Task 1.3

Title

Hydrothermal heat exploitation and storage

Projects (presented on the following pages)

Simulations of chemical processes during high-temperature aquifer thermal energy storage
Peter Alt-Epping, Daniela B. Van den Heuvel, Christoph Wanner, Larryn W. Diamond

Seismic stimulation of fractured reservoirs
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Modeling Ground Surface Deformation at the Swiss HEATSTORE Underground Thermal Energy Storage Sites
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3-D Static Model to Characterize Geothermal Reservoirs for High-Temperature Aquifer Thermal Energy Storage (HT-ATES) in the Geneva Area, Switzerland
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Reactive Flow Model for Porosity Reduction by Quartz Dissolution and Precipitation
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Sensitivity Analysis of High Temperature Aquifer Thermal Energy Storage (HT-ATES) using TH Simulations
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Experimental Thermo-Hydro-Mechanical test site to quantify heat exchange characteristics of fractured limestone aquifers
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Investigating mineral reactions during high-temperature aquifer thermal energy storage (HT-ATES)
D.B. van den Heuvel. Ch. Wanner, U. Mäder, P. Alt-Epping, L.W. Diamond

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Simulations of chemical processes during high-temperature aquifer thermal energy storage

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Rock-Water Interaction, Institute of Geological Sciences, University of Bern

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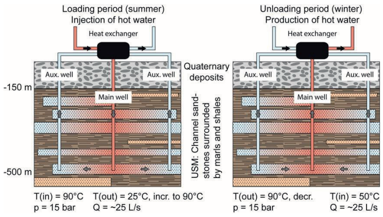
1) Introduction

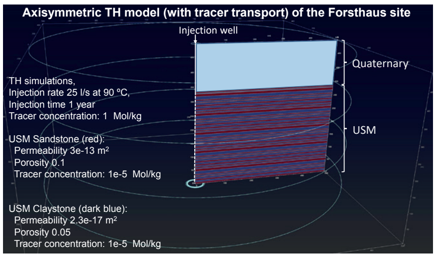
The aim of the Forsthaus heat storage project is to develop an aquifer thermal energy storage site at Bern, Switzerland where waste heat from various surface sources (e.g. municipal waste incinerators) is stored during the summer and recovered and fed into the district heating network during the winter months. The project, which is currently in the planning stage, is part of the Swiss contribution to the European GEOTHERMICA-Heatstore project. The target reservoir of the project is the Lower Freshwater Molasse (USM), a stratigraphic sequence of the Swiss Molasse Basin composed of several meters thick permeable sandstone aquifers surrounded by low-permeability shales.

Concept of typical injection (loading) and extraction (unloading) cycles during summer and winter, respectively, envisaged for the Forsthaus project.



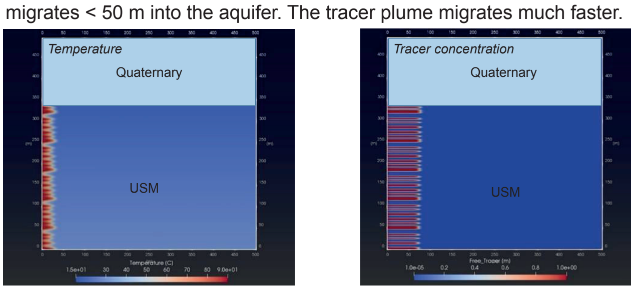
As part of the planning phase we developed reactive transport models to assess mineral scale formation in the installation and permeability changes of the aquifer material after repeated injection and extraction cycles. PFLOTRAN (*www.pflotran.org*) is used to carry out these simulations.

2) Constructing TH and THC models of the Forsthaus system



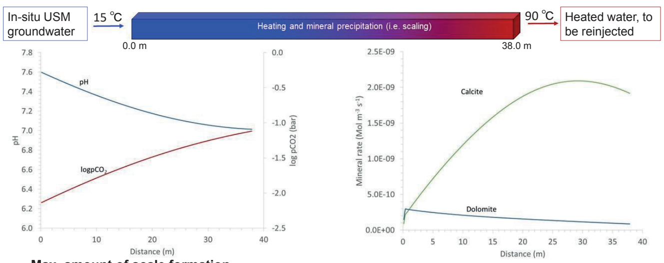
At the Forsthaus site the USM is about 350 m thick and overlain by 150 m of Quaternary unconsolidated sediments. The permeable sandstone layers constitute the target for fluid injection, heat will be stored within the entire USM rock sequence.

Axisymmetric TH models incorporating the entire stratigraphic sequence of the USM, reveal that within 1 year of injection at 25 l/s the thermal plume migrates < 50 m into the aquifer. The tracer plume migrates much faster.



3) Chemical processes in the Forsthaus system: Implications of heating USM groundwater to 90 °C

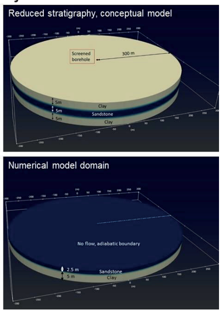
USM groundwater is heated from 15 °C to 90 °C in a simple 1D flowpath model 1) to assess the amount of mineral scaling to be expected upon extraction and 2) to compute the composition of the (re)injected hot water. The latter (2) is used in subsequent THC injection/extraction simulations.



Max. amount of scale formation
A flow rate of 25 l/s yields **18.9 m³** of carbonate scales per year or **11.15 m³** per injection cycle (216 days)

4) Simulations of injection-extraction cycles over 10 years

The dimension of the TH model (Section 2) is reduced to a simple sequence of clay-ss-clay assuming symmetry at mid-depth. The composition of the injected fluid at 90 °C is taken from the 1D simulations (Section 3).



- Axisymmetric cylindrical domain
- 3 layers: clay-sandstone-clay, 5 m each, actual model domain is truncated at the horizontal plane of symmetry at mid-depth
- Injection and extraction along perforated borehole at center
- Dirichlet condition representing «undisturbed conditions» at r = 300 m
- Impermeable, adiabatic top and bottom boundaries assuming symmetry
- Pressure dependent CO_2 g and carbonate mineral solubility
- Monitor possible CO_2 degassing in heat exchanger via «CO_2,s» precipitation
- Time-dependent material properties and chemical conditions to mimic processes in the well and heat exchanger

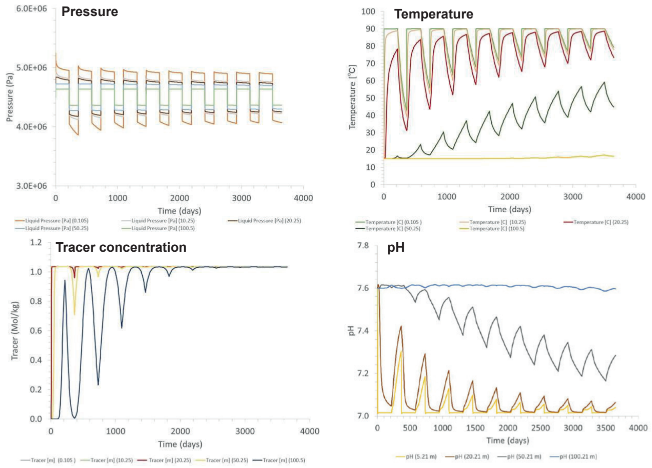
Annual injection/extraction cycle

Time [d]	Q [l/s]	T [°C]	Inject	Extract
0-216	25	90	x	
216-365	25	50		x

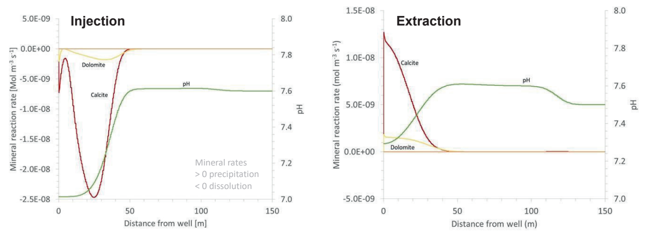
(total simulated time = 10 years)

