Combining CCS with CO_2-Plume Geothermal (CPG) power generation in Switzerland

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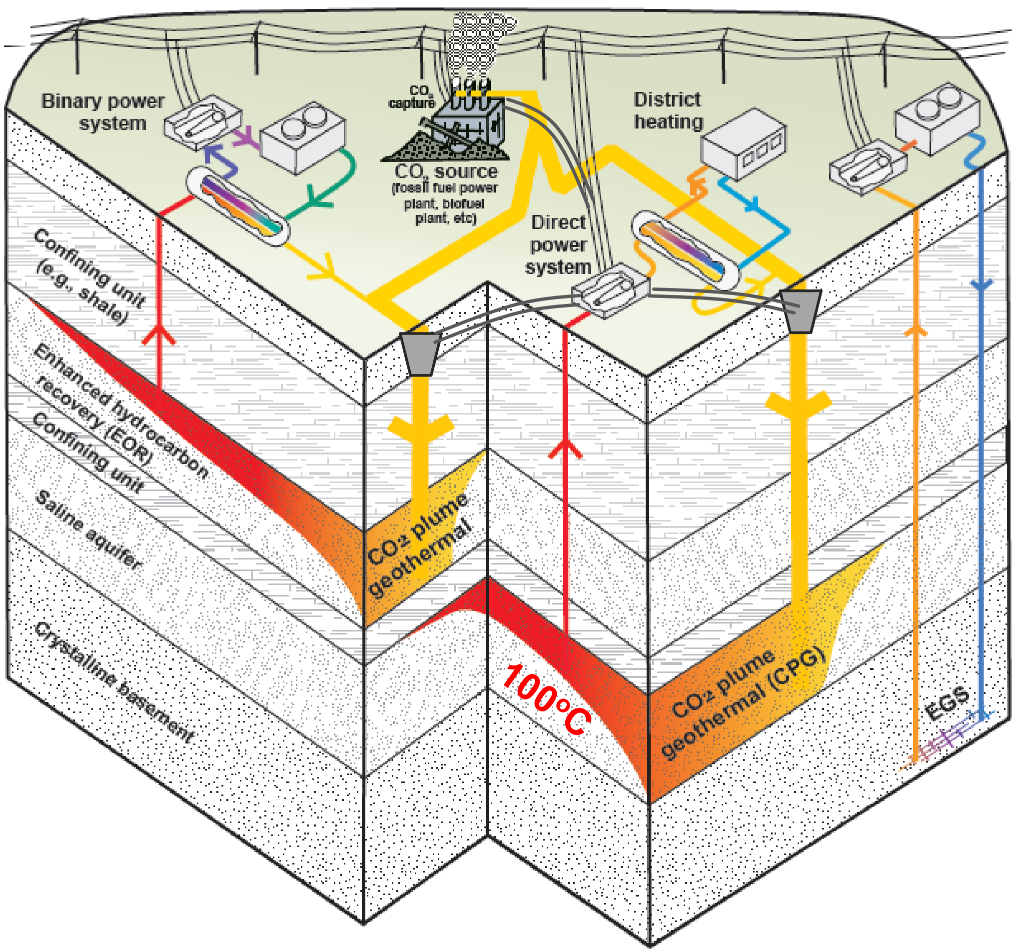
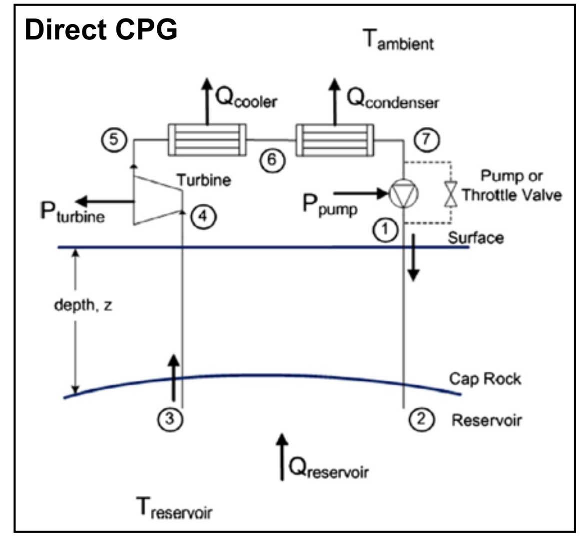
And also: **Andrea Moscariello**, **Luca Guglielmetti**, **Ovie Eruteya**, **Jonathan Ogland-Hand**, …..

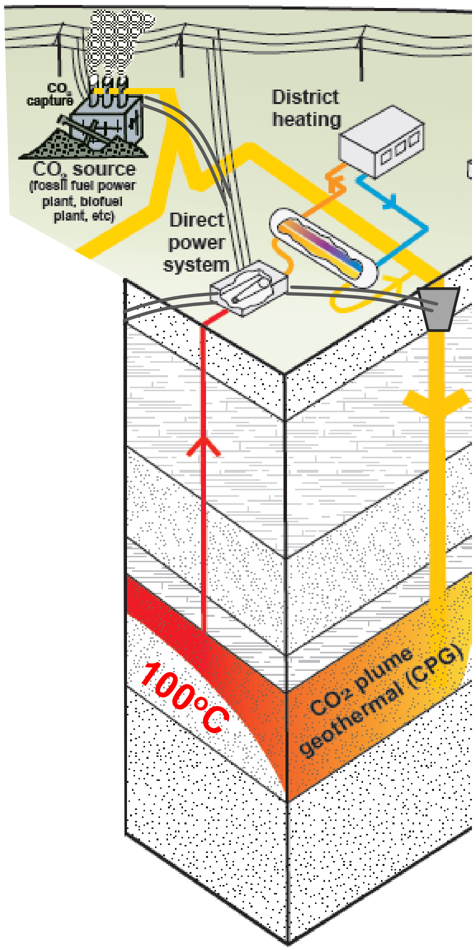


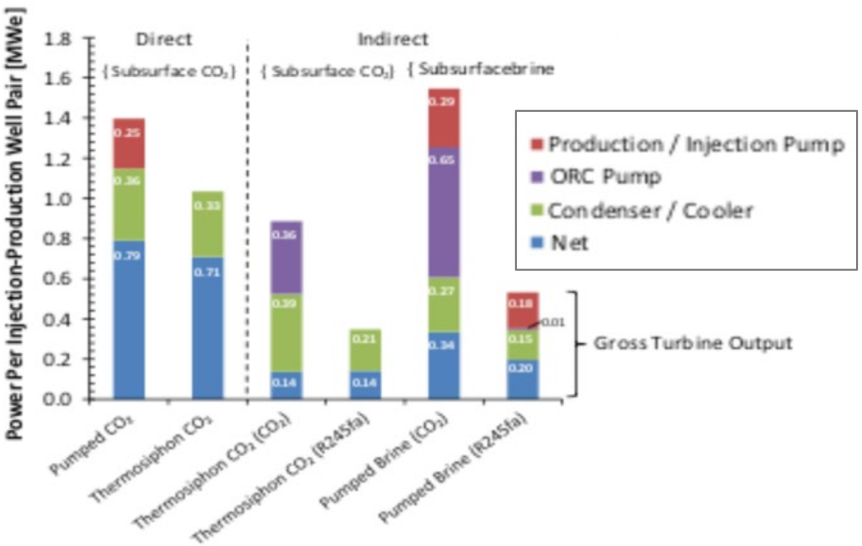


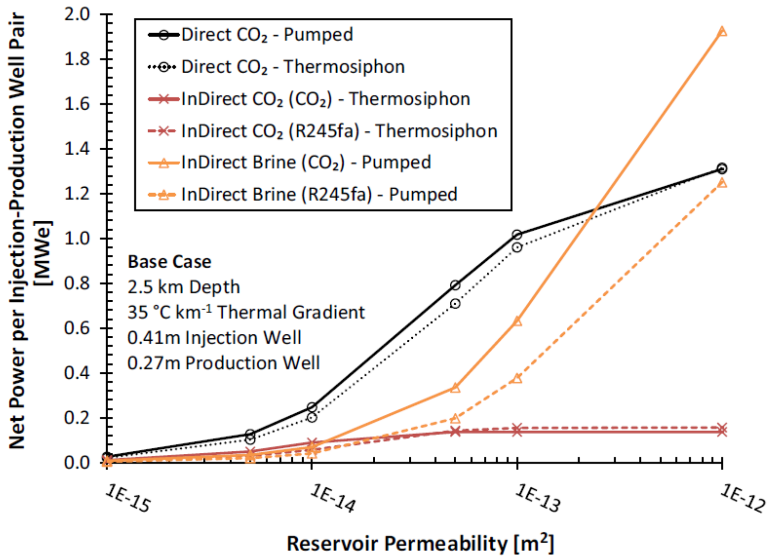
Selected Saar publications and patents on CPG and CPG Energy Storage (CPGES or Earth Battery):

Randolph & Saar, ***Geophysical Research Letters*** 2011
Saar et al., ***Patents*** 2012
Adams et al., ***Energy*** 2014
Adams et al., ***Applied Energy*** 2015
Garapati et al., ***Geothermics*** 2015
Fleming et al., ***Stanford Geothermal Workshop*** 2018
Saar and Adams, ***Patent Pending*** 2018
Adams et al., ***Proc. Applied Energy Symposium*** 2020
Ezekiel et al., ***Applied Energy*** 2020
Fleming et al., ***Geothermics*** 2020
Garapati et al., ***J. of CO_2 Utilization*** 2020
Hefny et al., ***International J. of Greenhouse Gas Control*** 2020

Direct CPG generates 2-3 times net electric power of brine + ORC (base case)



