Progress of the Heletz pilot injection project - workshop on pilot sites

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CO_2QUEST

CO2GeoNet 11th Venice Open Forum,
Venice 9-11 May, 2016

Outline

- Project outline, objectives and present status were presented in yesteraday's session, now focus on some specific topics:

- Some more about the site characterization

  > use of old and new data

- Instrumentation
- An example finding related to test design

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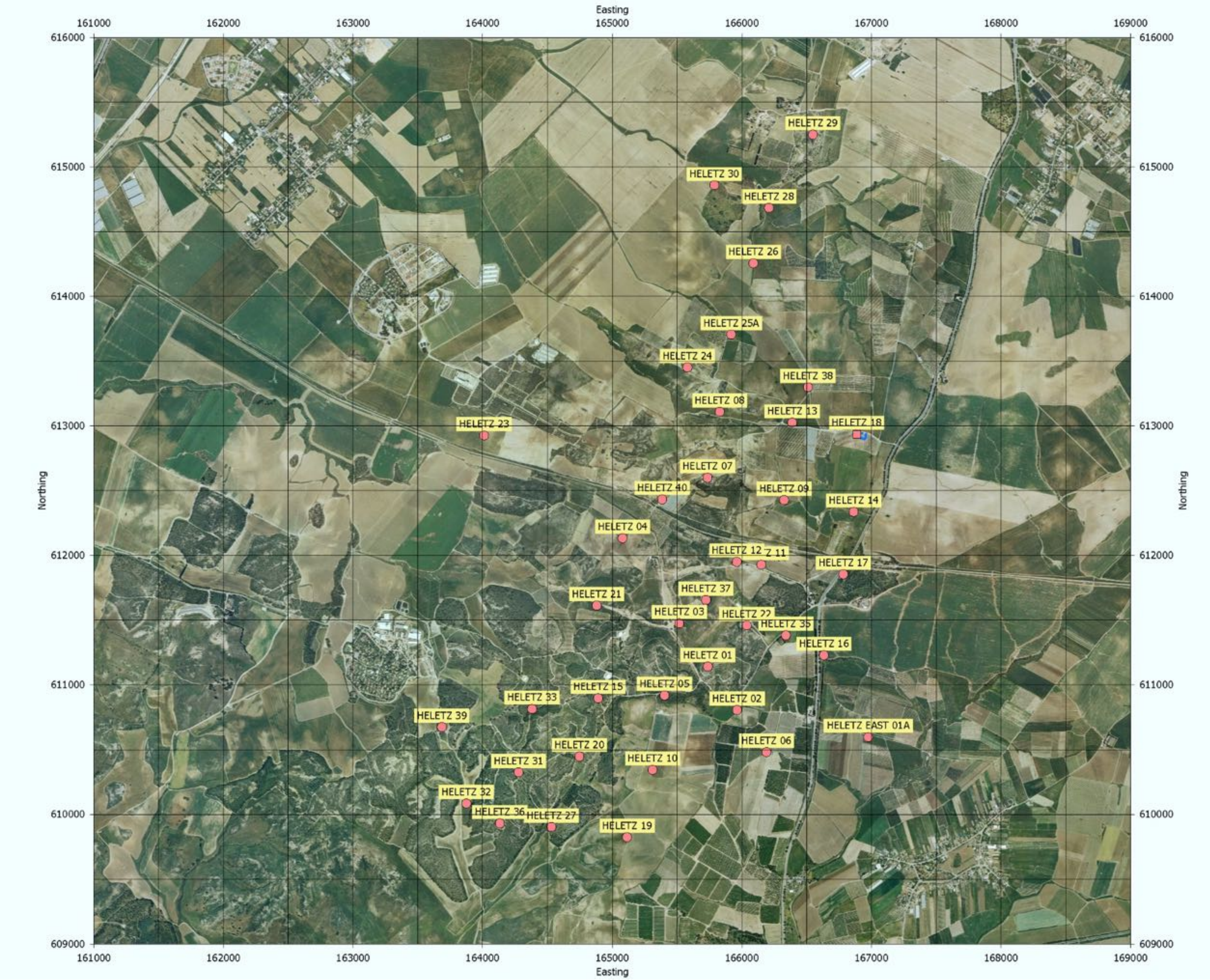

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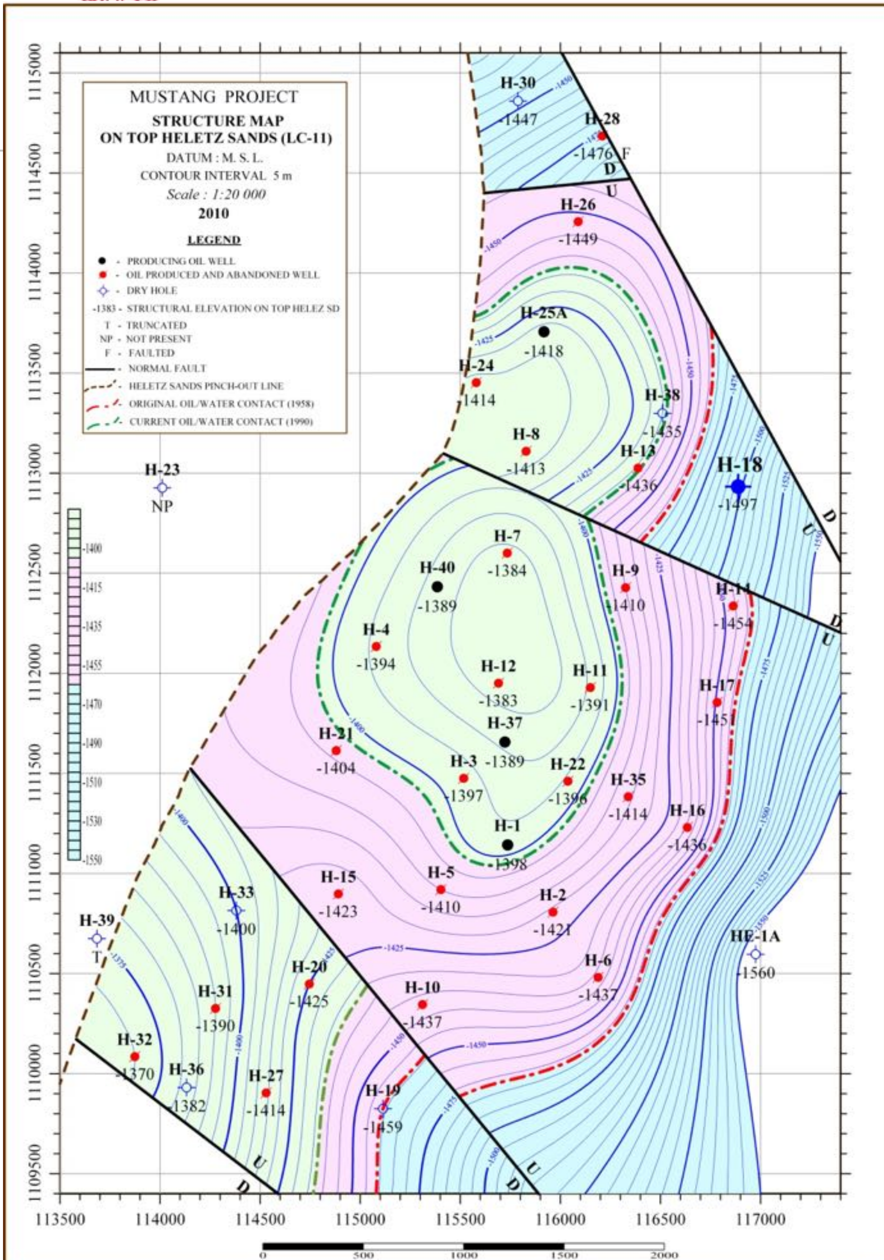
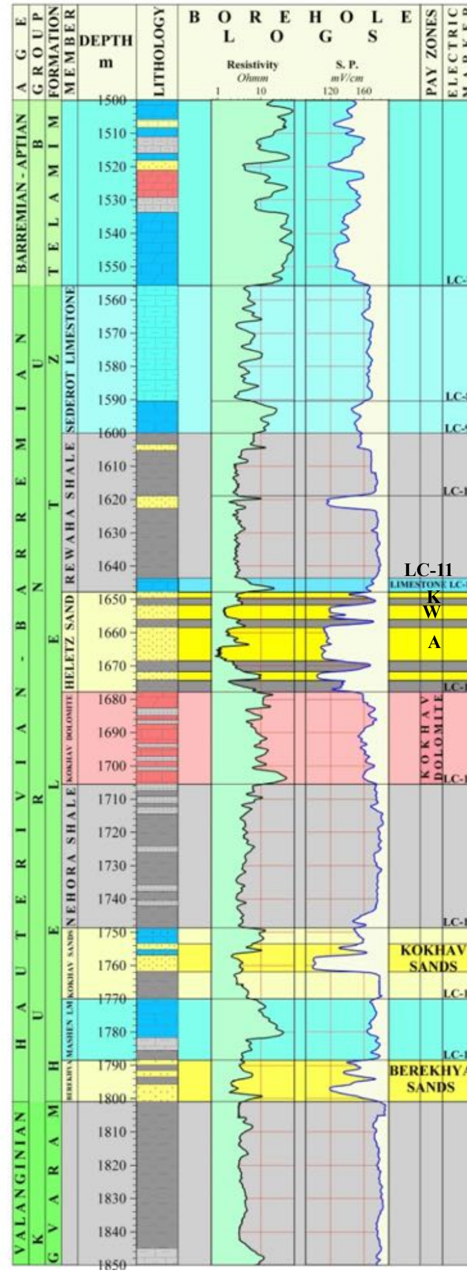
- The Heletz site was intensively explored for oil deposits, with over 50 wells drilled over a relatively small area (~9 km^2) and therefore with good geological information.
- The reservoir (the “K”,”W” and “A” sand layers) has a cumulative thickness of up to 20 m.
- There is an impervious layer (composed of clay) with a thickness of ~50 meters above the reservoir.
- Lapidoth has a concession on site so the permit process is limited to the permit to inject CO_2.

HELETZ RESERVOIR STRUCTURE





Cap rock (shales & marls)

Limestone layer (LC-11)

Three sand reservoir layers (K, W & A)

BUILDING 3D GEOLOGICAL MODEL

- Identifying the target reservoir layers ('K', 'W', 'A' and LC-11) and the cap rock
- Establishing layers' boundaries on all relevant logs
- Correlating between adjacent wells to check the results

Structural model

→ **Building structure and isopach maps for the reservoir and cap rock layers**

→ **Building geological cross-sections**

- Estimating porosity of the layers from various logs:
  - applying Archie law to electrical logs in water wells;
  - correcting the results for oil wells (based on estimated oil/water saturation);
  - computing porosity from acoustic logs (if available);
  - correlating with core analysis (if available).
- Correlating with adjacent wells to check the results
- Correcting the results of the previous steps
- Establishing permeability - porosity relationship using core data
- Estimating permeability of the reservoir layers

Physical parameters

→ **Building porosity and permeability maps**

→ **Building pressure and salinity maps**

Shtivelman et al; Mustang deliverable D2.2-4

STRUCTURAL MODEL & PETROPHYSICAL PARAMETERS

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Input – data from ~ 40 wells

- Geophysical well logs
- Cores and small cuttings
- Well testing
- Laboratory analysis

Output – set of digital files (tables) and graphic images (maps and cross-sections)

- Structural model
- Petrophysical parameters

STRUCTURAL MODEL

Structure maps

- Top of cap rock
- Top of sand reservoir
- Bottom of sand reservoir

Isopach maps

- Sand layers (‘K’, ‘W’ and ‘A’)
- Sand reservoir thickness (‘K’ + ‘W’ + ‘A’)
- Limestone layer (LC-11)
- Net reservoir thickness (LC-11 + ‘K’ + ‘W’ + ‘A’)
- Total reservoir thickness (top to bottom)
- Cap rock thickness

Oil-water contact map

Geological cross-sections

PETROPHYSICAL PARAMETERS

Porosity

- 3 sand layers (‘K’, ‘W’ and ‘A’)
- Average reservoir porosity (‘K’ + ‘W’ + ‘A’)
- Limestone layer (LC-11)

Permeability

- 3 sand layers (‘K’, ‘W’ and ‘A’)
- Average reservoir permeability (‘K’ + ‘W’ + ‘A’)