Results

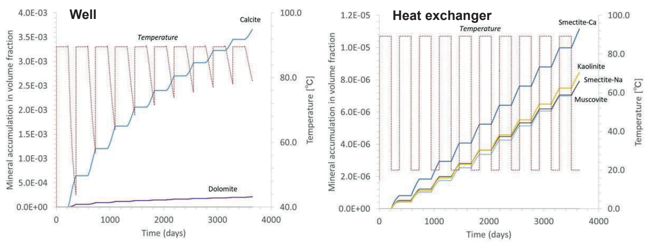
A) Time series of system aquifer properties (legend indicates distance from well in m)



B) Spatial profiles of mineral reaction rates and pH during injection and extraction



C) Time series of temperature and mineral scales in the well/heat exchanger during extraction



5) Conclusions

Reactive transport simulations of THC processes in the Forsthaus system suggest that carbonate scaling constitutes the greatest risk for a sustained operation. Simple heating of in-situ groundwater to 90 °C could clog the pipes of the surface installation. Minor scaling of clay minerals due to cooling occurs in the heat exchanger during operation. Mineral reactions in the aquifer following repeated injection extraction induce only small porosity changes and are not expected to affect the operation.

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Seismic stimulation of fractured reservoirs

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Summary

Experimental studies have shown that flow-driven mobilization of colloids can produce permeability changes in fluid-saturated porous media. Due to the well-known ability of seismic waves to induce transient fluid motion in porous media, this mechanism of permeability enhancement has been proposed to explain hydrogeological phenomena commonly associated with Earthquake events as well as a potential method for seismic stimulation of reservoirs (**Fig. 1**). We model the coupling between the dynamic strains imposed by a propagating seismic body wave and the development of oscillatory flow in porous media in the framework of Biot's theory of poroelasticity. We analyze the conditions (e.g., strain magnitude, frequency, wave mode) under which seismic waves may detach colloids from pores or fractures and, consequently, enhance permeability.

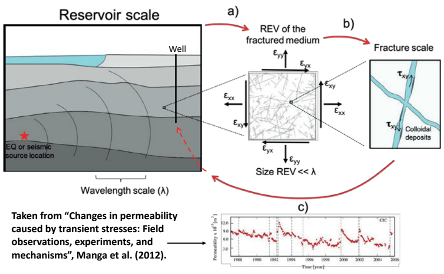


Figure 1: Illustration of permeability changes due to seismically induced fracture-unclogging. The plot in panel c) shows an example of permeability changes due to the action of seismic waves associated with Earthquake events (vertical dashed lines). Permeability is estimated from water level response to semidiurnal tides at a well.

Diffusive waves and colloidal mobilization

We follow Biot's theory of poroelasticity (Biot, 1962) to model seismic wave propagation in fluid-saturated porous rocks. The corresponding set of equations is given by

$$\tau_{ij}(\mathbf{u},\mathbf{w}) = 2\mu\varepsilon_{ij} + \delta_{ij}\left(\left(K_U - \frac{2\mu}{3}\right)\nabla\cdot\mathbf{u} + \alpha M\nabla\cdot\mathbf{w}\right), \quad (1a)$$

$$p_f(\mathbf{u},\mathbf{w}) = -\alpha M\nabla\cdot\mathbf{u} - M\nabla\cdot\mathbf{w}, \quad (1b)$$

$$-\omega^2\varrho_b\mathbf{u} - \omega^2\varrho_f\mathbf{w} = \nabla\cdot\boldsymbol{\tau}, \quad (1c)$$

$$-\omega^2\varrho_f\mathbf{u} + i\omega\frac{\eta}{\kappa}\mathbf{w} = -\nabla p_f, \quad (1d)$$

Symbols in Eqs. 1a-1d

- τ_{ij} and ε_{ij}: stress and strain tensors
- **u** and **w**: solid and fluid relative displacement
- p_f: fluid pressure
- K_U and μ: undrained bulk and shear moduli
- α and M: poroelastic parameters
- ϱ_f and η fluid density and viscosity
- ϱ_b, bulk density
- κ, permeability
- ω, angular frequency

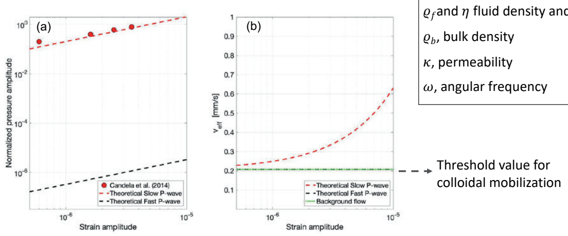


Figure 2: Assuming planar wave propagation, we compute the propagation characteristics of the slow and fast P-waves by solving the system of equations (1a)-(1d). a) Red dots show the ratio between imposed pressure oscillations and the background pressure drop driving flow as a function of the strain typically observed in laboratory stimulation experiments (Candela et al., 2014). Red and black dashed lines show the same relation predicted for propagating slow and fast P-waves, respectively. Panel b) shows the effective fluid velocity in the pores ($v_{eff} = \dot{w}/\varphi$, with φ being the porosity) generated by the slow and fast P-wave as well as by the background flow.

Relative permeability changes due to oscillatory fluid flow

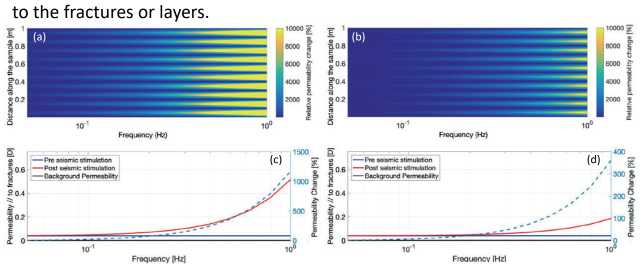
Laboratory experiments showed that permeability changes associated with colloidal mobilization are correlated with the ratio between the pressure oscillations ($\nabla p_f(\omega)$) and the pressure gradient driving background flow (∇p_f^0) as

$$\frac{\Delta\kappa}{\kappa_0} = a\left(\frac{\nabla p_f(\omega)}{\nabla p_f^0}\right)^b. \quad (2)$$

In the following, we use **Eq. 2** with *a*=0.7 and *b*=1.7 (Elkhoury et al., 2011) to predict seismically-induced permeability changes. ∇p_f^0 is set to 1kPa/m, which produces a Darcy flow velocity ~10 m/day in a conductive fracture. We first consider a low porosity Berea sandstone embedding a set of highly conductive and compliant fractures. Then, we consider a two layer medium composed by an alternation of low and high porosity sandstones.

Seismically-induced permeability changes in porous media

To obtain the seismically-induced $\nabla p_f(\omega)$, we numerically solve Biot's equations neglecting inertial terms in **Eqs. (1c)-(1d)** and applying boundary conditions representative of the strain state of a seismic body wave (**Fig. 1a**). Then, we use the seismically-induced $\nabla p_f(\omega)$ in **Eq. 2** to predict permeability changes. Permeability changes are computed for the permeability of the medium parallel to the fractures or layers.