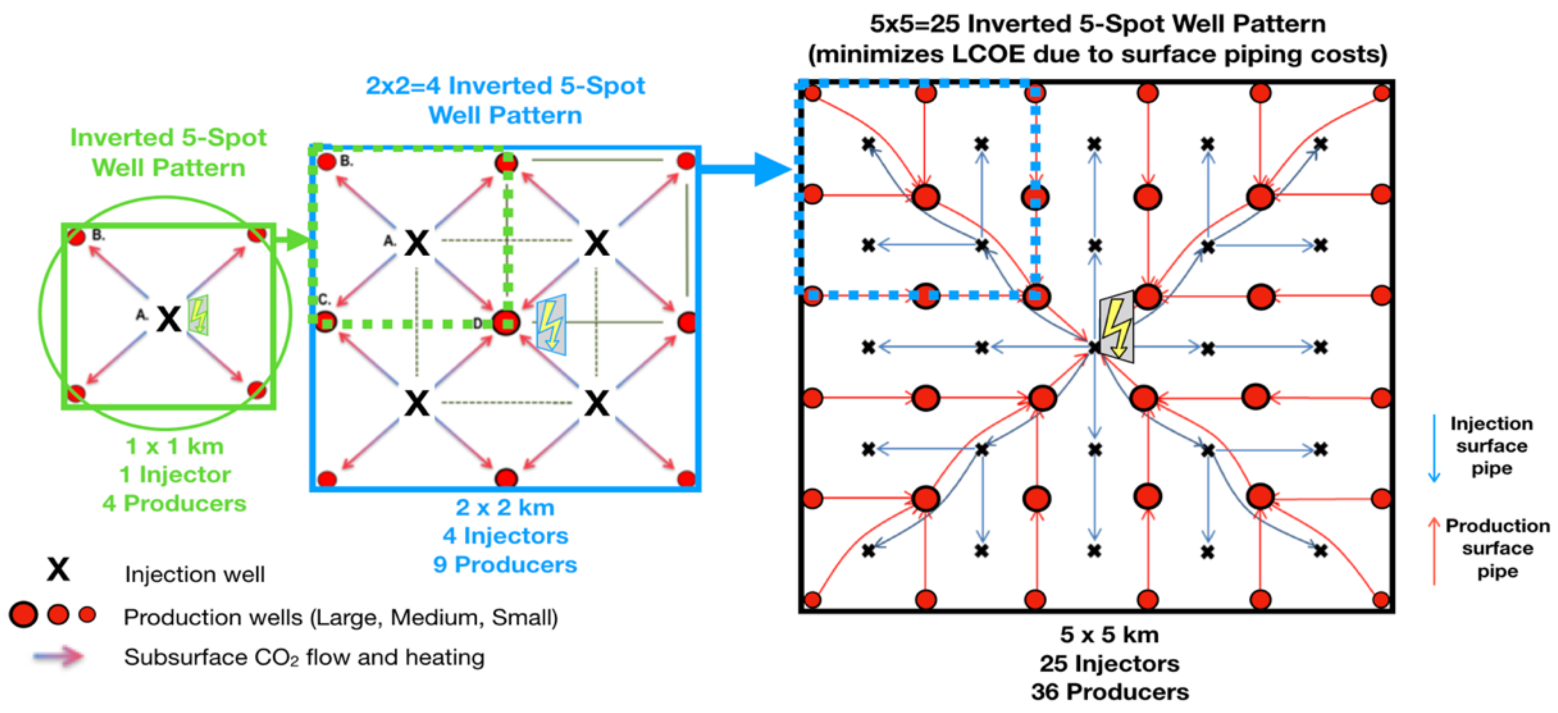




Adams et al., ***Applied Energy*** 2015

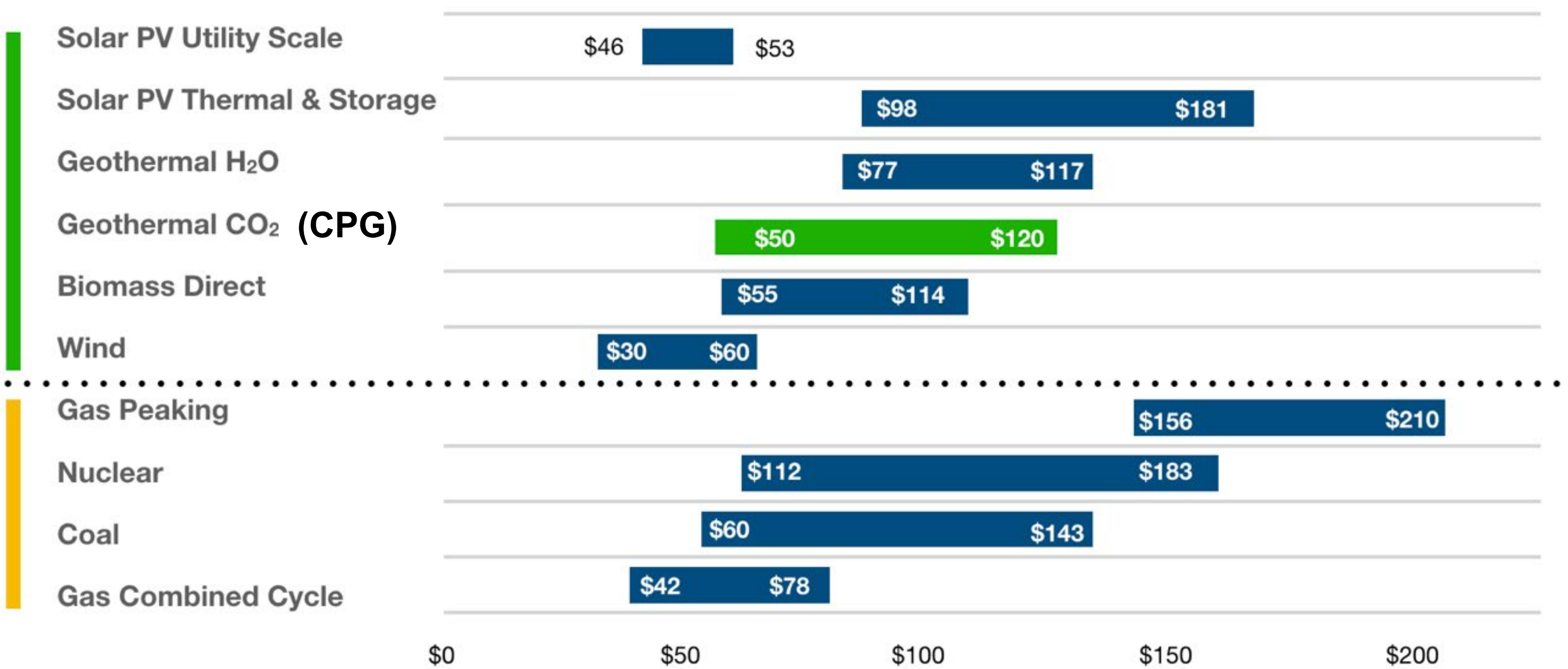
Approx. upscale by multiplying 5-spot well pattern footprint area of 1 km^2

Map view



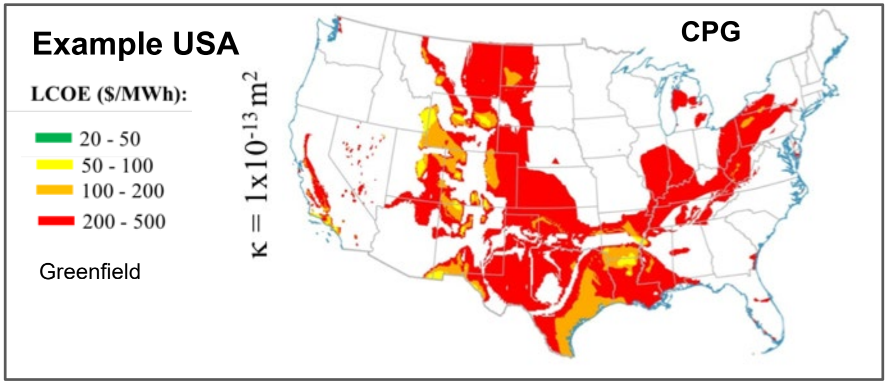
Levelized Cost of Electricity (LCOE)

Measured as $/MWh



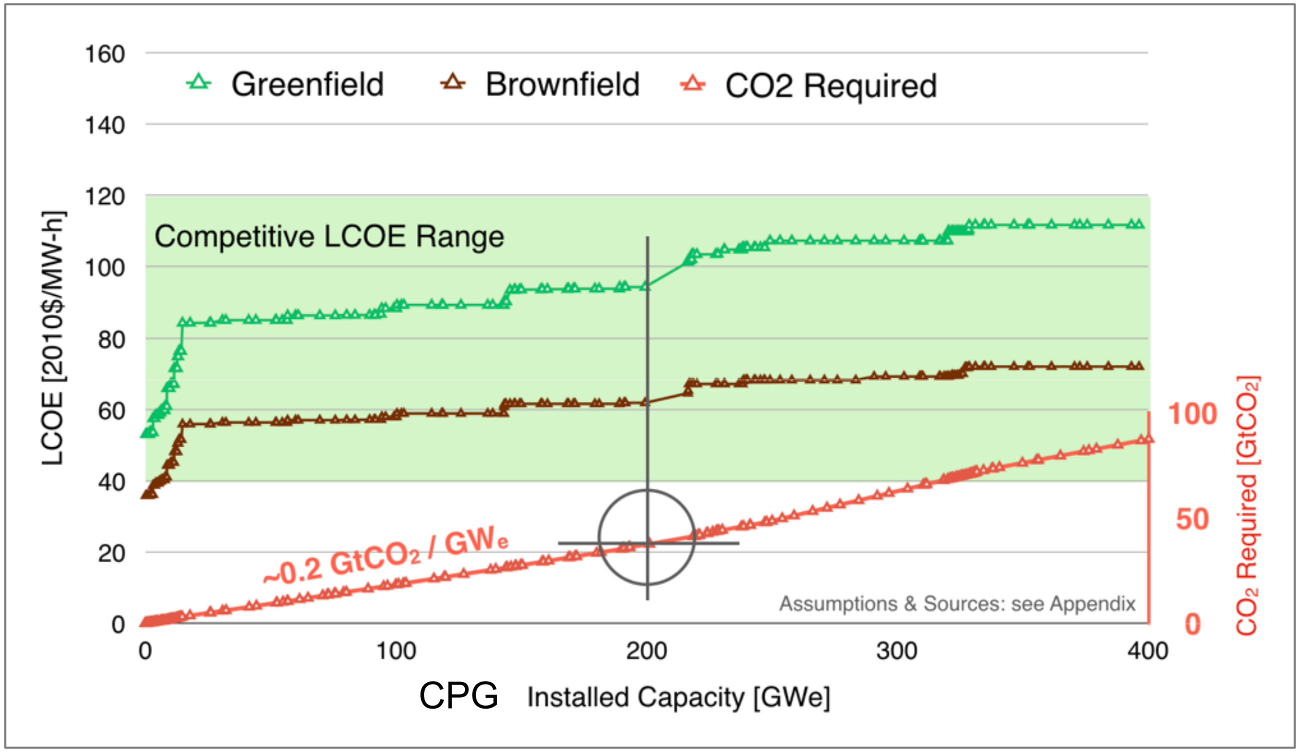
Source: Lazard 2017, https://www.lazard.com/perspective/levelized-cost-of-energy-2017/

Expansion of geothermal resource base (e.g. USA)



Only saline aquifers!

Cost-ordered available capacity

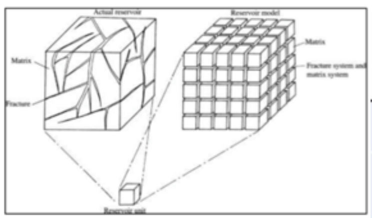


For Comparison
US: 1200 GWe Capacity

Adams and Saar (in prep. 2020)

Estimate of power generation at (depleted) Swiss hydrocarbon reservoir at 4.3 km depth

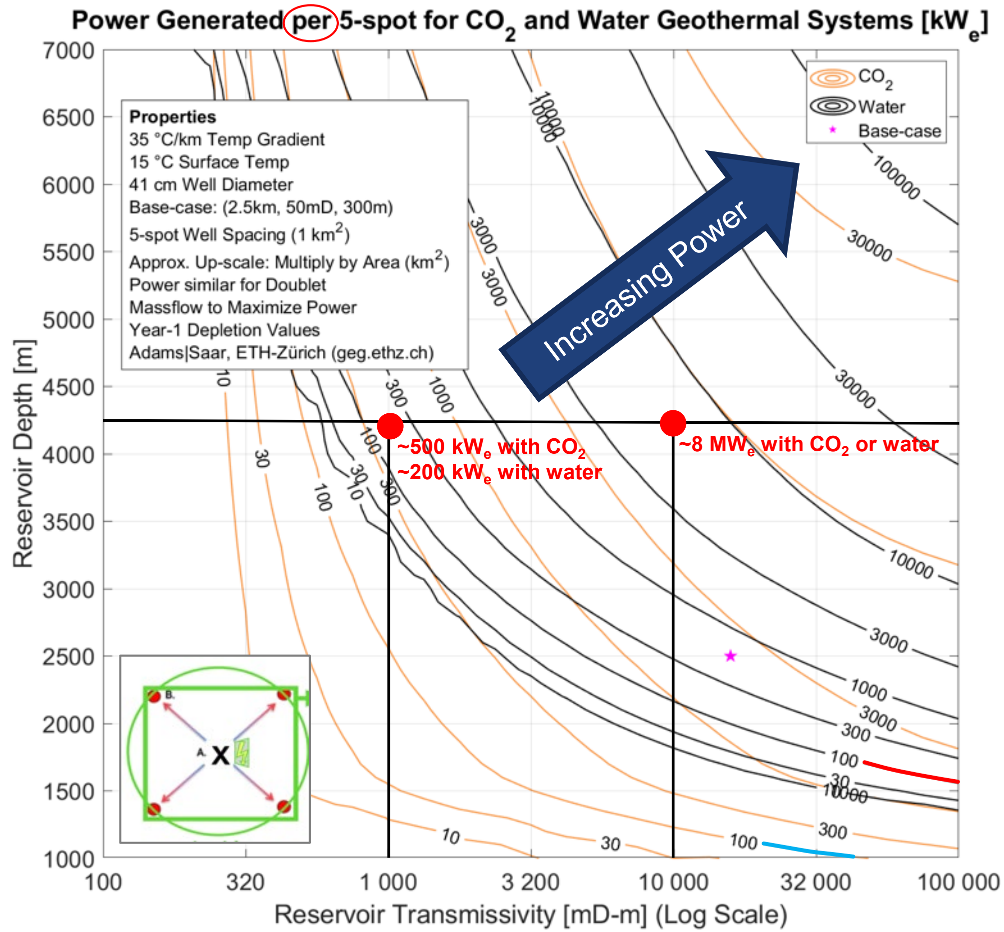
- Malm karst reservoir thickness: 20 m thick
- Dual permeability system (matrix + fracture)
- Permeability (with karst, fractures): 10 - 1'000 mD
- Effective Transmissivity: 20 - 20'000 mD-m
- Power generation: up to 10'000 KW_e = 10 MW_e per 5-spot well pattern (similar for doublet) of 1 km^2



	Effective Permeability [mD]	Fracture Permeability [mD] 10	100	1000
Fracture Porosity [m^3/m^3]	**0.001**	0.1	0.2	1.1
	0.01	0.2	1.1	10.1
	0.1	1.1	10.1	100.1

Background Permeability	0.1
Thickness [m]	20

	Effective Transmissivity [mD-m]	Fracture Permeability [mD] 10	100	1000
Fracture Porosity [m^3/m^3]	0.001	2.2	4.0	22.0
	0.01	4.0	22.0	202.0
	0.1	21.8	201.8	2001.8



Approx. upscale by multiplying footprint area of 1 km^2.

