Monitoring CO_2 in the reservoir

- demonstrated by the case study of the Ketzin pilot site -

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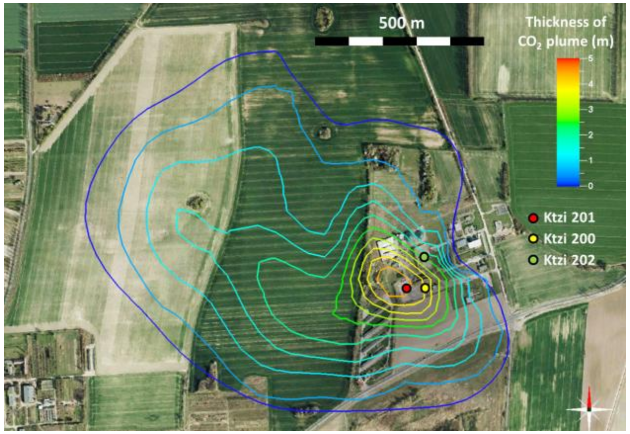
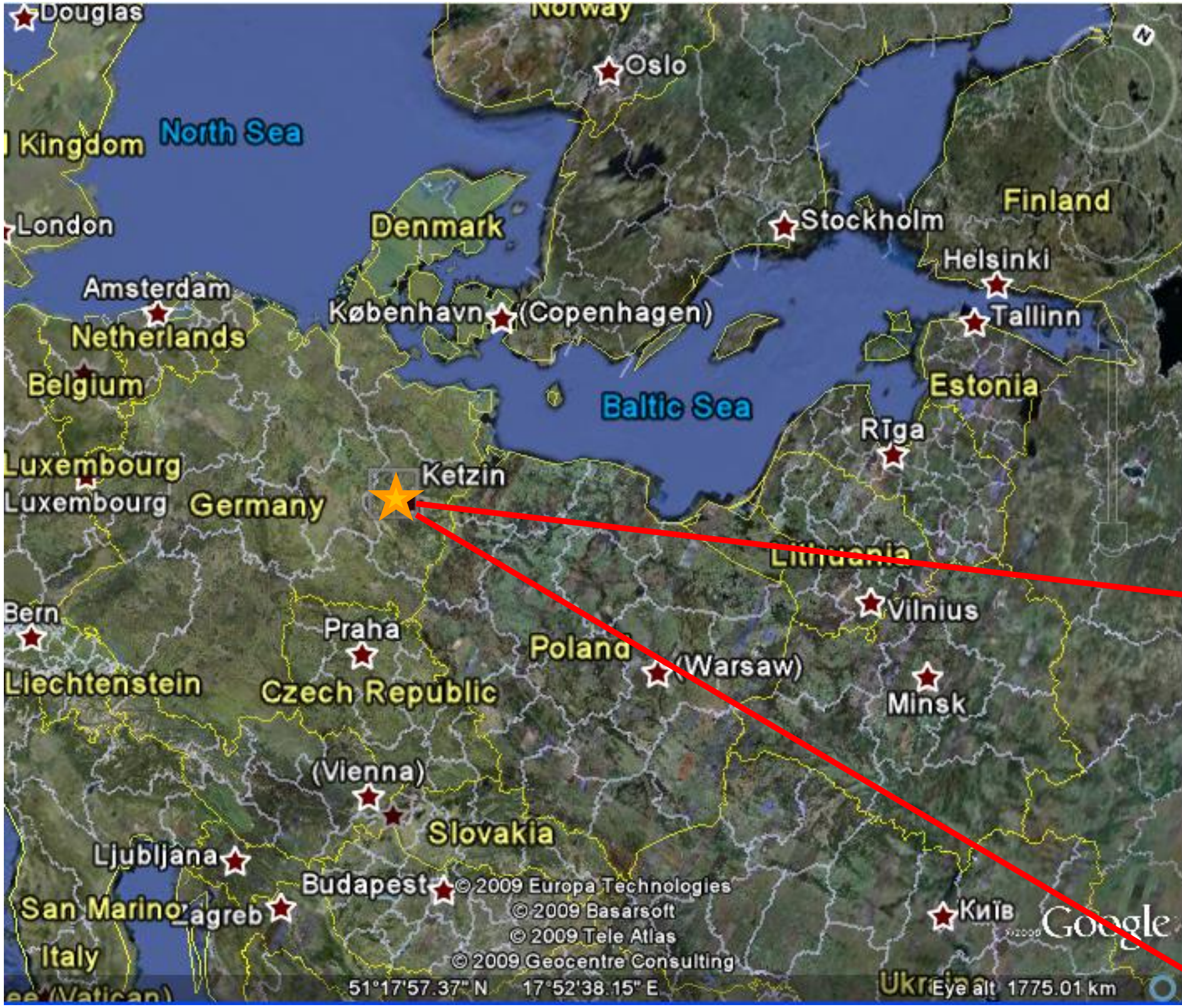
Section 6.3 Geological Storage