Pressure

Salinity

Shtivelman et al; Mustang deliverable D2.2-2.4

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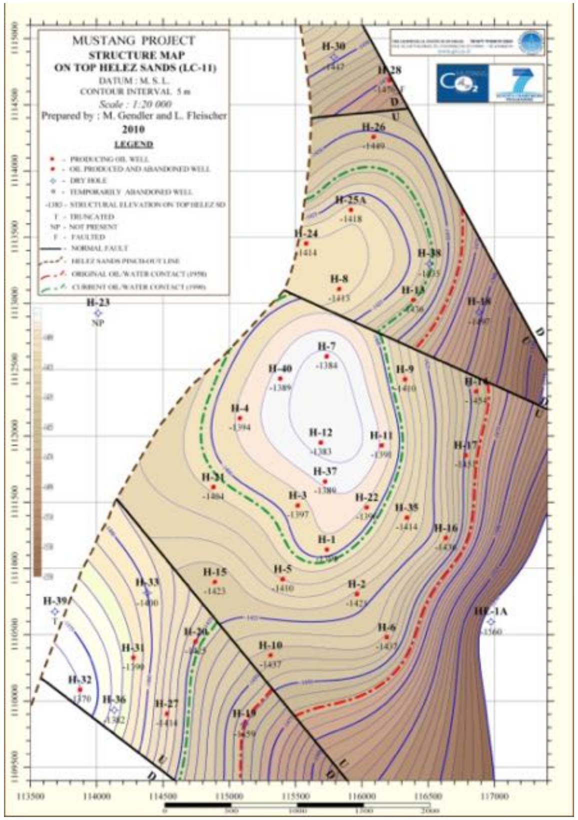
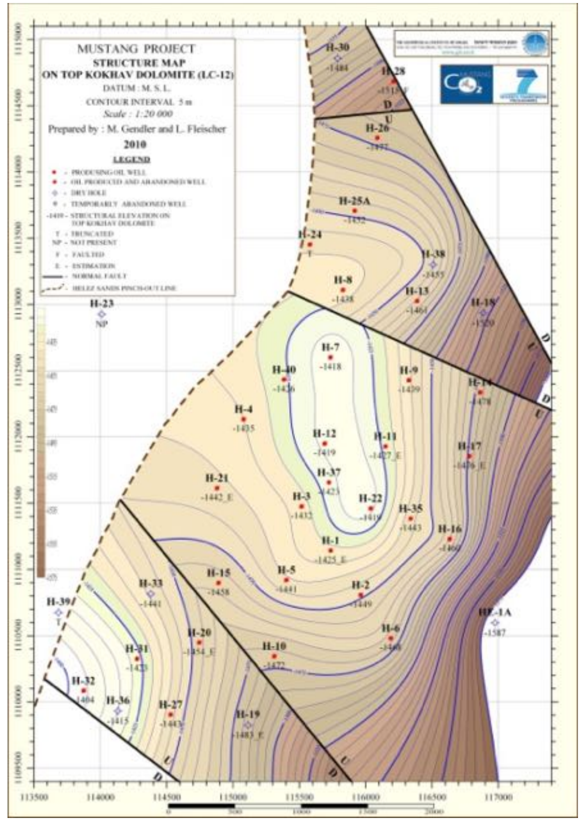
STRUCTURE MAPS OF SAND RESERVOIR

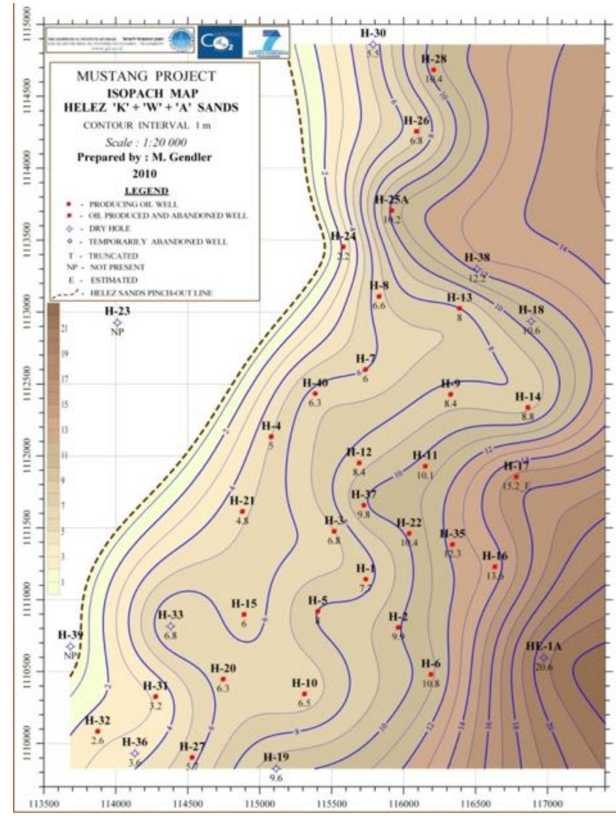
TOP OF SANDS (1370 – 1560 m)



BOTTOM OF SANDS (1400 – 1590 m)



THE TOTAL SANDS THICKNESS (0 – 21 m)



STRUCTURE MAPS OF CAP ROCK

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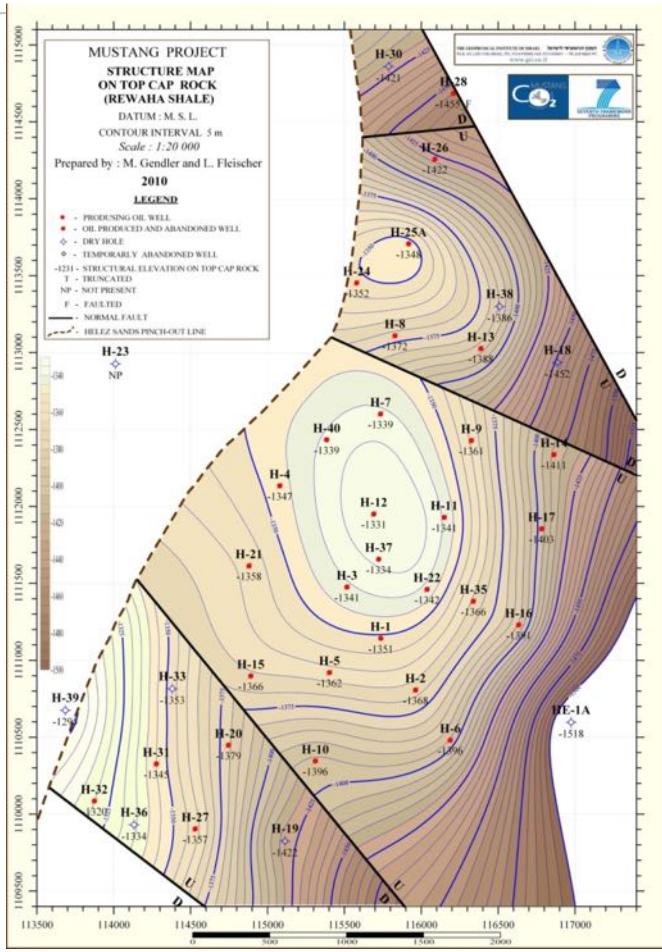
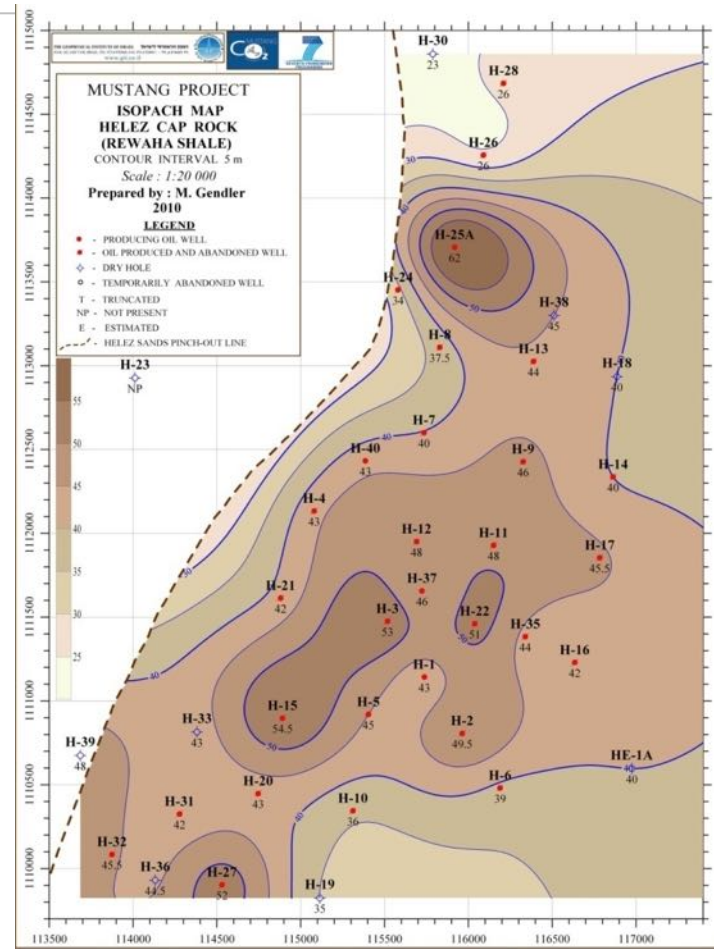
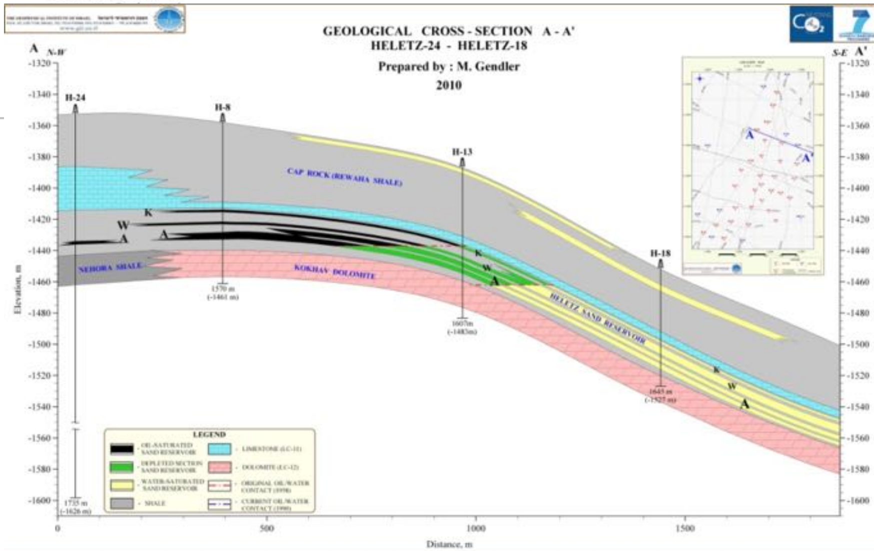
TOP CAP ROCK (1300 – 1520 m)

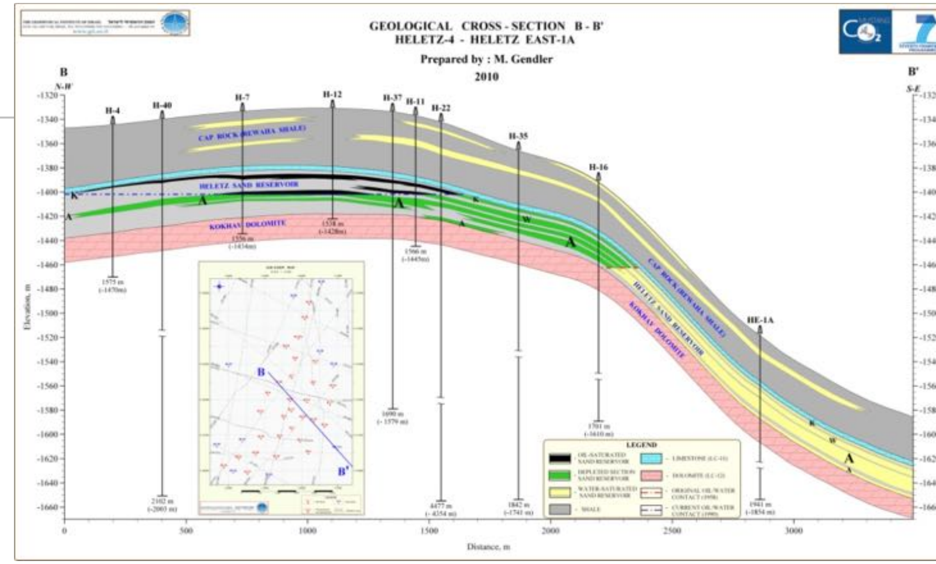


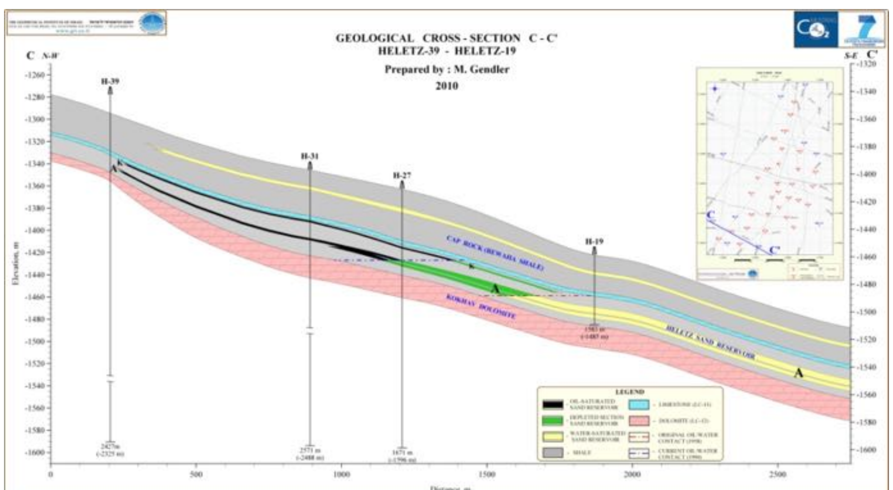
CAP ROCK THICKNESS (23 – 62 m)