Adams, B.M., Bielicki, J.M., Ogland-Hand, J.D., & Saar, M.O. (2020). Using geologically sequestered CO_2 to generate and store geothermal electricity: CO_2 Plume Geothermal (CPG). Proceedings of MIT A+B Applied Energy Symposium, 12-14 Aug, 2020. https://doi.org/10.3929/ethz-b-000444911

Where (else) to do CCS with CPG in Switzerland?

Risk & Uncertainty
- Low
- Medium
- High

No	Criterion	Global best practice Positive indicators (e.g Chadwick et al., 2008; NETL, 2017)	Site 1	Site 2	Site 3	Reference / remark
1	Storage capacity	> Planned CO_2 injection amount	Injection rate yet to be defined			Overall low storage capacity less than 1Mt may be suitable for a pilot project
2	Proximity to CO_2 source	Close to site	< 30 km	< 5 km	< 20 km	This study
3	Depth to reservoir/aquifer	> 800	4300 m	2042 m	2681 m	
4	Porosity	> 10%	No data	1-7.5%	2-6%	
5	Permeability	> 300 mD		< 2 mD	<1 mD	
6	Reservoir thickness	> 20 m	20 m	62.5 m	62 m	
7	Caprock thickness	> 10 m	> 10 m	> 10 m	> 10 m	
8	Faulting and Fracturing	Limited to moderate				
9	Seismicity	Limited-moderate				SED
10	Hydrocarbon resource	Absent or small				
11	Site accessibility	Road, well head				This study- Google Earth
12	Socio-environ. concerns	Protected areas	UNESCO	NPA		This study

CO_2 storage in the Swiss Molasse Basin Preliminary deductions?

Structure/Trap | **Porosity** | **Permeability** | **Thickness**

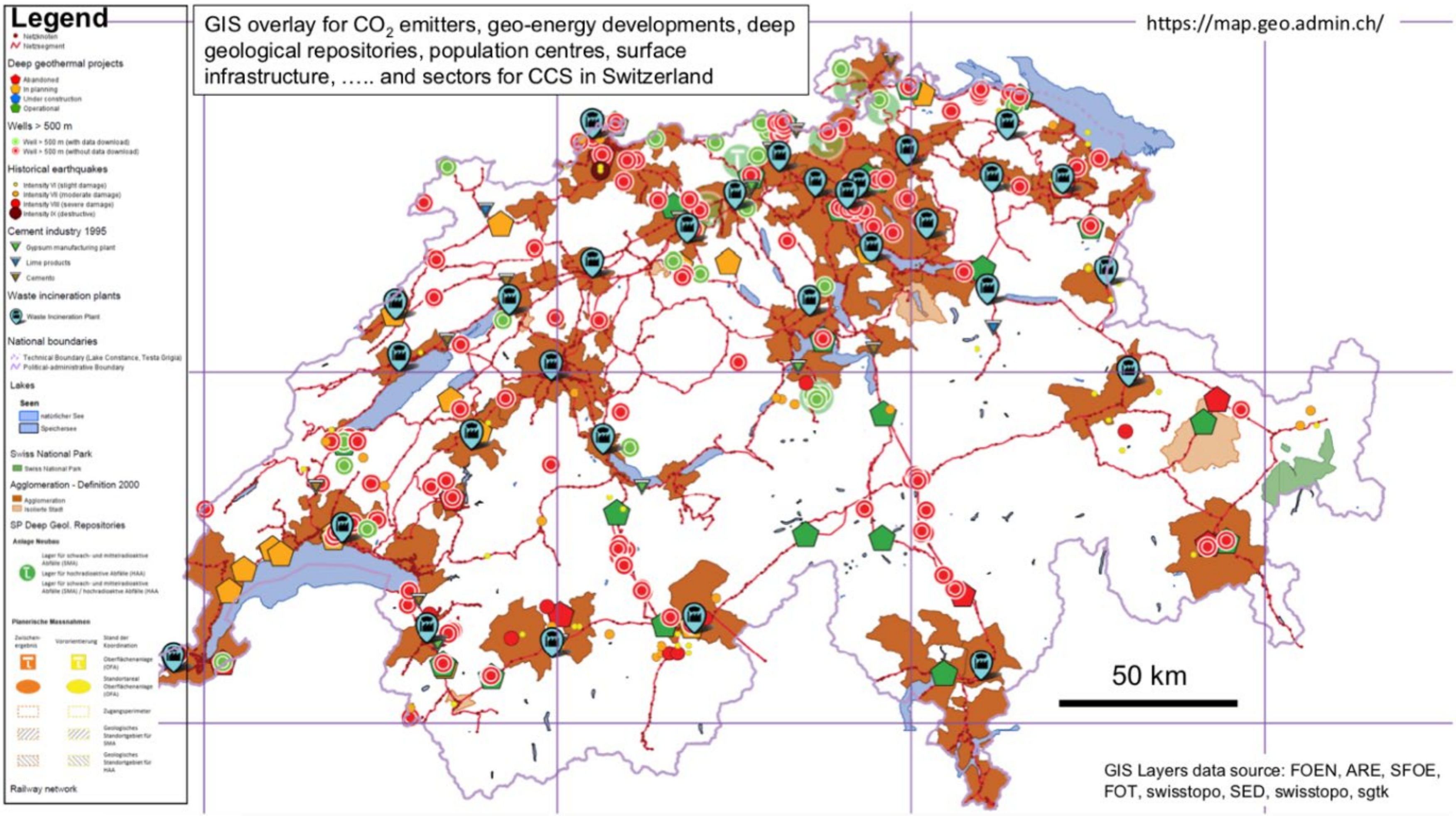
The way forward?

Further understanding of **fracture and karst porosity and permeability** in key reservoir and aquifers – core study & outcrop analogues

!

from Elegancy presentation by Ovie Emmanuel Eruteya and Andrea Moscariello, 2020

Where (else) to do CCS with CPG in Switzerland?

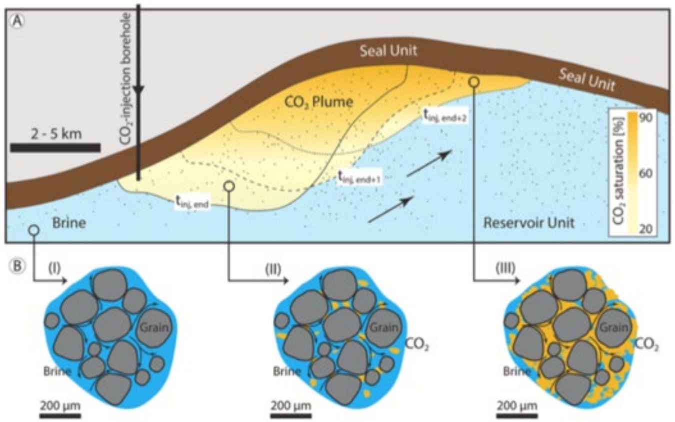


from Elegancy presentation by Ovie Emmanuel Eruteya and Andrea Moscariello, 2020

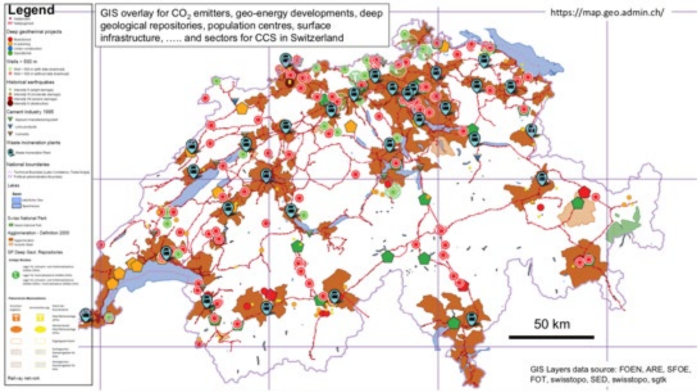
Where (else) to do CCS with CPG in Switzerland?

To answer, need to do <u>much more</u> geoscience and other research in Switzerland on site-specific factors, including:

- Reservoir characterization, particularly regarding:
  - dual/multiple porosity/permeability systems (with fractures, karst, etc.)
  - transmissivity
  - relative permeability, capillary pressure
  - pore-fluid pressure
  - formation temperature
  - usefulness for CPG Energy Storage
  - Geometry (3D seismic, MT, active EM, etc.)
- CO2 source and sink as well as transport (SimCCS?):
  - expected CO2 capture rate
  - CO2 source location in relationship to reservoir → CO2 transport (CO2 pipeline, train/truck)
  - CO2 sink locations (including Northern Lights)
  - Intermittent storage of CO2 in CH
- Power grid
  - Amount and type (dispatchable, etc.) power needed
  - Power grid proximity to potential CPG site
  - Proximity of intermittent power sources (wind/solar) for CPGES (Earth Battery)
- Economics factors:
  - taxes
  - Feed-in tariffs



Hefny et al., ***International J. of Greenhouse Gas Control*** 2020



Where (else) to do CCS with CPG in Switzerland?

What needs to be done! An example (1/6)

Fig. 1: Schematic diagram of key processes of CO2 sequestration in a saline aquifer.

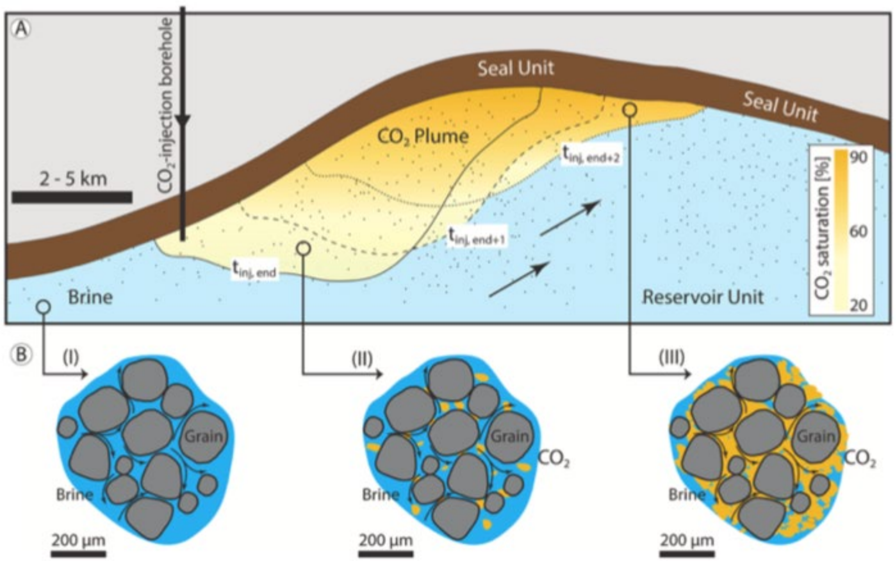
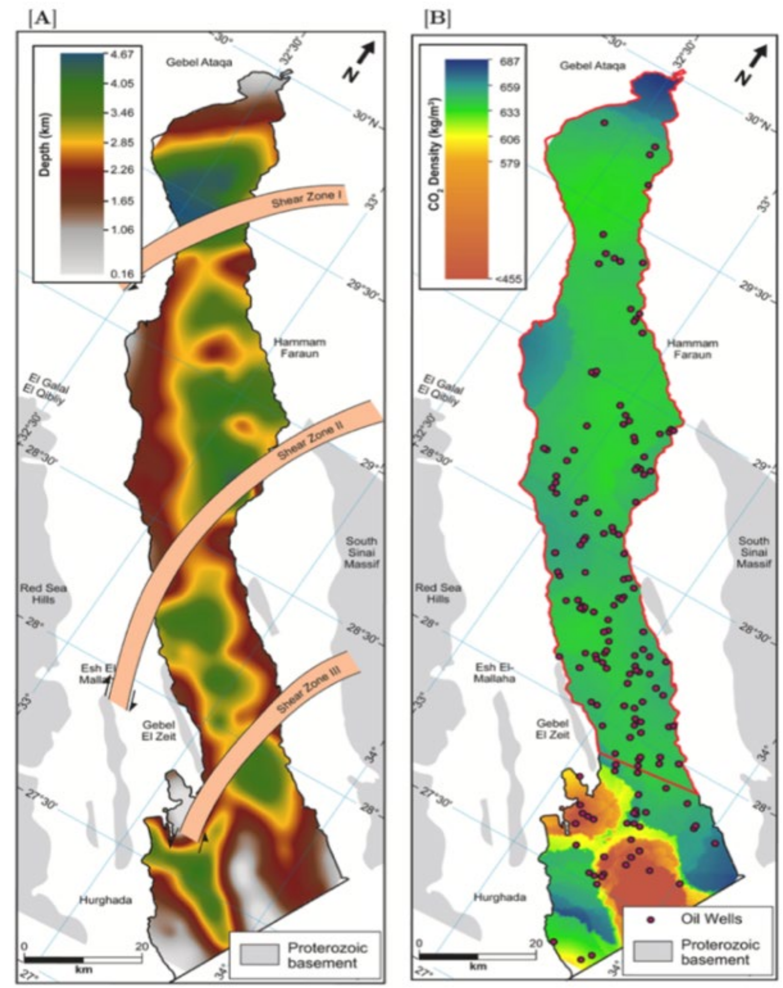