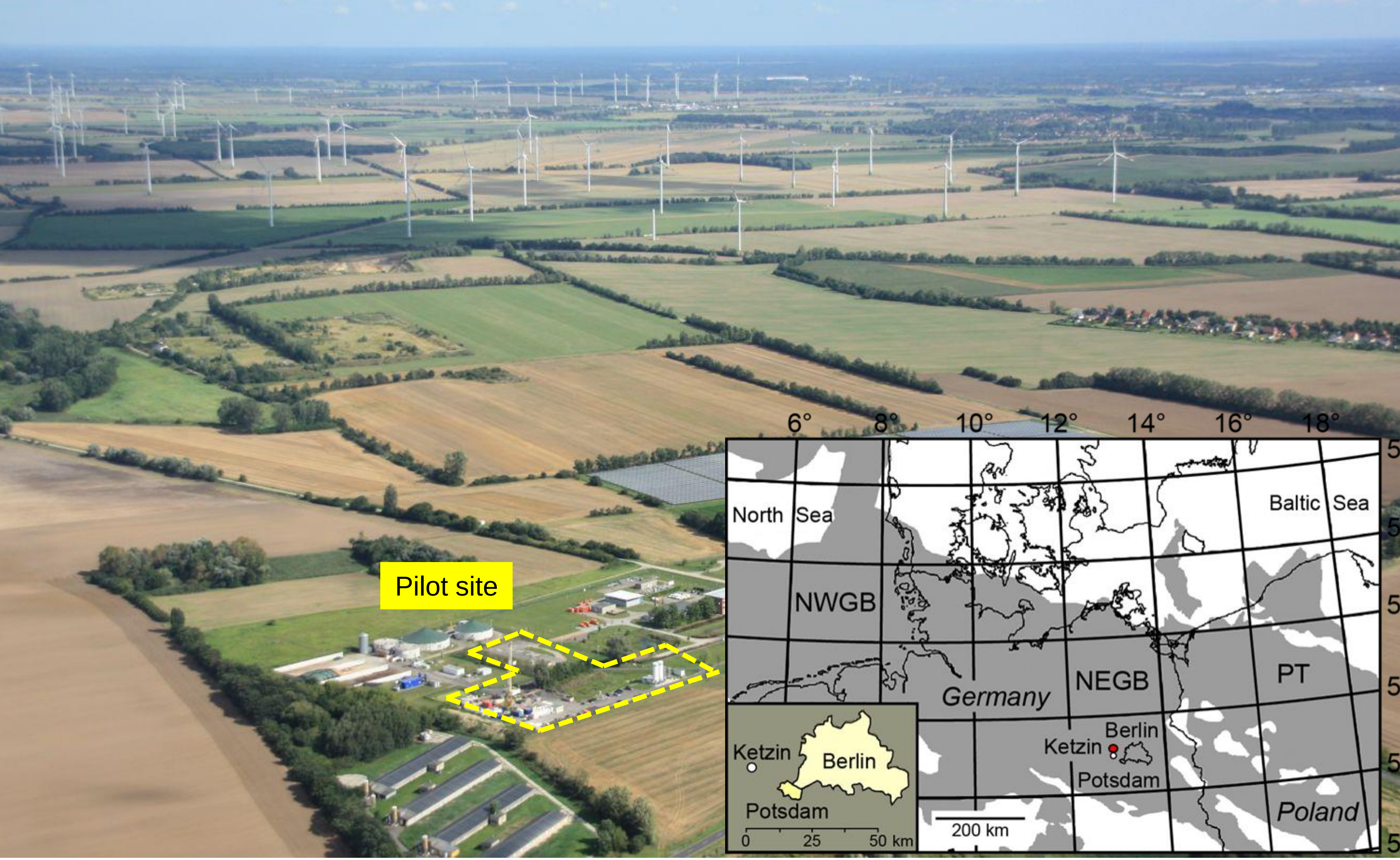



Location of the Ketzin Test Site

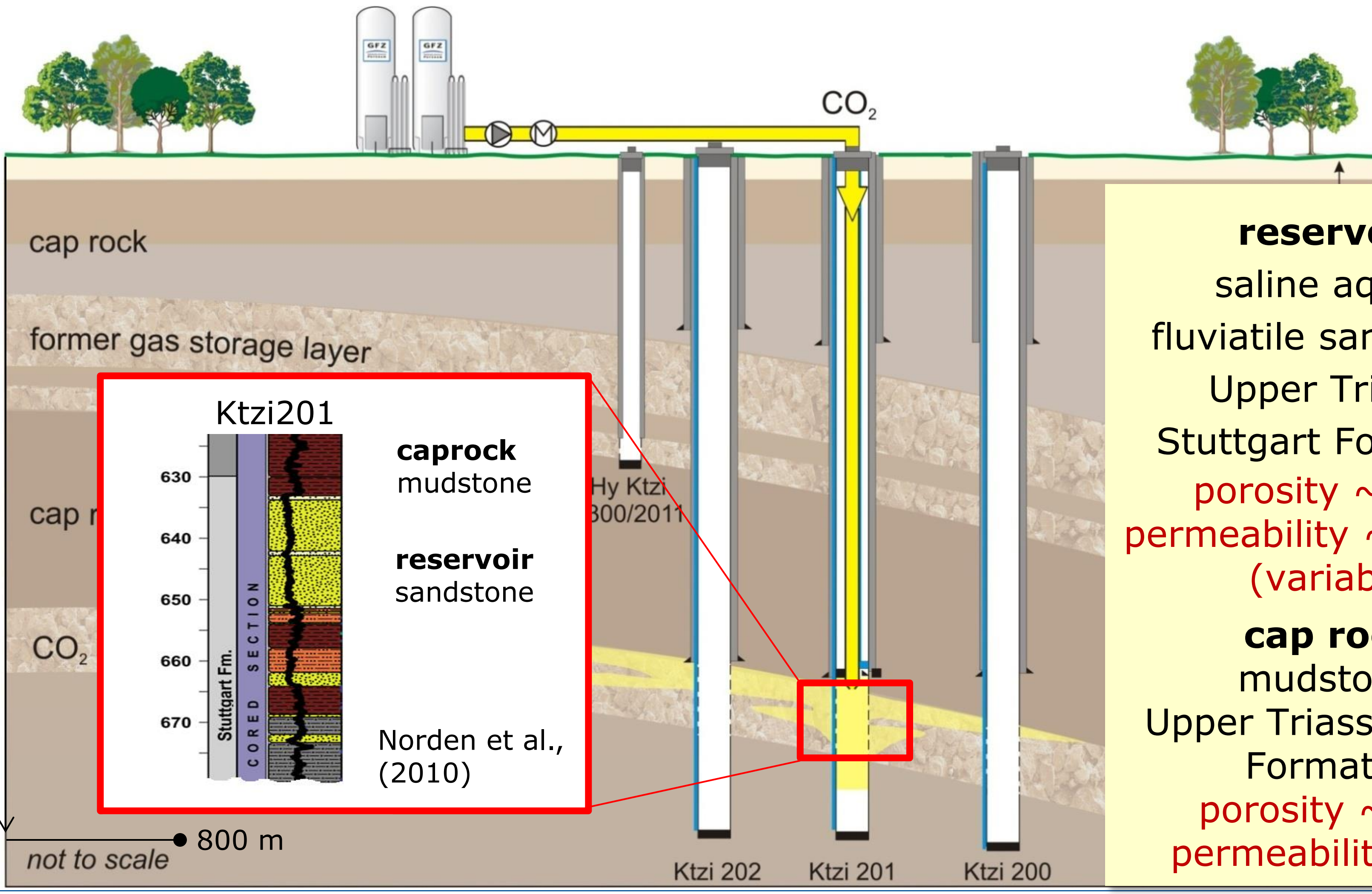


- ~ 25 km west of Berlin, in the North East German Basin
- In 1960s storage for natural gas imported from Siberia;
- Natural gas was stored in sandstones at shallow depth (250 – 400 m)
- Facility closed in 2004