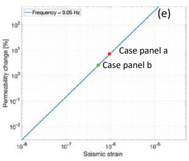


Figure 3: Predicted relative permeability change (**Eq. 2**) in a water-saturated fractured sandstone subjected to the action of a normally incident P-wave as a function of frequency. The P-wave strain is set to 1e−6 (a, c) and 5e-7 (b, d). Panel e) shows the strain dependence of the permeability changes for a frequency *f*=2πω=0.05 Hz.

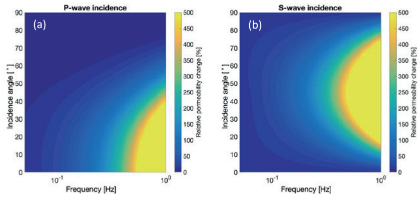


Figure 4: Angle and frequency dependence for (a) P- and (b) S-waves. Properties are the same as in **Fig. 3a**. Maximal permeability changes are expected at quasi-normal and ~45° incidence for P- and S-waves, respectively.

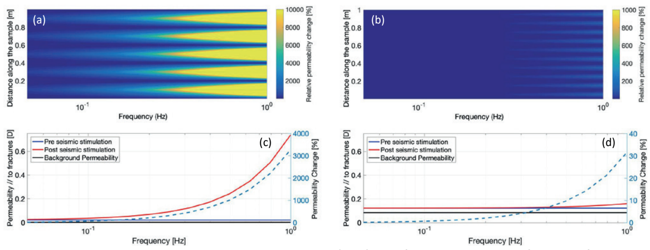


Figure 5: Same scenario as **Fig. 3a** but changing (a, c) the fracture intensity from 10 fractures per meter to 5 fractures per meter and (b, d) the background porosity from 0.035 to 0.1.

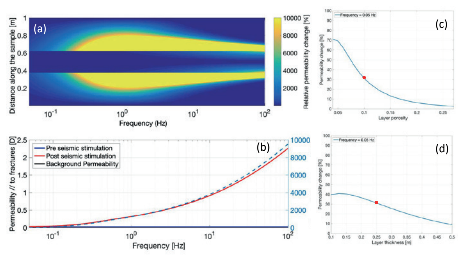


Figure 6: Predicted permeability change as a function of frequency in a water-saturated double porosity sandstone due to the action of a normally incident P-wave. The strain is set to 1e−6. Right panels show permeability changes for *f*= 0.05 Hz as a function of the porosity (c) and thickness (d) of the mid layer.

Conclusions

- We showed that only diffusive waves are able to induce flow rates in the pores that are in the order of those mobilizing fine particles (**Fig. 2**);
- In heterogeneous porous media (e.g., due to layering or fracturing), diffusive waves created as energy conversion from elastic waves at the interfaces separating two phases of the medium can induce permeability changes;
- For a medium containing conductive fractures, incident body waves of tenths of Hz and microstrains are able to induce hydrodynamic forces in the pores significantly larger than those associated with typical natural background flows, resulting in potential permeability increases >10% (**Fig. 3e**).

References: **Biot**, M. A., 1962, Mechanics of deformation and acoustic propagation in porous media. J. of App. Phys., 33; **Candela et al.**, 2014, Laboratory evidence for particle mobilization as a mechanism for permeability enhancement via dynamic stressing. Earth and Plan. Sci. Lett., 392; **Elkhoury et al.**, 2011, Laboratory observations of permeability enhancement by fluid pressure oscillation of in situ fractured rock. Journal of Geoph. Res.: Solid Earth, 116; **Manga et al.**, 2012, Changes in permeability caused by transient stresses: Field observations, experiments, and mechanisms. Rev. Geophys., 50.

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Modeling Ground Surface Deformation at the Swiss HEATSTORE Underground Thermal Energy Storage Sites

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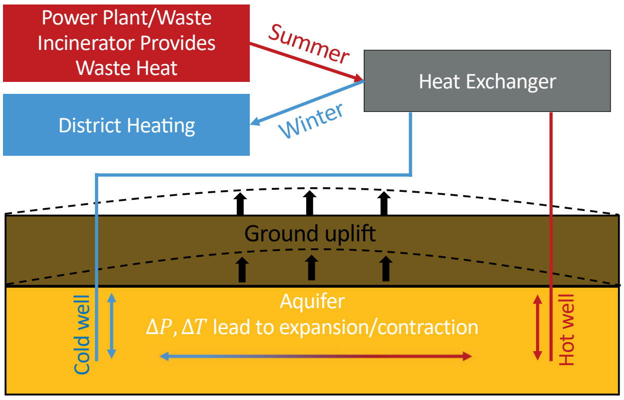
Background and Motivation

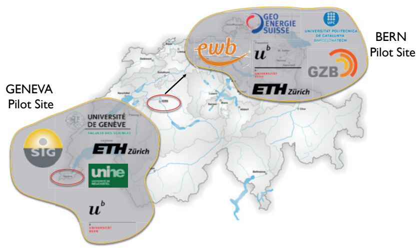
- Storing summertime waste heat for wintertime heating of buildings offers potential environmental and economic benefits
- High Temperature (25 – 90 °C) Aquifer Thermal Energy Storage (HT-ATES) is promising, but offers new challenges
- The potential for geomechanical/geotechnical problems (e.g. surface uplift) in HT-ATES is poorly studied
- How is ground uplift affected by aquifer depth, rock properties, well spacing, and operational decisions?



Adapted and expanded from Lu et al. (2019)

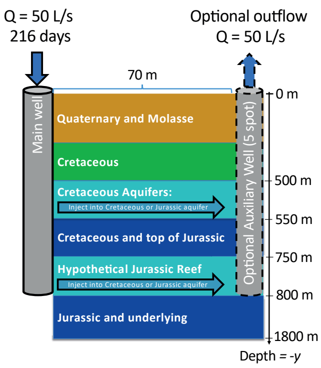
Partners

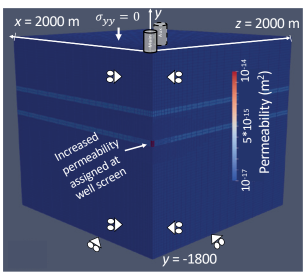
- HEATSTORE aims at developing subsurface storage techniques to reduce wasting heat.
- The Swiss contribution includes two HT-ATES pilot projects, industrial partners, and research institutions



Conceptual and Numerical Model

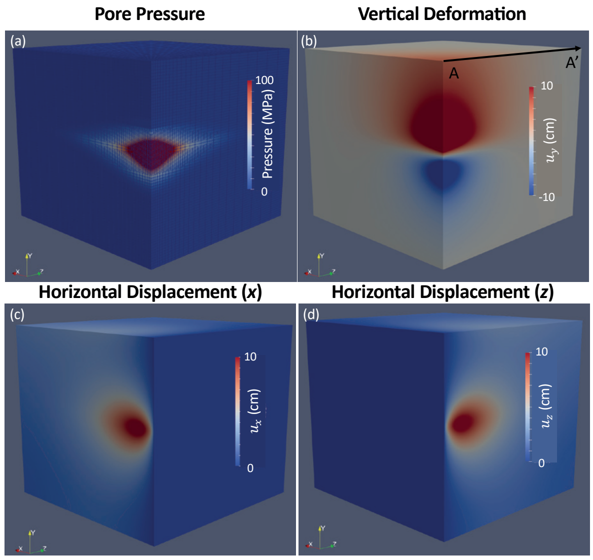
- Conceptual model based on simplified subsurface characterization and energy system scenario modelling at Geneva site
- Hydromechanical equations solved in MOOSE framework (Gaston et al., 2015)
- Base case uses push-pull injection; alternative scenarios also simulated