Fig. 15: [A] Depth to the top of the Nubian Sandstone sequence in the Gulf of Suez (Egypt). The map is constructed based on the interpretation of aeromagnetic and geological data by Mesheref et al. (1976) for basement rocks and modified after Farhoud (2009). [B] The distribution of in-situ CO2 densities across the Gulf of Suez.



Hefny et al., ***International J. of Greenhouse Gas Control*** 2020

Where (else) to do CCS with CPG in Switzerland?

What needs to be done! Examples.

Fig. 3: Pore throat diameters in Nubian Sandstone

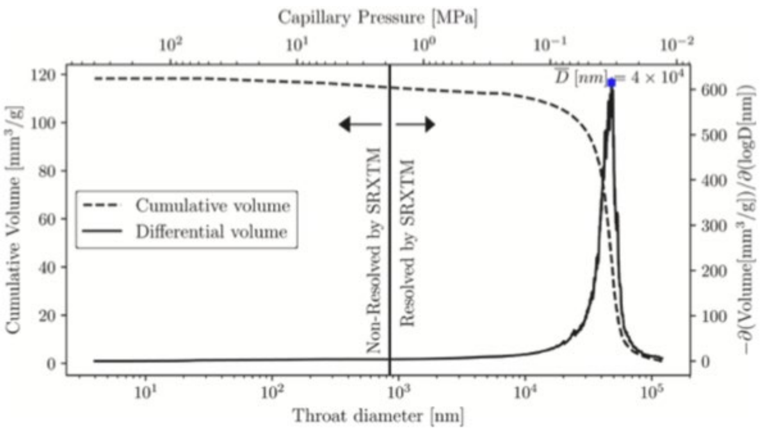


Fig. 4: Pore size distribution in Nubian Sandstone

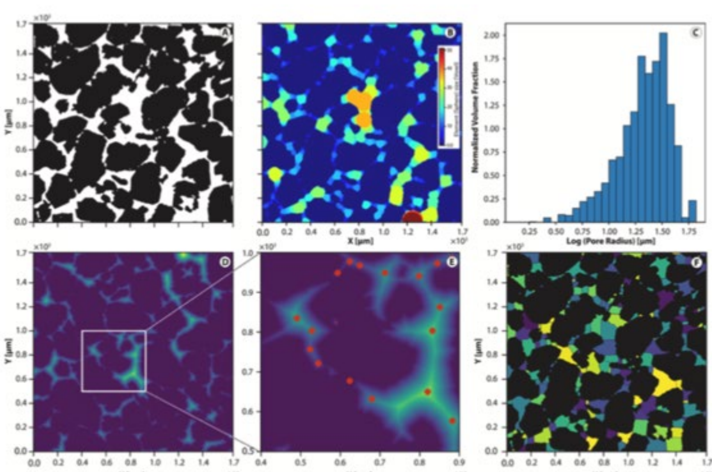


Fig. 5: 3D view of the pore-network in Nubian Sandstone

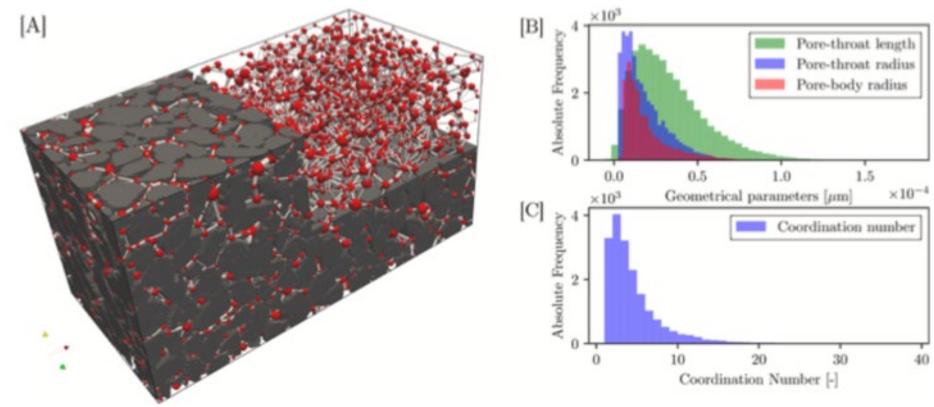
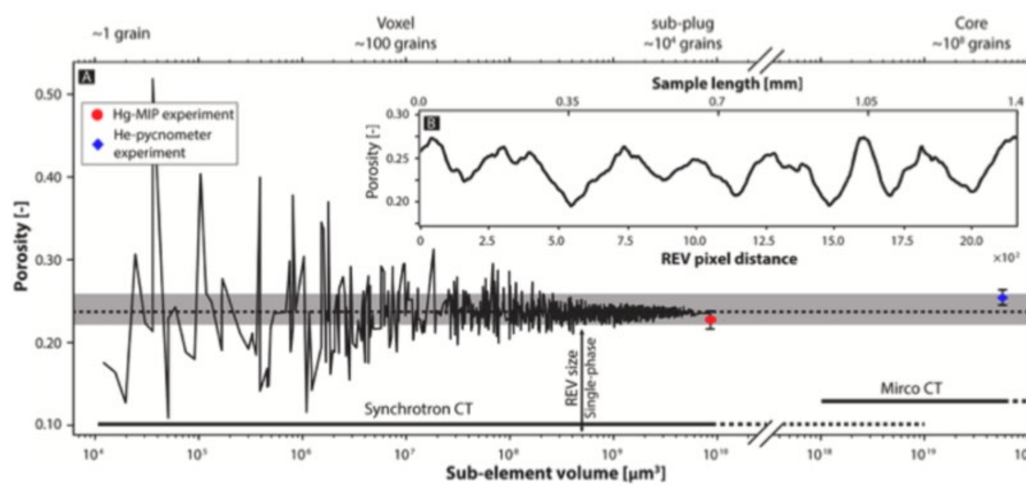


Fig. 6: Quantification of the porosity in Nubian Sandstone



Hefny et al., ***International J. of Greenhouse Gas Control*** 2020

Where (else) to do CCS with CPG in Switzerland?

What needs to be done! Examples.

Fig. 7: Wetting-phase (water in gray) distribution in a pore element

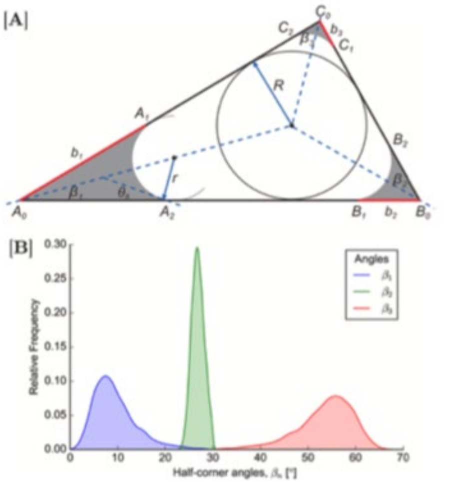


Table 3: Average values of hydraulic and capillary properties for Nubian Sandstone, determined by lab experiments and pore-network simulations

Parameter		Nubian Sandstone	Unit
Hydraulic properties			
Porosity; ϕ_{eff}	Laboratory[a]	0.269	[–]
	SRXTM[b]	0.254	
Permeability; k_{eff}	Laboratory[c]	1.70×10^{-12}	[m^2]
	PNM[d]	2.00×10^{-12}	
	LBM[e]	2.57×10^{-12}	
Capillarity properties			
Entry Pressure; P_e	MIP (Hg – air)	25347.6	[Pa]
	MIP (Leverett-J_d)	3.91×10^{-4}	[–]
	PNM (Leverett-J_i)	3.59×10^{-4}	
Irreducible Saturation; $S_{w,i}$[f]	MIP (Leverett-J_d)	0.089	[–]
	PNM	0.099	
van Genuchten parameters	m_d	0.466	[–]
	α_d	3.72×10^{-3}	[MPa^{-1}]
	m_i	0.580	[–]
	α_i	1.85×10^{-3}	[MPa^{-1}]

Fig. 8: PN model network calibration

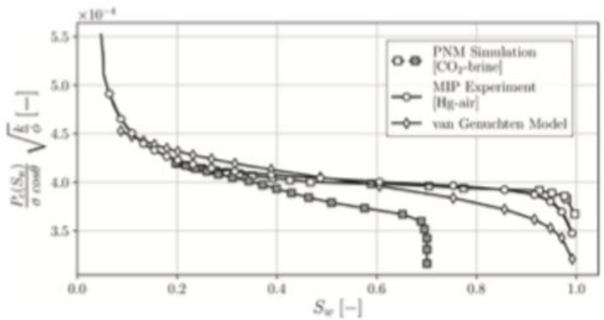


Fig 9: Simulations of CO2 (red) and brine (blue) saturation distributions

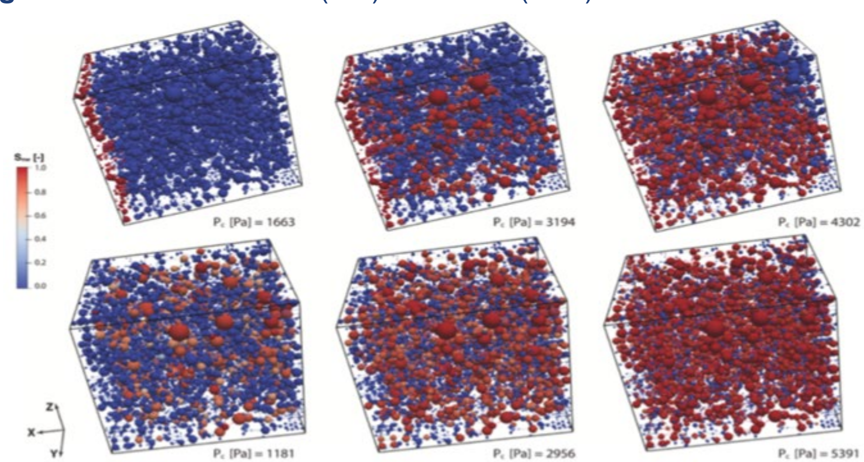
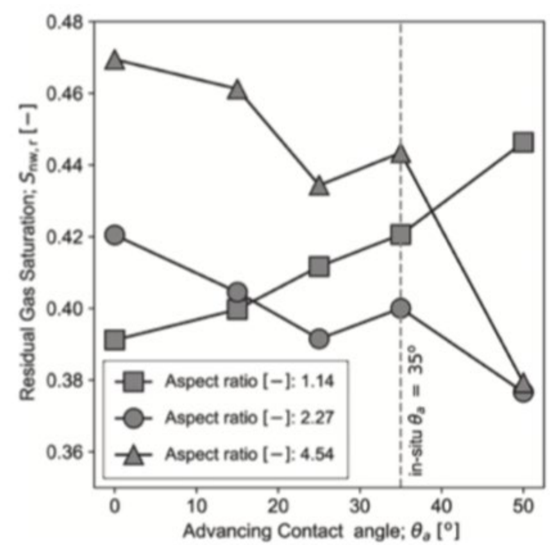


Fig. 10: Sensitivity of the residual CO2 trapping to different contact angles



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Where (else) to do CCS with CPG in Switzerland?