The Ketzin pilot site for CO_2 storage



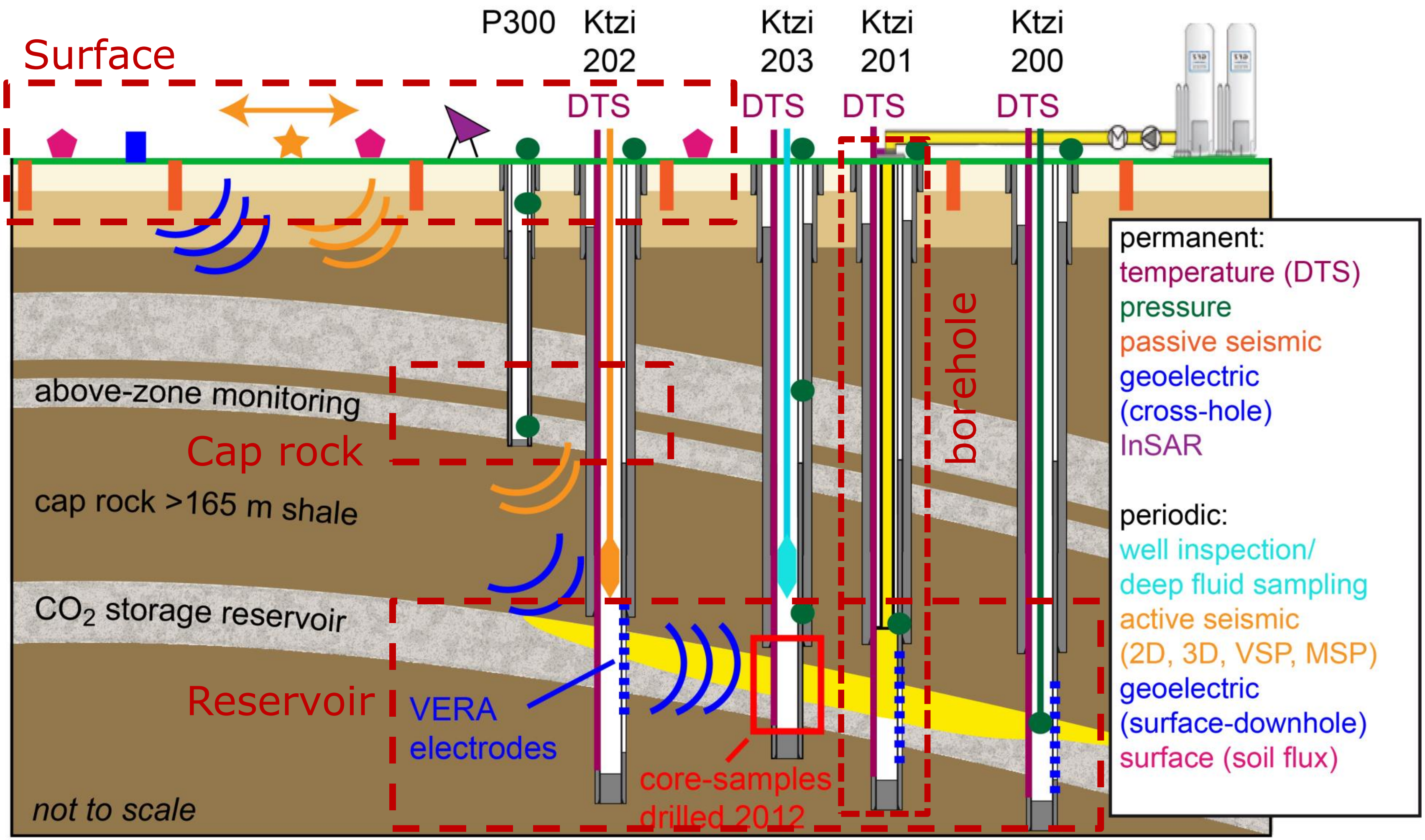
Geology and reservoir properties determine the monitoring layout



reservoir:
saline aquifer
fluviatile sandstones
Upper Triassic
Stuttgart Formation
porosity ~ 26%
permeability ~ 100 mD
(variable)

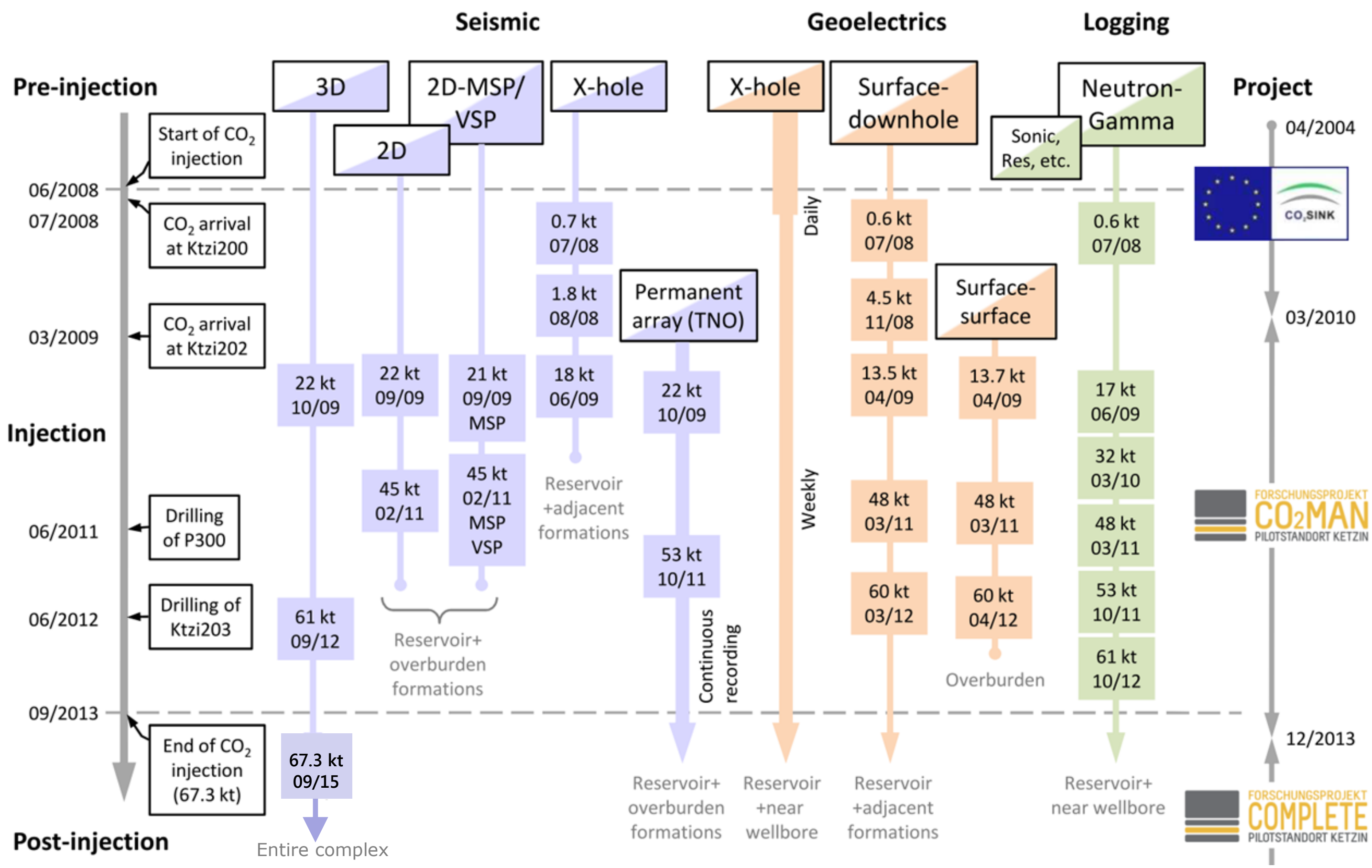
cap rock:
mudstones
Upper Triassic Weser
Formation
porosity ~ 8 %
permeability ~ µD

Multi-disciplinary monitoring concept



- This comprehensive concept combines **permanent** and **periodical** surveillance techniques on various temporal and spatial scales.

