Remobilization of residually trapped CO_2 – findings from field injection experiments and pore scale studies

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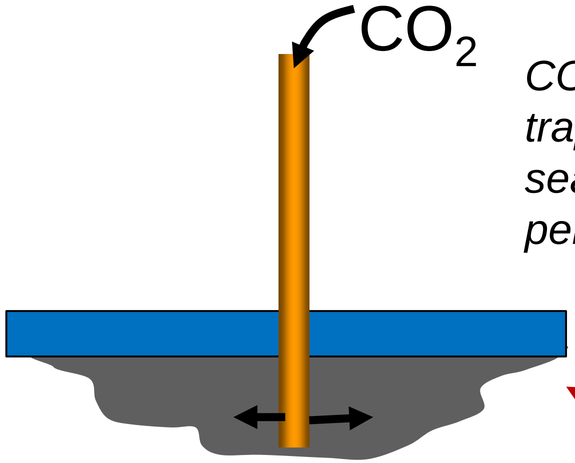
Outline

1) Findings on residual saturation from an EU-funded pilot injection project (Heletz, Israel)

2) On remobilization of residually trapped CO_2: residual saturation and critical saturation

How is CO_2 stored in the deep aquifer?



CO_2 gets physically trapped beneath the sealing cap-rock and low permeability layers

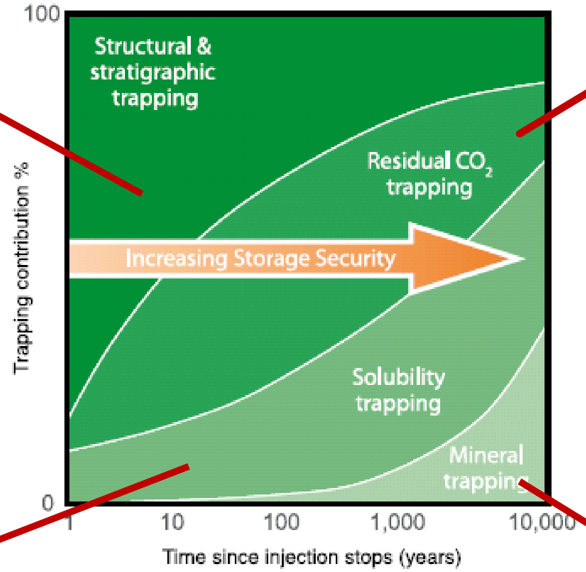
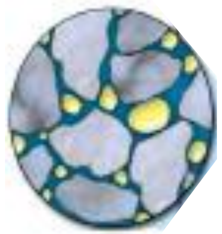
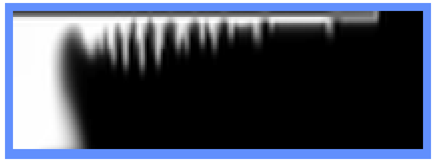


Figure 5.9 Storage security depends on a combination of physical and geochemical trapping. Over time, the physical process of residual CO_2 trapping and geochemical processes of solubility trapping and mineral trapping increase.



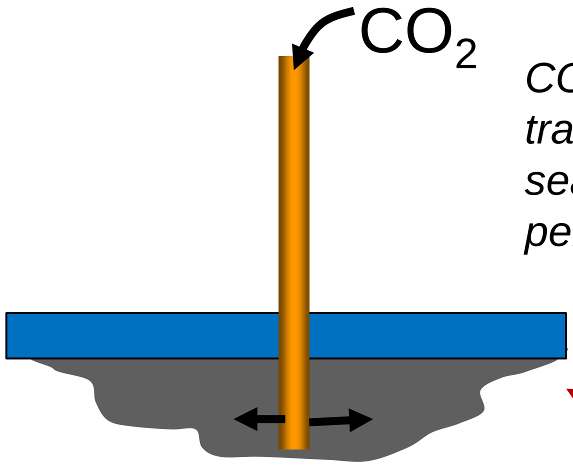
CO_2 gets trapped as immobile isolated residual 'blobs' in the pore space

CO_2 dissolves into water



CO_2 converts into solid minerals

How is CO_2 stored in the deep aquifer?



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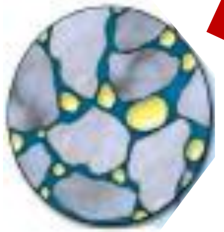
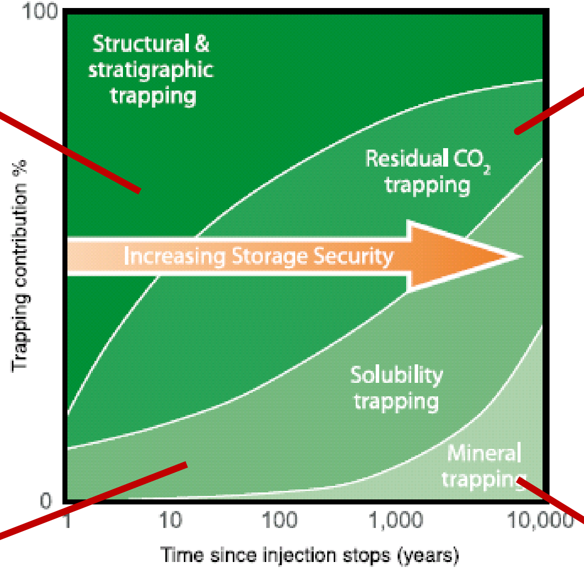


CO_2 gets trapped as immobile isolated residual 'blobs' in the pore space



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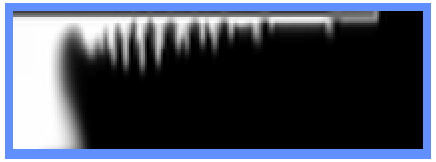
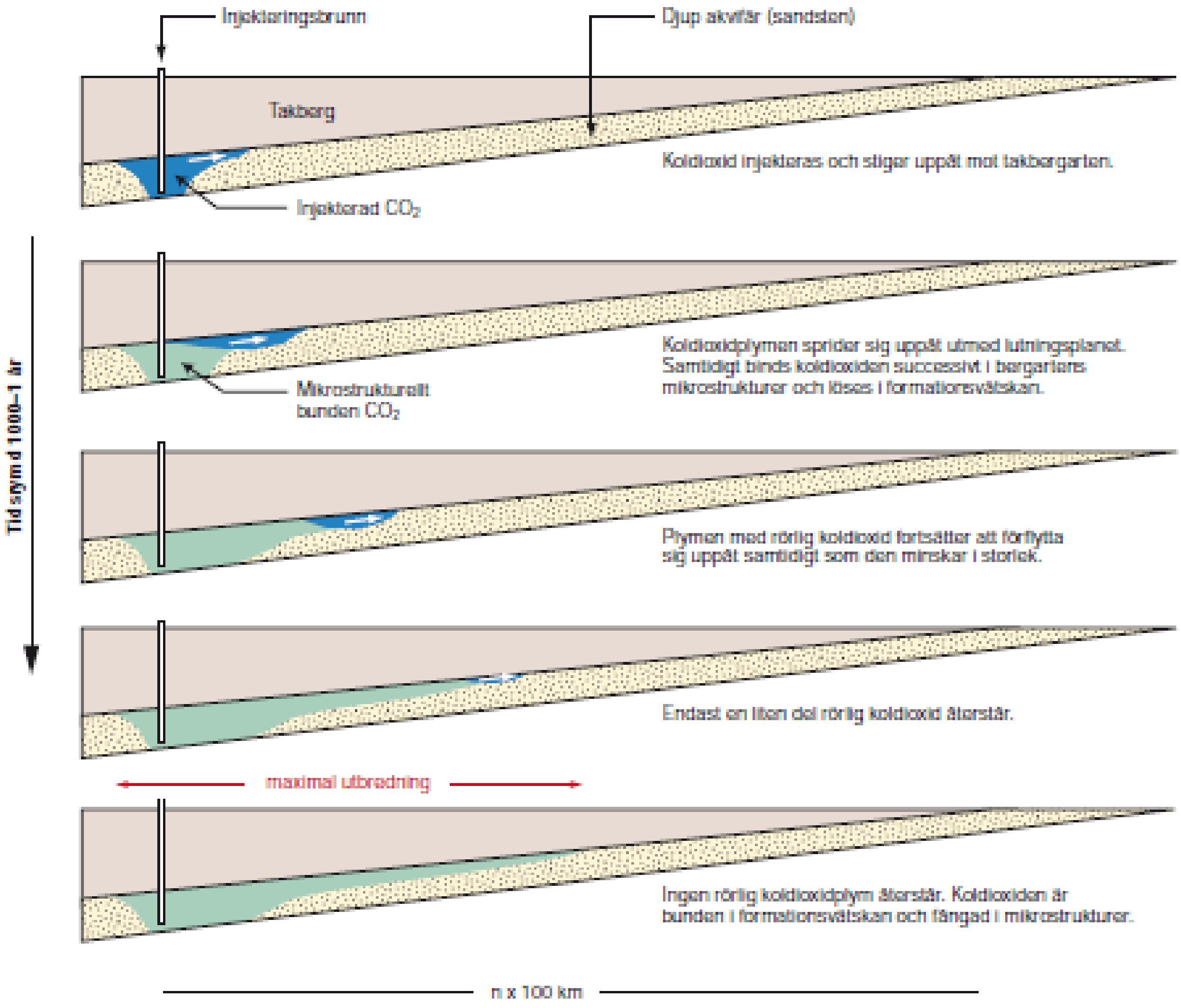
CO_2 dissolves into water