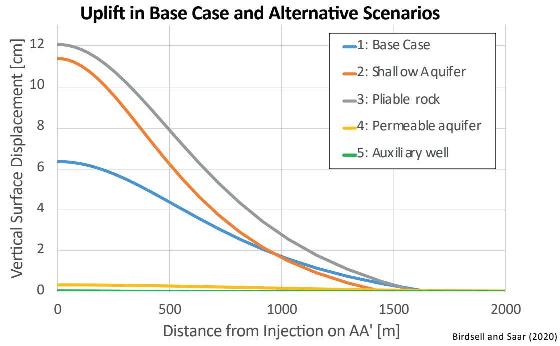




Birdsell and Saar (2020)

Results





Birdsell and Saar (2020)

Conclusions and Future Work

- Auxiliary well to balance pressure and sufficient permeability are key to reducing pore pressure and uplift
- Future work will expand to thermo-hydro-mechanical modeling and investigate well spacing, operating temperature, and incorporate more complex, site-specific geological and energy system information

Acknowledgements

HEATSTORE (170153-4401) is one of nine projects under the GEOTHERMICA – ERA NET Cofund aimed at accelerating the uptake of geothermal energy in Europe. The project is subsidized through the ERANET cofund GEOTHERMICA (Project n. 731117) by the European Commission, RVO (the Netherlands), DETEC (Switzerland), FZJ-PtJ (Germany), ADEME (France), EUDP (Denmark), Rannis (Iceland), VEA (Belgium), FRCT (Portugal), and MINECO (Spain). More information is available via http://www.heatstore.eu

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- Lu, H., Tian, P., Guan, Y., & Yu, S. (2019). Integrated suitability, vulnerability and sustainability indicators for assessing the global potential of aquifer thermal energy storage. *Applied* energy, 239, 747-756.
- Gaston, D. R., Permann, C. J., Peterson, J. W., Slaughter, A. E., Andrš, D., Wang, Y., ... and Zou, L.: Physics-based multiscale coupling for full core nuclear reactor simulation. Annals of Nuclear Energy, 84, (2015), 45-54.

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3-D Static Model to Characterize Geothermal Reservoirs for High-Temperature Aquifer Thermal Energy Storage (HT-ATES) in the Geneva Area, Switzerland

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FACULTY OF SCIENCE
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1. Background

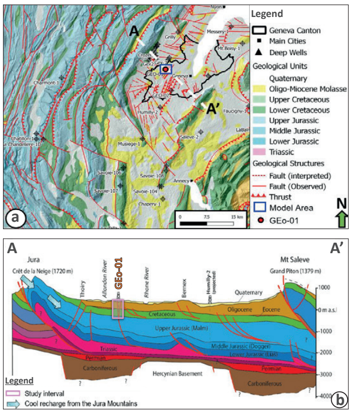

Figure 1a. Location of the study area. (b) Configuration of the Geneva Basin (Modified from Moscariello et al., 2020).

In the framework of the GEOTHERMICA ERA-NET co-funded project-HEASTORE, one of the main challenges related to assessing the technical feasibility and sustainability of High Temperature (~25°C to ~90°C) Aquifer Thermal Energy Storage (HT-ATES) is subsurface characterization.

In this study, we aim to develop a 3-D geologically robust static model in order to characterize the subsurface around the recently drilled GEo-01 geothermal exploration borehole in the Geneva Basin (Figure 1).

We focused on identifying possible candidate intervals suitable for HT-ATES within the Lower Cretaceous Carbonates in the Geneva Area. This was achieved by analyzing a suit of subsurface dataset (Figures 2 and 3).

2. Workflow

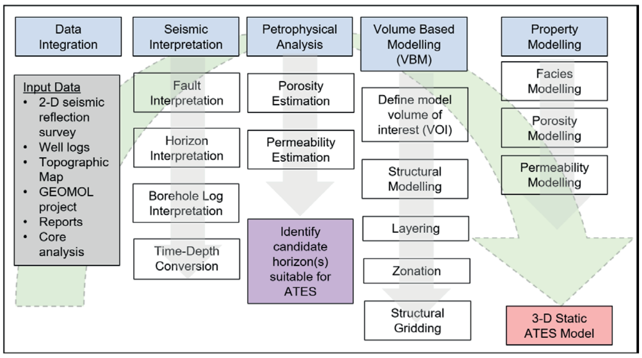

Figure 2. Workflow adopted to build the 3-D Static Model.

3. Seismic Interpretation

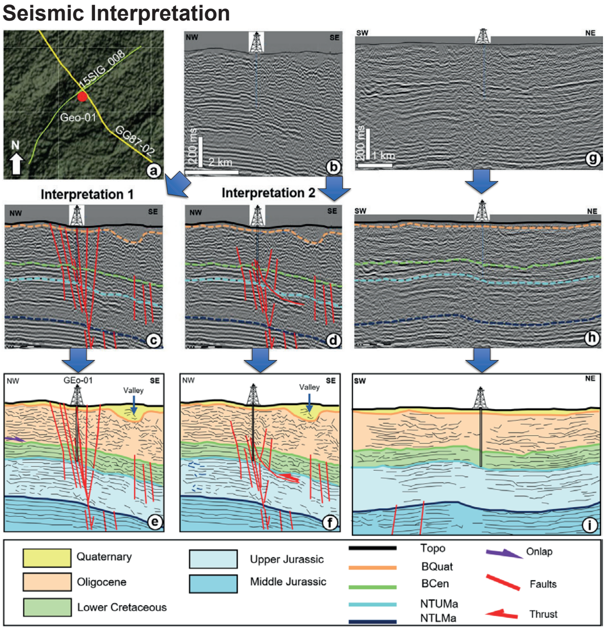

Figure 3. (a) Location of the seismic lines and Geo-01 well. (b - i) NW-SE and SE-NW seismic profile showing the subsurface structural situation around the Geo-01 borehole. Two plausible interpretations are presented for line GG 87-02 with a major difference being the introduction of a thrust fault in Interpretation 2.

4. Potential Storage Interval in the Lower Cretaceous: CT 1-3★

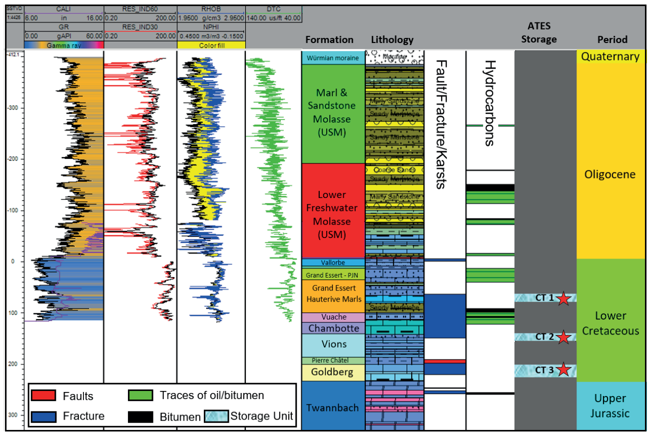

Figure 4. Well interpretation panel for GEo-01 borehole. Three candidate horizons have been identified as potential Lower Cretaceous targets (CT) suitable for HT-ATES in fractured intervals characterized by tested water outflows and devoid of hydrocarbon impregnation: (1) Grand Essert Fm / Pierre Jeune de Neuchatel + Marnes d'Hauterives Fm [CT1 – 10 m], (2) Vuache Fm - Chambotte- Chambotte inférieur [CT2 -12.5 m] and (3) Goldberg Fm [CT3 – 25 m].

