The approach in this project is to use numerical simulations and in-situ well tests in order to:

1) Define the relevant **key aquifer parameters** that must be determined to provide **reliable heat storage design** in fractured aquifers;
2) Propose **well testing approaches** (single well configuration) that can be deployed to estimate these key aquifers parameters;
3) Assess the **feasibility of these testing approaches** through numerical simulations and field tests;
4) Provide **testing protocols**, **simplified test design guidelines** and **application examples** in order to support the acceptance of these testing approaches as an industry standard for heat storage project development in fractured aquifers.

The fundamental assumption of this project is that standard well tests used to determine aquifer transmissivity are not sufficient to generate reliable design parameters for heat storage projects. In the following we present initial ideas concerning the key processes and parameters that need to be determined and possible single well test approaches that could be used to estimate these parameters.

Ambient flow

Natural flow occurs in aquifers and it is essential to characterise it for the design of a heat storage system. If ambient flow is too vigorous, the deployment of a heat storage system can even be precluded. In a single well configuration, a **dilution test** can be used to estimate ambient flow. A dilution test consist of mixing a tracer in the well volume and to measure at what rate the tracer is leaving the well, captured by the ambient flow (Figure 2).

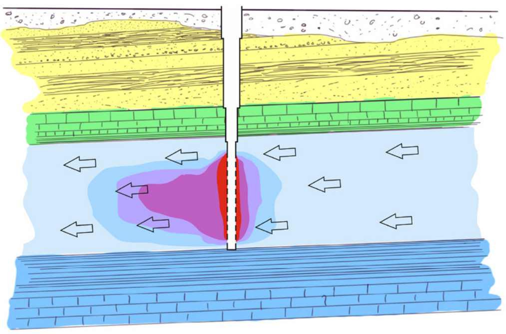

Figure 2: Schematic representation of ambient flow occurring in an aquifer and its impact on heat storage.

Heat exchanger geometry

The structures in the aquifer will control the **flow geometry** (Figure 3). At same bulk aquifer transmissivity, the flow geometry can differ significantly. This will have a large impact on **heat exchange properties** of the reservoir. **Push-pull tests** of hot water or of tracers mix with variable reactivity with the in-situ rocks can be used to quantify the exchange capacity of a reservoir, which reflect the heat exchanger geometry.

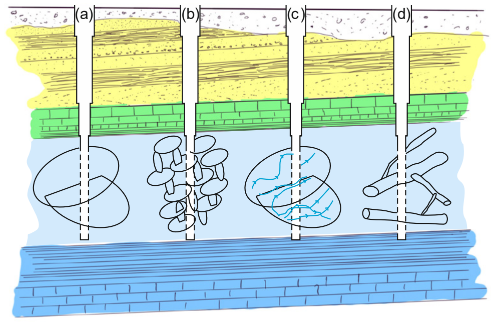

Figure 3: Schematic of various possible heat exchanger geometry. a) dominated by few large features; b) distributed and well connected network of features; c) channelling on planar features and d) conduits formed by karstic processes.

Thermo-elastic fracture closure

Hot fluid injection will induce a thermo-mechanical response of the rock that in turn can impact the hydraulic characteristic of the aquifer. For example, **thermo-elastic rock expansion** could induce fracture closure (Figure 4) and thus the transmissivity of the reservoir will decrease. It is required to measure the mechanical conditions in the reservoir (e.g. stress state) in order to assess the impact of such effects on an aquifer thermal storage system.

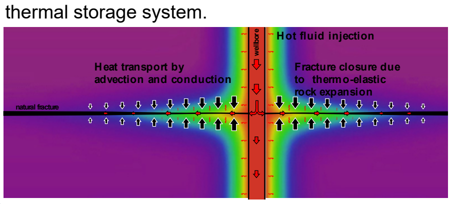

Figure 4: Schematic representation of fracture closure in response to hot water injection.

Acknowledgements

These initial ideas will be tested using numerical simulations and in-situ testing in the framework of the European Project Heatstore. It is supported by the Swiss Federal Office of Energy SFOE and is developed in collaboration with Industrial Services of Geneva (SIG).