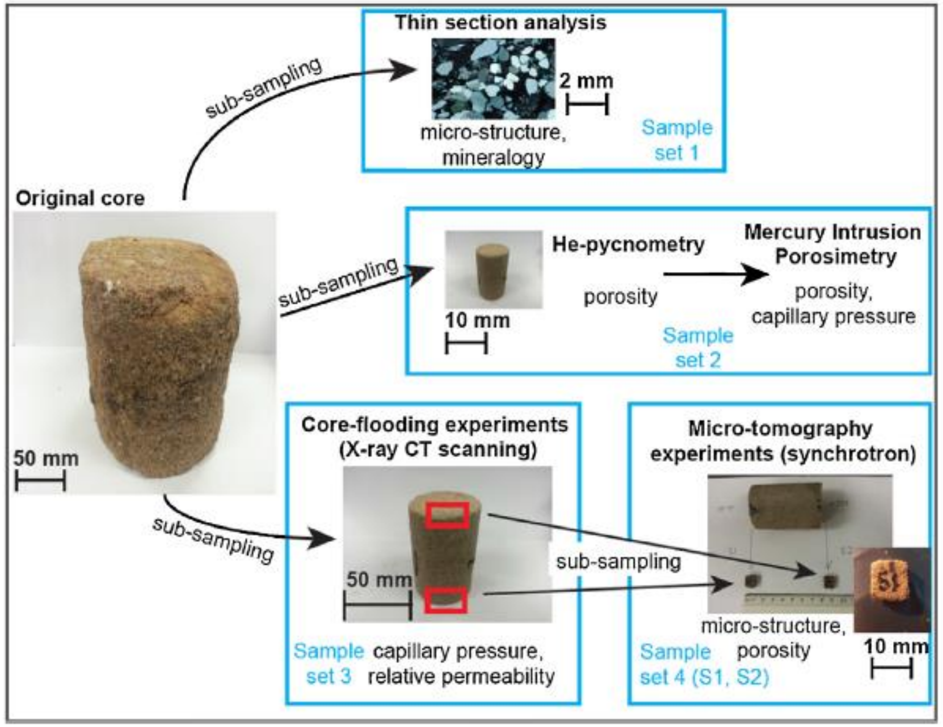
CO_2 converts into solid minerals

Evolution from mobile to residual CO_2



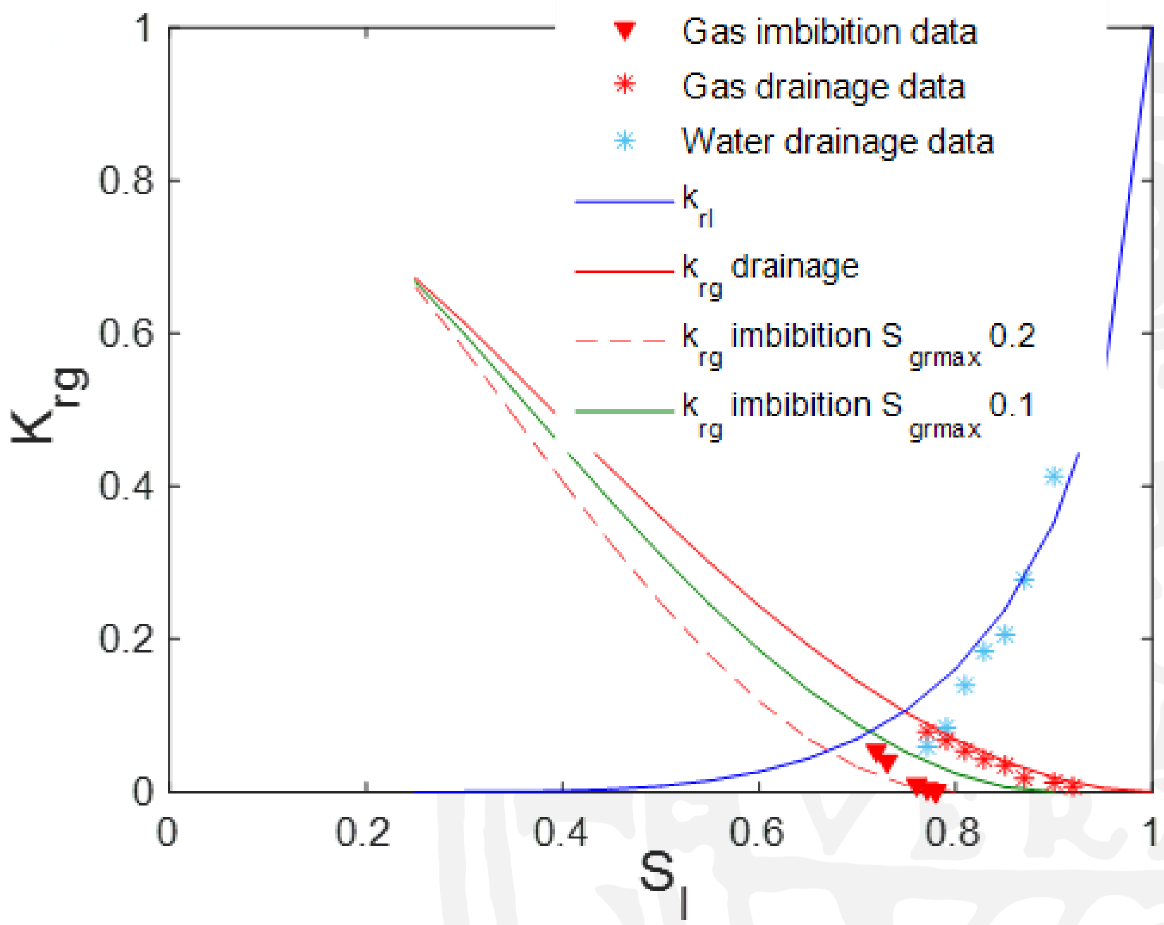
Erlström et al, SGU (Swedish Geological Survey) report 131

Determining residual saturation in the laboratory



work flow for the laboratory analysis

Hingrl et al., IJGHGC, 2016



laboratory determined relative permeability functions for Heletz cores

The CO2 injection site Heletz, Israel

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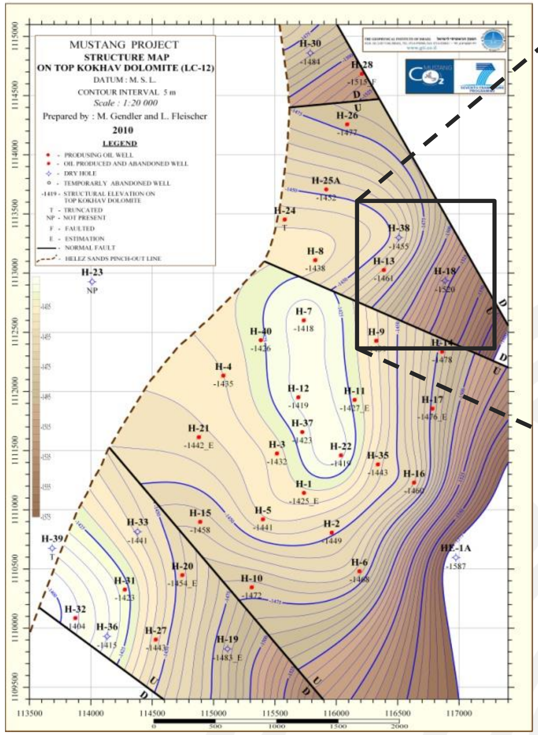
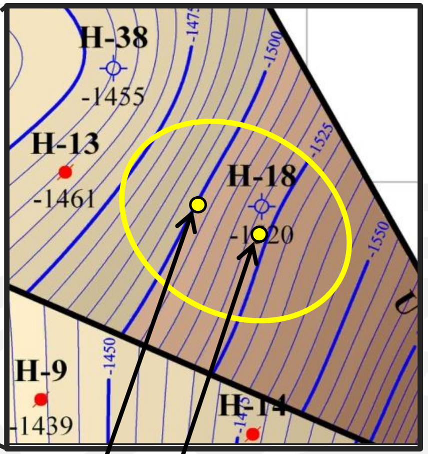
- Scientifically motivated CO_2 injection experiment site for scCO2 injection to a reservoir layer at 1600 m depth, with comprehensive monitoring and sampling

- Developed in the frame of EU FP7 projects MUSTANG, TRUST, PANACEA and CO2QUEST

Heletz

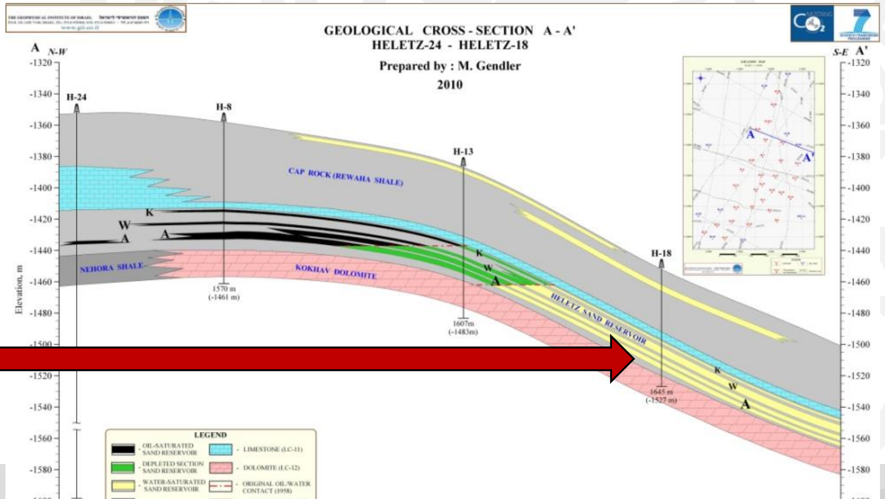


Heletz North



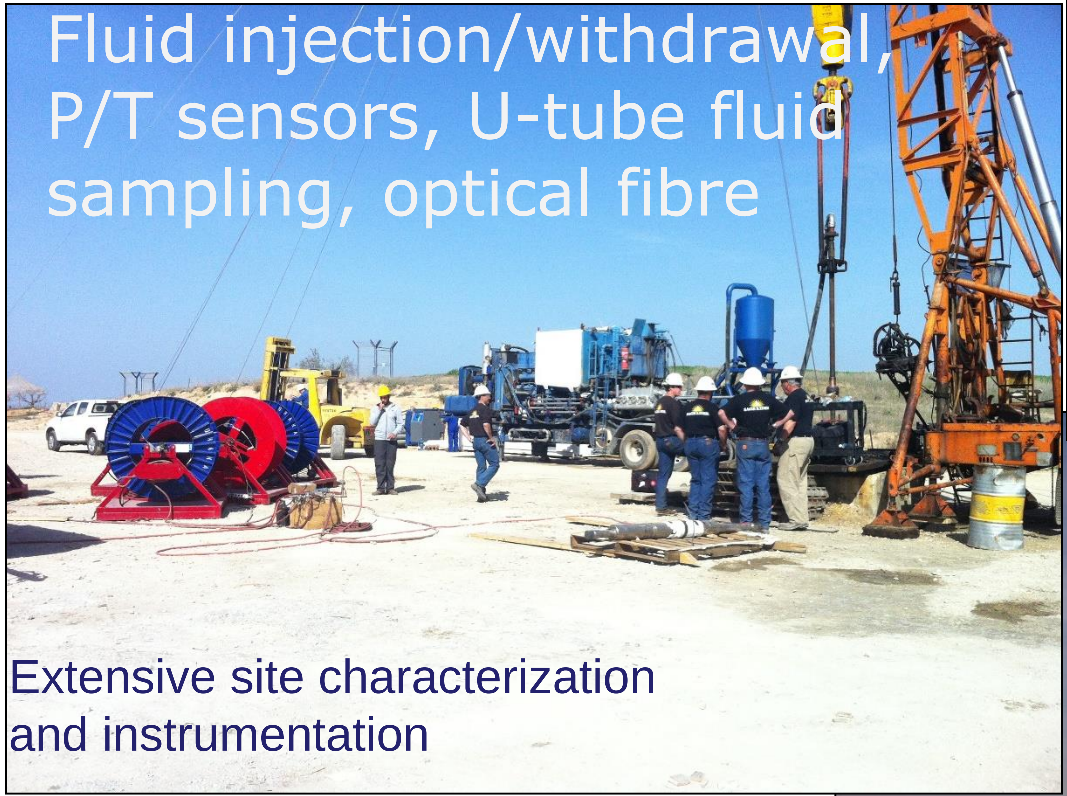
wells for CO2 injection experiments

Target reservoir layers of total ~11 m thickness



Well instrumentation and injection system

Fluid injection/withdrawal, P/T sensors, U-tube fluid sampling, optical fibre



Extensive site characterization and instrumentation

Niemi et al (Eds) <u>Special Edition</u> <u>IJGHGC</u> Vol (48) <u>2016</u>

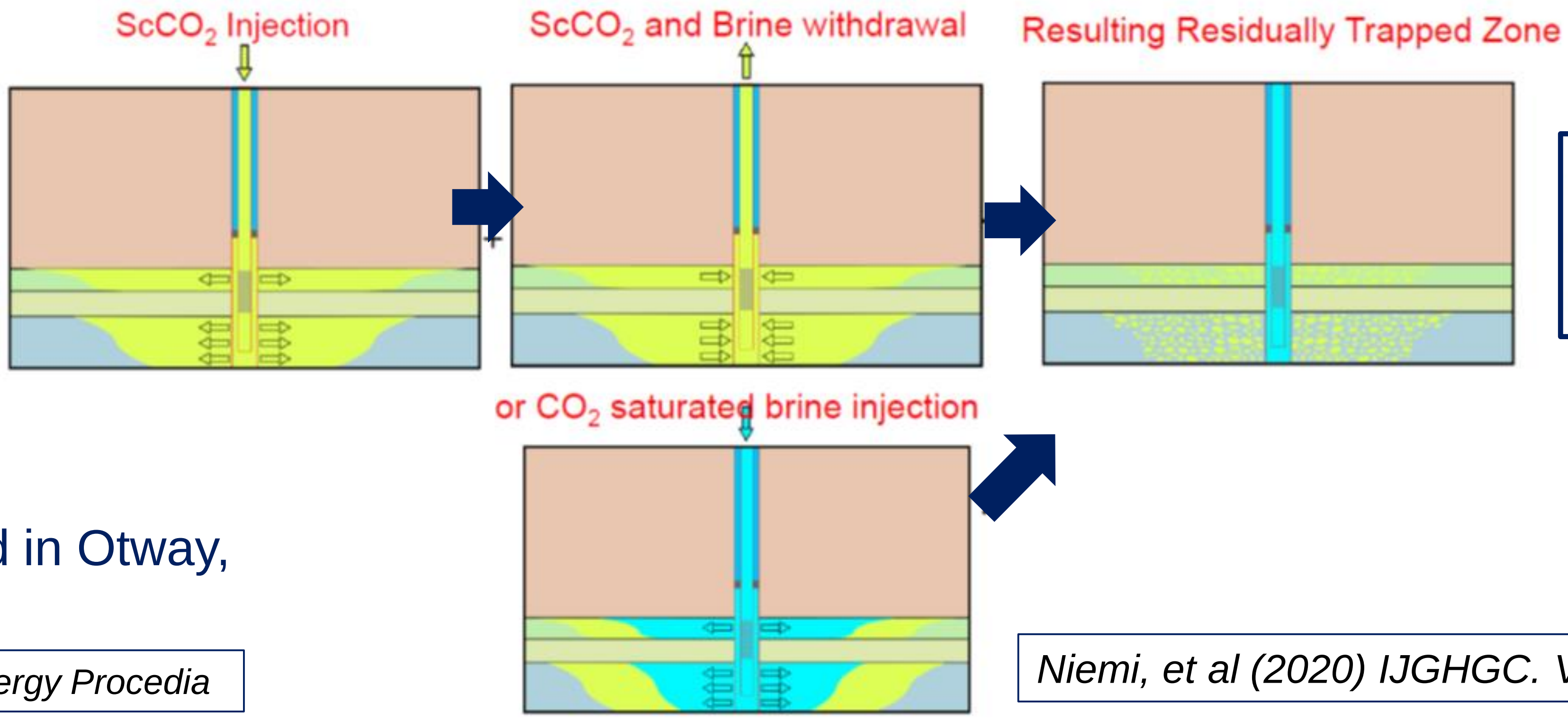
Determining residual saturation *in situ*