5. 3-D Static Model Development (1.5 x 1.5 x 1 Km) – Interpretation 1

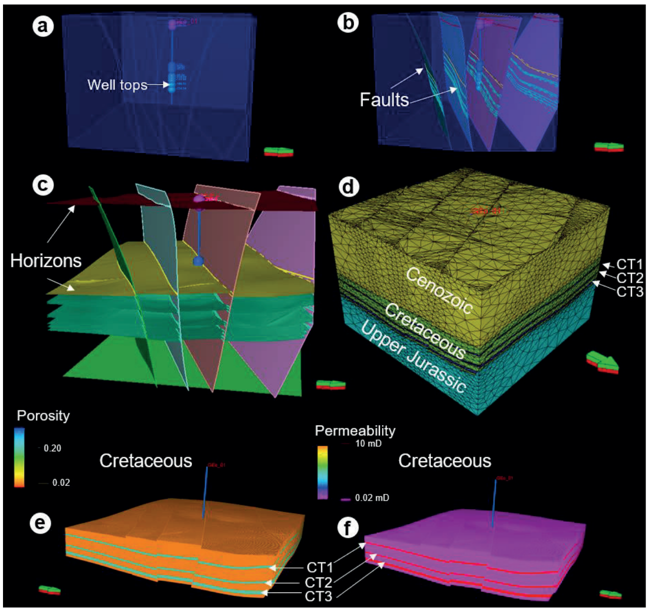

Figure 5. (a) Volume of interest (b) Faults interpreted (c) Fault and Horizons interpreted (d) Layering with the three candidate intervals for HT-ATES CT 1, CT2 and CT3. (e) Porosity model (f) Permeability model.

6. Outlook

- Uncertainties remain especially in the fault geometry and modelling and facies distribution which was assumed to be homogenous in this simplistic case presented here based on the low data density.
- The Lower Cretaceous unit are tight with low porosity and permeability values. The presence of karstified, faulted and fractured intervals locally enhance porosity and permeability. This permit large groundwater flows, making the well suitable for direct uses and only in a second instance favourable for storage.
- The 3-D static model presented here will be employed as input for numerical heat flow and predictive THMC models for the Geneva Basin.

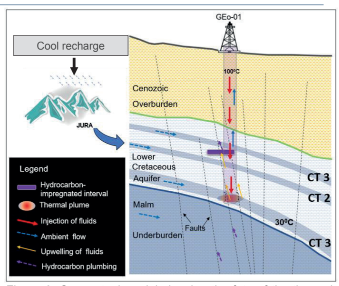

Figure 6. Conceptual model showing the fate of the thermal plume based on the GEo-01 well assuming high-temperature fluids are injected in the thickest and deepest aquifer CT3 in the Grand Essert formation. The natural recharge of the system here is from the Jura Mountain chains and circulation at depth is related to the hydraulic gradient. The presence of a highly conductive fault zone controlling the natural artesian flow observed at GEo-01 might reduce the likelihood for the development of an efficient HT-ATES system considering an extended period of thermal storage.

Acknowledgements
heatstore
Schlumberger

Reference Moscariello A. et al. Heat production and storage in Western Switzerland: advances and challenges of intense multidisciplinary geothermal exploration activities, 8 years down the road. *Proceedings* World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020. 12 pp.

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Reactive Flow Model for Porosity Reduction by Quartz Dissolution and Precipitation

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Introduction

Quartz dissolution and precipitation is an important pore reducing process in geothermal reservoirs. It also causes scaling, which affects the machinery and hinders the productivity of the geothermal energy project. Furthermore, permeability decrease due to quartz deposition has been proposed as an important factor in the temporal decay of aftershocks. In this work we present a reactive flow model to study the evolution of porosity, permeability and solute transport of the system. The geometry of the model assumes a porous medium block in which chemical reactions occur between the pore fluid and the rock matrix. The model assumes a coupling between heat and fluid mass transport. The Center for Hydrogeology and Geothermics has recently developed **"Efrack3D"**, a fully coupled 3D Thermo-Hydro-Mechanical (THM) model. We aim to ultimately integrate the reactive flow model with the THM model. Economic reservoir development requires a combined analysis of the thermo-hydro-mechanical and chemical processes.

Approach and model geometry

Quartz dissolution and precipitation is a surface controlled reaction, and is therefore highly temperature dependent. The solubility of silica increases rapidly with temperature, to almost double between 80°C and 110°C [1]. Fig.1 represents a road map of the **reactive flow** model. First, all temperature dependent parameters are calculated and initial and boundary conditions are defined. The REV of the system is a block composed of spherical shaped grains with an initial porosity. The change in contact area between the grains due to quartz precipitation and dissolution is calculated based on [2]. The solute transport equation includes both diffusion and advection terms, and is solved with finite difference method. Once the concentration is calculated, the porosity evolution is computed via the mass conservation equation. The new porosity is used to recalculate the contact surface area at each time step. Finally, the permeability is estimated as a function of time and space, allowing us to predict pore pressure evolution in the reservoir. In the beginning, to simplify the problem we assume no compaction of the grains, nevertheless, vertical stress and consolidation are controlling factors in the variation of the surface contact area.

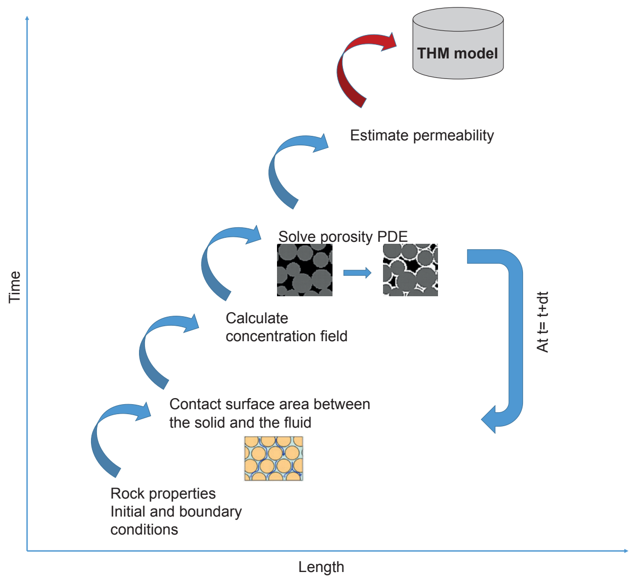

Figure 1: Road map for the reactive flow model as a function of time and length scales.

Mathematical model

$$H_4SiO_{4(aq)} = SiO_{2(s)} + 2H_2O_{(l)}$$

The precipitation rate constant k_{-} and the equilibrium quartz concentration c_{eq} are given by [3]:

$$\log k_{-} = -0.707 - \frac{2589}{T} \qquad \text{Eq. 1}$$

$$\log c_{eq} = -\left(\frac{1107}{T}\right) - 0.025 \qquad \text{Eq. 2}$$

Solute transport for quartz precipitation and dissolution in the rock matrix is described by the linear reaction equation:

$$\frac{\partial C'}{\partial t} = D_m \nabla^2 C' - \frac{K}{\emptyset} C' \qquad \text{Eq. 3}$$

We solve Eq.3 using total variation diminishing method, where $C' = c - c_{eq}$. The apparent precipitation rate constant K is given by:

$$K = \frac{A}{M} k_{-} \qquad \text{Eq. 4}$$

Where A is the interfacial area between the solid and the fluid of mass M [2]. Mass conservation of silica is governed by:

$$\frac{\partial(\emptyset c)}{\partial t} + \frac{\partial(uc)}{\partial x} = -\emptyset K\left(c - c_{eq}\right) \qquad \text{Eq. 5}$$

Assuming a constant flow rate, Eq. 5 represents porosity evolution and is solved using finite difference scheme.