Monitoring the full life-cycle of the reservoir



- complemented by continuous surface gas monitoring since 01/2005, in-well P-T monitoring and above-zone monitoring (pressure, fluid sampling; since 2011)
- 4 years of post-injection monitoring

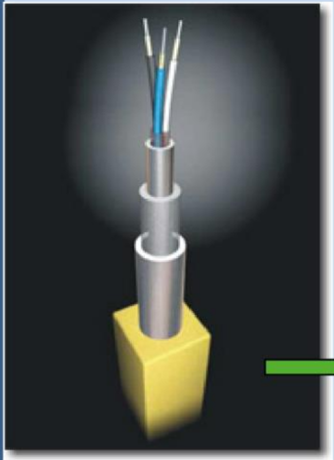
Ketzin injection history overview

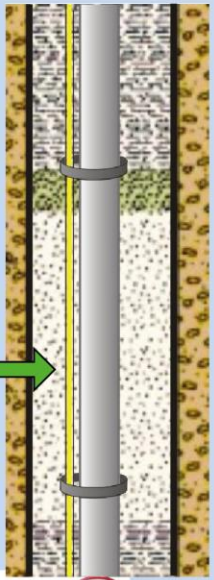
- Start of injection: June 30, 2008
- End of injection: August 29, 2013

- CO_2 sources and quality:
  - Food-grade CO_2 > 99.9%
  - May to June, 2011: 1,515 t CO_2 from Schwarze Pumpe oxyfuel pilot plant (Vattenfall), > 99.7%
  - March to June, 2013: 3,000 t CO_2 injected during "cold injection" experiment
  - July to August, 2013: 650 t CO_2-N_2 (95:5) co-injection experiment

- **Total mass injected: 67 kt CO_2**

Fiber-optic pressure/temperature sensing





Technical installation of fiber optic monitoring at injection string of Ktzi201 (injection well)

WFD Downhole fiber optic cable:

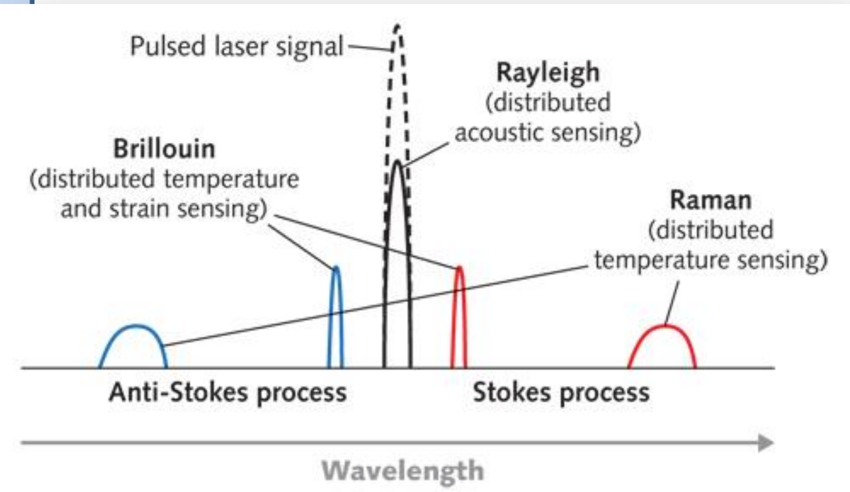
2 single-mode fibers for bottom-hole pressure / temperature

1 multimode fiber for DTS logs

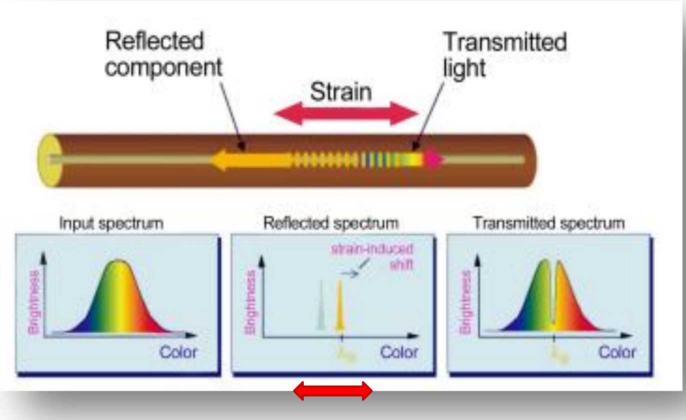
Pressure-Temperature point-gauge @ 549,08 – 548,41 m depth (end of injection tubing), carried by mandrel

Two Fiber-Bragg grating sensors: one for pressure measurement and one as temperature reference