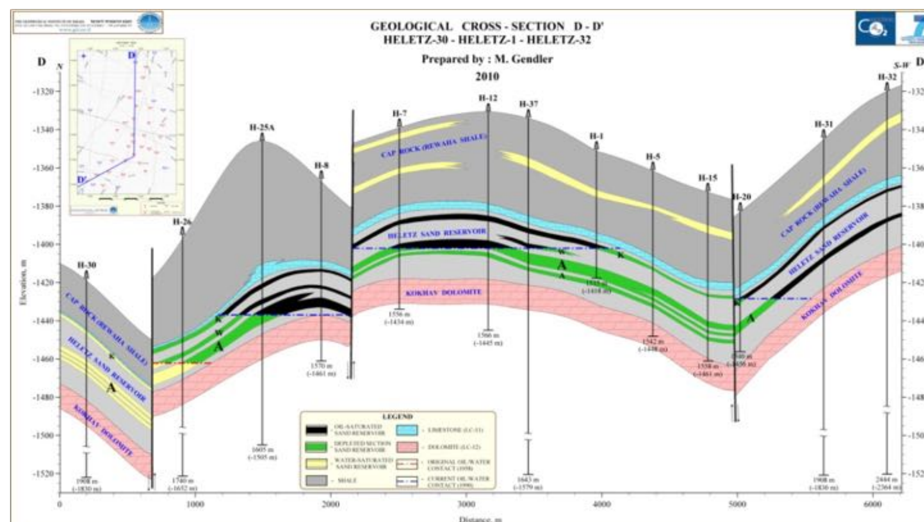


GEOLOGICAL CROSS-SECTIONS



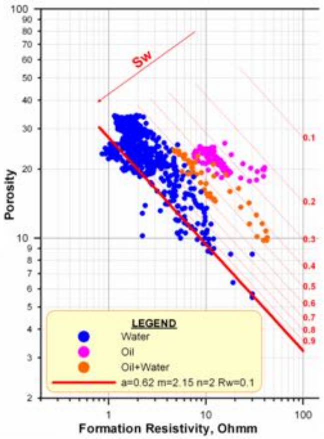






POROSITY & PERMEABILITY OF RESERVOIR LAYERS

ESTIMATING POROSITY FROM RESISTIVITY LOGS IN WATER & OIL WELLS



Archie law

$R_t / R_w = a / \phi^m$

R_t - formation resistivity
R_w - water resistivity
ϕ - porosity

For water wells

$\phi = (aR_w / R_t)^{1/m}$

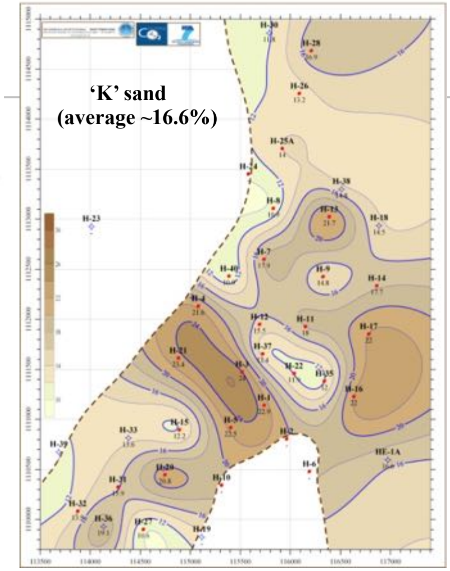
a = 0.62, m = 2.15

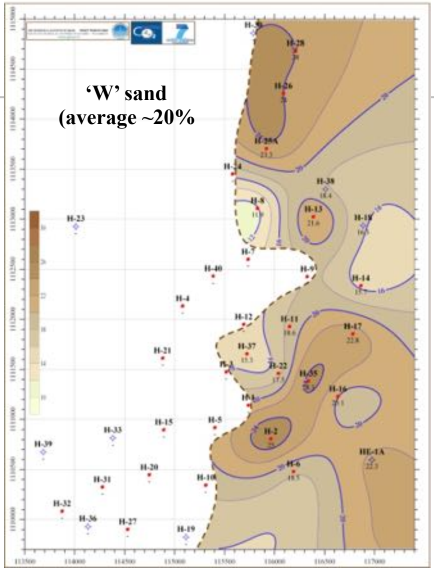
For oil wells

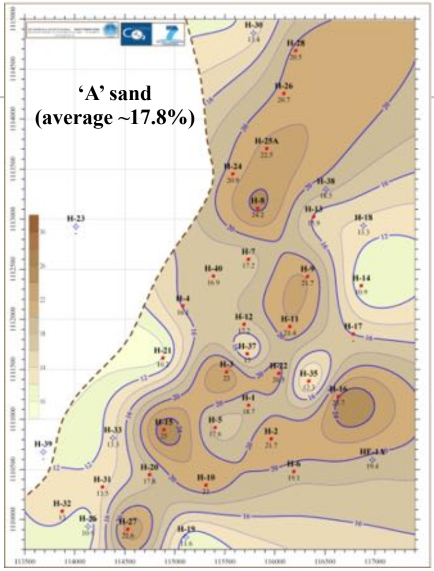
$\phi = (aR_w / R_t S_w^n)^{1/m}$

S_w - water saturation
S_w = 0.37, n = 2

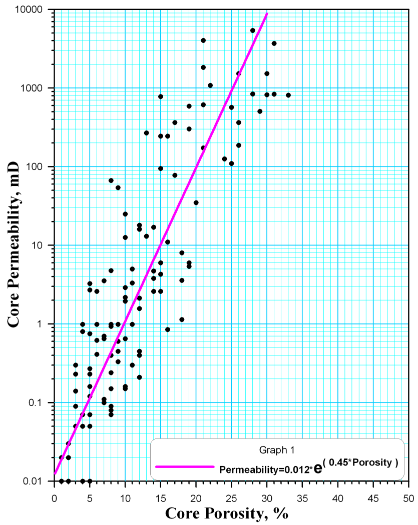
POROSITY MAPS



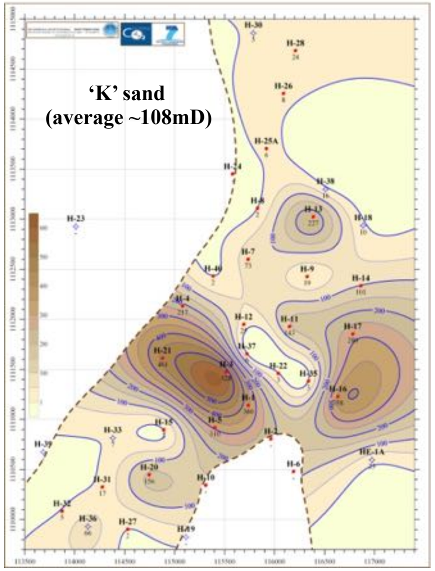


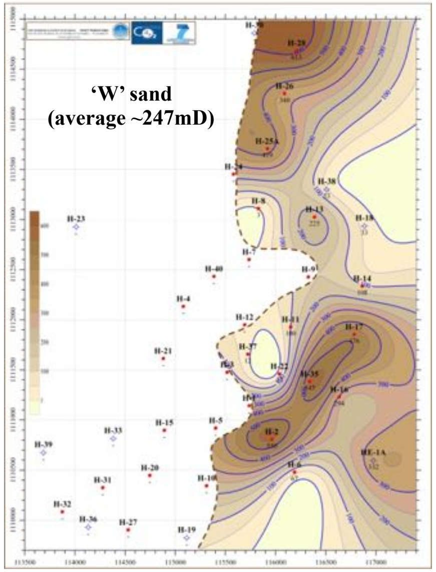


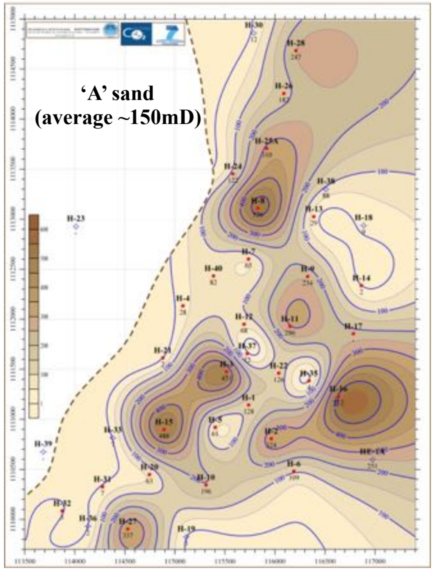
PERMEABILITY – POROSITY RELATIONSHIP



PERMEABILITY MAPS







PRESSURE & SALINITY IN RESERVOIR LAYERS

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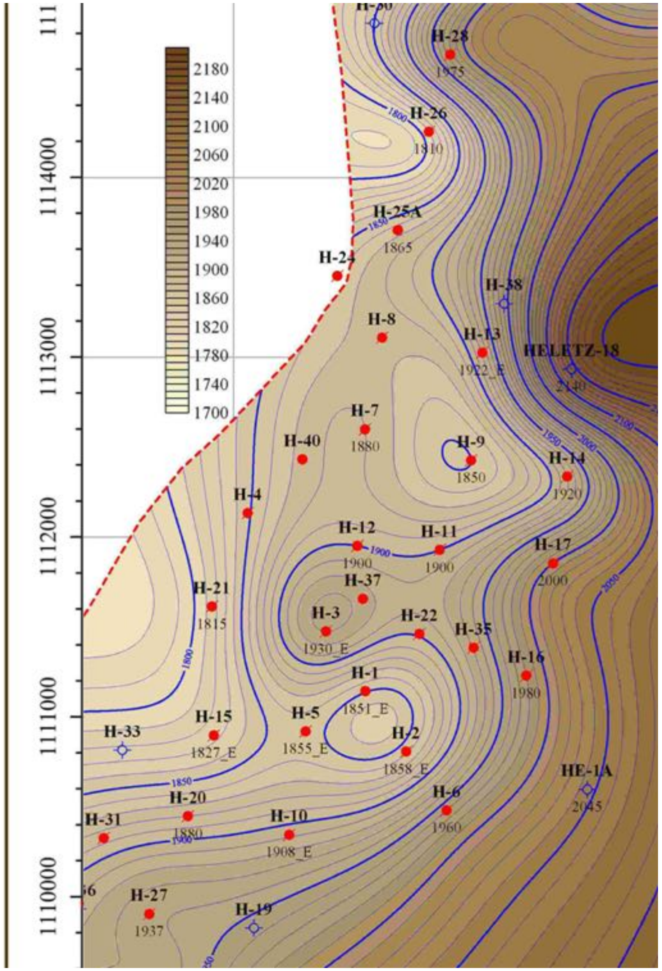
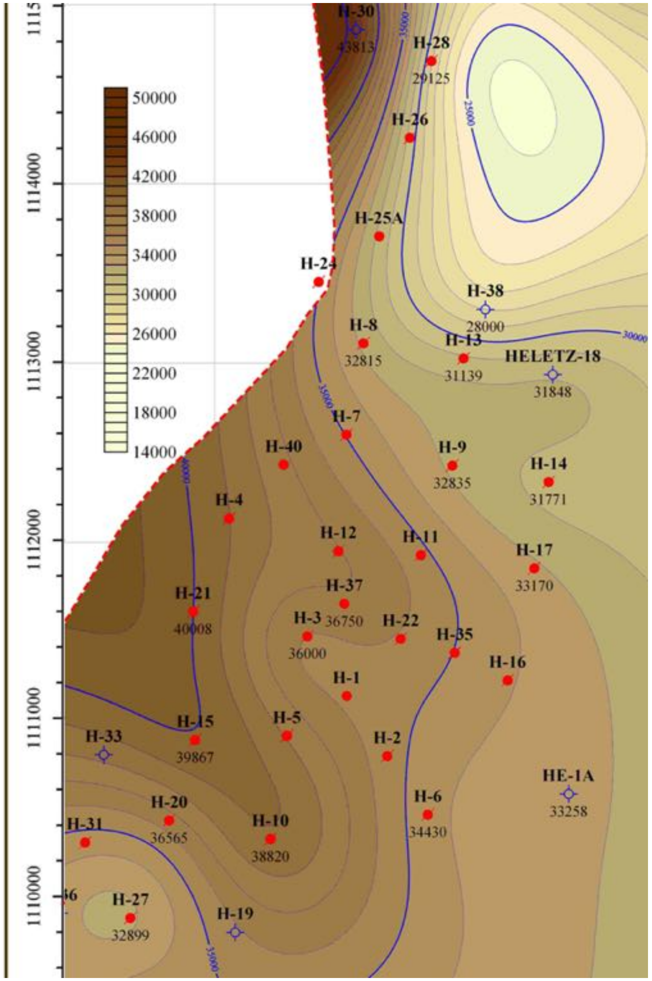
FINAL SHUT-IN PRESSURE (1800 – 2200 psi)



TDS (25000 – 44000 mg/l)



Original plan was to open old wells H18 and/or H38

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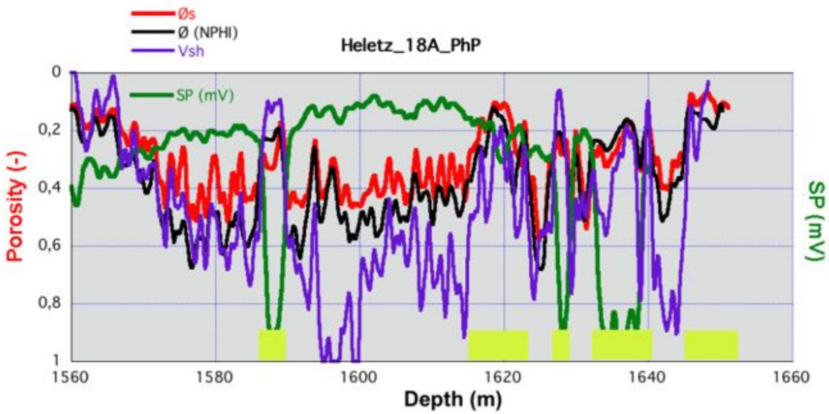
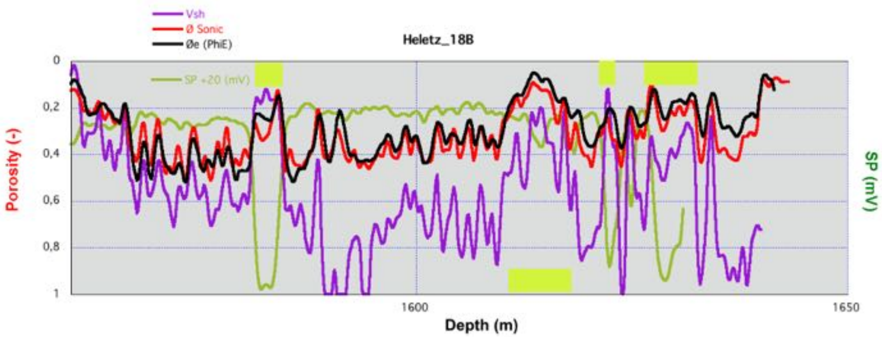
Finally, two new wells were drilled in the vicinity of H18 (H18A and H18B)