Finally, permeability is estimated using the Cozeny-Carman Equation.

Outlooks

We ultimately aim to investigate the consequences of quartz dissolution and precipitation on the mechanical response of the rock matrix. It is essential for sustainable wellbore productivity and development. The porosity and permeability evolution terms may be integrated to the Efrack3D to visualize pore pressure development and analyze the geomechanics. Furthermore, this may allow us to visualize possible localized cracking due to pore pressure developement and better understand fluid driven aftershocks, as it has been stated that repeated fracturing events followed by crack healing are in connection with earthquakes [4].

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Sensitivity Analysis of High Temperature Aquifer Thermal Energy Storage (HT-ATES) using TH Simulations

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Abstract / Background

The Geneva-section of the HEATSTORE project has set its goals on the assessment of the feasibility of an HT-ATES system to be operated in the Swiss Canton of Geneva. The studied area has been characterized as geologically and logistically challenging [1] as a result of its prospective aquifers being intersected and offset by faults and the relatively high population density. Given these challenges, using a numerical tool becomes essential to carry out a virtual exploration of possible scenarios. A sensitivity analysis can thus be performed and insight be obtained to characterize response, determine feasibility, and deliver fundamental understanding of the effects of geologic heterogeneities, operational strategies, and groundwater conditions on ATES efficiency. Such a study was carried out previously by [2], using a different numerical approach and addressing similar questions regarding the effects of possible parameters via the consideration of a doublet well pattern. It is our intent to contribute and compare to this previously-made analysis, by expanding the parameter space and introducing some of the advantages of simulating Discrete Fracture and Matrix models with a view towards the faulted/fractured complexity of the Geneva basin.

We present results and insights obtained during our first design iteration of TH simulations with particular focus on the geology of the Geneva Basin, although the insight obtained may be applicable elsewhere. By using a numerical tool to simulate a large number of scenarios we have worked towards a better understanding of an HT-ATES system response to variations in essential design factors.

Modelling approach

Through exploring a multi-dimensional parameter space composed of the terms explained in Tables 1 and 2, we produced a range of site-relevant scenarios to be numerically simulated. Well and fracture setup is described in Figure 2.

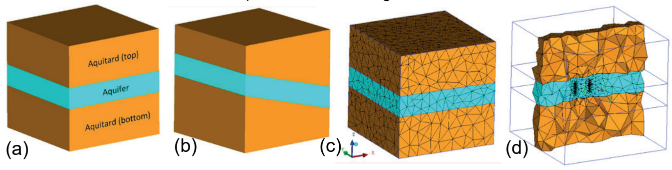

Figure 1 : *Geometrical/Geological model representing the basic elements of an ATES, depicting (a) a flat version of the model, (b) a version of the model possessing an aquifer with a 15° angle of dip, (c) the volumetric tetrahedral tesselation (i.e. mesh) of the flat geometrical model using the ICEMCFD software, and (d) mesh cutplane depicting variable resolution when approaching regions containing wells.*

Aquifer Permeability	Aquifer Thickness	Well Strategy	Groundwater	Fracture Configuration	Aquifer Dip
K13	L200	single	YGW	F0	FLAT
5K13	L300	doublet	NGW	FU	INCL
K12	L400	5spot		FD	

Table 1 : *Summary of sub-scenario variant codes. When combined, these codes produce the different simulation case names*

Parameter	Units	Aquitard (top)	Aquifer	Aquitard (bottom)
Density (r_r)	[kg/m³]	2450	2450	2680
Permeability (*k*) (original matrix)	[m²]	10^{-17}	10^{-15}	10^{-17}
Permeability K13 (*k*) (fractured, effective)	[m²]	10^{-17}	10^{-13}	10^{-17}
Permeability 5K13 (k) (fractured, effective)	[m²]	10^{-17}	$5 \cdot 10^{-13}$	10^{-17}
Permeability K12 (k) (fractured, effective)	[m²]	10^{-17}	10^{-12}	10^{-17}
Porosity (*f*) (matrix, effective)	[-]	0.01	0.2	0.01
Permeability (k) (fracture, effective)	[m²]	N/A	10^{-11}	N/A
Porosity (*f*) (fracture, effective)	[-]	N/A	0.5	N/A
Fracture thickness	[m]	N/A	0.1	N/A
Specific Heat Capacity ($c_{p,r}$)	[J/(Kg °K)]	860.2	832.9	849.9
Thermal Conductivity l_r (λ_r)	[W/(m °K)]	2.275	2.806	2.692
Thickness L200 (L)	[m]	400	200	400
Thickness L300 (L)	[m]	350	300	350
Thickness L400 (L)	[m]	200	400	400
Groundwater velocity (v_{gw}) (assumed)	[m/yr]	N/A	2	N/A

Table 2: *Summary rock material parameters [3]*

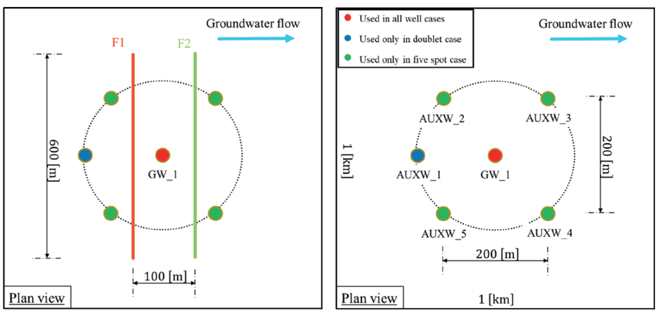

Figure 2: (left) Fracture locations with respect to wells, and (right) the specific x-y plane view of well locations and respective names .

Results

Having observed that system efficiencies increase monotonically over time, we found it practical to use the values at the end of the ATES lifetime (i.e. 15 years) for our analyses. A summary of exergy efficiency values at the end of life of the ATES for each of 324 simulations is presented in Figure 3. Snapshots of selected results are presented in Figures 4 and 5.

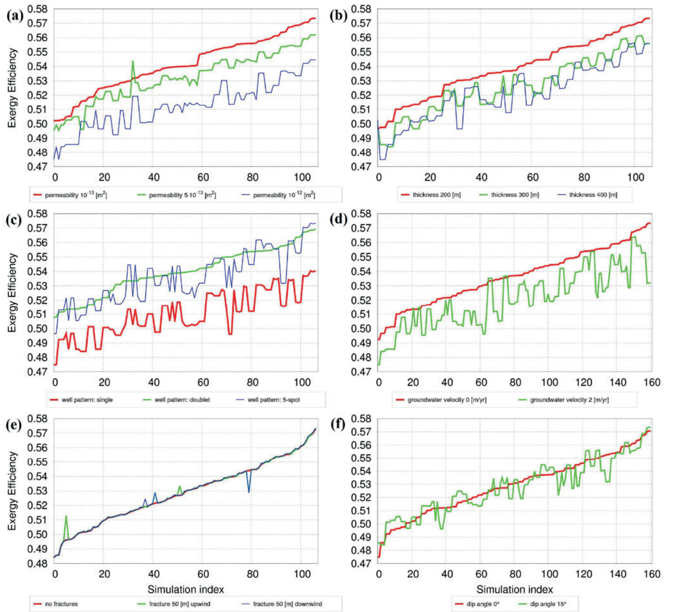

Figure 3:*Exergy efficiency measured at the end of the ATES lifetime. Each graph represents a particular horizontal ordering of the same set of results, sorted in increasing exergy efficiency w.r.t. a particular variant code (see Table 1). The simulation index is an arbitrary number guide pointing to a subset of otherwise identical simulations that only differ by one particular parameter: (a) aquifer permeability, (b) aquifer thickness, (c) well pattern, (d) groundwater velocity, (e) fracture configuration, and (f) aquifer dip angle.*