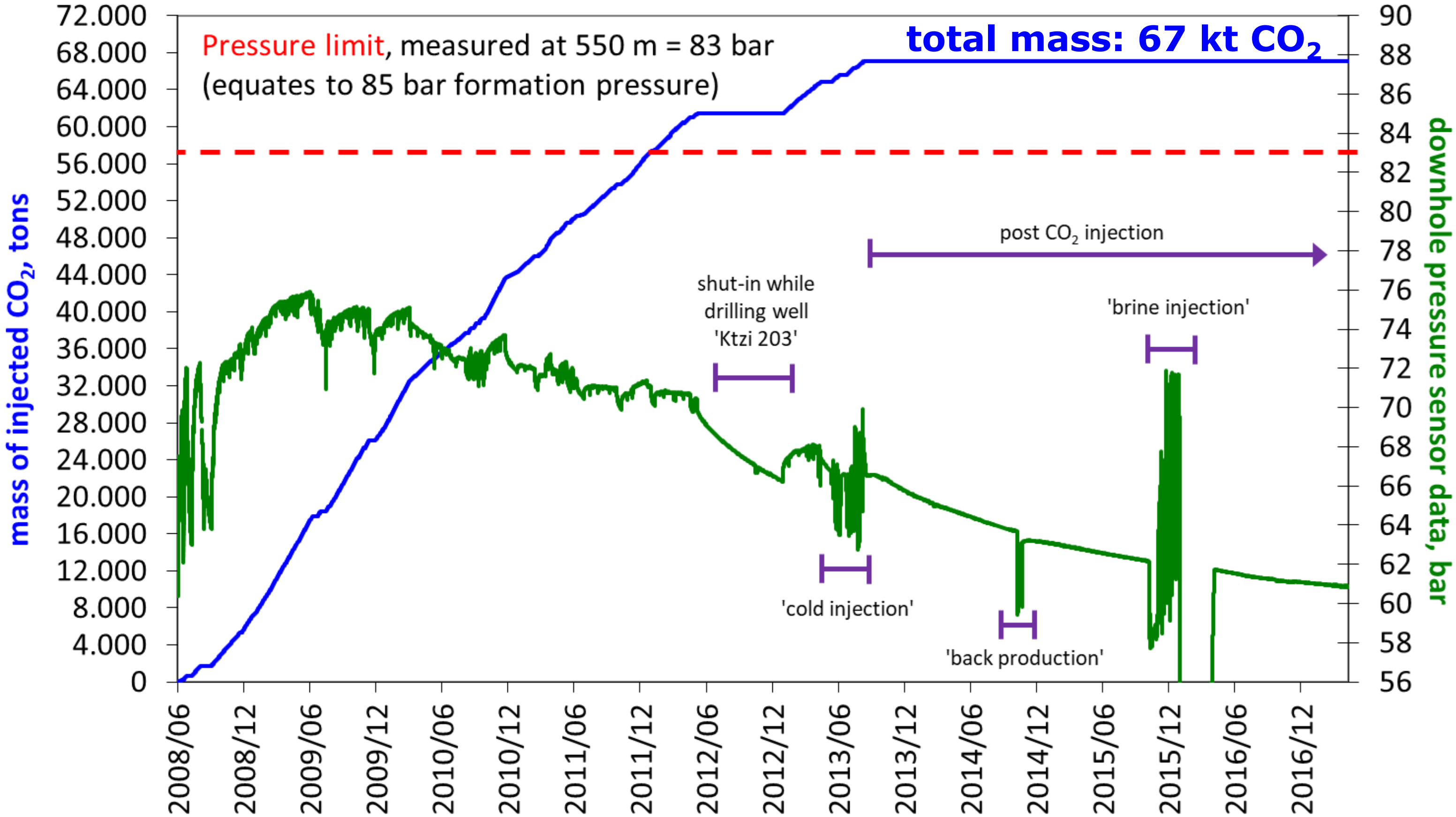
Distributed Temperature Sensing (Raman effect)



Fiber Bragg Grating (Strain sensing)