What needs to be done! Exaples.

Fig. 11: Comparison between the predicted and the experiment-based relative permeability curves for brine vs. CO2

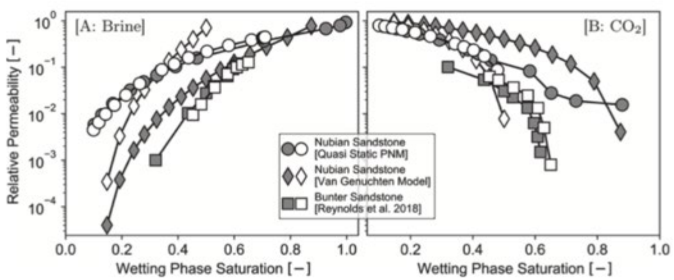


Fig. 12: Predicted residual trapping of CO2 in Nubian Sandstone, compared to Berea Sandstone.

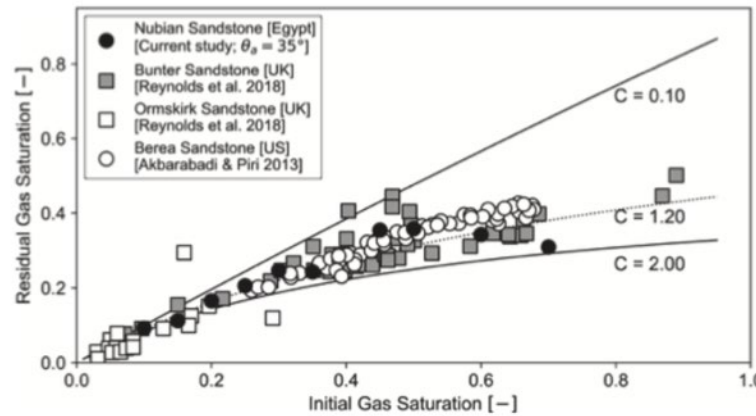
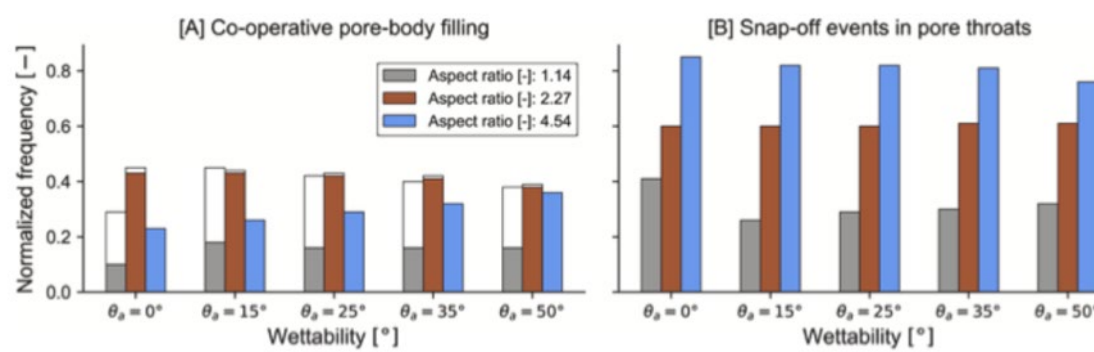


Table 4: Sensitivity analysis statistics of the impact of the wettability changes on the fluid displacement and trapping mechanisms after a complete cycle of primary drainage, main imbibition quasi-static pore-network modeling for Nubian Sandstone.

Fluid displacement &trapping	Advancing contact angle (θ_a)				
	θ_a = 0[°]	θ_a = 15[°]	θ_a = 25[°]	θ_a = 35[°]	θ_a = 50[°]
Drainage					
Piston-like advance in pore body	2626 (53%)	2588 (52%)	2532 (51%)	2465 (50%)	2346 (47%)
Piston-like advance in pore throat	7519 (79%)	7431 (78%)	7298 (76%)	7136 (75%)	6782 (71%)
Imbibition					
Piston-like advance	3522 (71.2%)	3550 (71.7%)	3594 (72.6%)	3625 (73.3%)	3712 (75%)
Cooperative pore-body filling	1386 (28%)	1369 (27.7%)	1327 (26.8%)	1299 (26.3%)	1202 (24.3%)
Snap-off event	39 (0.8%)	29 (0.6%)	26 (0.5%)	23 (0.5%)	33 (0.7%)

Fig. 13: Comparison between the uid-displacement mechanisms in the pore-network model of the Nubian Sandstone as a function of wettability and minimum aspect ratio.



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Where (else) to do CCS with CPG in Switzerland?

What needs to be done! Examples.

Fig. 14: Volume fraction (saturation) of the trapped nonwetting phase (CO_2) in the pore network

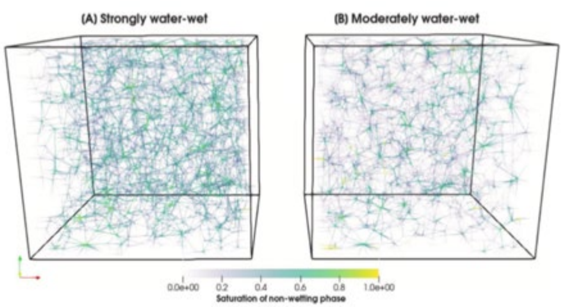


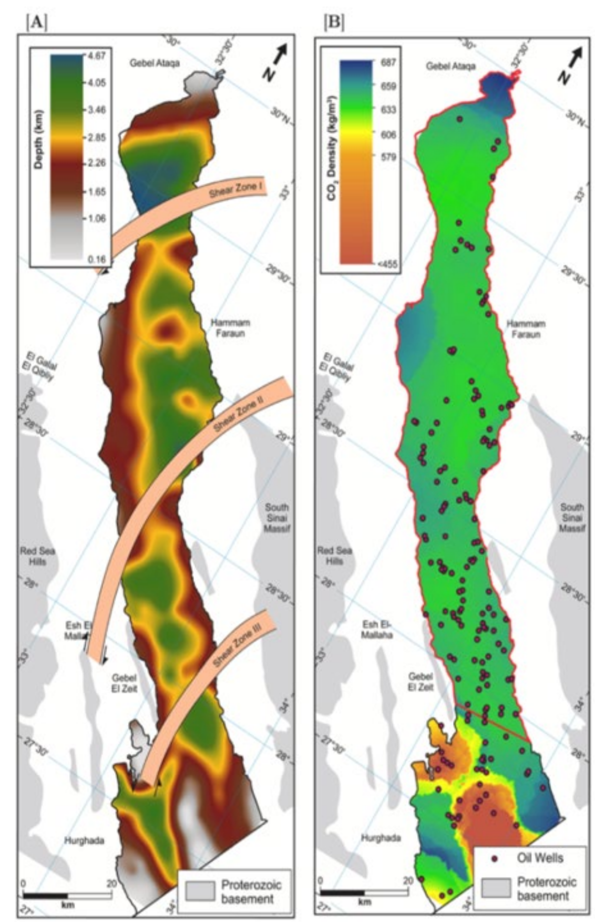
Table 5: The physical parameters used to calculate the storage capacity of Nubian Sandstone in Gulf of Suez basin (Egypt).

Parameter	Value	Model
S_g [–]	0.4	current study
S_l [–]	$1 - S_g$	–
χ_l^g [kg/kg]	0.057 [a]	Duan et al. (2006)
ρ_g [kg/m^3]	647.7 [a]	Span and Wagner (1996)
ρ_l [kg/m^3]	959.47 [a]	Driesner (2007)
C_d [–]	0.05	–
$\bar{\phi}_{avg}$ [–]	0.12	–
C_l [–]	0.45	–
C_g [–]	0.19–0.63	Kopp et al. (2009)
C_h [–]	0.5	van der Meer (1995)
ζ_{eff} [%]	0.5 – 1.7	–
Surface area [km^2]	9950 [b]	–
V_{res}^{bulk} [km^3]	4477.5 [c]	–

Selected Conclusions

- This investigation included (1) constructing a realistic 3D pore network model that represents the characteristic features of Nubian Sand- stone, (2) developing a quasi-static pore-network numerical simulator that mimics in-situ conditions that are similar to those prevailing at a CO_2-storage site, at the trailing edge of the CO_2 plume, and (3) predicting the two-phase flow characteristics.
- Two-phase constitutive relationships, including the capillary pressure and relative permeability curves, were computed for water-wet rocks at a low capillary number. We determine a Land trapping coefficient of C = 1.2 for the Nubian sandstone sample. These relationships can be employed in field-scale numerical models to estimate the extent of CO_2-plume migration, at a representative geological scale.
- The estimated capillary-trapping curves for Nubian Sandstone are in good agreement with those observed experimentally for similar rocks. This confirms, that residual trapping due to hysteresis can be a key mechanism for long-term CO_2 storage in Nubian Sandstone.
- **The pore-network model developed in this work improves our understanding of the different trapping mechanisms in Nubian Sand-stone, as they pertain to CCS- and CPG-related applications.**

Fig. 15: [A] Depth to the top of the Nubian Sandstone sequence in the Gulf of Suez (Egypt). The map is constructed based on the interpretation of aeromagnetic and geological data by Mesheref et al. (1976) for basement rocks and modified after Farhoud (2009). [B] The distribution of in-situ CO_2 densities across the Gulf of Suez.



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Where (else) to do CCS with CPG in Switzerland?

What needs to be done! Examples.

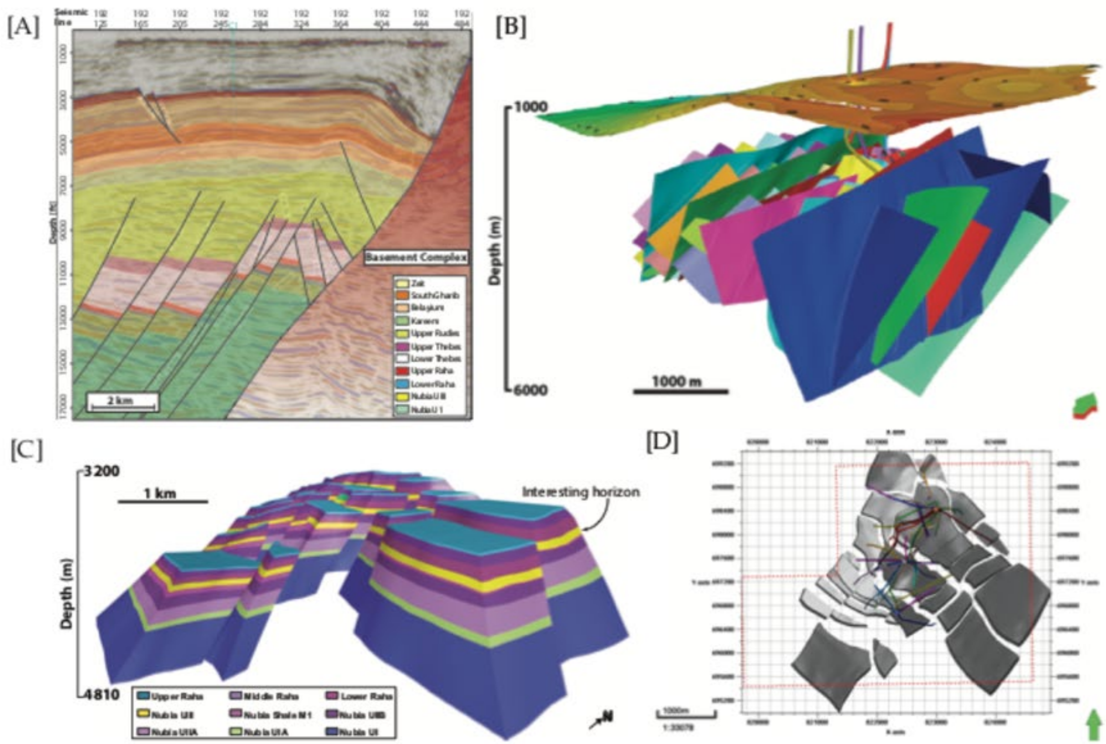


Figure 3.3: [A] Interpreted geo-seismic faults of NE on seismic crossline (No. 328) from the Ras Budran PSDM 3D survey and borehole data. The seismic profile was selected to demonstrate the structural framework of the study area. [B] Three-dimensional visualization of 72 fault planes which are robustly extracted, separated, and labeled using the integration of seismic data and well logging. [C] 3D view of the final structural and geological model for Paleozoic-Mesozoic formations. [D] Spyder map showing the trajectory of the boreholes that reaching the top of Nubian III blocks. The reddish dash lines represent the lease concession boundary. Its location is referred to Figure 3.1B.