1. Characterization tests

2. Creating the residually trapped zone

3. Reference tests

- Hydraulic tests
- Thermal tests
- Tracer tests



- Hydraulic tests
- Thermal tests
- Tracer tests

First implemented in Otway, Australia

Paterson et al, 2013. Energy Procedia

Niemi, et al (2020) IJGHGC. Vol (101). 103129

Heletz Residual Trapping Experiments

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Residual Trapping Experiment I (2016)

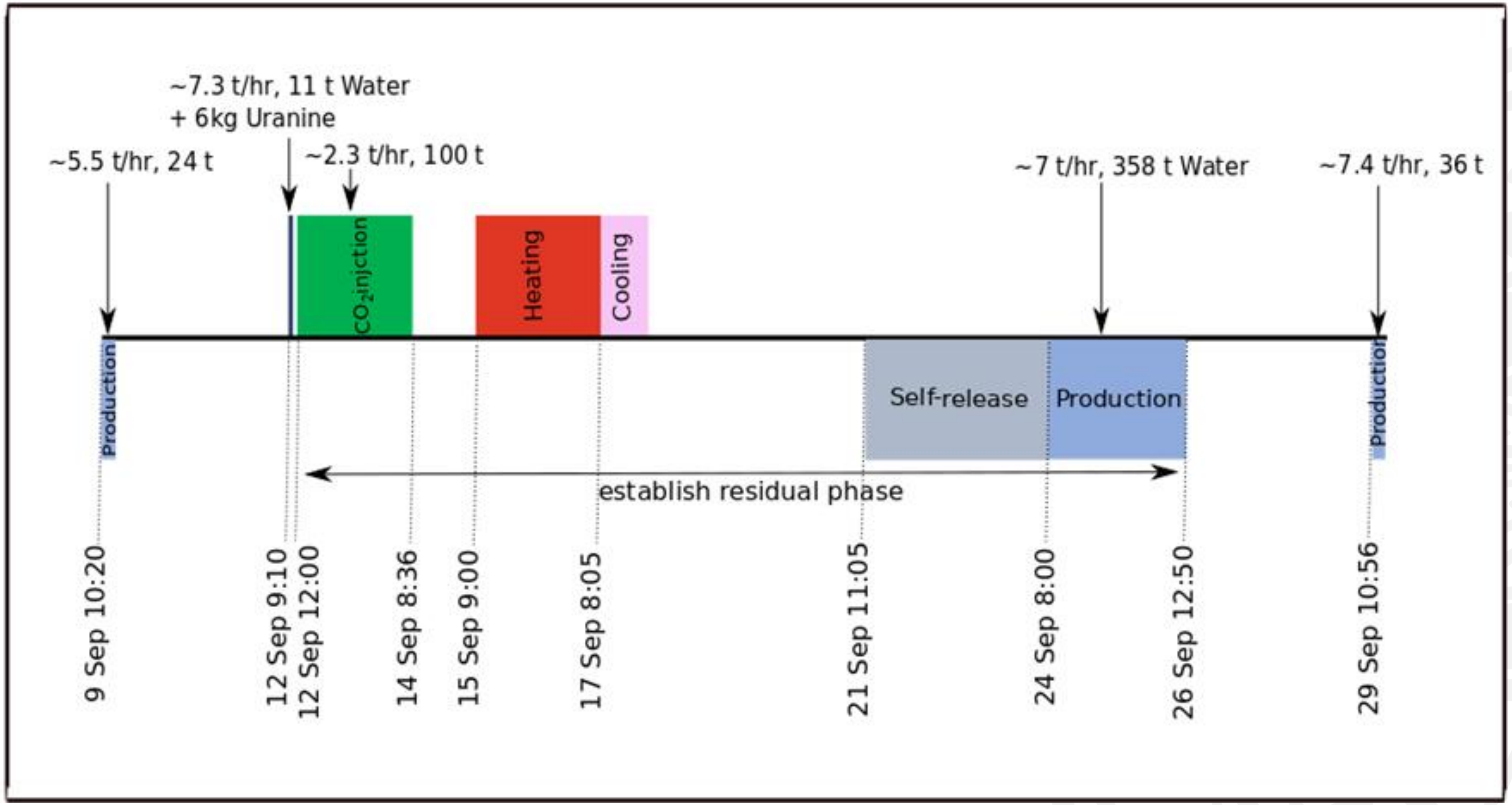
- based on the difference in hydraulic and thermal test response before and after creating the residually trapped zone
- zone of residually trapped CO_2 was created by CO_2 injection followed by fluid withdrawal until residual state was achieved

Residual Trapping Experiment II (2017)

- based on the difference in hydraulic test, thermal and partitioning tracer test response before and after creating the residually trapped zone
- zone of residually trapped CO_2 was created by CO_2 injection followed by injection of CO_2 saturated water to push the mobile CO_2 away

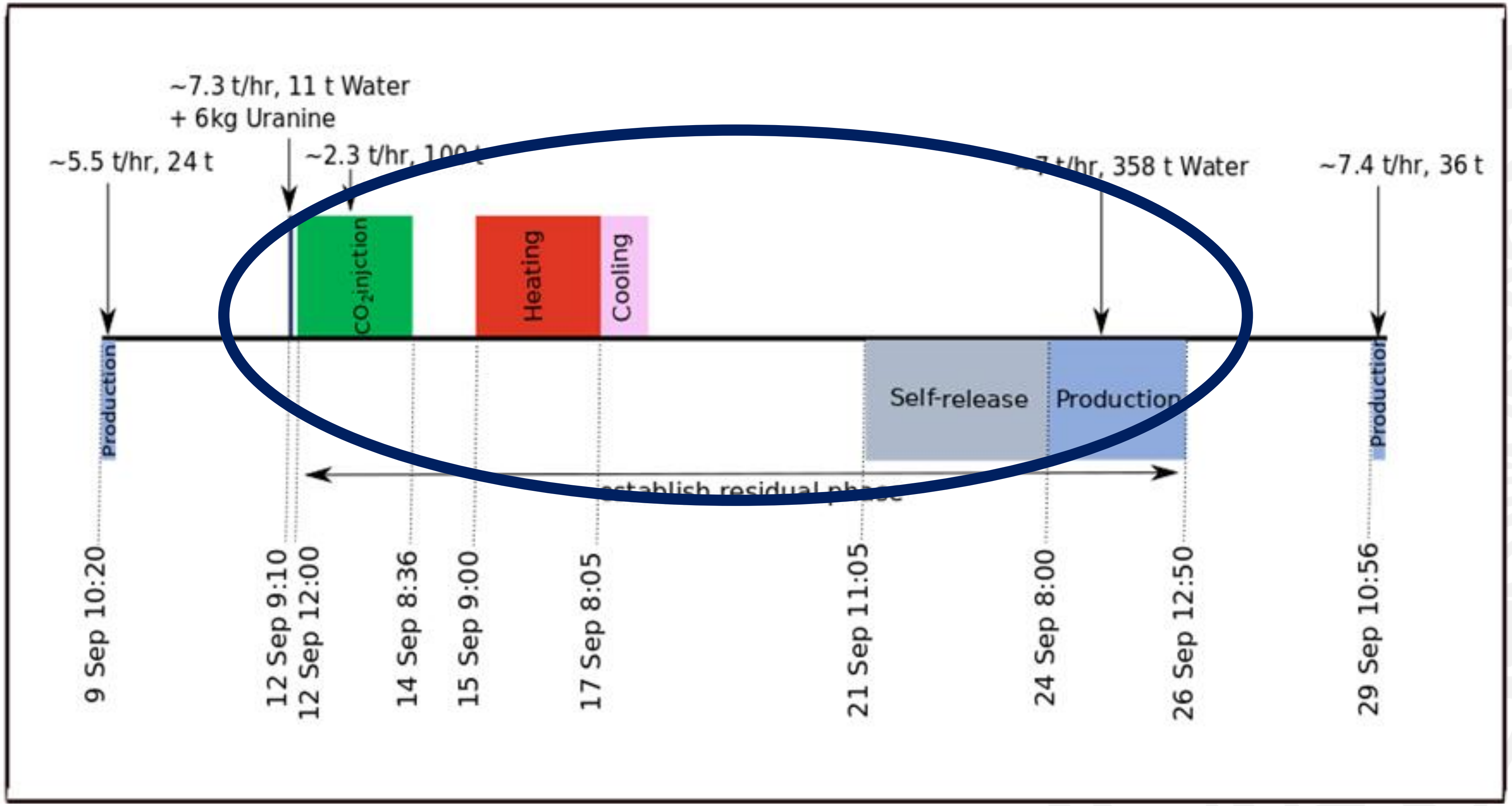
Niemi, et al (2020) IJGHGC. Vol (101). 103129

Residual Trapping Experiment I - Test sequence (Sept 2016)



Niemi, et al (2020) IJGHGC. Vol (101). 103129

Residual Trapping Experiment I - Test sequence (Sept 2016)



Niemi, et al (2020) IJGHGC. Vol (101). 103129

Residual Trapping Experiment I
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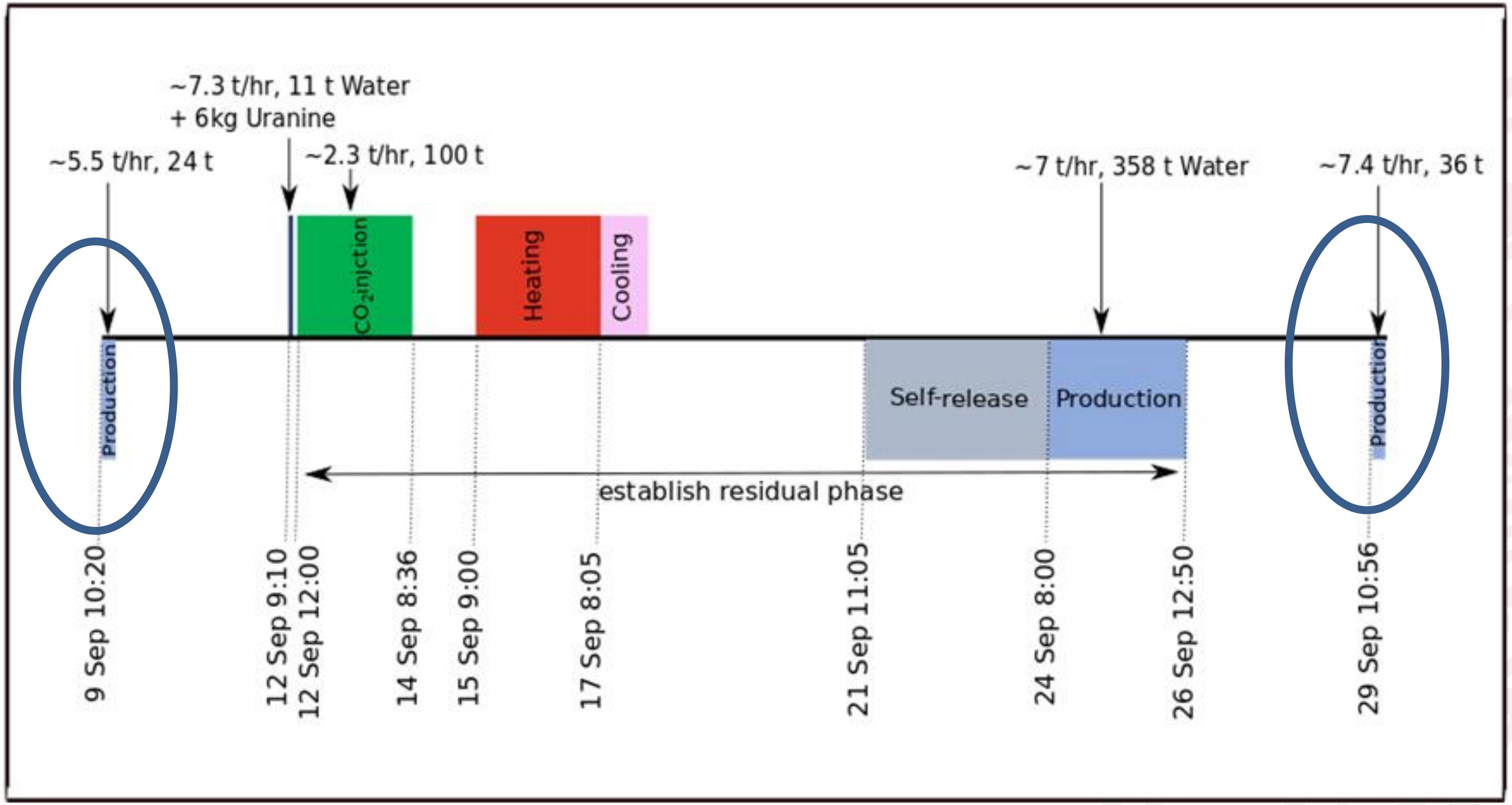