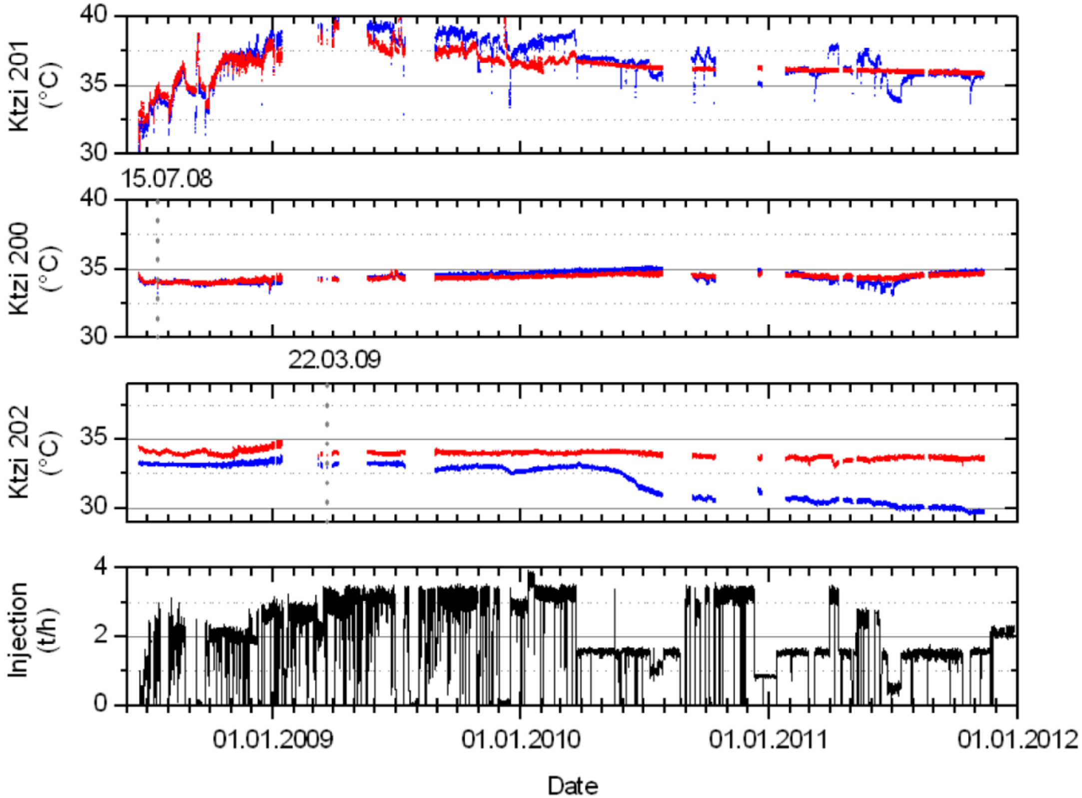


Operational monitoring – pressure/temperature/ CO_2 mass flow

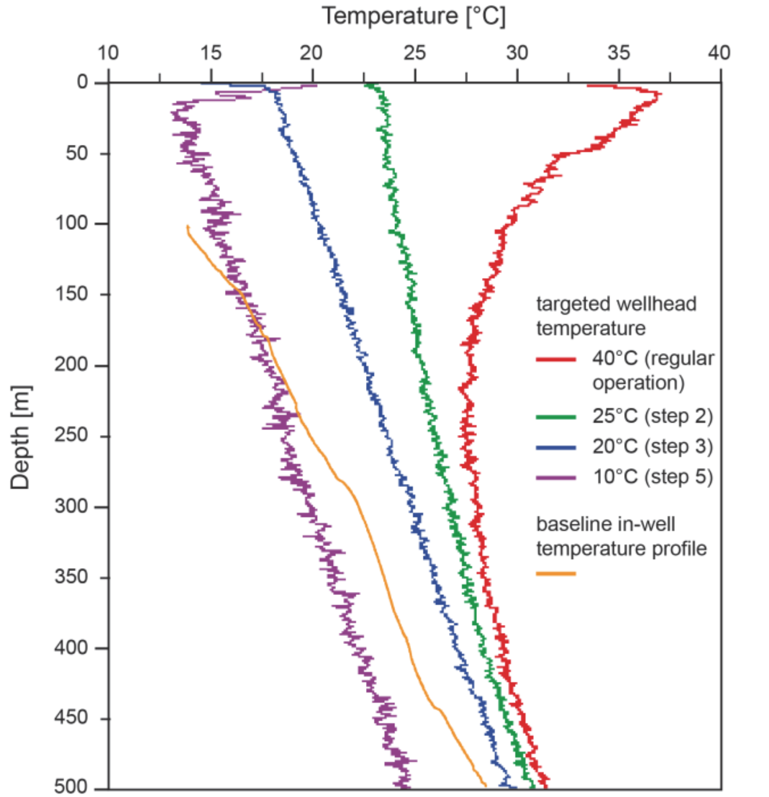


- smooth injection process, maximum pressure increase ~16 bar
- no safety issues, downhole pressure « formation pressure (p-limit)
- continuous p-decline after stop of injection (towards long-term stability)

DTS monitoring @ Ktzi 200, 201, 202



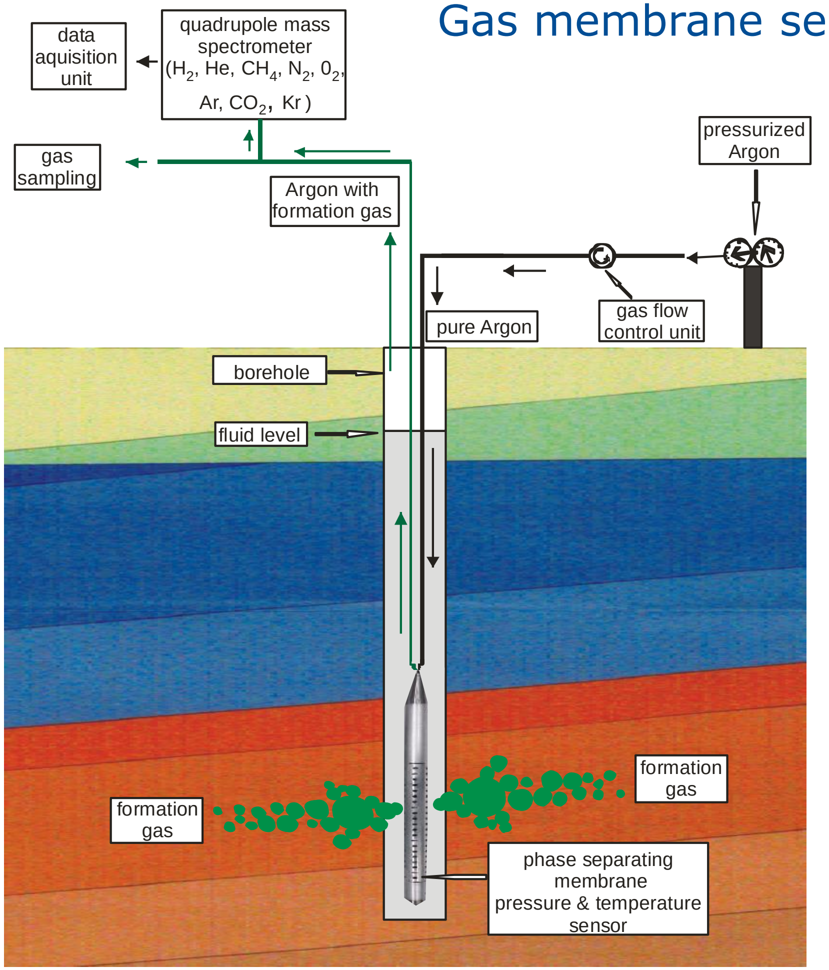
Long-term monitoring of the injection history
Henninges (2012)

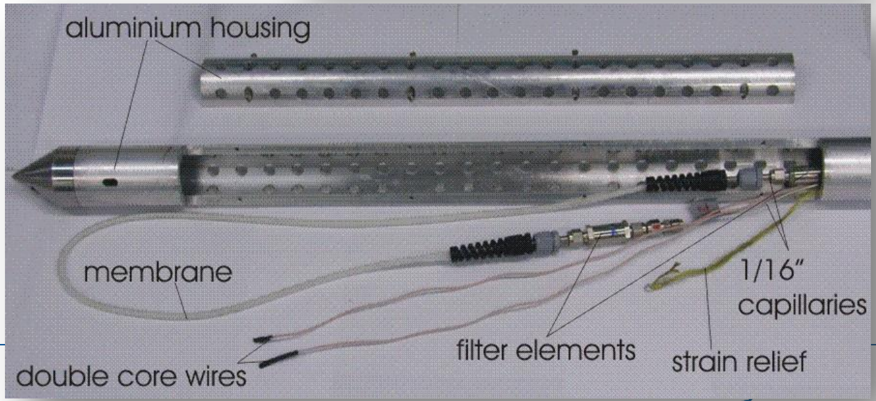


Process monitoring (cold injection)
Möller et al. (2014)

In-situ gas monitoring for CO_2 detection

Gas membrane sensor (GMS)