Hefny, ***PhD Thesis*** 2020

Where (else) to do CCS with CPG in Switzerland?

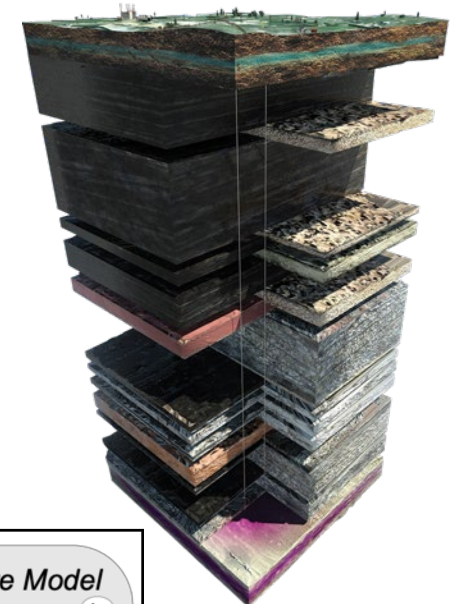
What needs to be done! Examples

Aquistore in Canada

320 ktons CO_2 present in the subsurface

- densely monitored
- open-minded management

Arial view of the coal-fired Boundary Dam power plant (Accessed on 20.09.2020 from: https://ccsknowledge.com).



Visualization of the Aquistore site. (Accessed on 20.09.2020 from: https://ptrc.ca).

- ❑ **Part 1:** Theoretical Approach
- ❑ **Part 2:** CO_2 Injection Model
- ❑ **Part 3:** CO_2 Circulation Model
- ❑ For two sets of k_{rel} and four different k_{abs}

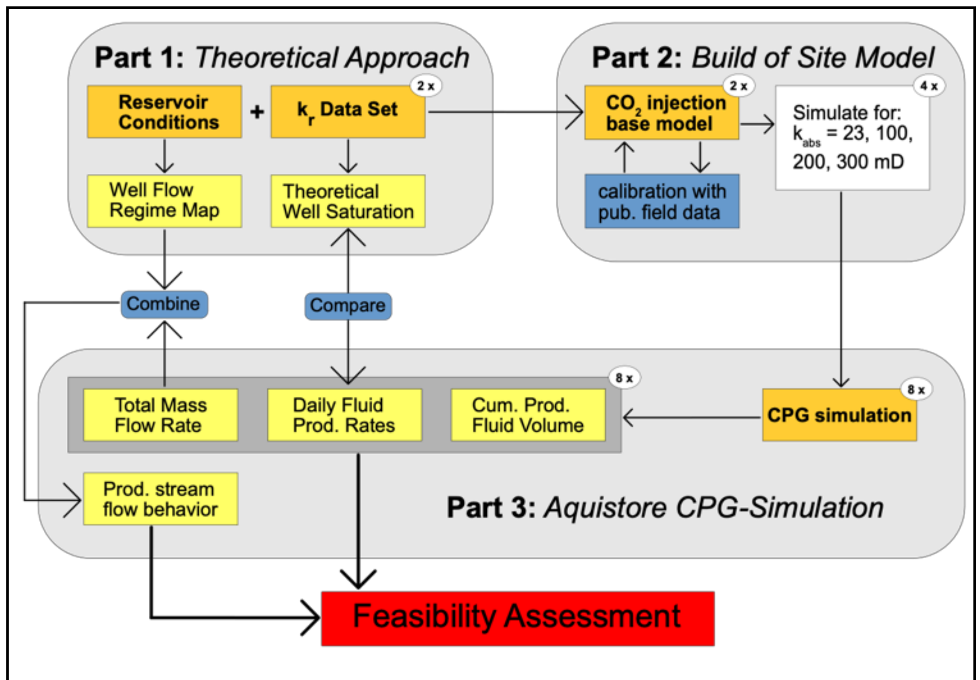


Figure 8: Flowchart of the workflow used in the MSc thesis of Kevin Hau (2020).

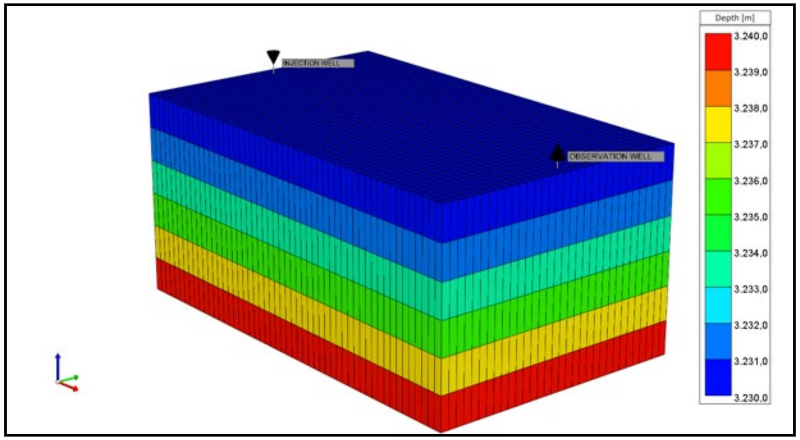
Where (else) to do CCS with CPG in Switzerland?

What needs to be done! Examples

Aquistore in Canada

Parameter	Value
Model size	156 m x 96 m x 12 m
Prorosity	7.3 %
Eff. permeability:	
- IJ-direction	23.8 mD
- K-direction	2.38 mD
Components	Brine, CO_2 and CH_4 (trace comp.)
Salinity	300 000 ppm
Reservoir Temperature	120°C
Reservoir Pressure	32.5 MPa
Equation of state	Peng-Robinson
Injection well (Max. BHP)	42,5 MPa
Initial conditions	Hydrostatic equilibrium, no heat flow, fully saturated reservoir

Overview over some of the model array parameters.



view of the conceptual model. The colou bar indicates the depth at the top of each cell.

	Reference Value	Rel. Perm. Data: Bennion et al. 2005	Rel. Perm. Data: Guyant et al. 2015
Cum. CO_2 Volume as of July 2020 [m^3]	≈ 6.37E7	≈ 5.92E7	≈ 5.91E7
Initial ρ_{brine} [kg/m^3]	1186	1144	1146
Breakthrough time	Dec 2015 - Feb 2016	February 10th, 2016 E6	December 20th, 2015 E6
Cum. CO_2 Volume at Breakthrough [m^3]	≈ 5E6	≈ 5.53E5	≈ 4.24E5

Comparison of field data with obtained simulation data (gas volume at surface conditions).

Where (else) to do CCS with CPG in Switzerland?

What needs to be done! Examples

Aquistore in Canada

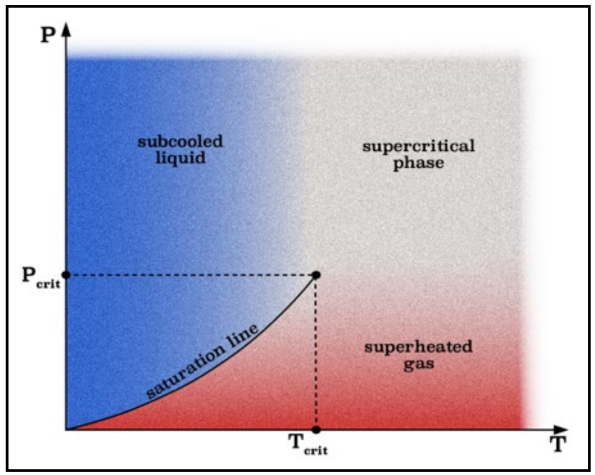
- Geothermal energy extraction by circulation of supercritical CO_2
- Geothermal power:

$$W_{geoth} = \frac{c_p \rho_{fluid}}{\mu} \frac{r^4 \Delta T \Delta P}{8 \pi l}$$

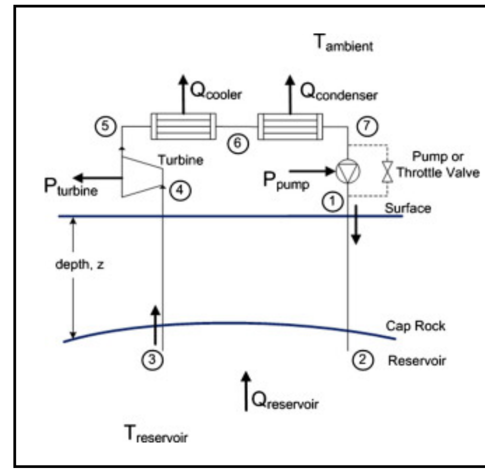
		sCO_2	H_2O	brine
c_p	[J/g K]	1920	4170	3160
ρ	[kg/m³]	620	960	1210
μ	[Pa s]	$5 \cdot 10^{-5}$	$2.4 \cdot 10^{-4}$	$3 \cdot 10^{-4}$
$\frac{c_p \rho_{fluid}}{\mu}$	[1/K s]	$2.4 \cdot 10^{7}$	$1.7 \cdot 10^{7}$	$1,3 \cdot 10^{7}$

(T = 120 °C and P = 32.5 MPa)

Phase properties of supercritical CO_2, brine (sal = 300 000 ppm) and pure water (Bell et al. 2014, Ezekiel et al. 2020).



Simplified phase diagram of CO_2 (modified from Pruess, 2006).



Concept of a direct CO_2 Plume geothermal system (Adams et al., 2015).

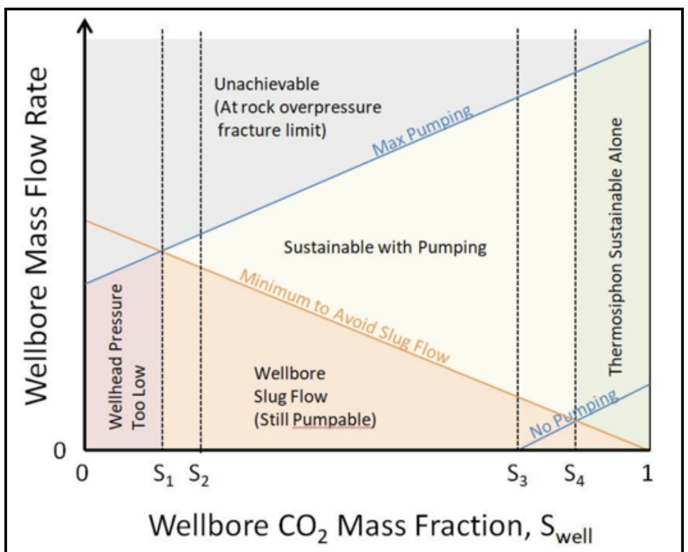
Where (else) to do CCS with CPG in Switzerland?

What needs to be done! Examples

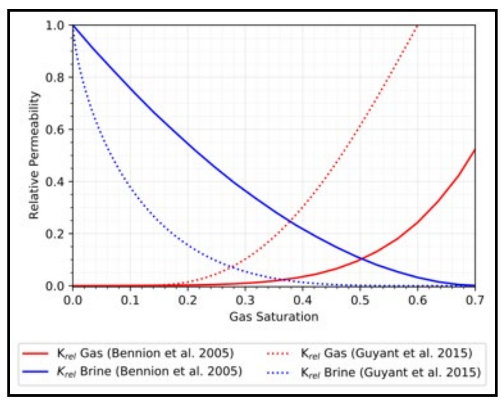
Aquistore in Canada

Based on Buckley and Leverett (1942):

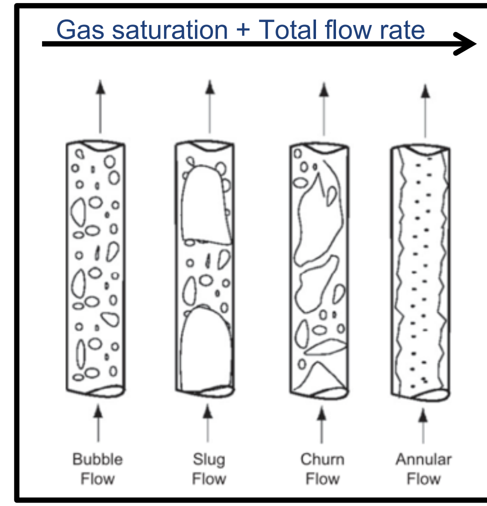
- **Relative Permeability:** $k_r = \frac{k_{eff}}{k_{abs}}$
- Mobility of a phase **α**: $\lambda_\alpha = \frac{k_{r\alpha}}{\mu_\alpha}$
- Fractional flow of a phase **α**: $f_\alpha(S_\alpha) = \frac{\lambda_\alpha}{\lambda_\alpha + \lambda_\beta}$



Conceptual diagram showing the effects of CO_2 saturation and mass flow rate on the production stream.