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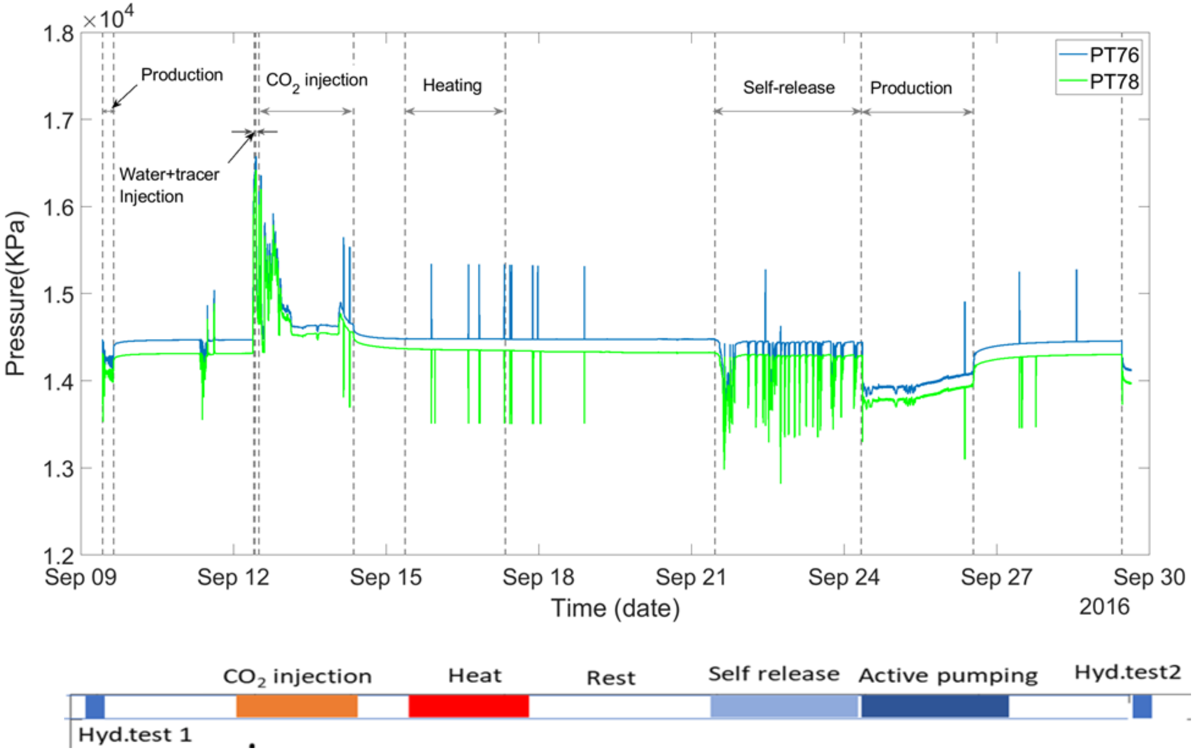
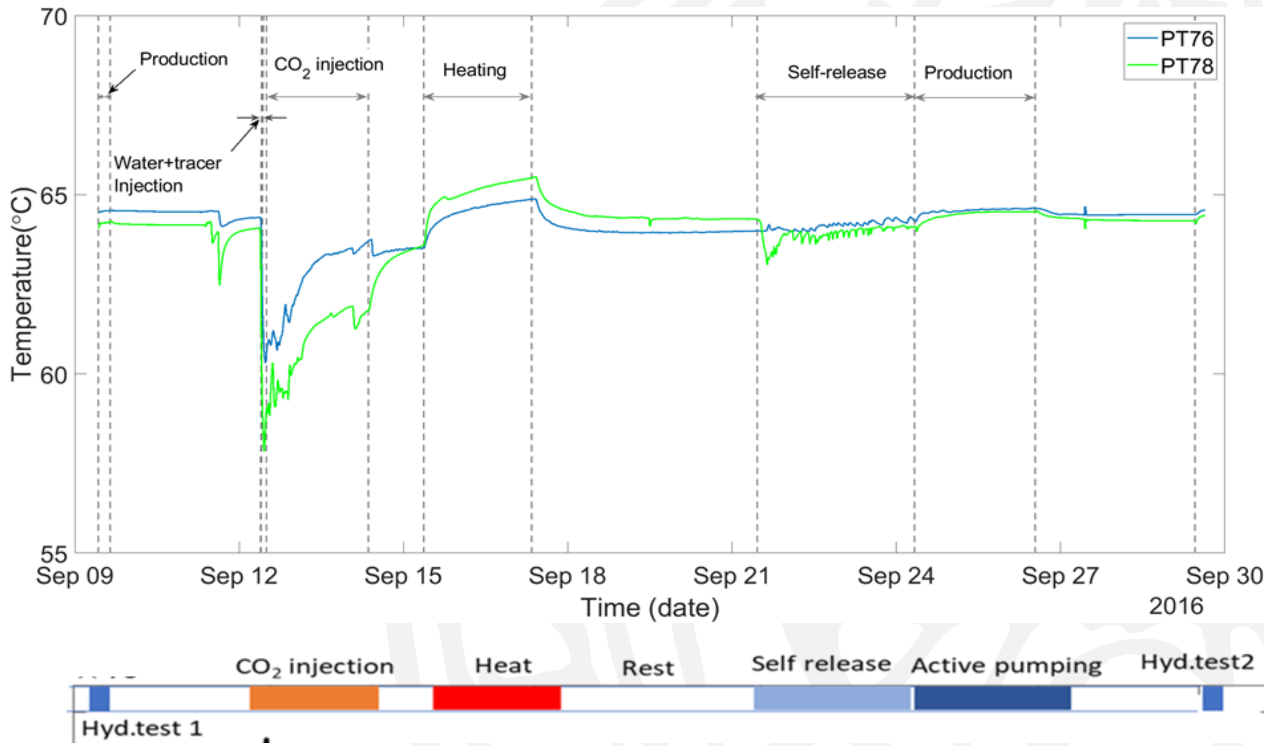
Residual Trapping Experiment I

Measured pressure and temperature RTE I

Pressure



Temperature



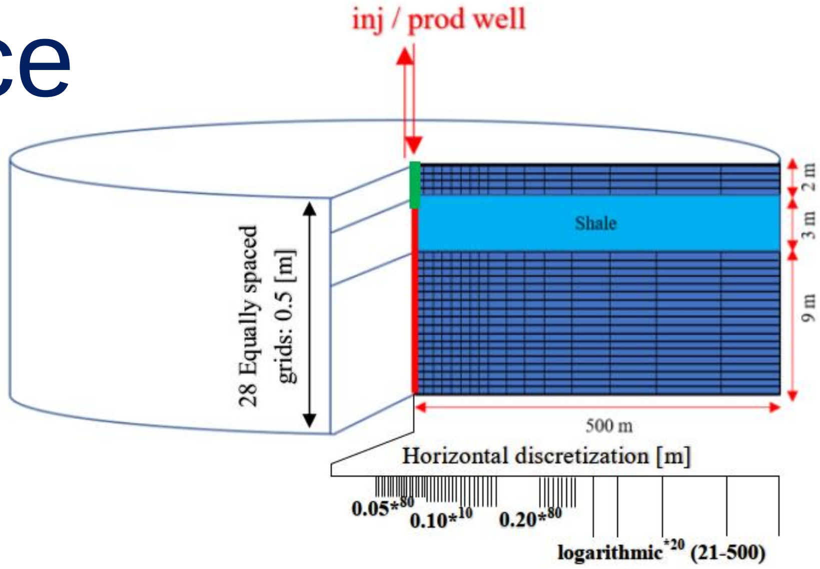
Niemi, et al (2020) IJGHGC. Vol (101). 103129

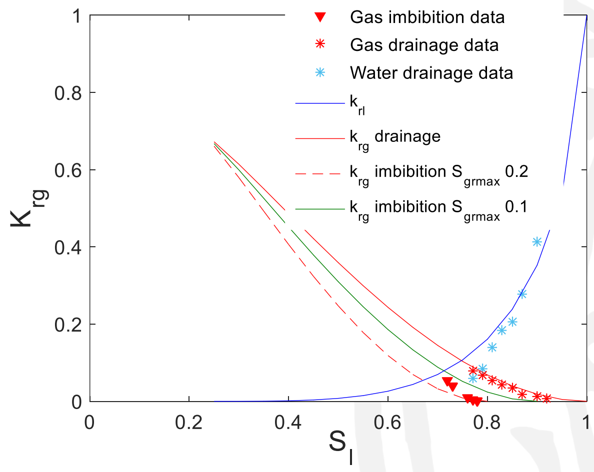
TOUGH2 simulation of the entire test sequence

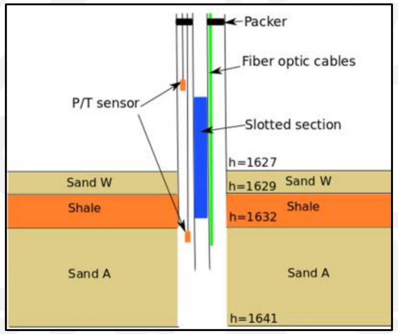
- vary permeability, porosity, characteristic two-phase functions (residual saturation) and thermal properties within the range of measured data

- good data constrains from site characterization program

- variability between
  the two layers?