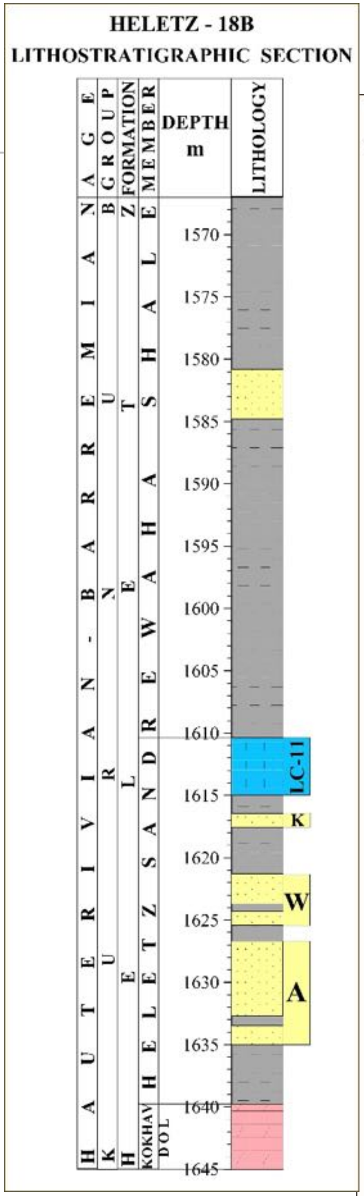
Heletz site – Caprock and Target layers

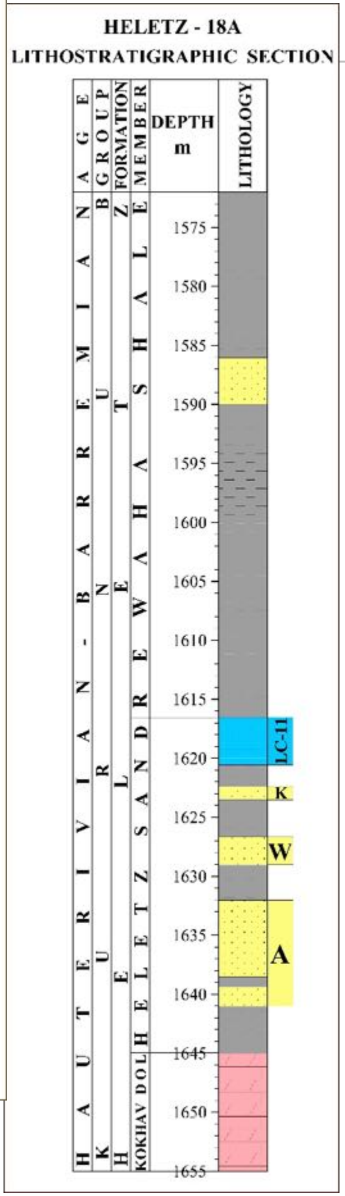


Heletz 18A (Pezard, 2012)



Heletz 18B (Pezard, 2012)





Shtivelman et al, GII, 2012

Seismic baseline
SOURCE & RECEIVER LAYOUT

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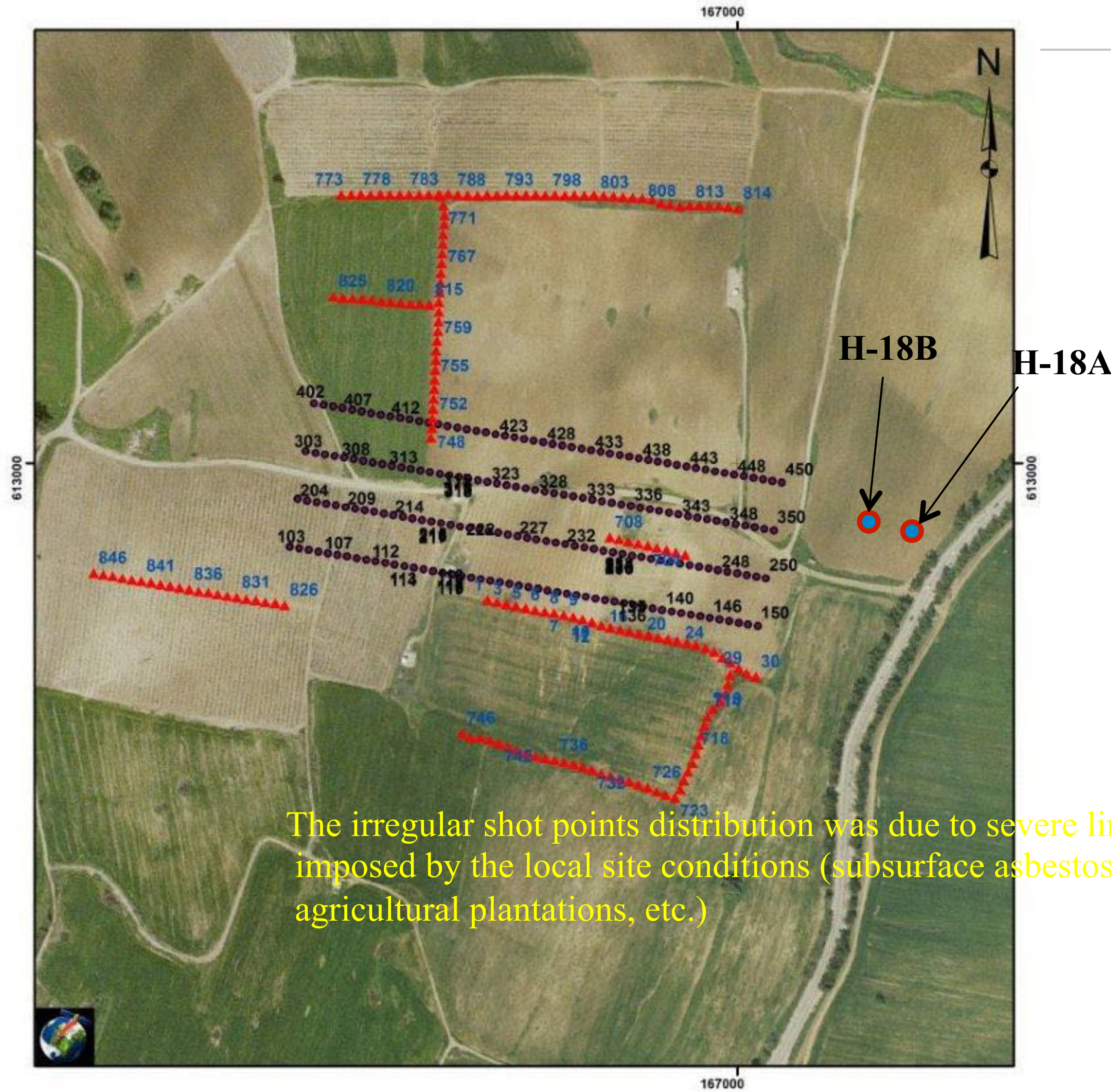
The Geophysical Institute of Israel
המכון הגיאופיסי לישראל



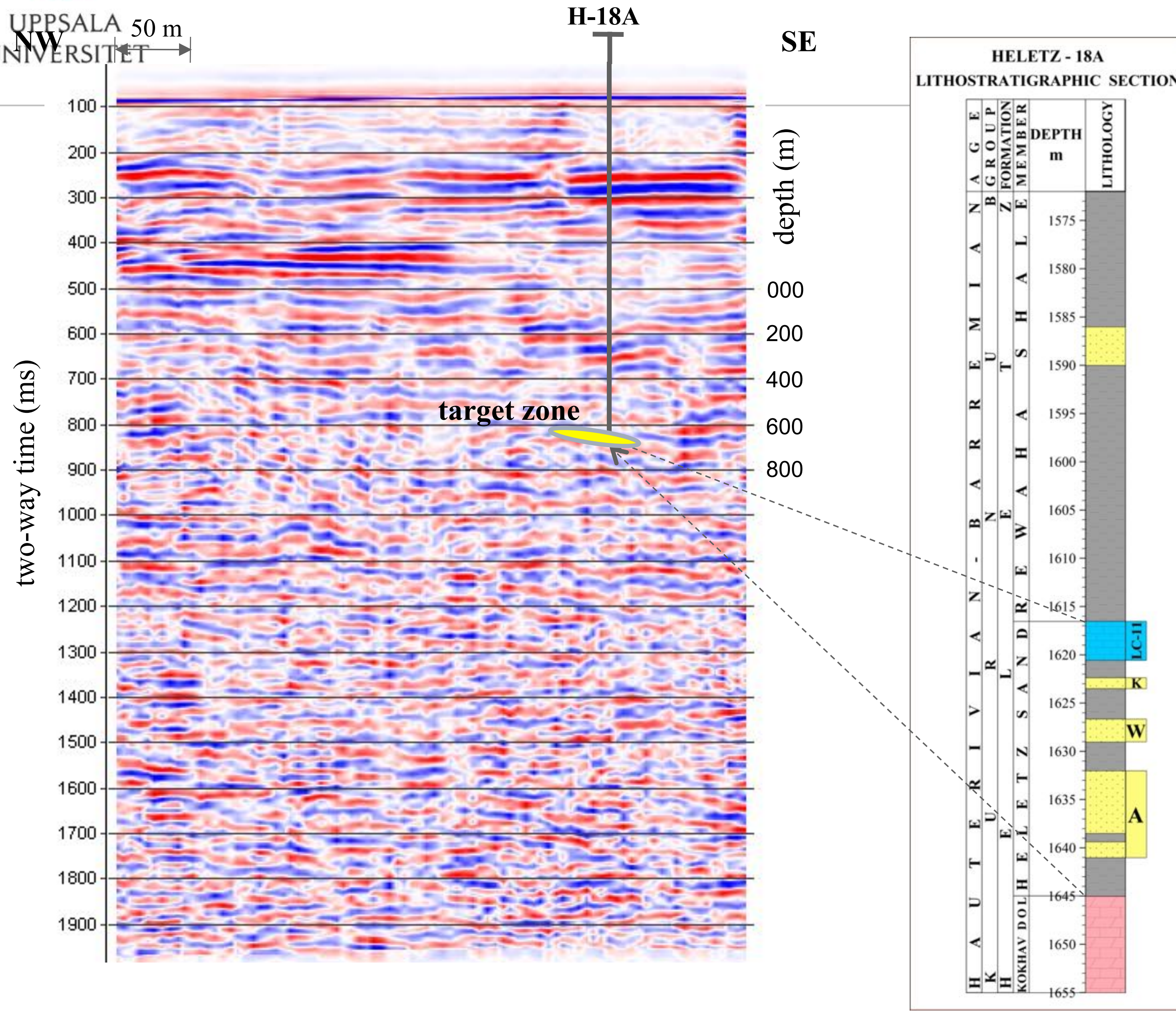
The irregular shot points distribution was due to severe limitations imposed by the local site conditions (subsurface asbestos pipes, agricultural plantations, etc.)

source lines

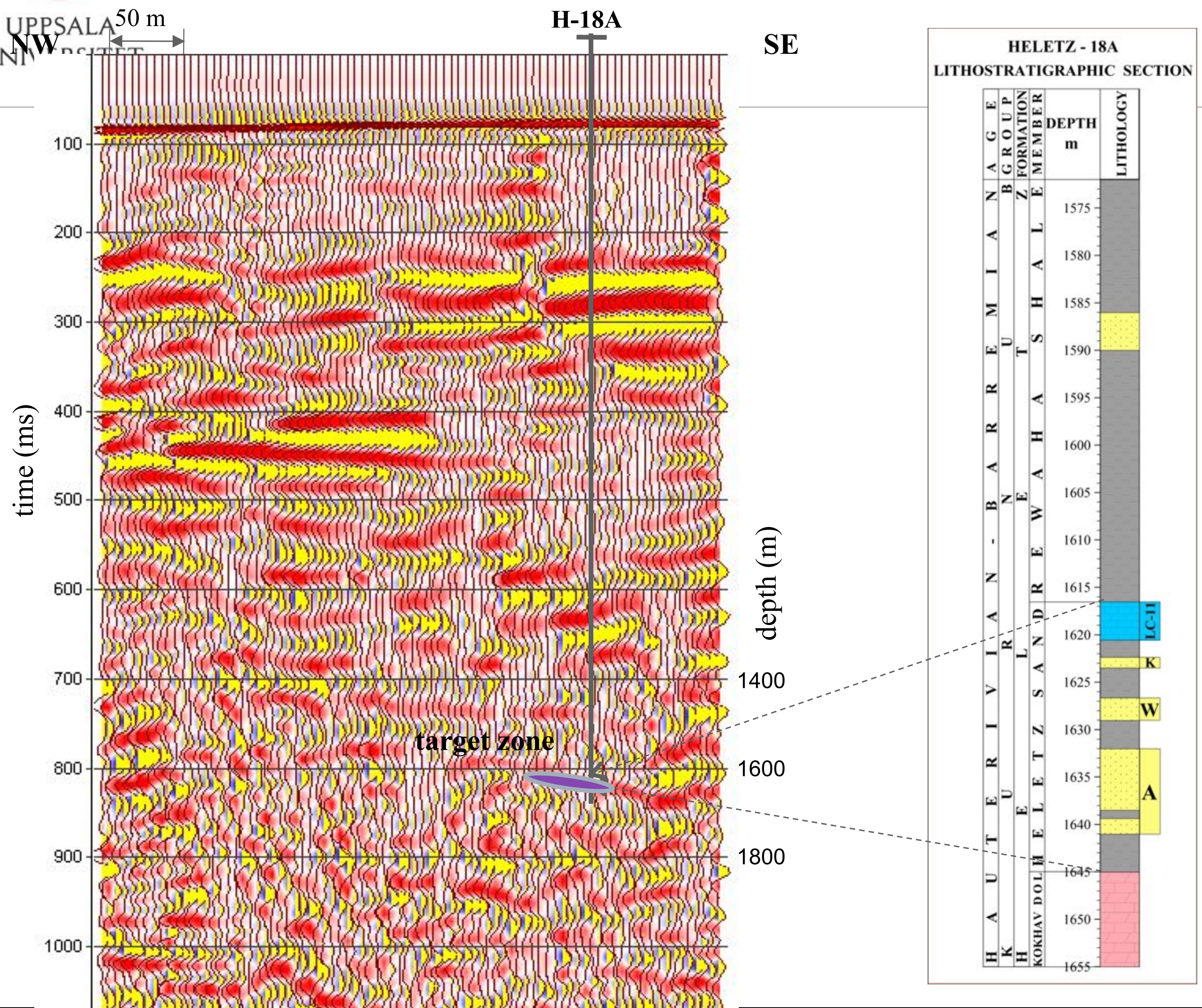
receiver lines

OUTPUT – TIME SECTIONS ALONG 5 LINES

TIME SECTION ALONG LINE 3



TIME SECTION ALONG LINE 3 (ZOOMED IN)