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Investigating mineral reactions during high-temperature aquifer thermal energy storage (HT-ATES) in the Swiss Molasse Basin

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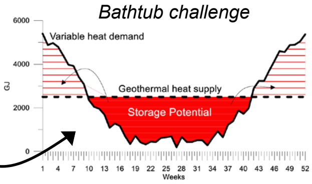
High-temperature aquifer thermal energy storage (HT-ATES)

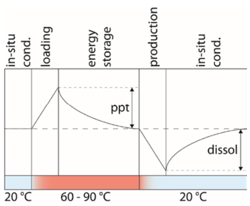
What: Storage of excess industrial heat (e.g. from waste incineration) in the subsurface by injecting warm/hot (25 to 90 °C) water into a confined aquifer

Why: Conserve excess heat during summer, then extract hot water during winter for district heating

Bathtub challenge



Geochemical challenges during HT-ATES



Evolution of SI(cc) close to main well

Dissolution/precipitation reactions in the carbonate system (retrograde solubility)

- Precipitation during loading/storage — Clogging?
- Dissolution during production — Does loose sand form?

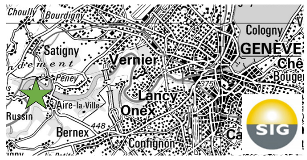
⇒ Can porosity/permeability of the reservoir be maintained?

Dissolution/precipitation of sulphides and silicates (normal solubility)

- Dissolution during loading/storage — Release of toxic metals?
- Precipitation during production — Scaling in heat exchanger?

Pilot projects planned in Switzerland

Forsthaus
T = 60 – 90 °C
In porous USM Sandstones
2019 - 2023?



Les Cheneviers
T > 50 °C
In karstified Cretaceous limestone
2018 - 2020

Other potential problems

- Corrosion
- Microbial activity: Clogging due to biofilm formation and microbially-induced corrosion (MIC)
- Thermal stratification of aquifer due to density differences

Example HT-ATES Forsthaus: Planned geochemical studies at the Institute of Geological Sciences, UniBe

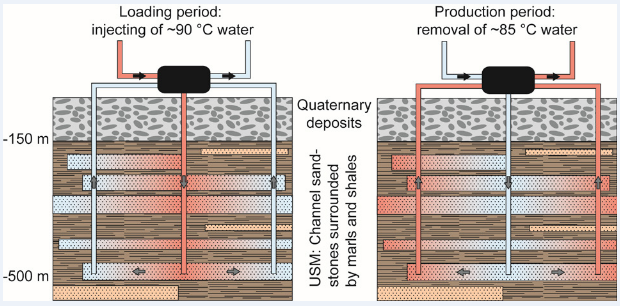
1. Preliminary study

A: Characterisation of **USM sandstones** (composition, porosity, permeability) and comparison with literature data

B: Experimental calibration of **mineral reactions** in contact with synthetic formation water during heating to 60 and 90 °C respectively; partly time-resolved

C: Base-case **reactive transport simulations** using the thermodynamic and kinetic data obtained during the experiments

(preliminary study performed on USM drill cores from a 2017 well drilled at Bern RBS)



System schematic: Main well in centre surrounded by ≥ 2 auxiliary wells to aid in injecting and extracting from the sandstone layers

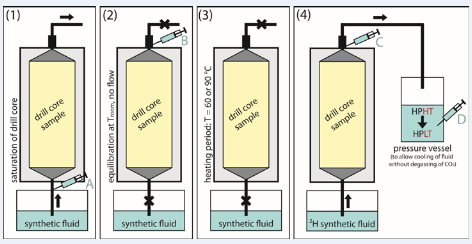
2. Geochemical supervision of drilling and testing at site

A: Characterisation of **USM sandstones** at Forsthaus site (composition, porosity, permeability)

B: Sampling and analysis of **formation water**

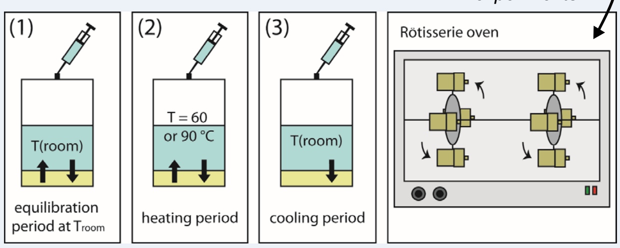
C: Characterisation of in-situ **microbial community** in collaboration with GFZ Potsdam

Optionally: Determination of **corrosion rates** of casing and pipes/heat exchanger in collaboration with ETHZ



Experimental setup of drill core experiments.