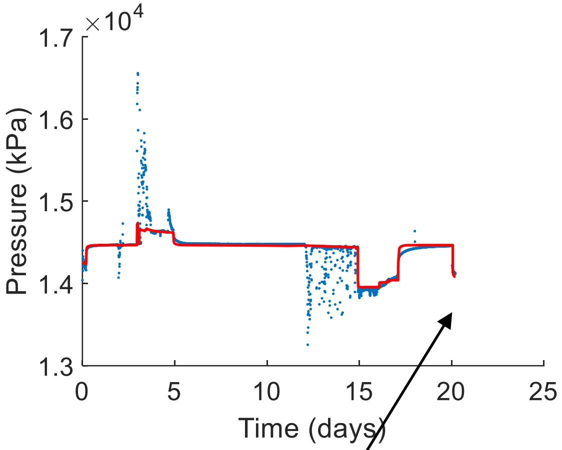


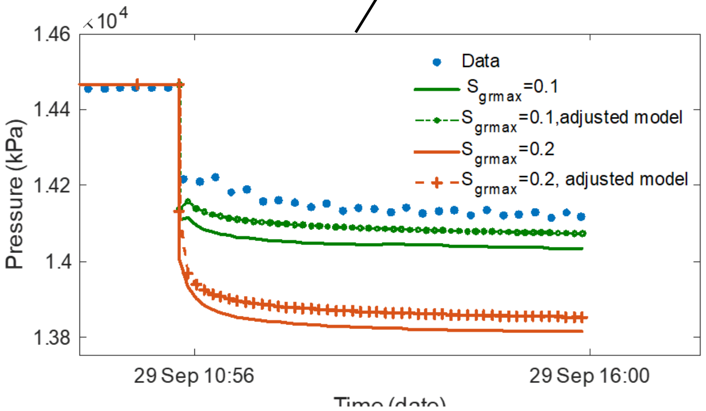


Joodaki, S. et al (2020). IJGHGC. Vol (97). 103058

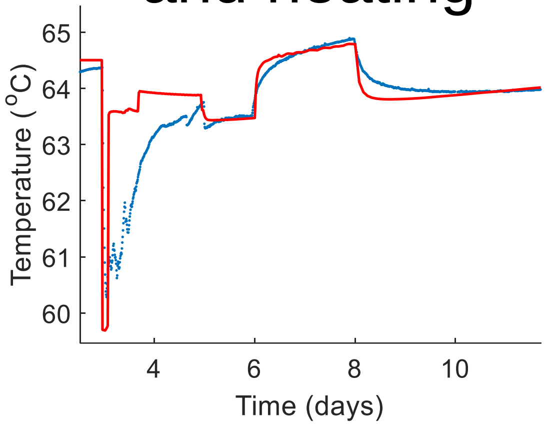
Model with best overall agreement

Pressure

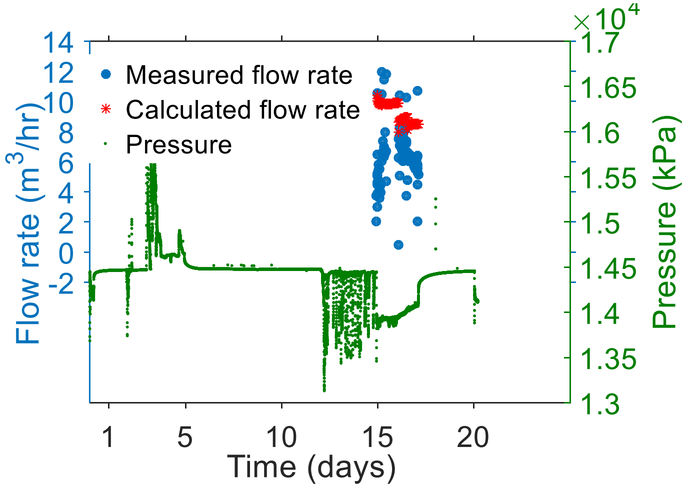




Temperature during injection and heating



Flow rate



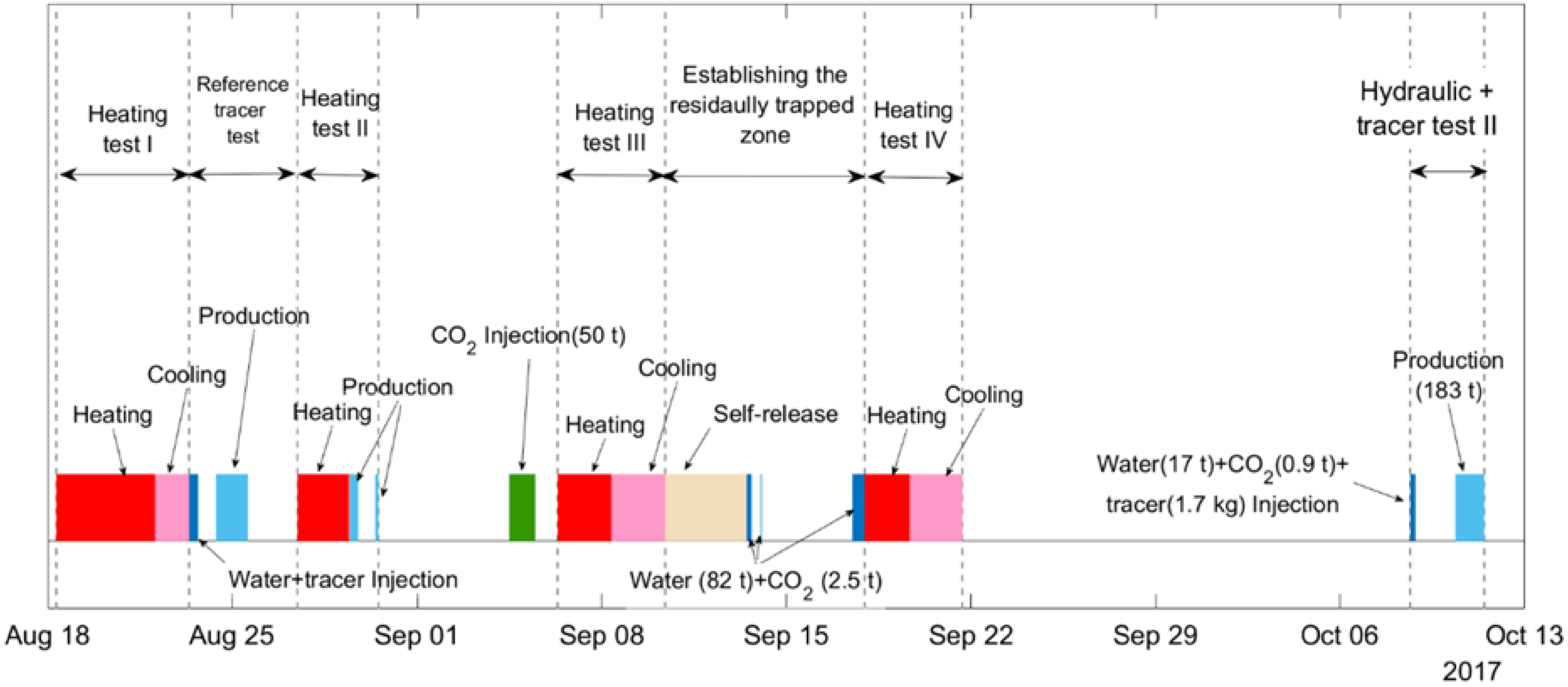
- Hysteretic relative permeability with residual trapping of 0.1,
- k=400 mD in both layers and
- reduced flow into the lower layer

Joodaki, S. et al (2020). IJGHGC. Vol (97). 103058

Conclusions from RTE I

- hydraulic test gave a good estimate of the overall residual gas saturation, clear difference in signal
- temperature data provided additional information about the gas distribution between the two reservoir layers
- model analysis suggested that most of the injected gas tended to enter the upper layer.
- estimated maximum residual gas saturation from the field experiment (S_{grmax}) was 0.1, lower than the core scale laboratory measurements of about 0.2

Residual Trapping Experiment II – Test Sequence (Aug – Oct 2017)



Niemi, et al (2020) IJGHGC. Vol (101). 103129

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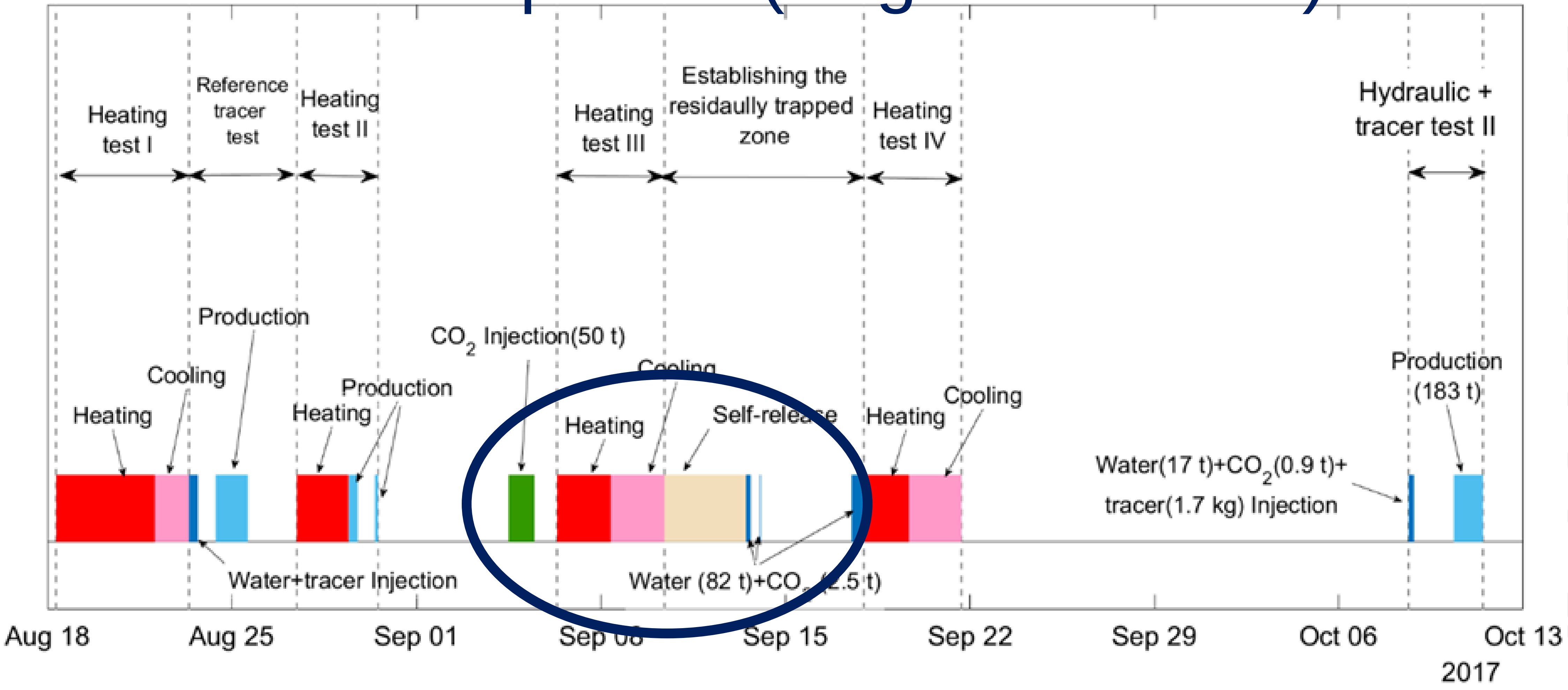

Niemi, et al (2020) IJGHGC. Vol (101). 103129

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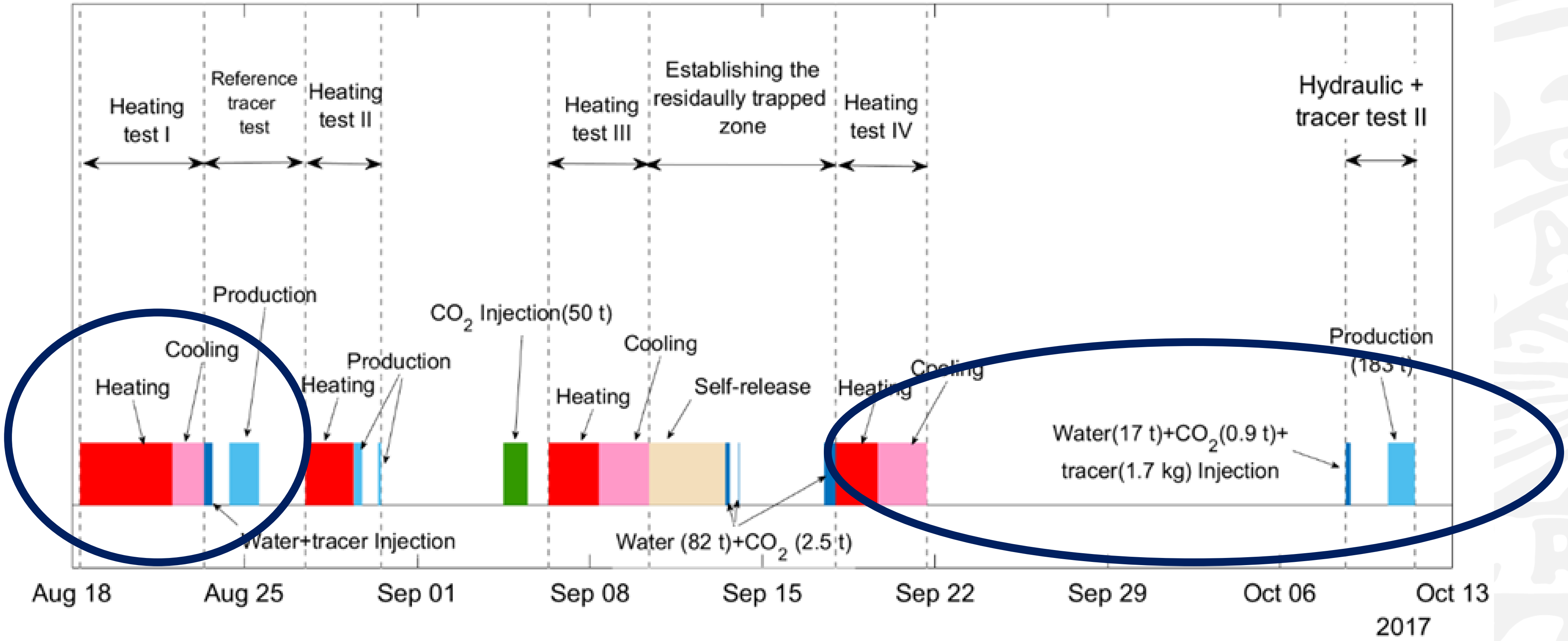