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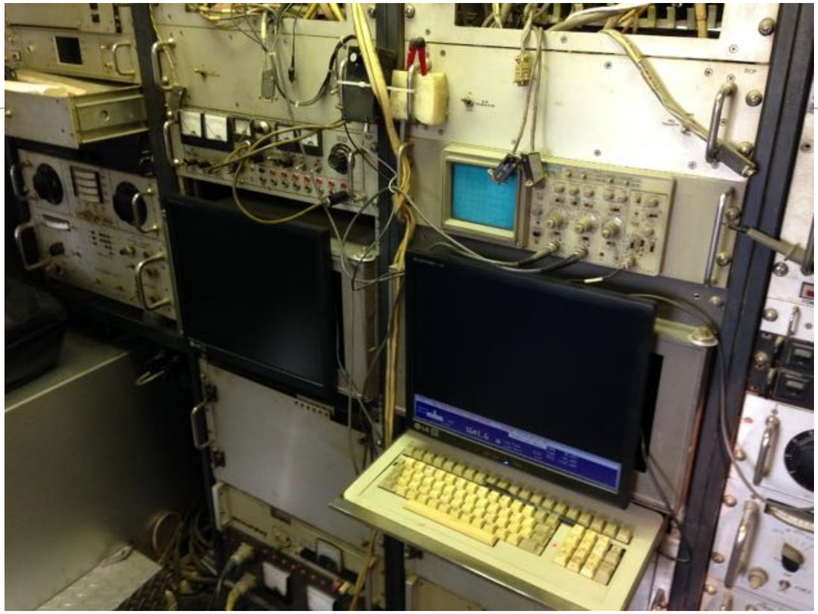
- In view of the rock properties we took the decision to install a 7 inch casing the monitoring well.
- The wells were perforated for the “W” and “A” horizons, using a 10 shots/foot density.



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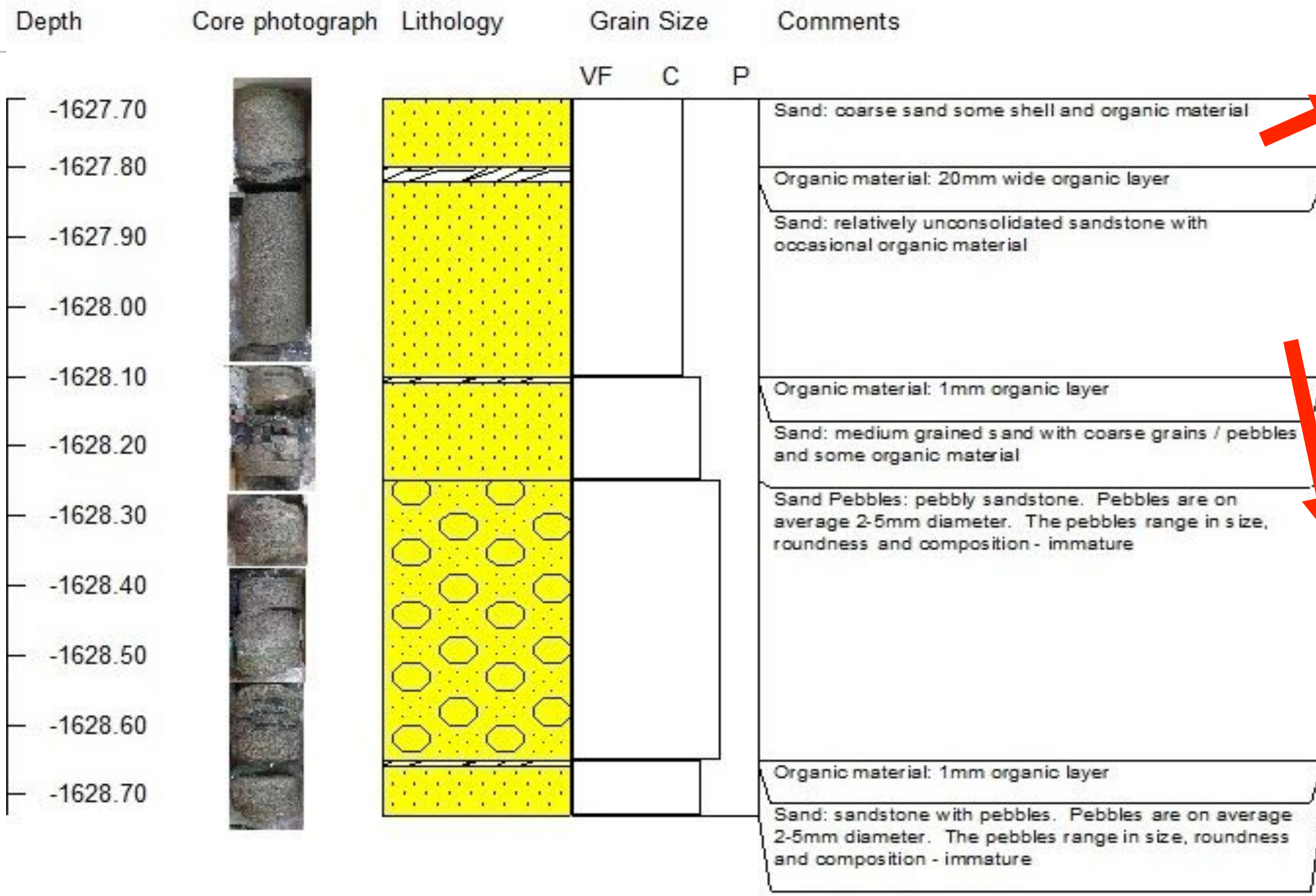
Rock testing program

- Petrophysical properties, permeability, relative permeability, capillary pressure
- Mineral composition
- Behavior of rock (and fractures) when in contact with CO2 and/or CO2/brine mixtures
- Rock mechanical properties

Laboratories: CNRS, Univ. of Edinburgh, Univ. Göttingen, Stanford University, Luleå Univ Technlogy, Uppsala Univ. CanMet, Canada

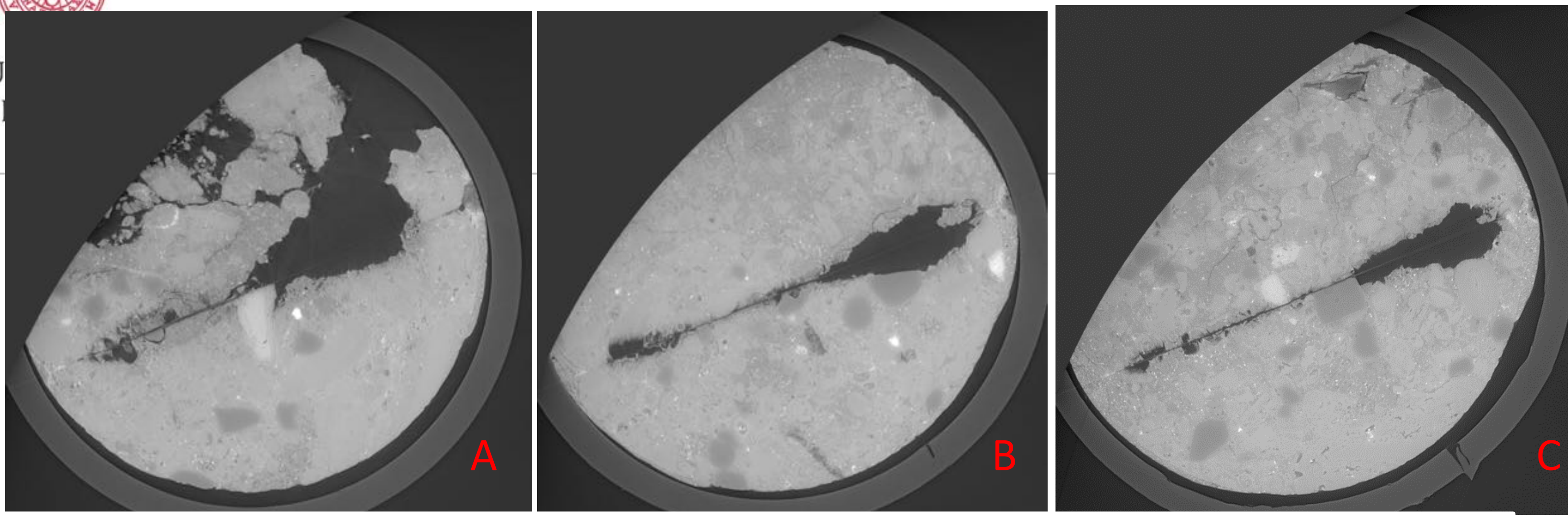
Reservoir rock sampling

Heletz Well 18B core run 1627.70 - 1628.73

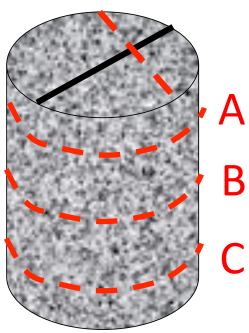


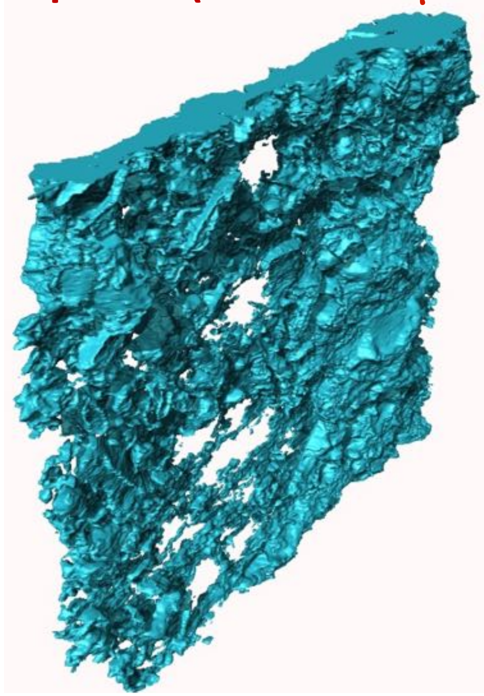
Difficult to core → we used recompacted samples

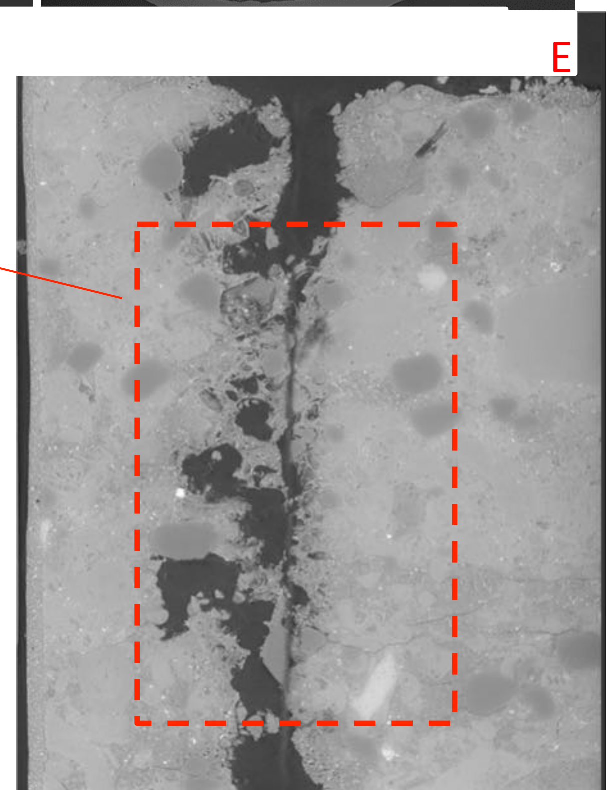
Microtomography image for experiment 2



Initially the fracture was planar (a= 17 ± 0.5μm)







Conclusions – rock testing program

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RESERVOIR

- When CO_2-rich brine is pumped through the sandstone we observed an increase of permeability related to localized dissolution and precipitation processes :

  Dolomite and ankerite are dissolved
  Clays (kaolinite and chlorite) precipitate locally.
  No gypsum precipitation was observed, but suspected.