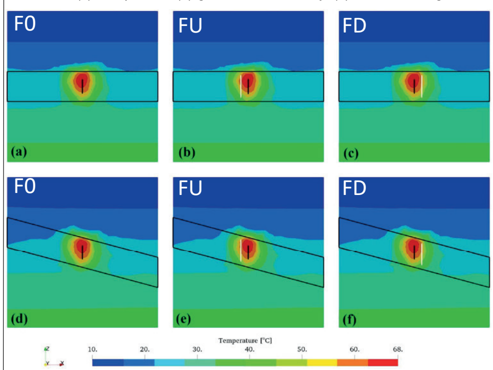

Figure 4:*Fracture and dip angle effects on the temperature signature at the end of the ATES lifetime in a full-domain middle x-z planar cross section for 6 simulations with equal permeability (K12), thickness (L200), well pattern (single), and no groundwater flow (NGW). Well GW_1 and aquifer perimeter are demarcated by black lines, while fractures are shown as white lines.*

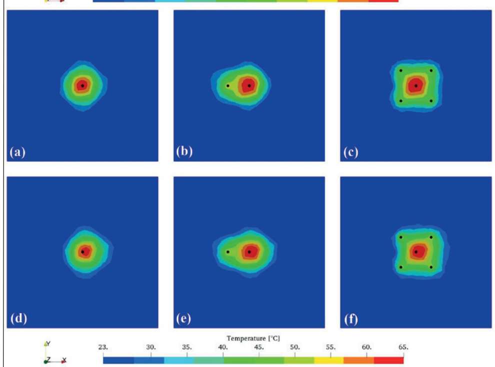

Figure 5: *Well pattern and groundwater effects on the temperature signature at the end of the ATES lifetime in a full-domain middle x-y planar cross section for 6 simulations with no inclination (FLAT), no fractures (F0), equal permeability (K12), and equal thickness (L200). Row-wise, NGW (a,b,c), and YGW (d,e,f), groundwater conditions have been applied to the top, and bottom rows respectively, while column-wise, single (a,d), doublet (b,e), and 5spot (c,f) have been applied to the left, middle and right columns of simulations, respectively.*

Conclusions & Outlook

Our study [4] further confirms some observations that have already been made in the literature, particularly with respect to groundwater drift and buoyancy effects present in high permeability aquifers. We have also observed that when active, auxiliary wells help mitigate pressure-peak related effects, improve the thermal front sweep, and also provide some measure of shielding against the drift due to the flow of groundwater.

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Experimental Thermo-Hydro-Mechanical test site to quantify heat exchange characteristics of fractured limestone aquifers

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Motivation

Providing to our societies greenhouse-gas free energy sources is a main challenge tackled by the energy turnaround initiated in many countries. Heat demand and supply are off-phase over seasonal cycles. Storing heat in time of surplus and providing it when needed is part of the tools required to reduced the energy footprint. Underground Thermal Energy Storage (UTES) [1] is one solution for this process. Various configuration of UTES are used including Aquifer Thermal Energy Storage (ATES). Until now many studies have shown the potential of ATES in shallow porous geological media. But conflict of use, aquifer availability and environmental regulations pushes for going to deeper, hard rock aquifers for which characterization approaches and suitability evaluation for heat storage need to be developed.

Methods

In hard rock aquifers and more specifically in limestone aquifers, fractures and karst (dissolution conduits) carry most of the flow. This results in complex flow geometry. The hydrodynamic characterization of such system is approached by coupling classic well tests analyses and geostatistical geo-structure distribution as Discrete Fractured Network (DFN) or conduit distribution (Karst) network.

The complexity of such systems make hard predicting the real shape of the reservoir and almost impossible to quantify the exchange area available for heat transfer between fractured or karstified structures and the rock matrix. The structures in the aquifer will control the flow geometry. At same bulk aquifer transmissivity, the flow geometry can differ significantly. This will have a large impact on heat exchange properties of the reservoir. Approaches needs to be further develop for heat storage application in order to assess heat transport and storage in fractured and karstified rock masses.

The methodology proposed is simple. We focus on the temperature that we can store in the reservoir via an injection test in satured condition and the thermal response of the push-pull experiment will allow us to determine experimentally and numerically, if the aquifer has the potential volume required considering simple structure (fractures or conduits) to store any heat demand (Figure 1).

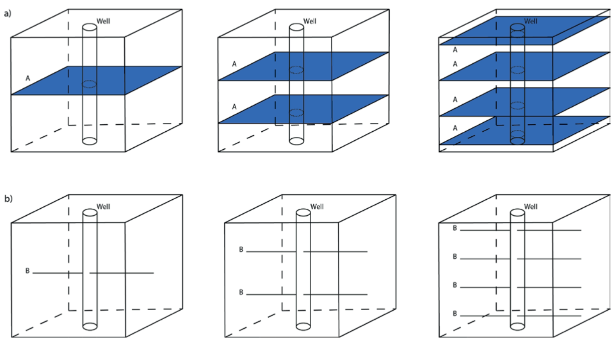

Figure 1: Simple conceptual model considering a) fractures network or b) conduits network.

Experimental site

The first ATES experiment in porous media was performed by the Centre of Hydrogeology and Geothermics (CHYN) at the University of Neuchâtel (Switzerland) in 1974 [2],[3],[4]. Further countries such as U.S.A, France, Japan, Germany, or Canada started participating in ATES research with their own experimental field sites.
Here, the idea is to develop a new experimental test site in fractured and karstified rocks in Concise (VD) Switzerland (Figure 2) and to perform hot water push-pull tests during several days in order to devise a thermo-hydraulic characterization approach for ATES in fractured media.

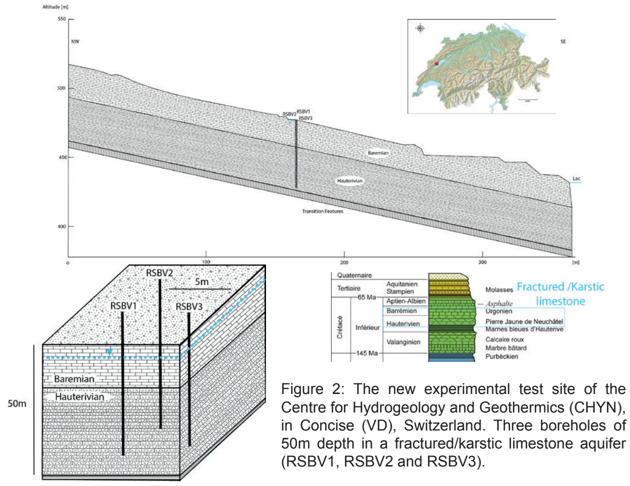

Figure 2: The new experimental test site of the Centre for Hydrogeology and Geothermics (CHYN), in Concise (VD), Switzerland. Three boreholes of 50m depth in a fractured/karstic limestone aquifer (RSBV1, RSBV2 and RSBV3).

In addition to thermo-hydraulic processes, we also consider the impact of thermo-hydro-mechanical (THM) 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 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.