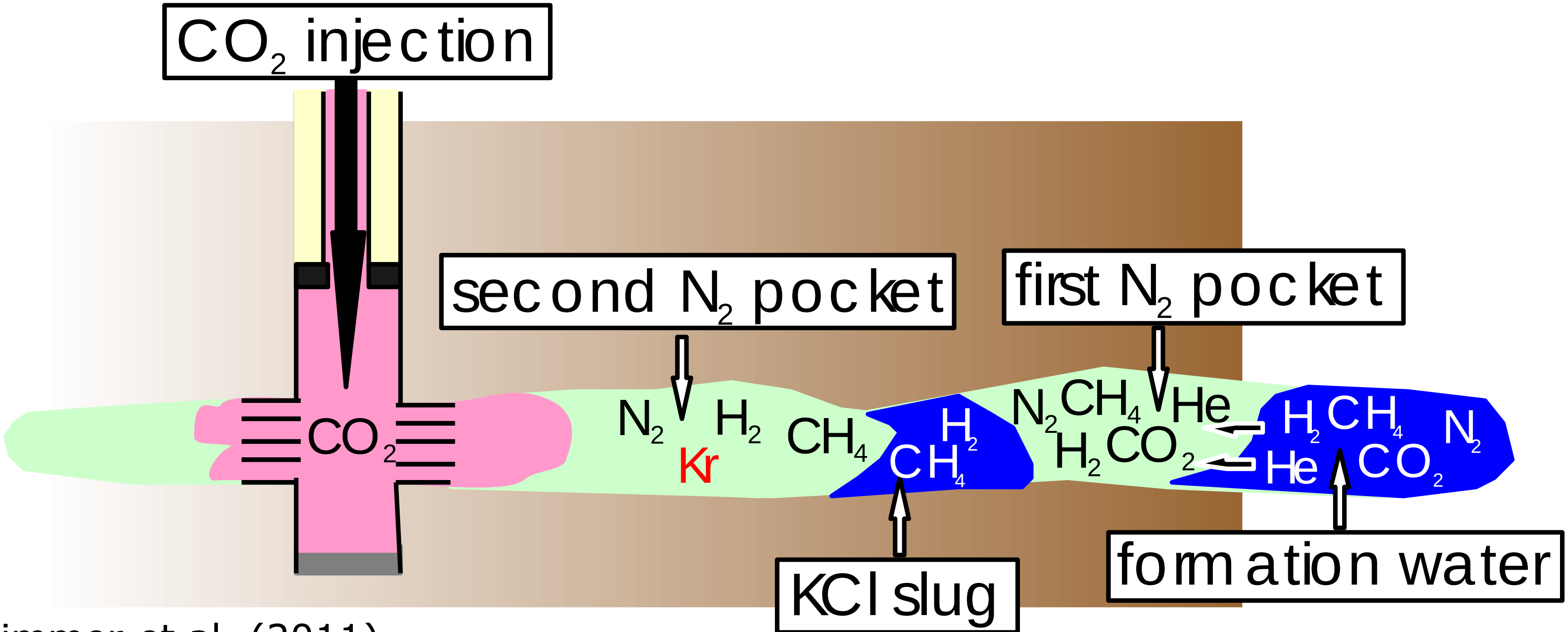




Patent No. US 7523680 B2

First CO_2 injection (24th June, 2008)

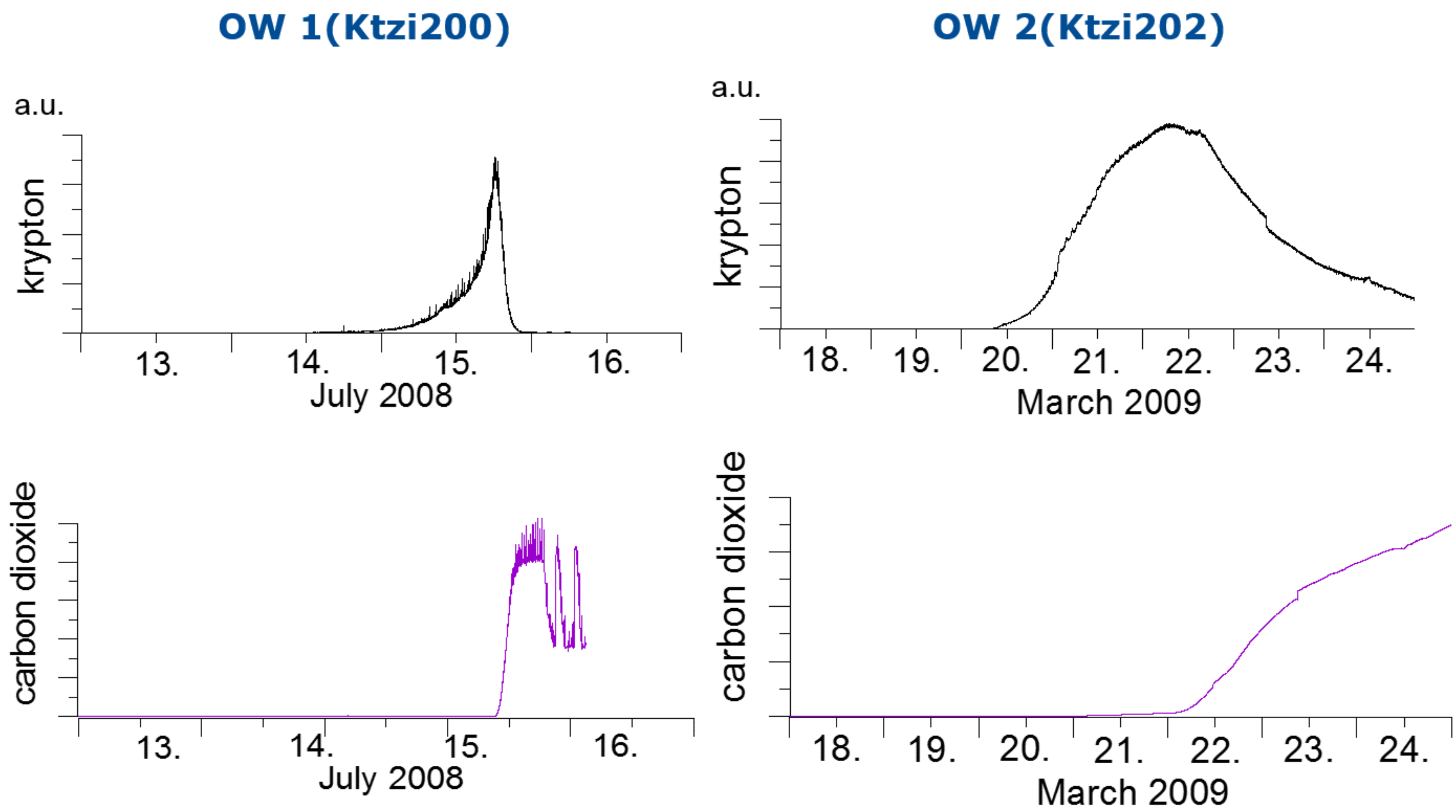
Conceptual model for processes occurring in the injection well Ktzi201:



Zimmer et al. (2011)