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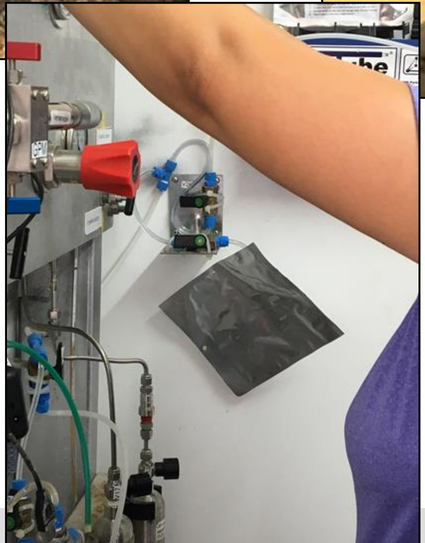

Tracer data analysis

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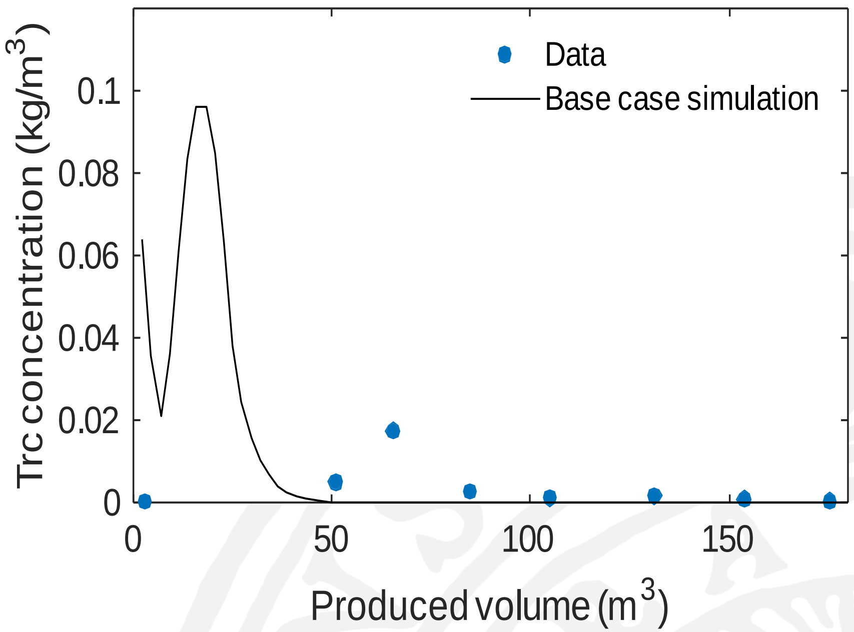
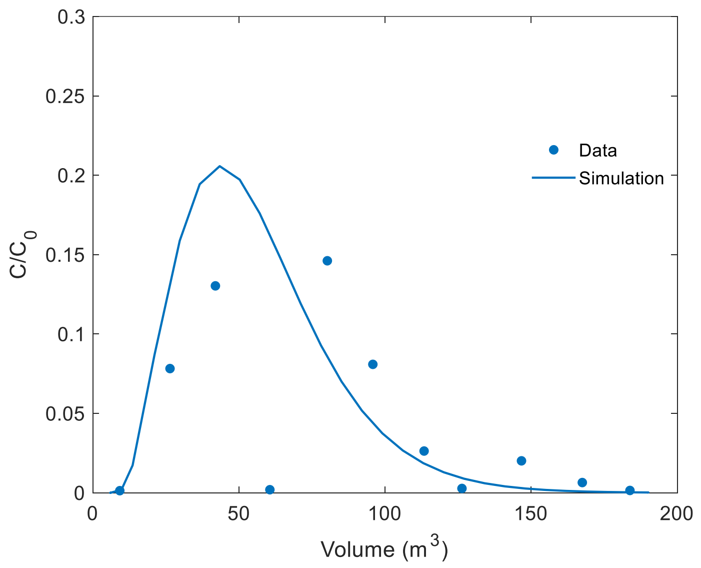
Residual tracer test



Reference tracer test



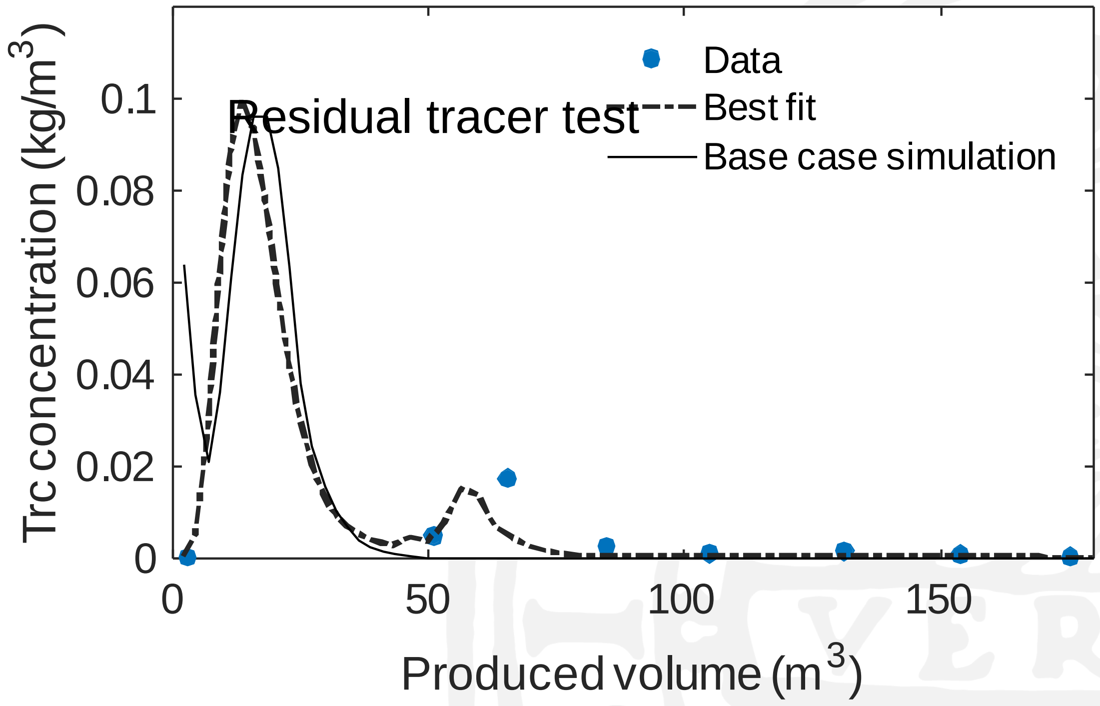
- Tracer arrival without CO2 in agreement with the previously calibrated model from RTE I

Joodaki, S. et al (2020) IJGHGC. Vol (101). 103134

- With residual CO2 in the system, the delayed peak was difficult to match
- Extensive set of simulations by varying formation parameters, partitioning coefficients, detailing the well structure and considering stochastic heterogeneity

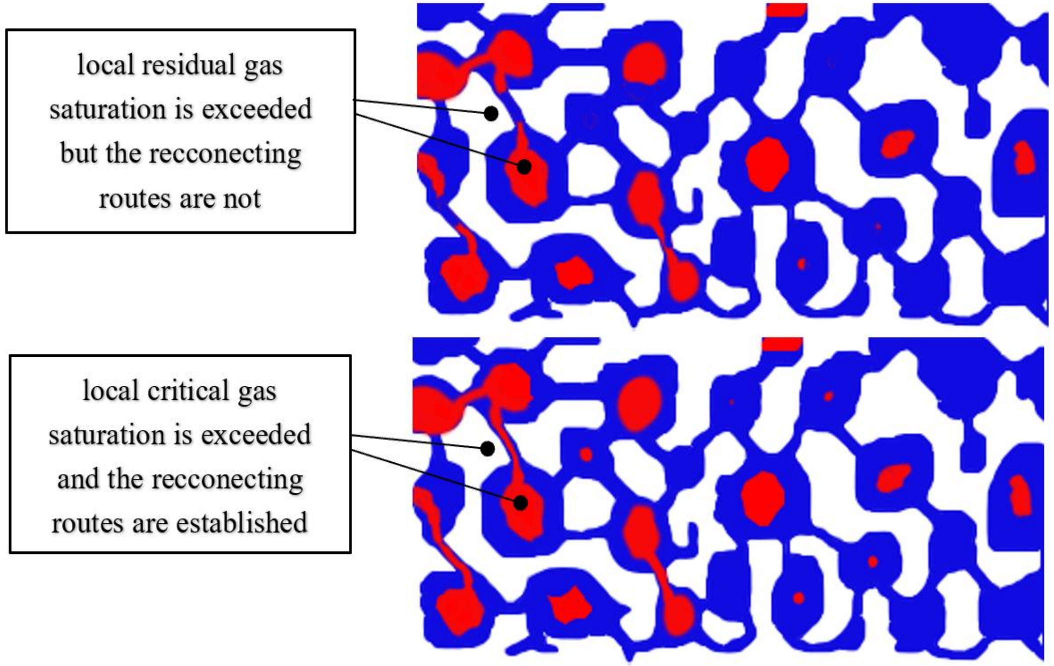
Tracer analysis – best agreement

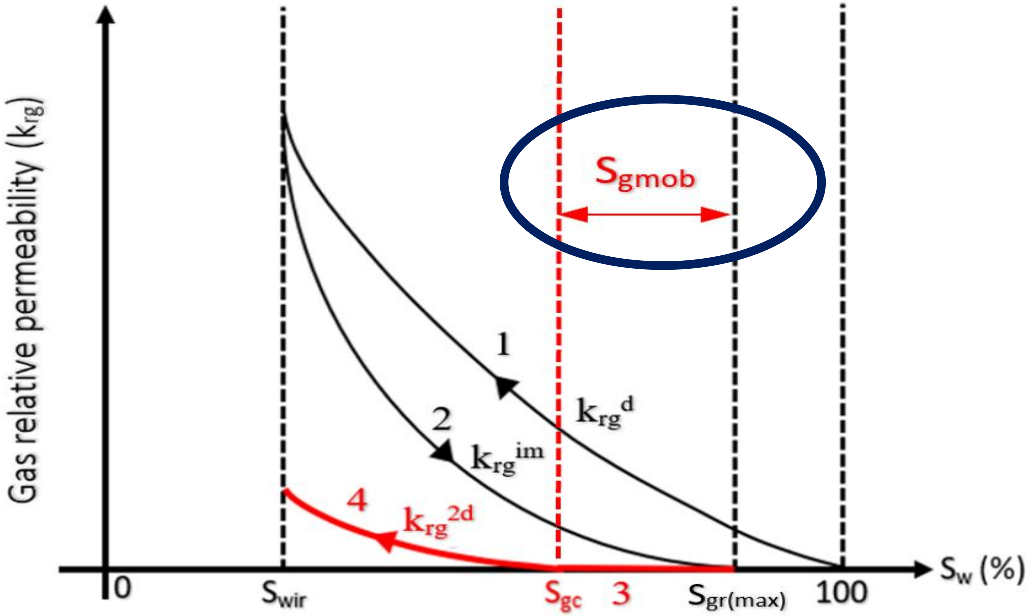
- Most of the CO_2 enters the upper reservoir
- Water and tracer enter into the top of the lower reservoir
- For the first five hours of fluid production, flow in the top of the lower sand is blocked