The thermal response will be different considering granular, fractured or karstic rock. Through analyses of the thermo-hydraulic field response with different numerical simulations, we will be able to better understand the flow and heat exchange geometry in the vicinity of the well. These is a requirement to assess the characteristics and predict the performance within local hydrogeological conditions of a given ATES site.

Conclusion and Outlooks

This research aims at developing thermo-hydro-mechanical tests in fractured / karstic rock that will enable characterization and design of the next generation ATES in such environments. The outcome of this research will include experimental protocols and analyses modelling tools required to predict performance and assess viability of ATES. This method include simple approach to make the link between storage capacity and real storage underground possibilities addressing a need of engineers and regulators for Heat Storage Projects. The research will provide improved approaches to quantify system connectivity, complex geo-structure, hydrogeology and storage volume, based on physical experiments. The proposed method will be tested and validated on a in-situ ATES analog test site in fractured and karstified rocks.

Advances from the program include:

- In-situ heat transport parameters determination
- Flow measurements and hydraulic: efforts to characterize and model flows at various scales will also be pursued
- Evaluation of thermo-hydro-mechanical coupled process in ATES
- Validation of numerical simulator against field data in order to improve the predictive capability of the simulation tools

Acknowledgements

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Investigating mineral reactions during high-temperature aquifer thermal energy storage (HT-ATES)

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Background

Industrial processes (e.g. waste incineration, manufacturing) generate **constant surplus heat** ⇒ **Heat demand strongly seasonal** → Excess energy to be **stored** during summer and fed into district heating network during winter to reduce wasting of energy/consumption of fossil fuels

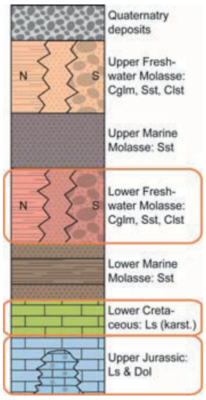
Aquifer thermal energy storage (ATES) = using porous lithologies with little/no groundwater flow to seasonally store warm waters in the geosphere[1]

Low-T ATES (T_{inject} < 40 °C)
- Many successful systems installed in Europe (esp. NL) [1]

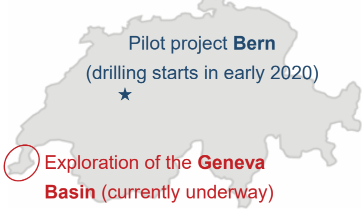
High-temp. ATES (T_{inject} > 40 °C, often > 70 °C)
- 5 operational + many failed systems around the world[1]

⇒ Challenges related to HT-ATES need to be overcome to increase contribution of ATES to the future heating energy supply

HT-ATES projects in Switzerland



Heat sources: waste-to-energy plants



Target lithologies investigated for HT-ATES (porous but laterally constrained): Channel Sst (BE, GE), karstified Ls (GE), reef complex Ls/Dol (GE)

Geochemical challenges

Surface installations (during heating):
- Carbonate scaling[2]

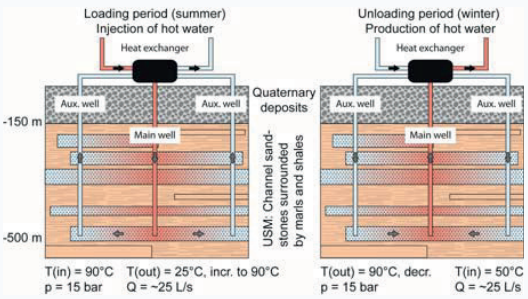
Surface installations (during cooling):
- Silicate scaling

In the reservoir (during storage):
- Carbonate precipitation around injection well → Clogging[3]
- Dissolution of silicate/other minerals → Release of heavy metals[4] As Cd Pb
- Swelling of clay minerals → Surface uplift (up to 2.5 cm)[5]
- Microbial activity → Clogging (biofilms), scaling, MIC[6]
- Thermal stratification of aquifer → Reduced yield[7]

In the reservoir (during reinjection):
- Carbonate dissolution (cement) and release of fines → Clogging[4]

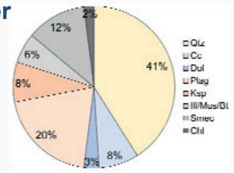
Investigations into the planned Bern HT-ATES pilot site

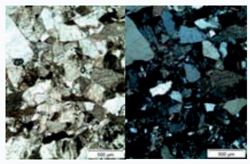
Planned system parameters

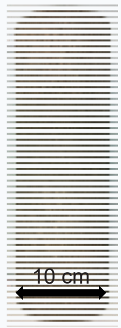


Characterisation of Sst & form. water

- Medium- to coarse-grained **channel Sst** (layers generally 2-8 m thick[8]) of the LFM
- **Composition**: Monomineralic and lithic grains cemented by Cc and clay minerals
- **Porosity**: 18 vol.%, **Permeability**: 370 mD
- **Water-type**: Na-Mg-Ca-Cl-SO_4-(HCO_3) TDS ~ 350 mg/L, pH 8.1 Temperature (in-situ) 13.7°C







Simulation of loading – unloading cycle (PHREEQC, equilibrium approach)

① Equilibrate with aquifer minerals @ 20 °C
↓
② Heat solution to 90 °C in heat exchanger
↓
③ Equilibrate with aquifer minerals @ 90 °C
↓
④ Cool solution to 20 °C in heat exchanger

	SI > 0 (supersat.)	SI < 0 (undersat.)
①	Dol, Kaol, Musc, Qtz	Alb, Cc, Chl, Ill, Kspr, Montm
②	Cc, Dol	*Heat exch., ppt only*
③	Alb, Cc, Chl, Musc, Qtz	Dol, Ill, Kspr, Montm
④	Alb, Ill, Kaol, Kspr, Montm, Qtz	*Heat exch., ppt only*

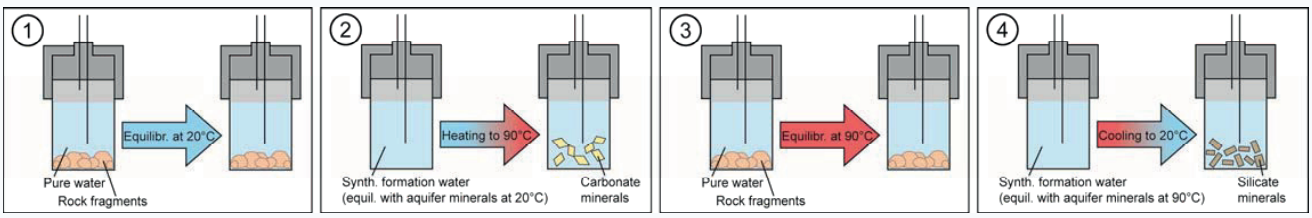
Equilibrium approach ok for storage period ③ (lasts several months) but not for heating/cooling ②/④ (lasts a few minutes) → **Kinetics** to be taken into account

More soluble, less/non-crystalline polymorphs often precipitate instead of the least soluble mineral (e.g. Chal/$SiO_{2(am)}$ instead of Qtz)
- Kinetic data of such phases generally not well constrained

⇒ **Lab experiments to identify mineral reactions and quantify reaction rates**

⇒ **Use as input in reactive transport modelling of the site (PFLOTRAN)**

Precipitation experiments in Ti-vessels: monitoring of solution chemistry f(time) (ongoing)



Testing of **different physicochemical parameters**: Temperatures, rock types, fluid chemistry, pCO_2… ⇒ Cover a range of possible conditions to **predict potential mineral reactions** and generate a dataset to allow predictions to be made for other sites (e.g. Geneva)

In collaboration with: Université de Genève, unine, ETH, Geo Energie Suisse, ewb, SIG
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