Both relative permeability data sets used in this study.



Existing flow patterns in a gas production well (Mokhatab and Poe, 2012).

		sCO_2	H_2O	brine
c_p	[J/g K]	1920	4170	3160
ρ	[kg/m³]	620	960	1210
μ	[Pa s]	$5 \cdot 10^{-5}$	$2.4 \cdot 10^{-4}$	$3 \cdot 10^{-4}$
$\frac{c_p \rho_{fluid}}{\mu}$	[1/K s]	$2.4 \cdot 10^7$	$1.7 \cdot 10^7$	$1,3 \cdot 10^7$

(T = 120 °C and P = 32.5 MPa)

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Where (else) to do CCS with CPG in Switzerland?

What needs to be done! Examples

Aquistore in Canada

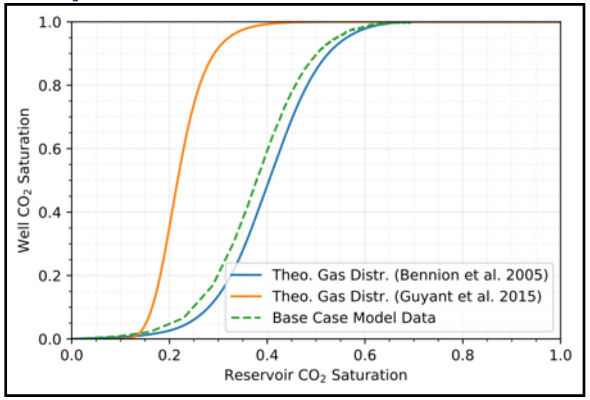


Figure 12a: Model gas distribution around the breakthrough time (k_{rel} = Bennion et al. 2005).

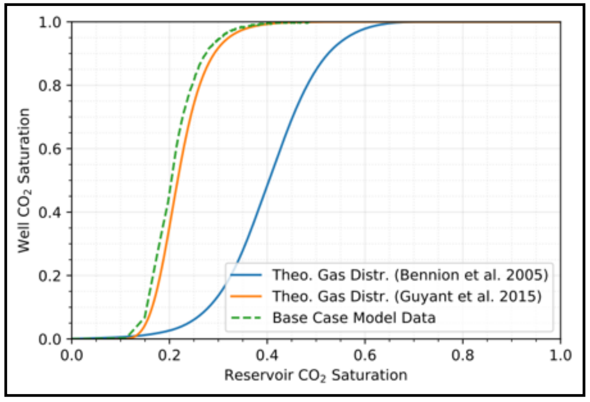


Figure 12b: Model gas distribution around the breakthrough time (k_{rel} = Guyant et al. 2015).

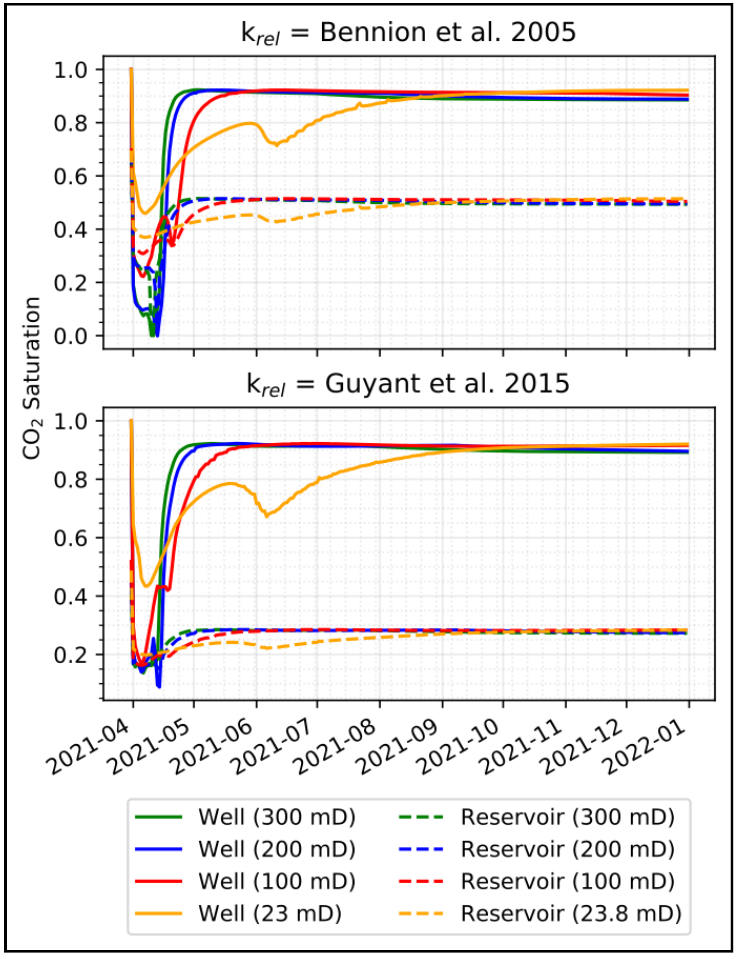


Figure 13: Model gas saturation over time for both relative permeability data sets.

Where (else) to do CCS with CPG in Switzerland?

What needs to be done! Examples

Aquistore in Canada

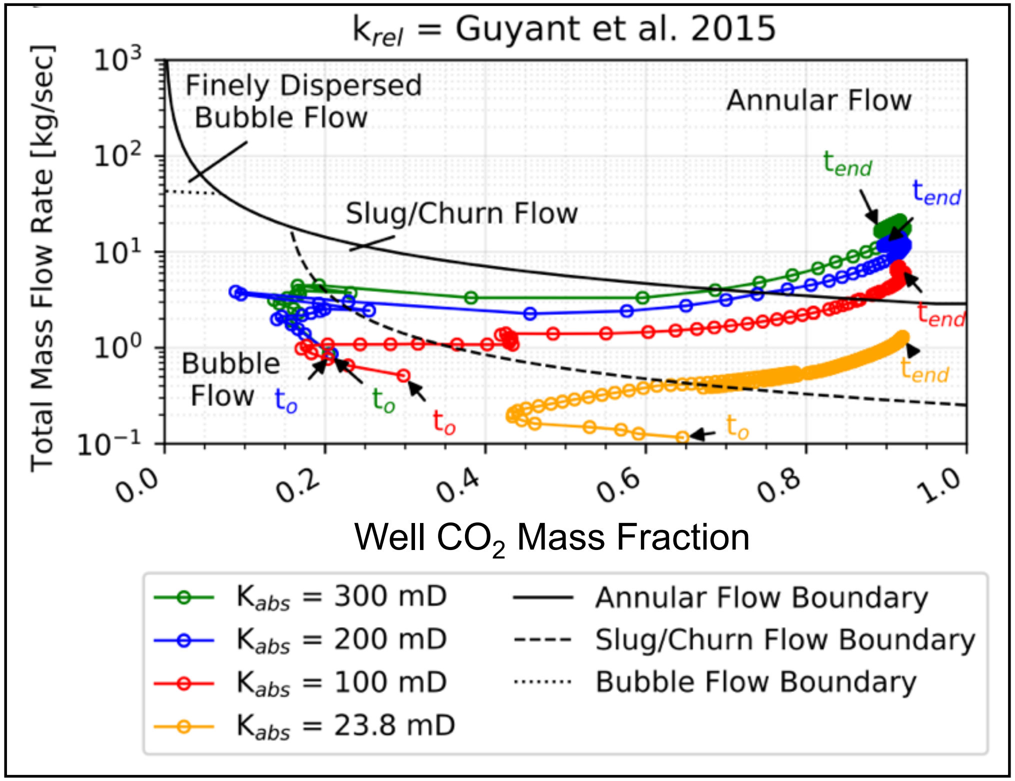
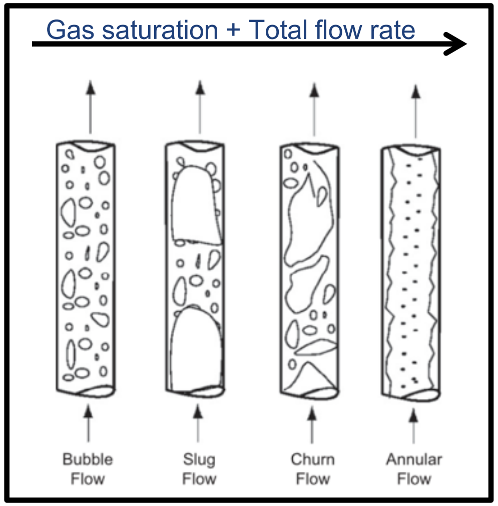


Figure 16: Production stream flow behaviour, simulated for different absolute permeabilities, based on the relative permeability data from Guyant et al. 2015

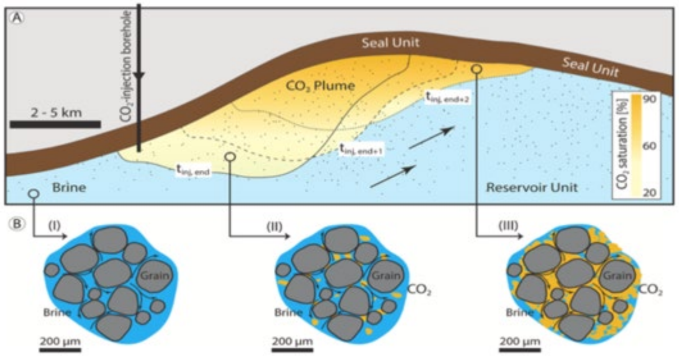


Existing flow patterns in a gas production well (Mokhatab and Poe, 2012).