CAPROCK

- Injection of CO_2-rich brine in fractured caprock induces strong alteration of the material -> dissolution of the feldspar, calcite and silica.

- The effect of these mass exchanges on the permeability is complex (there is probably both particle motions and clay swelling). At short terms it seems that the permeability stays globally unchanged, but the dissolution features are important and one can speculate that the leakage may increase eventually (need further experiments).

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Site characterization and site properties - summary

- A summary of the characterization work is publisehd in a Mustang/Heletz ***Special Edition of International Journal of Greenhouse Gas Control*** Niemi, Gouze, Bensabat (eds.); 2016 (in Press, available online) ***Characterization of formation properties for geological storage of CO_2 – Experiences from the Heletz CO_2 injection site and other example sites from the EU FP7 project MUSTANG***

- ***Overview article*** summarizing the site properties is given in

Niemi, A. Bensabat, J, Shtivelman, V, Edlmann, K, Gouze, P., Luquot, L., Hingerl,F, Benson, S.M., Pezard, P.A, Rasmusson, K., Liang,T., Fagerlund, F., Gendler, M., Goldberg,I, Tatomir,A., Lange, T., Sauter, M., and Freifeld, B. (2016) ***Heletz experimental site overview, characterization and data analysis for CO2 injection and geological storage*** *Int. J. of Greenhouse Gas Control*. In press.
http://dx.doi.org/10.1016/j.ijggc.2015.12.030

Special Edition of International Journal of Greenhouse Gas Control (Niemi, Gouze, Bensabat (eds.); 2016)

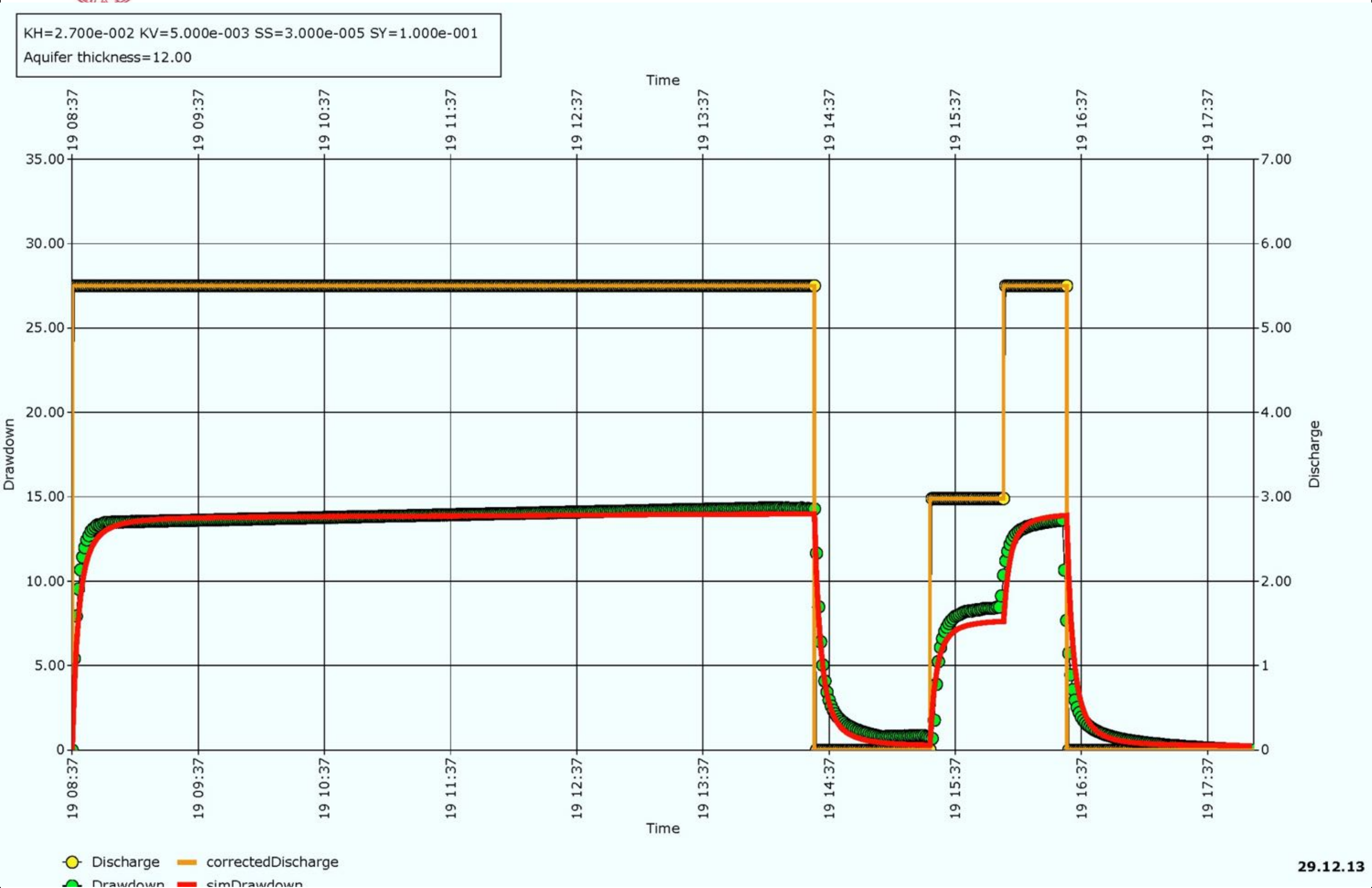
Pezard et al.	Time-lapse downhole electrical resistivity monitoring of subsurface CO2 storage at the Maguelone shallow experimental site (Languedoc, France).
McDermott et al.	Experimental investigation and hybrid numerical analytical hydraulic mechanical simulation of supercritical CO2 flowing through a natural fracture in caprock.
Elhami et al.	Physical- and geomechanical properties of a drill core sample from 1.6 km depth at the Heletz site in Israel: some implications for reservoir rock and CO2 storage
Edlmann et al.	Mineralogical investigation of the caprock of the field scale experimental CO2 injection site, Heletz, and its reactivity to scCO2 injection
Tatomir et al.	An integrated core-based analysis for the characterization of flow, transport and mineralogical parameters of the Heletz pilot CO2 storage site reservoir
Soler-Sagarra et al.	Simulation of chemical reaction localization using a multi-porosity reactive transport approach
Hingerl et al.	Characterization of Heterogeneity in the Heletz Sandstone from Core to Pore Scale and Quantification of its Impact on Multi-Phase Flow
Niemi et al.	Heletz experimental site overview, characterization and data analysis for CO2 injection and geological storage
Abdoulghafouri et al.	Characterization and modeling of the alteration of fractured class-G Portland cement flowed by CO2-rich brine
Davila et al.	Efficiency of magnesium hydroxide as engineering seal in the geological sequestration of CO2
Davila et al.	Interaction between a fractured marl caprock and CO2-rich sulfate solution under supercritical CO2 conditions
Zhang et al.	A feasibility and efficiency study of seismic waveform inversion for time-lapse monitoring of onshore CO2 geological storage sites using reflection seismic acquisition geometries
Luquot et al.	CO2-rich brine percolation experiments through Heletz reservoir rock samples (Israel): Role of the flow rate and brine composition

- Overall, the general picture of the site, including structures and layers, water quality etc. were in good agreement between the old and new data
- Exceptions also, especially the local permeability in the test area

Permeability measurements in the field

- pump test in the injection well.
- We installed a pump a depth of 270 meters, to which we attached a pressure sensor.
- Water was run through a flow control cell instrument with an Ultrasonic flow meter, PH and EC sensors.

Field scale permeability (horizontal) was >700mD



Permeability measurements in the lab

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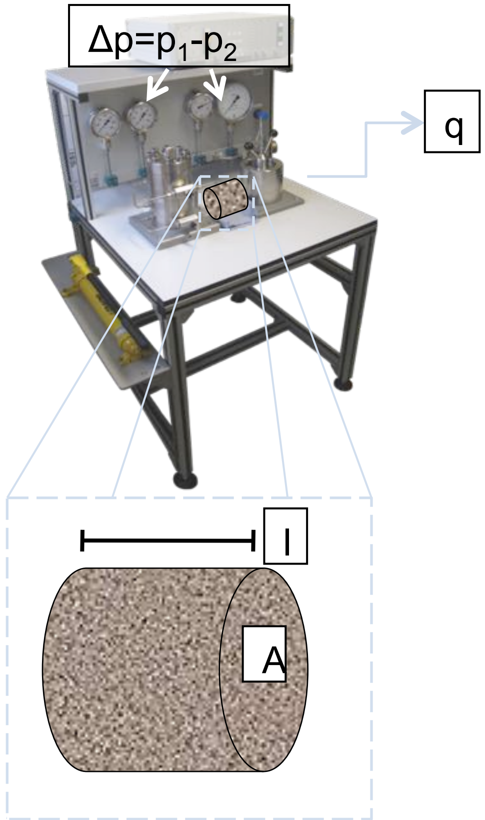

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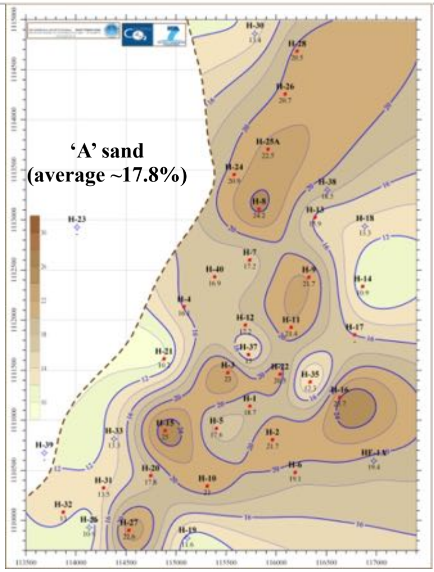
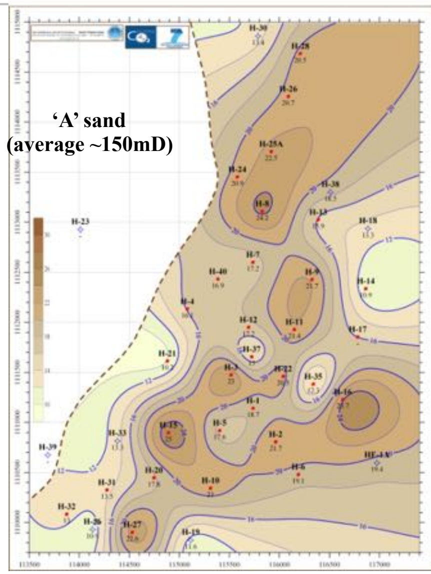
steady state permeametry
@ LIAG, Hannover, Germany

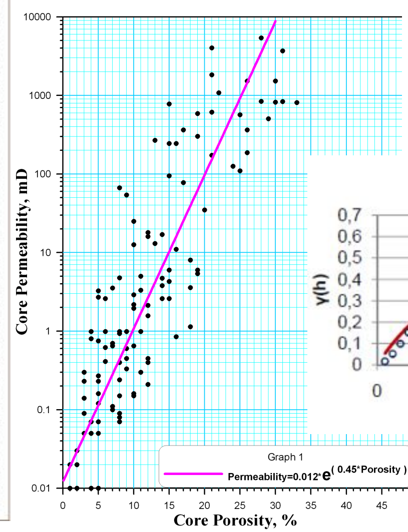
#	Fine core (H18A), Direction I	Fine core (H18A), Direction II	Coarse core (H18B), Direction I	Coarse core (H18B), Direction II
1	449	469	339	351
2	441	465	358	343
3	431	467	355	343
4	459	453	349	342
5	449	449	343	341
6	440	456	341	339
7	426	442	348	338
8	441	453	346	335
9	455	442	348	331
10	439	447	344	329
AVERAGE	**443**	**454.3**	**347.1**	**339.2**

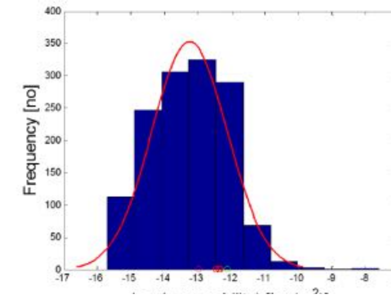
No noticeable anisotropy at core level

Summary of conductivity/permeability









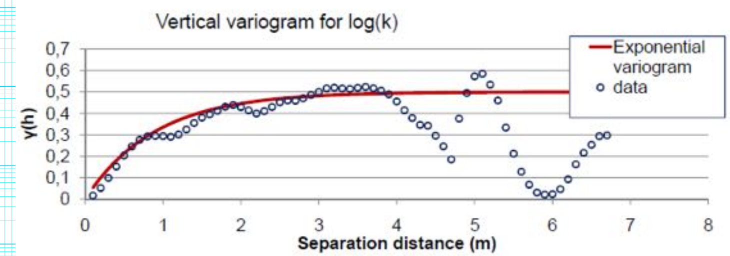


Table 10: Statistical data for Heletz sand layer permeabilities

Parameter	Values	Layer	Data base
Data from entire Heletz formation			
μ, σ (m^2 and mD)(1 of model to log-converted data(2	-13.25, 1.1 (log m^2) 2.1, 1.1 (log mD)	A	borehole porosity logs
-‘’-	-12.9, 1.1 (log(m^2): 1.7, 1.1 (log mD)	W	-‘’-
Data from old wells in the vicinity of experimental area			
m, s (mD) from log-converted data(3	1.43, 0.725	Layers A,W, K	Borehole porosity logs, wells H-13, H-18 and H-38 only
Parameters for exponential model fitted to variogram data(4 a, nugget (C_0), sill (ω)	All layers 0.9,0, 0.526	-‘’-	-‘’-
Data from the new drilled wells			
Range of values (mD)(5 Range of values (log transformed, m^2)	100-410 ~-13-12.4	Layer A	Core samples, only tests with in-situ P/T conditions included
Horizontal/ Vertical permeability (mD)	735/135	Layers A, W	In-situ well test, provides an ‘upscaled’ value for the entire layer