Joodaki, S. et al (2020) IJGHGC. Vol (101). 103134

Residual saturation and critical saturation



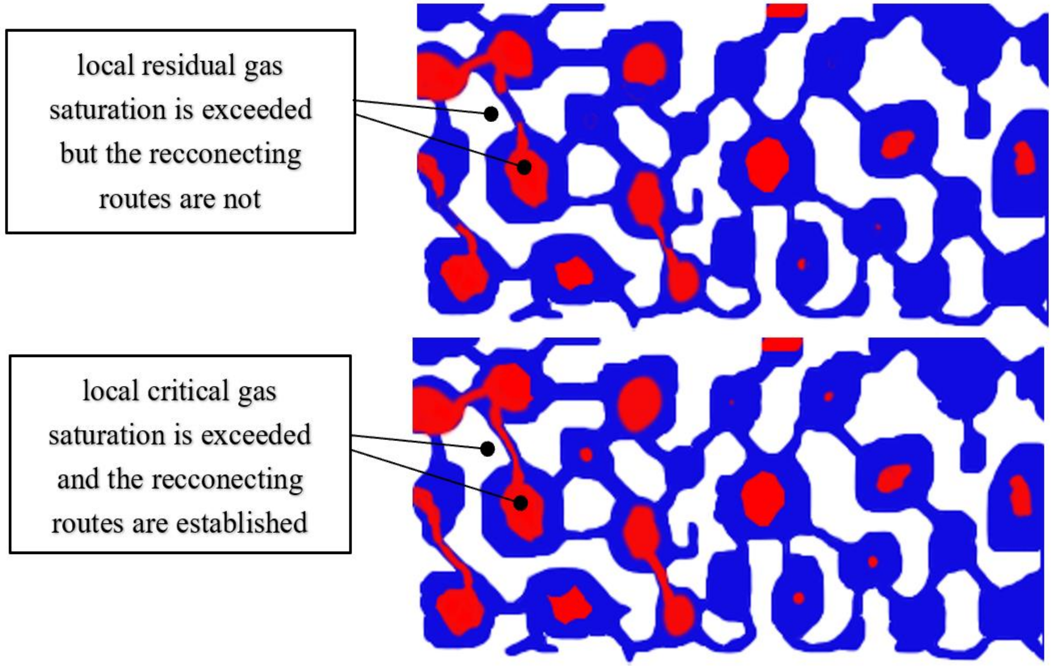


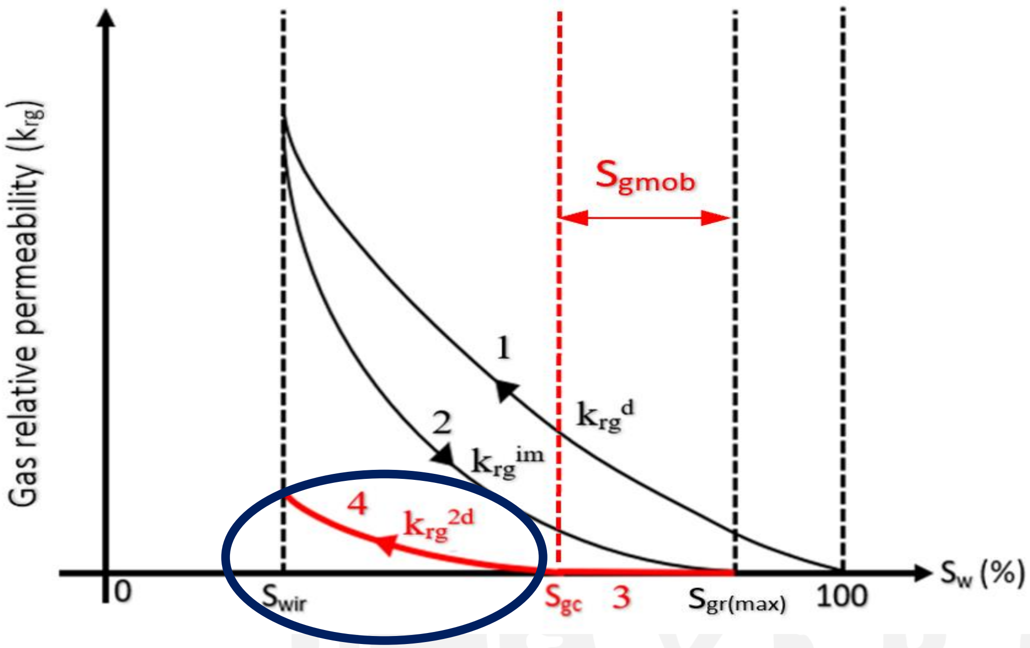
Upon secondary drainage due to exsolution, gas does not remobilize immediately but only when the gas phase is connected again

Relative permeability functions need to be adjusted to account for this

Moghadasi, R. et al (2022) IJGHGC.

Residual saturation and critical saturation





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Moghadasi, R. et al (2022) IJGHGC..

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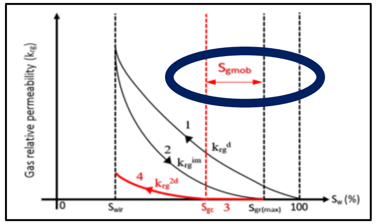
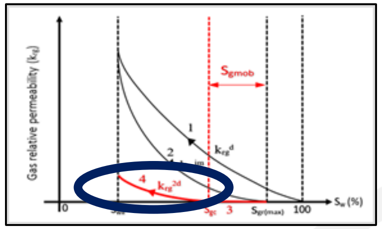
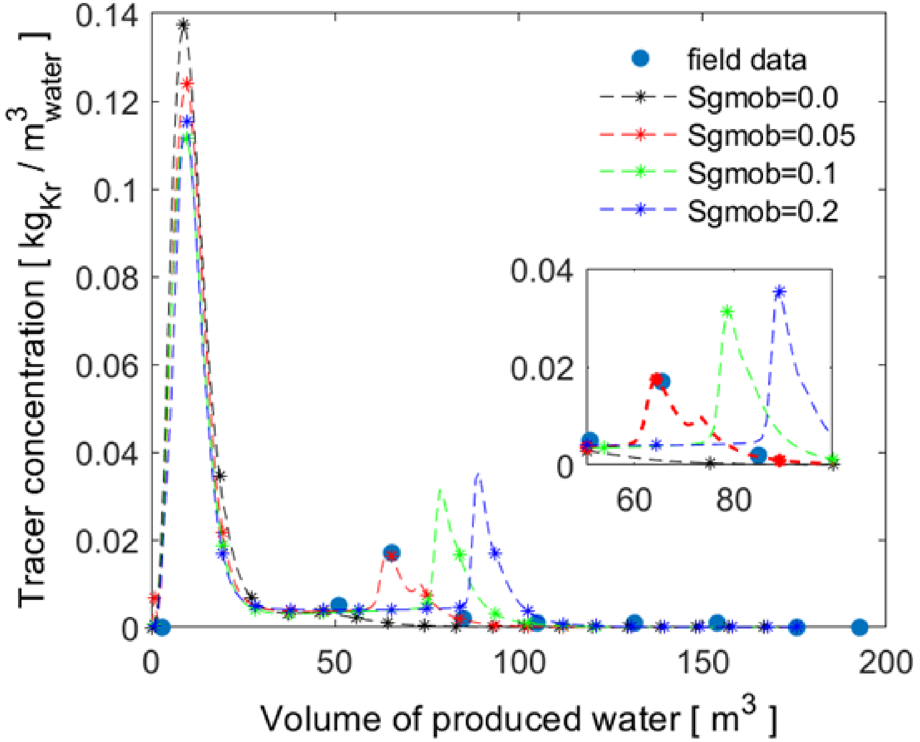
Tracer arrival when critical saturation included

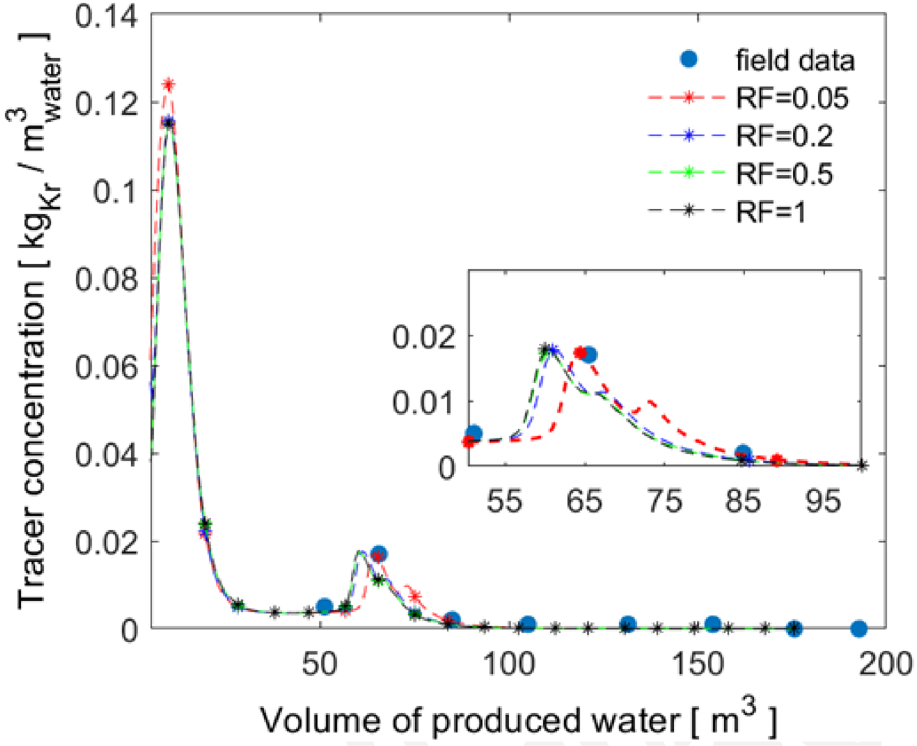




Effect of Smob



Effect of RF



Moghadasi, R. et al (2022) IJGHGC. Acc. with revision.

Conclusions and implications (1/3)

- Procedures and interpretations for determining residual gas saturation in situ have been presented
- The estimated residual gas saturation from the two field experiments was similar (S_{grmax}=0.1) and less than the laboratory value (S_{grmax}=0.2)
- Hydraulic tests give a clear signal concerning the overall effective residual saturation of the interval

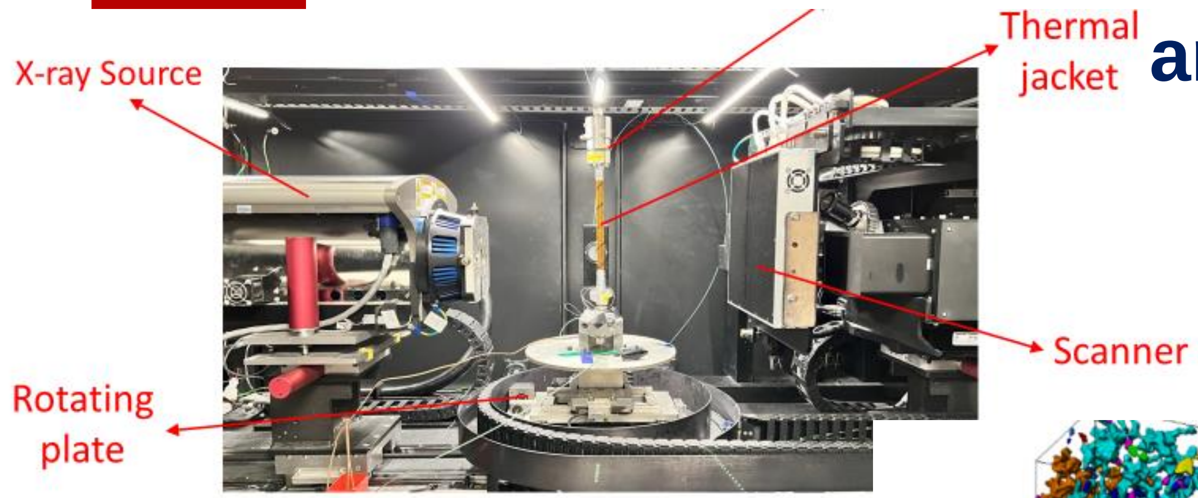
Conclusions and implications (2/3)

- Thermal tests give additional information about the gas distribution, as does monitoring of the pressure profile in the injection interval
- Partitioning tracer tests are more complicated to carry out and to interpret, but provide more detailed information on the gas distribution

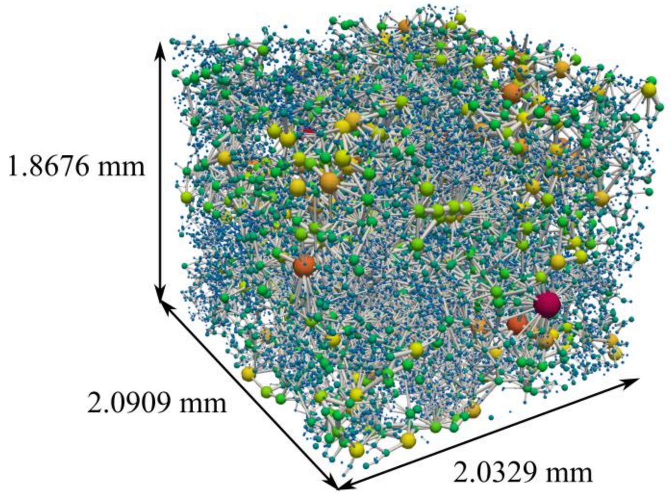
Conclusions and implications (3/3)