Conclusions

To evaluate Switzerland's CCS and CPG potential properly, a lot more needs to be done, including:

- Reservoir characterization, particularly regarding:
    - dual/multiple porosity/permeability systems (with fractures, karst, etc.)
    - transmissivity
    - relative permeability, capillary pressure
    - pore-fluid pressure
    - formation temperature
    - usefulness for CPG Energy Storage
    - Geometry (3D seismic, MT, active EM, etc.)
- CO2 source and sink as well as transport (SimCCS?):
    - expected CO2 capture rate
    - CO2 source location in relationship to reservoir → CO2 transport (CO2 pipeline, train/truck)
    - CO2 sink locations (including Northern Lights)
    - Intermittent storage of CO2 in CH
- Power grid
    - Amount and type (dispatchable, etc.) power needed
    - Power grid proximity to potential CPG site
    - Proximity of intermittent power sources (wind/solar) for CPGES (Earth Battery)
- Economics factors:
    - taxes
    - Feed-in tariffs



"We barely scratched the surface regarding CCS+CPG in Switzerland…"
(approx. Andrea Moscariello in a recent Elegancy meeting)

But some of this "surface scratching" was presented here and is presented next…

Selected Saar publications and patents on CPG and CPG Energy Storage (CPGES or Earth Battery):

Randolph & Saar, ***Geophysical Research Letters*** 2011
Saar et al., ***Patents*** 2012
Adams et al., ***Energy*** 2014
Adams et al., ***Applied Energy*** 2015
Garapati et al., ***Geothermics*** 2015
Fleming et al., ***Stanford Geothermal Workshop*** 2018
Saar and Adams, ***Patent Pending*** 2018
Adams et al., ***Proc. Applied Energy Symposium*** 2020
Ezekiel et al., ***Applied Energy*** 2020
Fleming et al., ***Geothermics*** 2020
Garapati et al., ***J. of*** CO_2 ***Utilization*** 2020
Hefny et al., ***International J. of Greenhouse Gas Control*** 2020

ETHzürich   SCCER-SoE Annual Conference 2.11.2020   Geothermal Energy and Geofluids

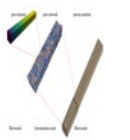
The Geothermal Energy and Geofluids (GEG) Group
More than just CPG

The Geothermal Energy and Geofluids (GEG) Group at ETH Zürich (June 2019)

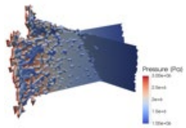
Current GEG Projects

Reactive transport

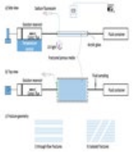
Analyzing spatial scaling effects in mineral reaction rates in porous media with a hybrid numerical model



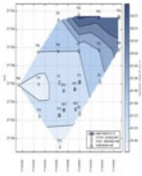
Solute transport in 3D fractured reservoirs



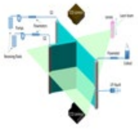
Simultaneous visualization of fluid flow and mineral precipitation in fractured porous media



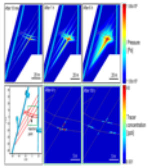
Evaluation of DNA-labeled silica nanoparticles for use as hydrogeologic tracers: field study and column experiments



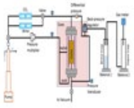
A new paradigm in imaging and characterizing flow structures and solute transport in three dimensions



Tracer-based characterization of stimulation enhanced pore volume and application of novel DNA nanotracers in fractured rock

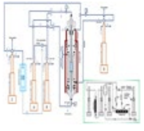


Evolution of permeability and porosity due to mineral precipitation in natural and/or artificial granite fractures



Software Development: Reaktoro, a unified framework for modeling chemically reactive systems

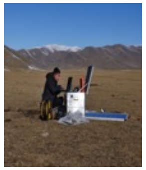
Chemical stimulation of geothermal reservoirs using reactive flow-through system



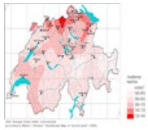
MT and Heatflow

Magnetotelluric investigation of active rifting and the formation of geothermal energy resources in Ethiopia (MIRIGE)

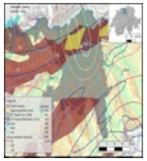
Development of a geoscientific framework for geothermal exploration and energy utilization in Mongolia



Magnetotelluric Investigation of the Northern Swiss Heat Flow Anomaly



Pilot Study Geothermal Energy Aargau

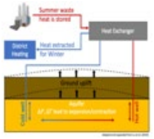


Unmanned Aerial Vehicle (UAV) based geomagnetic mapping and thermal imaging

Poroelasticity

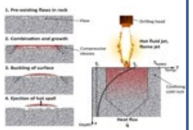
Hydro-mechanical processes in natural and 3D printed fractures

Thermo-Hydro-Mechanical (THM) Processes in Aquifer Thermal Energy Storage (ATES)



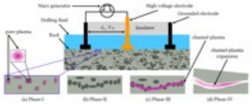
Drilling

Modeling thermal spallation drilling

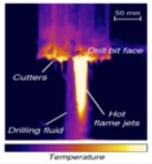


Modeling the Hydraulic Fracture Stimulation performed for Reservoir Permeability Enhancement at the Grimsel Test Site, Switzerland

Plasma Pulse Geo-Drilling (PPGD)

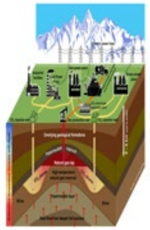


Combined Thermo-Mechanical Drilling (CTMD) technology to facilitate deep geo-resource utilization

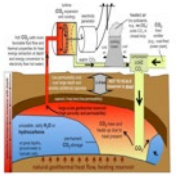


CPG & Earth Battery

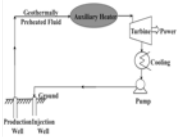
Assessment and optimization of carbon storage and combined EGR-CPG development from high-temperature natural gas reservoirs



Numerical Modeling of CO2-Plume Geothermal (CPG) Systems



Auxiliary heating of low- to moderate-temperature geothermal resources to boost electricity production



ETH zürich SCCER-SoE Annual Conference 2.11.2020 Geothermal Energy and Geofluids

The Geothermal Energy and Geofluids (GEG) Group More than just CPG

The Geothermal Energy and Geofluids (GEG) Group at ETH Zürich (June 2019)

2020 Publications with GEG authors (underlined)

33. Middleton, R, J Ogland-Hand, B Chen, J Bielicki, K Ellet, D Harp, and R Kammer **Identifying Geologic Characteristics and Operational Decisions to Meet Global Carbo**
32. Garapati, N., B.M. Adams, M.R. Fleming, T.H. Kuehn, and M.O. Saar **Combining brine or CO2 geothermal preheating with low-temperature waste heat: A higher-effic**
31. Hefny, M., C.-Z. Qin, M.O. Saar, and A. Ebigbo **Synchrotron-based pore-network modeling of two-phase flow in Nubian Sandstone and implications for capillary tra**
30. Zhang, S., and X. Ma **Global Frictional Equilibrium via Stochastic, Local Coulomb Frictional Slips** ESSOAr, 2020. [Download PDF]
29. Krietsch, H., V.S. Gischig, J. Doetsch, K.F. Evans, L. Villliger, M. Jalali, B. Valley, S. Löw, and F. Amman **Hydromechanical processes and their influence on the stimula**
28. Gischig, V.S., D. Giardini, F. Amann, "et al.", Keith F. Evans, "et al.", A. Kittilä, X. Ma, "et al.", M.O. Saar, and "et al." **Hydraulic stimulation and fluid circulation experime**
27. Lima, M., P. Schädle, C. Green, D. Vogler, M.O. Saar, and X.-Z. Kong **Permeability Impairment and Salt Precipitation Patterns during CO2 Injection into Single Natura**
26. Vogler, D., S.D.C. Walsh, and M.O. Saar **A Numerical Investigation into Key Factors Controlling Hard Rock Excavation via Electropulse Stimulation** Journal of Rock
25. Leal, A. M. M., S. Kyas, D. Kulik, and M. O. Saar **Accelerating Reactive Transport Modeling: On-Demand Machine Learning Algorithm for Chemical Equilibrium Calc**
24. Ma, X., M.O. Saar, and L.-S. Fan **Coulomb Criterion - Bounding Crustal Stress Limit and Intact Rock Failure: Perspectives** Powder Technology, 374, pp. 106-110, 202
23. Vogler, D., S.D.C. Walsh, Ph. Rudolf von Rohr, and M.O. Saar **Simulation of rock failure modes in thermal spallation drilling** Acta Geotechnica, 15/8, pp. 2327-2340, 20
22. von Planta, C., D. Vogler, P. Zulian, M.O. Saar, and R. Krause **Contact between rough rock surfaces using a dual mortar method** International Journal of Rock Mechani
21. Ma, J., L. Querci, B. Hattendorf, M.O. Saar, and X.-Z. Kong **The effect of mineral dissolution on the effective stress law for permeability in a tight sandstone** Geophys
20. Hefny, M., A. Zappone, Y. Makhloufi, A. de Haller, and A. Moscariello **A laboratory approach for the calibration of seismic data in the western part of the Swiss Molas**
19. Fleming, M.R., B.M. Adams, T.H. Kuehn, J.M. Bielicki, and M.O. Saar **Increased Power Generation due to Exothermic Water Exsolution in CO2 Plume Geothermal (CP**
18. Tutolo, B., A. Luhmann, X.-Z. Kong, B. Bagley, D. Alba-Venero, N. Mitchell, M.O. Saar, and W.E. Seyfried **Contributions of visible and invisible pores to reactive transp**
17. Kyas, S., S. Repin, J. M. Nordbotten, and K. Kumar **Guaranteed and computable error bounds for approximations constructed by an iterative decoupling of the Biot**
16. Kittilä, A., M.R. Jalali, M.O. Saar, and X.-Z. Kong **Solute tracer test quantification of the effects of hot water injection into hydraulically stimulated crystalline rock** G
15. Ziegler, M., and K.F. Evans **Comparative study of Basel EGS reservoir faults inferred from analysis of microseismic cluster datasets with fracture zones obtained f**
14. Krietsch, H., L. Villiger, J. Doetsch, V. Gischig, K.F. Evans, B. Brixel, M.R. Jalali, S. Loew, D. Giardini, and F. Amann **Changing Flow Paths Caused by Simultaneous She**
13. Ezekiel, J., A. Ebigbo, B. M. Adams, and M. O. Saar **Combining natural gas recovery and CO2-based geothermal energy extraction for electric power generation** App
12. Rossi, E. , M.O. Saar, and Ph. Rudolf von Rohr **The influence of thermal treatment on rock-bit interaction: a study of a combined thermo-mechanical drilling (CTMD)**
11. Jia, Y., W. Wu, and X.-Z. Kong **Injection-induced slip heterogeneity on faults in shale reservoirs** International Journal of Rock Mechanics and Mining Sciences, 131, pp.
10. Kaufl, S., V. Grayver, J. Comeau, V. Kuvshinov, M. Becken, J. Kamm, B. Erdenechimeg, and D. Sodnomsambuu **Magnetotelluric multiscale 3-D inversion reveals crusta**
9. Comeau, J., M. Becken, S. Kaufl, V. Grayver, V. Kuvshinov, Ts. Shoovdor, B. Erdenechimeg, and D. Sodnomsambuu **Evidence for terrane boundaries and suture zones a**
8. Rossi, E., S. Jamali, V. Wittig, M.O. Saar, and Ph. Rudolf von Rohr **A combined thermo-mechanical drilling technology for deep geothermal and hard rock reservoirs** G
7. Rossi, E., S. Jamali, M.O. Saar, and Ph. Rudolf von Rohr **Field test of a Combined Thermo-Mechanical Drilling technology. Mode I: Thermal spallation drilling** Journal
6. Rossi, E., S. Jamali, D. Schwarz, M.O. Saar, and Ph. Rudolf von Rohr **Field test of a Combined Thermo-Mechanical Drilling technology. Mode II: Flame-assisted rotary**
5. Kittilä, A., M.R. Jalali, M. Somogyvári, K.F. Evans, M.O. Saar, and X.-Z. Kong **Characterization of the effects of hydraulic stimulation with tracer-based temporal mome**
4. Nejati, M., A. Aminzadeh, T. Driesner, and M.O. Saar **On the directional dependency of Mode I fracture toughness in anisotropic rocks** Theoretical and Applied Fracture
3. von Planta, C., D. Vogler, X. Chen, M.G.C. Nestola, M.O. Saar, and R. Krause **Modelling of hydro-mechanical processes in heterogeneous fracture intersections using**
2. Ahkami, M., A. Parmigiani, P.R. Di Palma, M.O. Saar, and X.-Z. Kong **A lattice-Boltzmann study of permeability-porosity relationships and mineral precipitation patter**
1. Walsh, S.D.C., and D. Vogler **Simulating Electropulse Fracture of Granitic Rock** International Journal of Rock Mechanics and Mining Sciences, 128, pp. 104238, 2020. [Do

Conclusions

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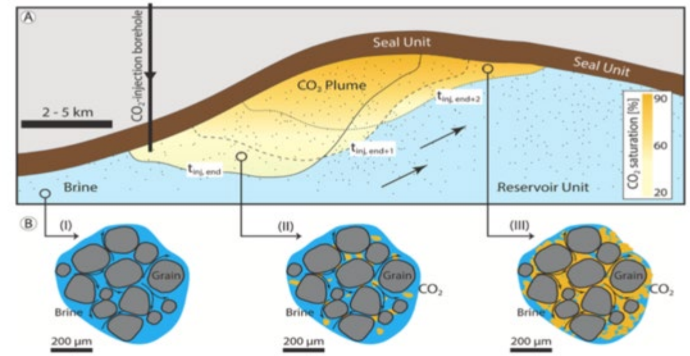
Martin Saar, Chair of Geothermal Energy and Geofluids (**GEG.ethz.ch, saarm@ethz.ch**)

Thank you!



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Saar and Adams, ***Patent Pending*** 2018
Adams et al., ***Proc. Applied Energy Symposium*** 2020
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Fleming et al., ***Geothermics*** 2020
Garapati et al., ***J. of CO_2 Utilization*** 2020
Hefny et al., ***International J. of Greenhouse Gas Control*** 2020