Niemi, A. et al (2016) Int. J. of Greenhouse Gas Control. In press, available online

Summary of conductivity/permeability

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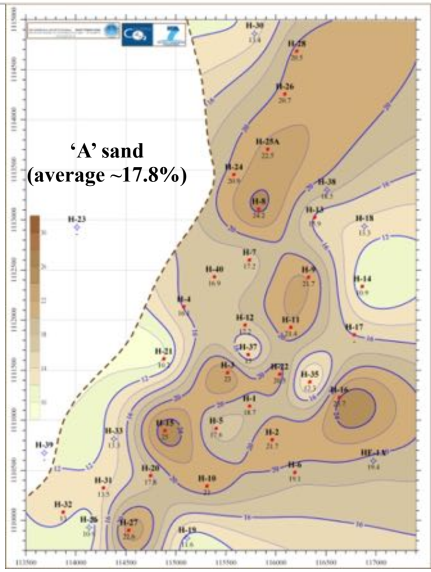

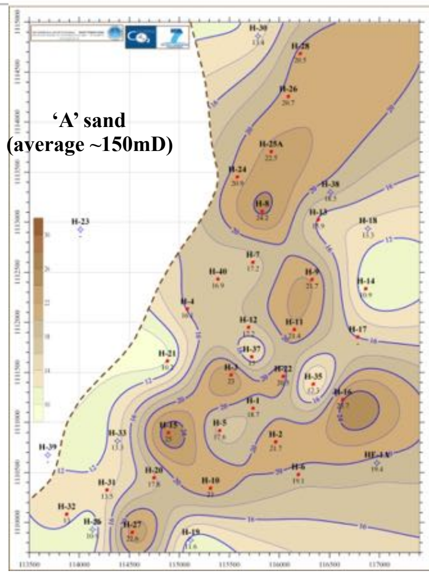

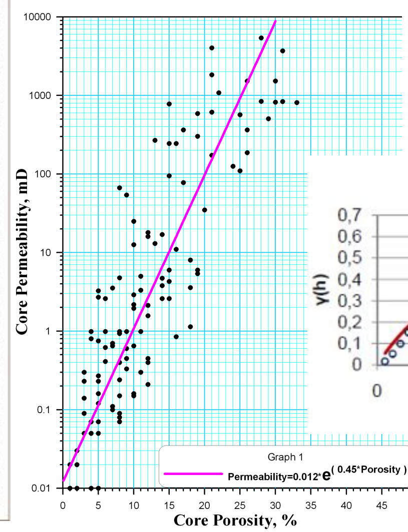

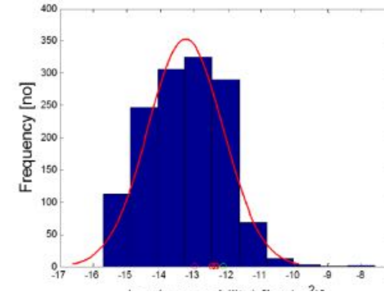

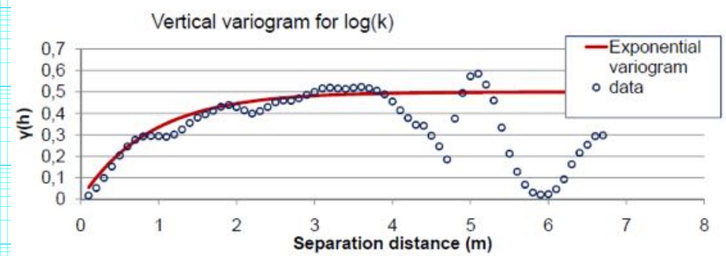

Table 10: Statistical data for Heletz sand layer permeabilities

Data from entire Heletz formation			
Parameter	*Values*	*Layer*	*Data base*
μ, σ (m^2 and mD) (1 of model to log-converted data (2	-13.25, 1.1 (log m^2) 2.1, 1.1 (log mD)	A	borehole porosity logs
-‘’-	-12.9, 1.1 (log(m^2): 1.7, 1.1 (log mD)	W	-‘’-
Data from old wells in the vicinity of experimental area			
m, s (mD) from log-converted data (3	1.43, 0.725	Layers A,W, K	Borehole porosity logs, wells H-13, H-18 and H-38 only
Parameters for exponential model fitted to variogram data (4 a, nugget (C_0), sill (ω)	All layers 0.9,0, 0.526	-‘’-	-‘’-
Data from the new drilled wells			
Range of values (mD) (5 Range of values (log transformed m^2)	100-410 ~-13-12.4	Layer A	Core samples, only tests with in-situ P/T conditions included
Horizontal/ Vertical permeability (mD)	735/135	Layers A, W	In-situ well test, provides an 'upscaled' value for the entire layer

Niemi, A. et al (2016) Int. J. of Greenhouse Gas Control. In press, available online

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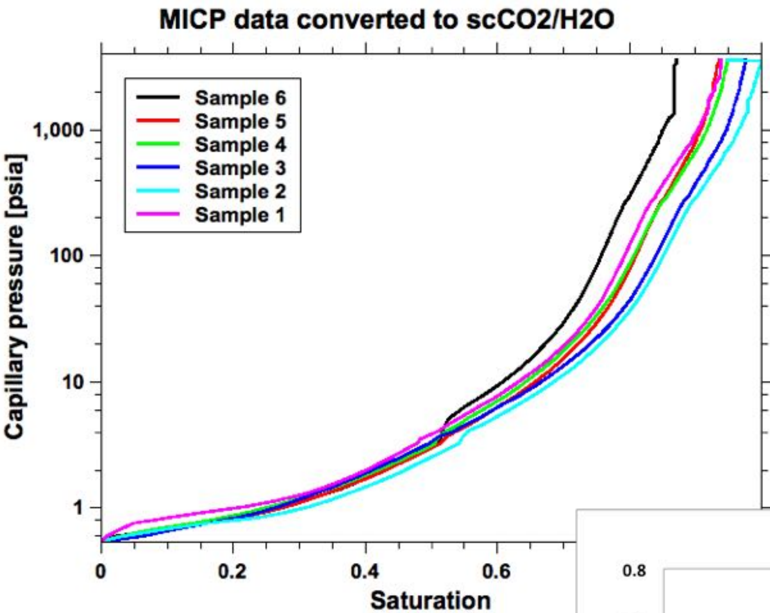
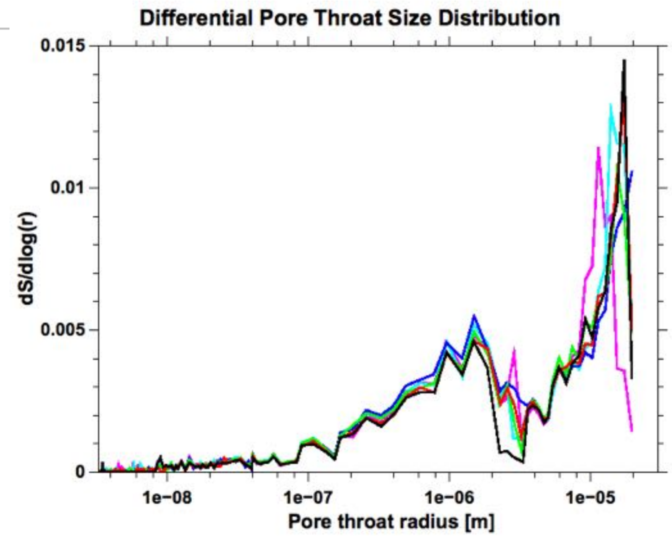
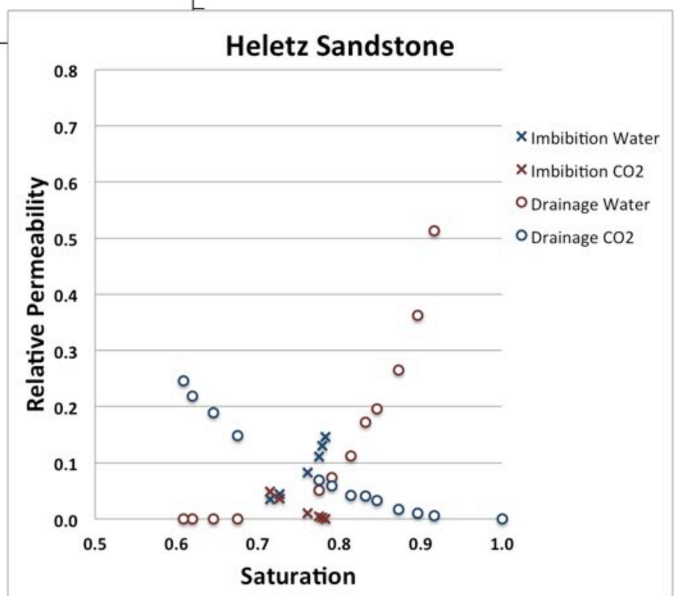
A few words about two-phase flow properties







Use for pore-network modeling, to get an understanding of trapping at the pore level

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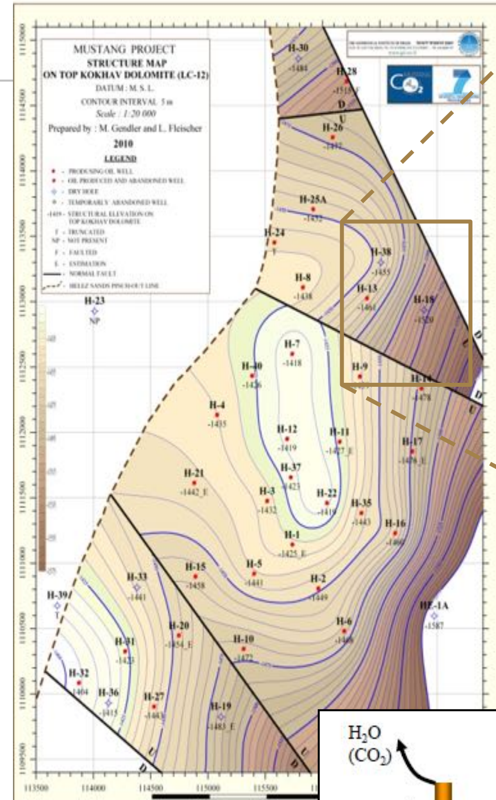
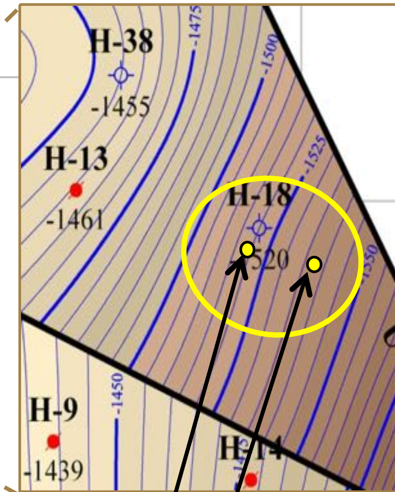
Site setup for the experiments

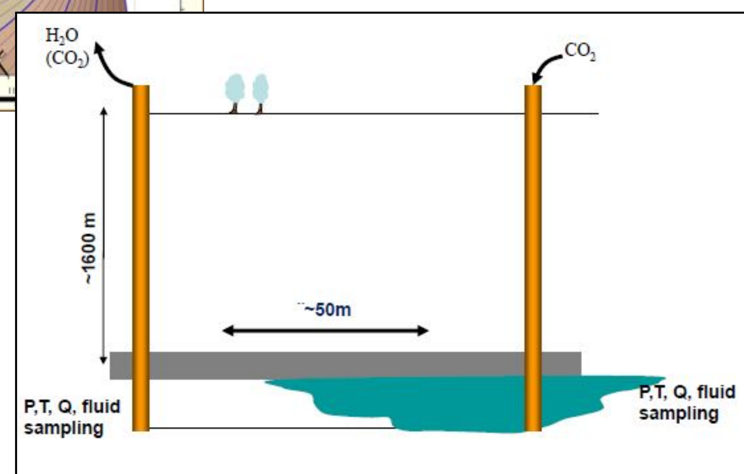
Location of monitoring well

Injection well





wells for field experiments



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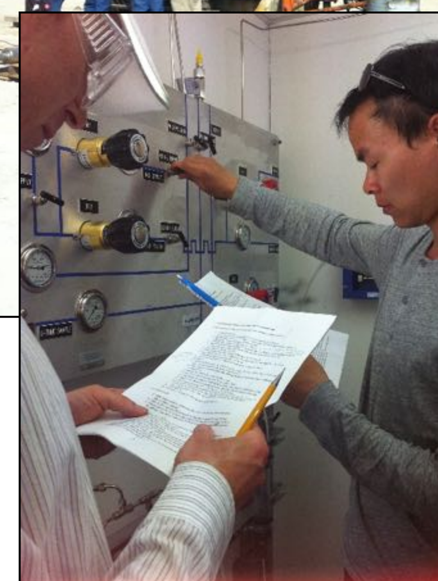
Well instrumentation

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



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Instrumentation details

- Injection well: 1) pressure and temperature sensors at bottom and top of the perforated horizon (redundant); 2) optical Fiber for DTS; 3) optical fiber for DAS; 4) Tube in tube sampling system (formerly UTUBE); 5) mandrel for air-lift; 6) CO2 injector at 1,000 meters for saturating water with CO2 (see push-pull experiment).
- Monitoring well: 1) pressure and temperature sensor at top of the perforated horizon; 2) optical Fiber for DTS; 3) optical fiber for DAS; 4) 2 Tube in tube sampling system (formerly UTUBE); 5) mandrel for air-lift;

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Injection system

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The injection kit

- CO_2 Injection capacity of up to 4 tons/hour at 80 bar and a temperature of up to 35 at the wellhead;
- Low-flow injection of CO_2 for saturating water;
- Possibility to inject tracers, both as batch and continuous;
- High degree of safety;
- Ease of operation;
- Semi automatic operation;
- Online Reporting pressure/Temperature at strategic locations
- Easy to install and dismantle.
- TRIMERIC to train our personnel for operating the system
- TRIMERIC to supervise the installation of the system and the first CO2 injection
- Possibility to add impurity gases

Objectives of the experimental program

- To gain understanding and develop methods to determine the two key trapping mechanisms of CO_2 - *residual trapping and dissolution trapping* - at field scale, evaluate the impact of heterogeneity (push-pull and dipole experiments)

- Estimate *how to enhance trapping* by different modes of injection (in dipole mode; look at the effect of different injection scenarios)

- *Effect of impurity gases* in CO_2 stream (CO2QUEST project)

CO_2QUEST

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CO_2QUEST

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Testing program (3/4) Determine enhanced trapping when altering CO2 and water injection schemes

Table 4 Schedule of alternative injection strategies.
[A]Corresponds to 0.10 volumetric flow of water during co-injection.