Experimental setup of batch experiments



3. Experimental simulation of mineral reactions

A: Identify & quantify **mineral reactions** f(time) under **normal operating conditions (60 and 90 °C)**

B: Assess **mineral reactions** under different chemical conditions (e.g. temperature, pH, pCO_2, salinity, redox conditions)

Two setups: Drill core experiments and batch experiments using powdered or SelFrag samples

Step by step: Preparation of samples – mounting – saturation with synthetic formation water – equilibration at T_{room} – heating period – cooling period
→ Samples taken at each step to identify mineral reactions taking place

4. Numerical simulation of Forsthaus system

Expand preliminary simulations with site-specific data:
- Guide testing and system layout (placing of more auxiliary wells)
- Assess long-term behaviour
- Run different scenarios (e.g. reservoir stimulation by injection of CO_2)
- Extrapolate findings to other sites (e.g. Les Cheneviers)

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Industry uses about 92% of their total energy requirement for generating process heat

50% of the total energy consumed in Switzerland is needed to supply heat.

Households and services use about 92% of their total energy needs for heating applications

86% of the required heat is generated by the burning of fossil fuel

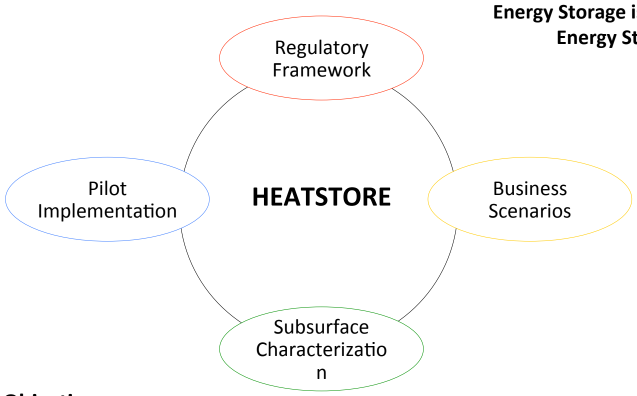
Waste heat generated from domestic and industrial processes is continuously discharged into the the environment

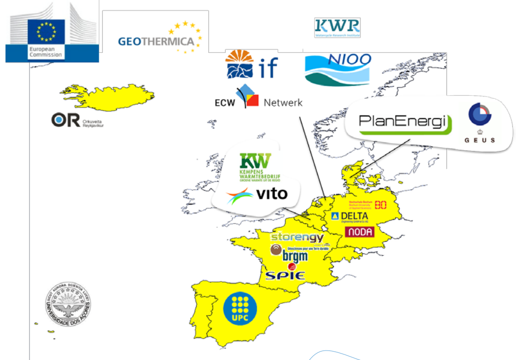
Let's **convert waste** heat **into** a **resource**

In Switzerland hundreds of industrial activities can be suitable for this technology ad different scales of application

Underground Heat Storage provides several solutions to optimize the whole energy system and reduce the CO_2 footprint by replacing fossil fuels

Energy Storage is one of the most important key elements within the Swiss Federal Energy Strategy in order to meet the CO_2 emission reduction targets.





Objectives:

- De-risk and prove the feasibility of deep (>300m) high-temperature (25-130°C) aquifer thermal energy storage (HT-ATES)
- Characterize the geological, hydrogeological, and hydro-chemical settings
- Develop a toolbox to predict and optimise the subsurface dynamics, performances and economics
- Design and implement pilot demonstration projects
- Monitor the performance
- Determine the current and required stakeholder engagement and adapt the regulatory conditions
- Deliver a fast-track market uptake from demonstration to commercial deployment