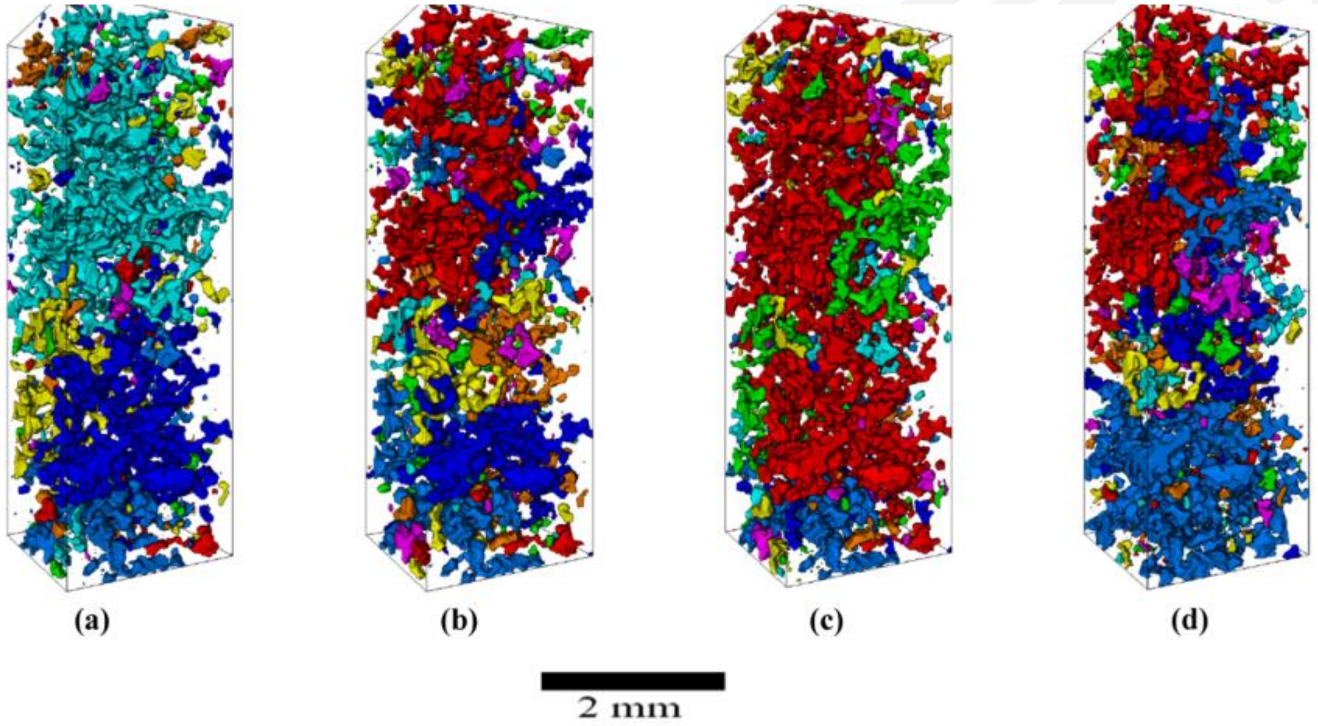
- The tracer results here required introducing the concept of critical saturation, a phenomenon relevant if gas saturation increases due to pressure decrease rather than injection
- Critical saturation is well studied in oil/gas industry but not considered in CCS
- Needs to be accounted for when modeling scenarios with unexpected pressure decrease due to leakage etc. and related gas exsolution and expansion

Results confirmed in pore scale analyses



Observing gas remobilization by high-resolution 3D X-ray microtomography



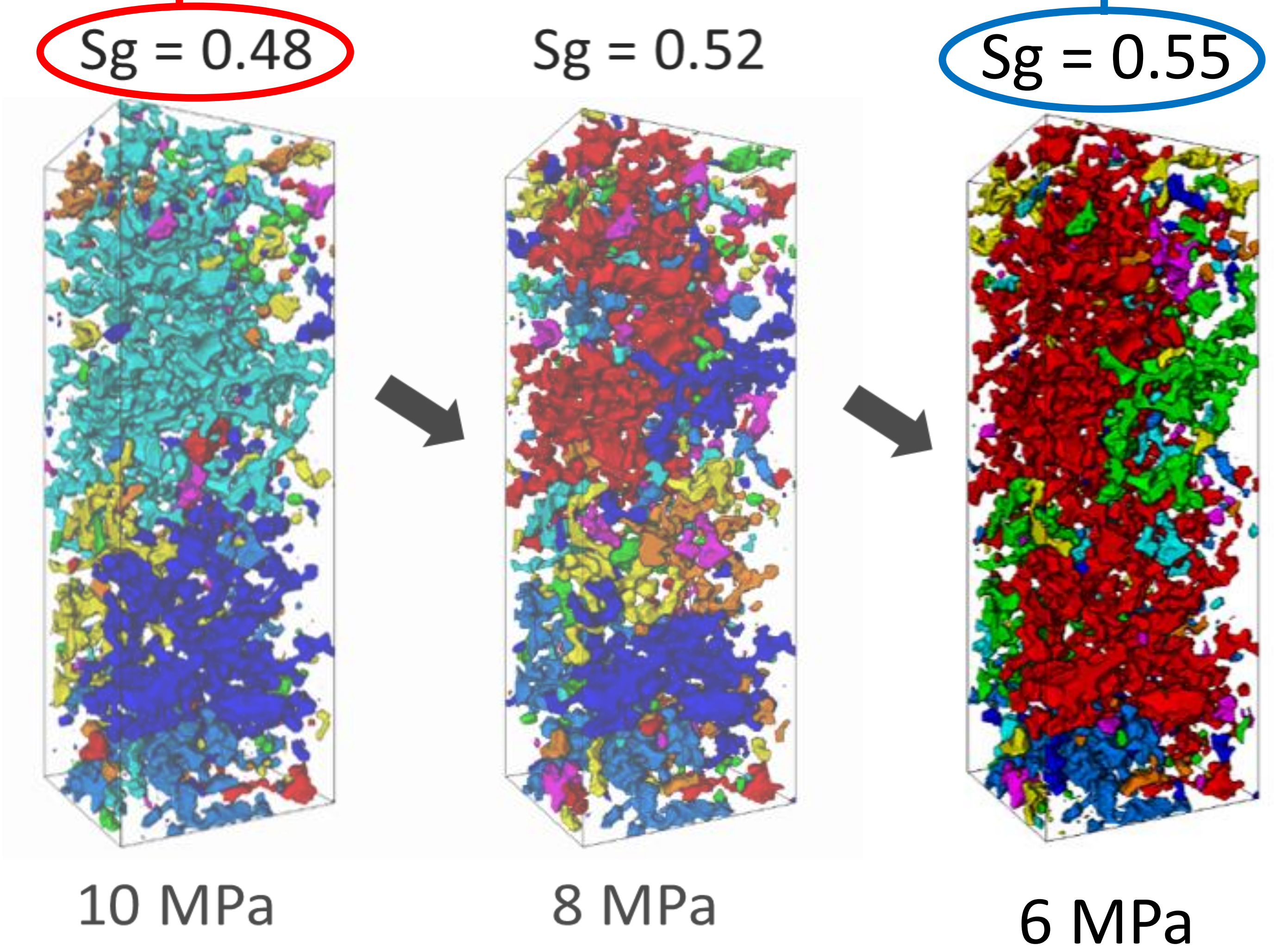


3D visualization of CO_2 in pore space
a) 10 MPa b) 6 MPa, c) 5MPa

Moghadasi, et al. (2023) Adv in Water Resources. 179, 104499

Moghadasi, et al. (2023) WRR. 59 (6)

Gas ganglia remobilization



S_{gr} = 0.48

S_{gc} = 0.55

The difference indicates
Sgmob = 0.06-0.07

Ongoing work

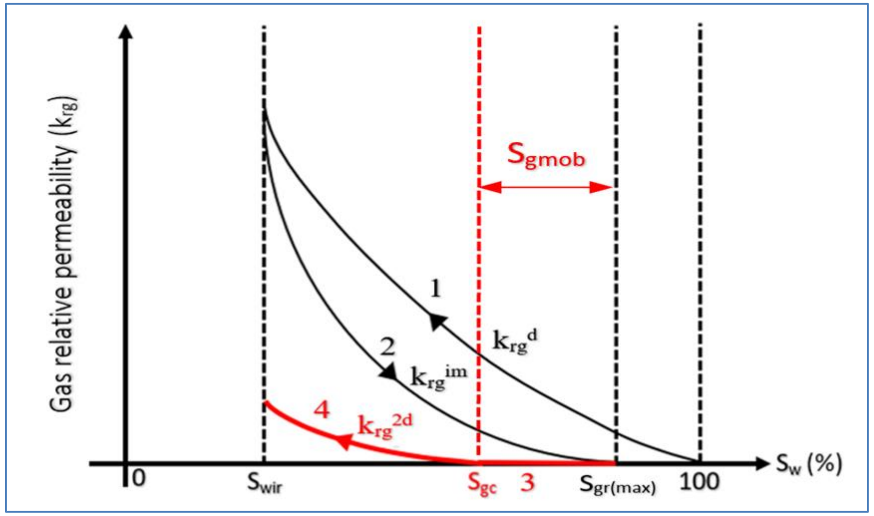
- With pore network modeling (calibrated against the experimental data) investigate how remobilization takes place in different types of rocks as well as the value of critical saturation in them

- Heletz, Bentheimer, Berea, samples S1…S9 from IC library

Critical saturation - Conclusions

- The delayed and slower remobilization is a safety enhancing phenomenon in CCS

- Needs to be accounted for when modeling scenarios with pressure decrease (due to leakage, pressure maintenance etc.)



Especially acknowledged co-workers

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Ramin Moghadasi, UU
Zhibing Yang, UU and Wuhan University, China
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Stanislav Levchenko,, EWRE
Fritjof Fagerlund, UU
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Sally Benson, Stanford University, USA
Ferdinand Hingerl, Stanford University
Tian Liang, UU
Byeonju Jong, UU

Rona Ronen, EWRE
Yoni Goren, EWRE
Igal Tsarfis, EWRE
Alon Shklarnik, EWRE
Jawad Hassan, Univeristy of Ramallah, Palestine
Philippe Gouze, CNRS, France
Barry Freifeld, Class VI Solutions and LBNL, USA
Kristina Rasmusson, UU
Maria Rasmusson, UU
Lehua Pan, LBNL, USA
Alexandru Tatomir, Göttingen University, Germany
Martin Blunt, Imperial College, UK
Steven McDougall, Heriot-Watt Univ., Scotland
TRUST and Mustang partners

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Thank you for your attention!

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Key references

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Site Charactetization

Special Edition in International Journal of Greenhouse Gas Control, (2016) 'Characterization of formation properties for geological storage of CO2 - Experiences from the Heletz test injection site and other example sites from the EU project MUSTANG' Edited by Auli Niemi, Philippe Gouze, Jacob Bensabat Volume 48, Part 1, Pages 1-186 (May 2016)

Injection experiments

Special Section in *International Journal of Greenhouse Gas Control, (2021)*
Niemi, et al. (Eds) (2021) 'CO2 residual trapping experiments at Heletz, Israel pilot injection site' Special section in *International Journal of Greenhouse Gas Control*
https://www.sciencedirect.com/journal/international-journal-of-greenhouse-gas-control/special-issue/10HLVB906S1

Niemi, A., Bensabat, J., Joodaki, S., et al. (2020) Characterizing CO_2 residual trapping in-situ by means of single-well push-pull experiments at Heletz, Israel, pilot injection site – experimental procedures and results of the experiments. *International Journal of Greenhouse Gas Control,* Vol (101).

Joodaki, S., Yang, Z., Bensabat, J., Niemi, A. (2020) Model analysis of CO_2 residual trapping from single-well push pull test based on hydraulic withdrawal tests – Heletz, residual trapping experiment I. *International Journal of Greenhouse Gas Control,* Vol (97).

Joodaki, S., Moghadasi, R., Basirat, F., Yang, Z., Bensabat, J., Niemi, A. (2021) Model analysis of CO_2 residual trapping from single-well push pull test based on hydraulic withdrawal tests – Heletz, residual trapping experiment I. *International Journal of Greenhouse Gas Control,* Vol (101) 103134

Critical saturation

Moghadasi, R., Basirat, F., Bensabat J., Doughty , C. and Niemi, A. (2022) Role of critical gas saturation in the interpretation of a field scale CO_2 injection experiment. *International Journal of Greenhouse Gas Control. Vol 115. 103624. https://doi.org/10.1016/j.ijggc.2022.103624*

Moghadasi, R., Basirat, F., Foroughi, S., McDougall, S., Bijeljic, B., Blunt, M.J., Tatomir, A., Niemi, A. (2023)
Pore-scale determination of residual gas remobilization and critical saturation in geological CO2 storage: a pore-network modelling approach. *Water Resources Research*. 59
2023.

Moghadasi, R., Goodarzi S., Zhang, Y., Branko Bijeljic, B., Blunt, M.J. Niemi, A (2023)
Pore-scale characterization of residual gas remobilization in CO2 geological storage. Advances in Water Resources. 179, 104499.