Injection strategy	Description	Total observation time [d]
1: Conventional injection	-CO_2 injection (500 tons, 1 kg/s)	30
2: Chased injection	-CO_2 injection (500 tons, 1 kg/s) -Chase water injection (125 tons, 0.8 kg/s)	30
3: Co-injection	-Co-injection of CO_2 with a small portion of water (500 tons, 1 kg/s and 85 tons, 0.17 kg/s, respectively)[A]	30
4: Mixed co-injection and chased injection	-Co-injection of CO_2 with a small portion of water (500 tons, 1 kg/s and 85 tons, 0.17 kg/s, respectively) -Chase water injection (125 tons, 0.8 kg/s)	30
5: Cyclic injection	-CO_2 injection (250 tons, 1 kg/s) -Break (0.9 days) -CO_2 injection (250 tons, 1 kg/s)	30
6: Small WAG injection	-CO_2 injection (250 tons, 1 kg/s) -Water injection (62.5 tons, 0.8 kg/s) -CO_2 injection (250 tons, 1 kg/s) -Water injection (62.5 tons, 0.8 kg/s)	30

Model the effect on residual and solubility trapping (index)

Testing program (3/4) Determine enhanced trapping when altering CO2 and water injection schemes

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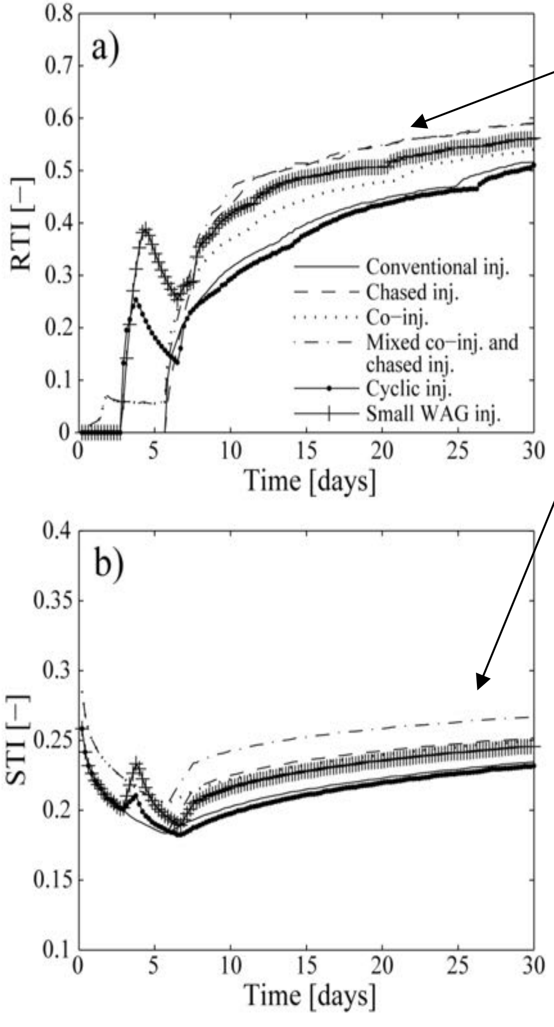
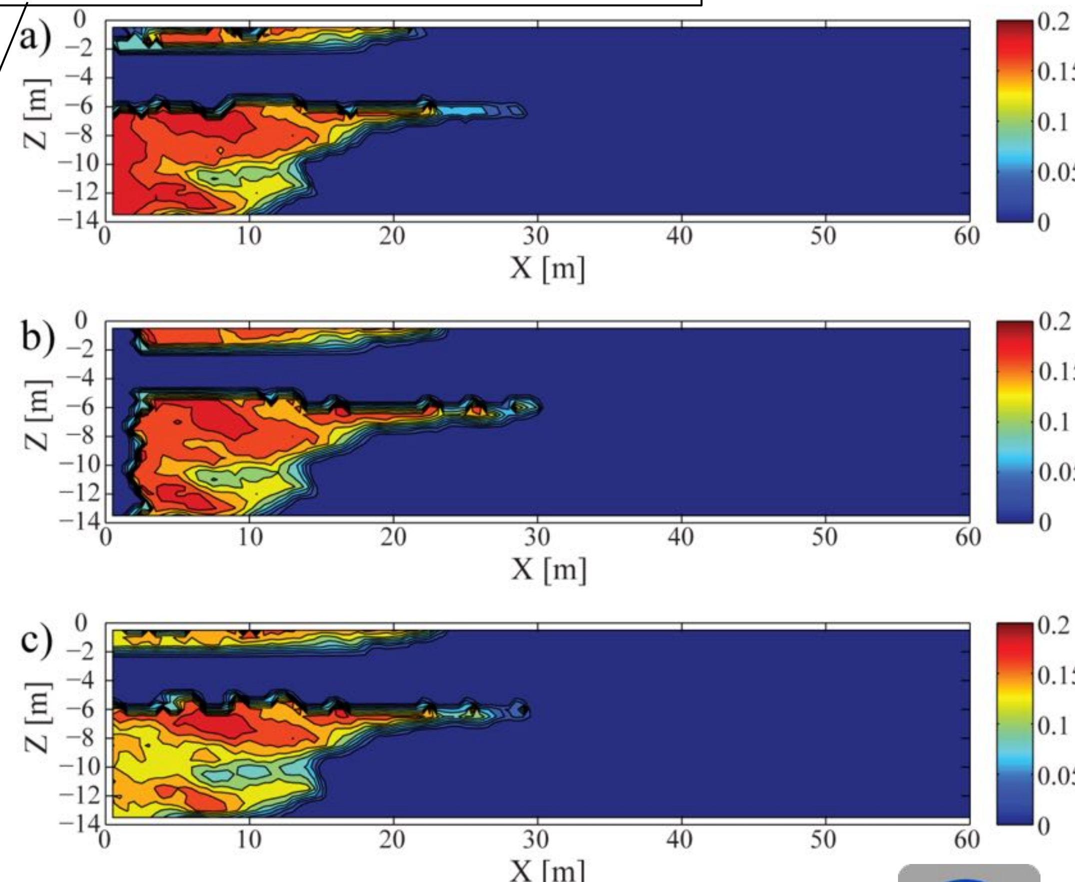
Injection schemes where water is added improve the trapping

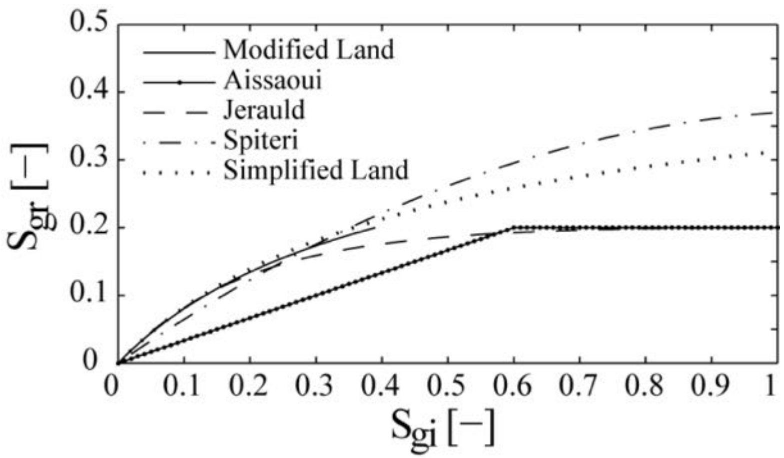




Rasmusson et al. (2016) "A simulation study of the effect of trapping model, geological heterogeneity and injection strategies on CO2 trapping *Int. J. of Greenhouse Gas Control.* Accept. with minor rev.

TRUST 2

…but the trapping model used can also have a signifinat effect



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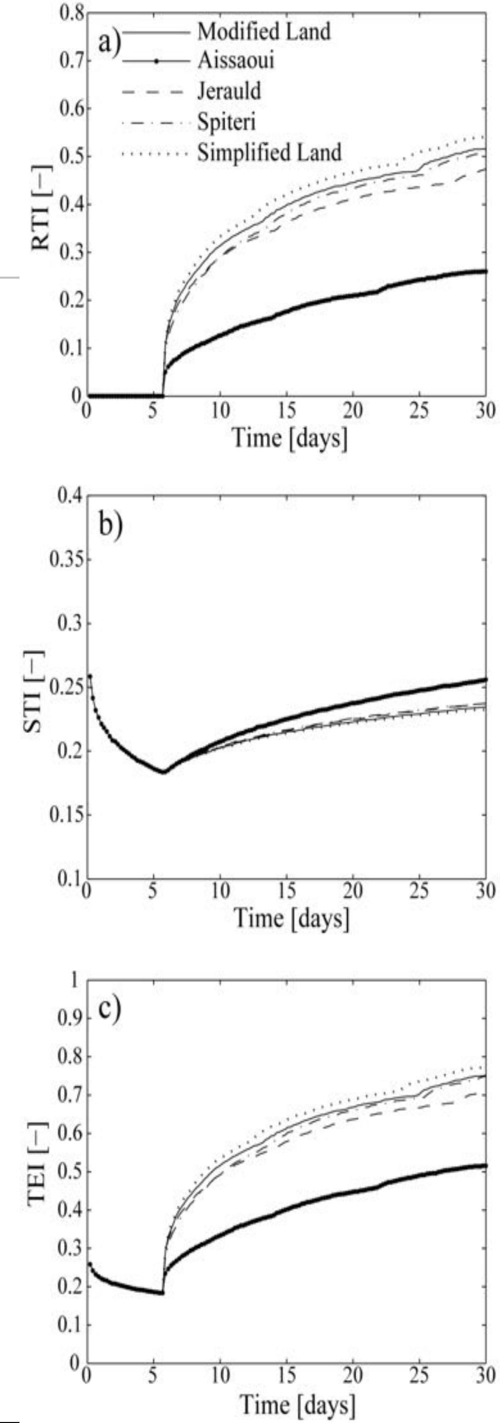


Testing program (4/4)
Effect of impurity gases is CO2 stream

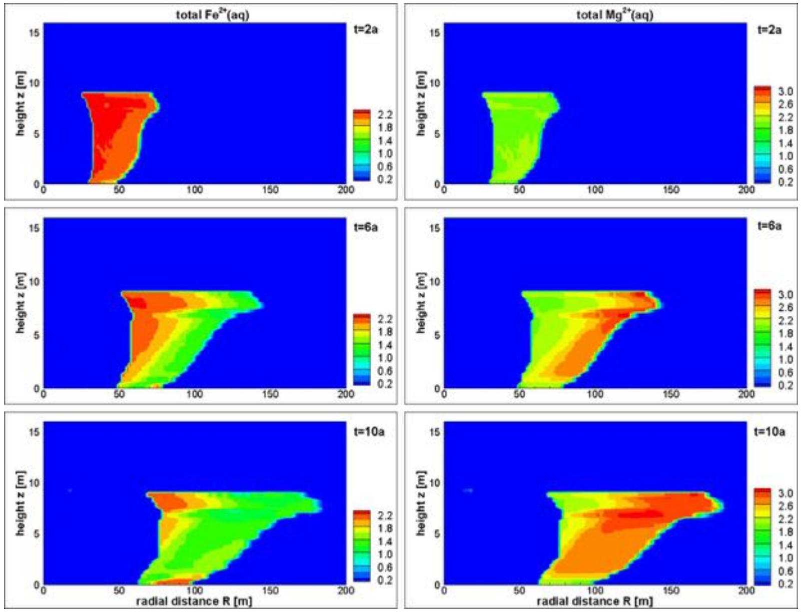
Use SO_2 and N_2 as impurity gases

- SO2 effects will be chemical,

N2 physical

- For comparison, laboratory experiments

on rock cores are being carried out by CanMet, Canada



Wolff et al. (2016) Manuscript

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Kristina Rasmusson, Uppsala
Sally Benson, Stanford University
Ferdinand Hingerl, Stanford University
Andrew Wigston, CanMet, Canada

and all MUSTANG, TRUST and CO2QUEST partners

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Thank you for your attention!

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