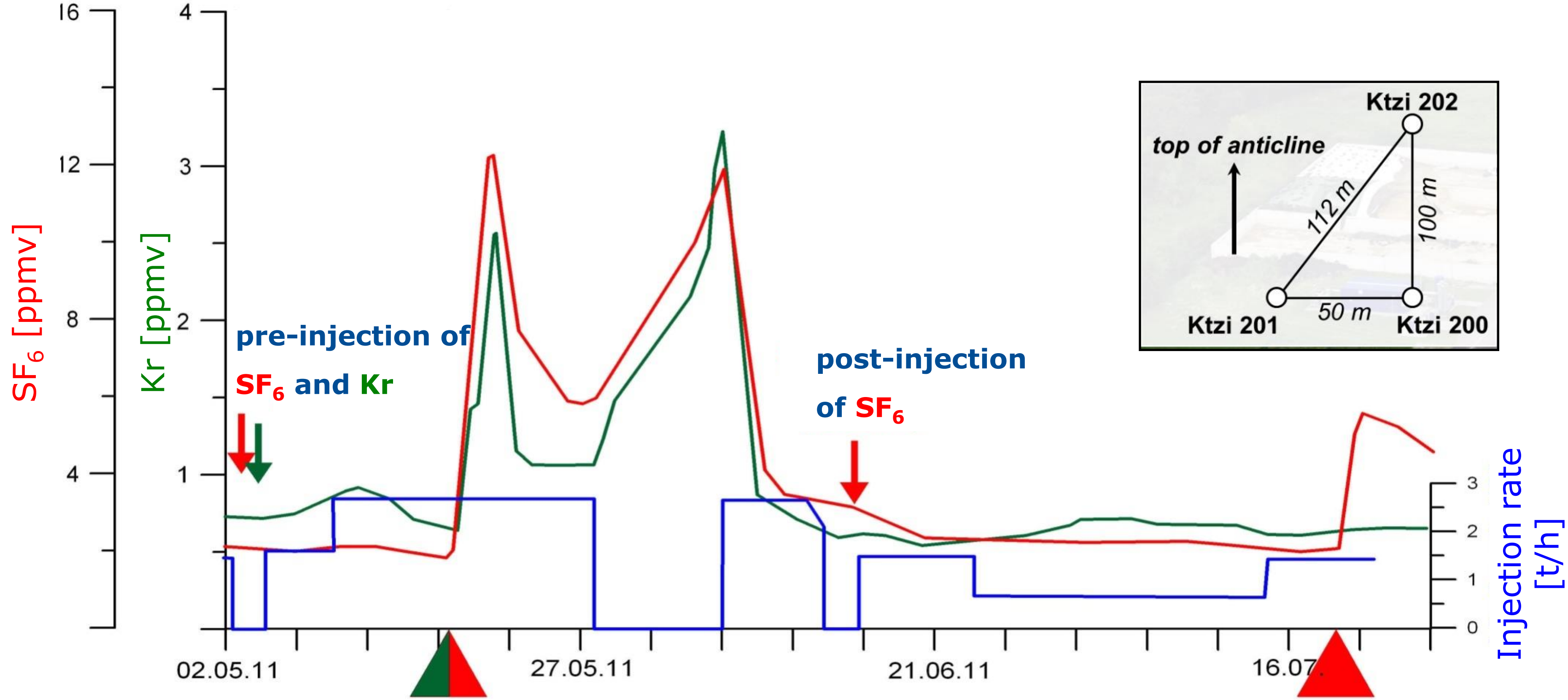
- GMS registered changes during the storage process to detect the arrival of CO_2 at the observation wells.
- Displacement of formation water and residual gas by the injected CO_2 has been observed, bioactivity in the filter screen was seen.

Arrival of Krypton (Tracer) and CO_2



(Zimmer et al., 2011)

Tracer tests with SF_6 and Kr indicate CO_2 from Schwarze Pumpe pilot plant

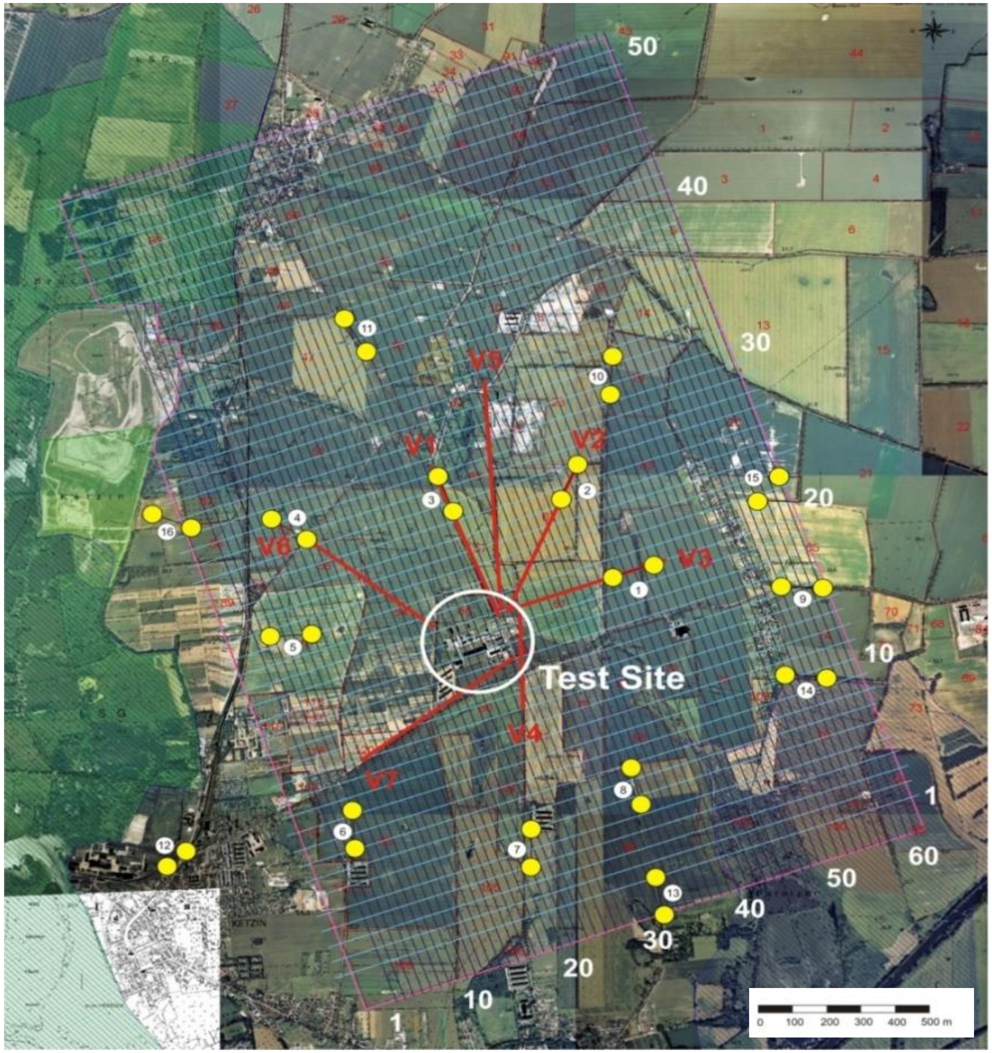


detection of pre-SF_6 and pre-Kr in Ktzi 200
18.05.2011

detection of post-SF_6 in Ktzi 200
19.07.2011

CO_2 injected at Ktzi 201	Schwarze Pumpe	Linde
CO_2 at Ktzi 200	Linde / Schwarze Pumpe	Linde

Geophysical methods with different spatial resolution are applied



Active seismic methods

surface-surface:
3-D (grid), 2-D star (red lines)

surface-downhole:
vertical seismic profiling VSP
moving source profiling MSP

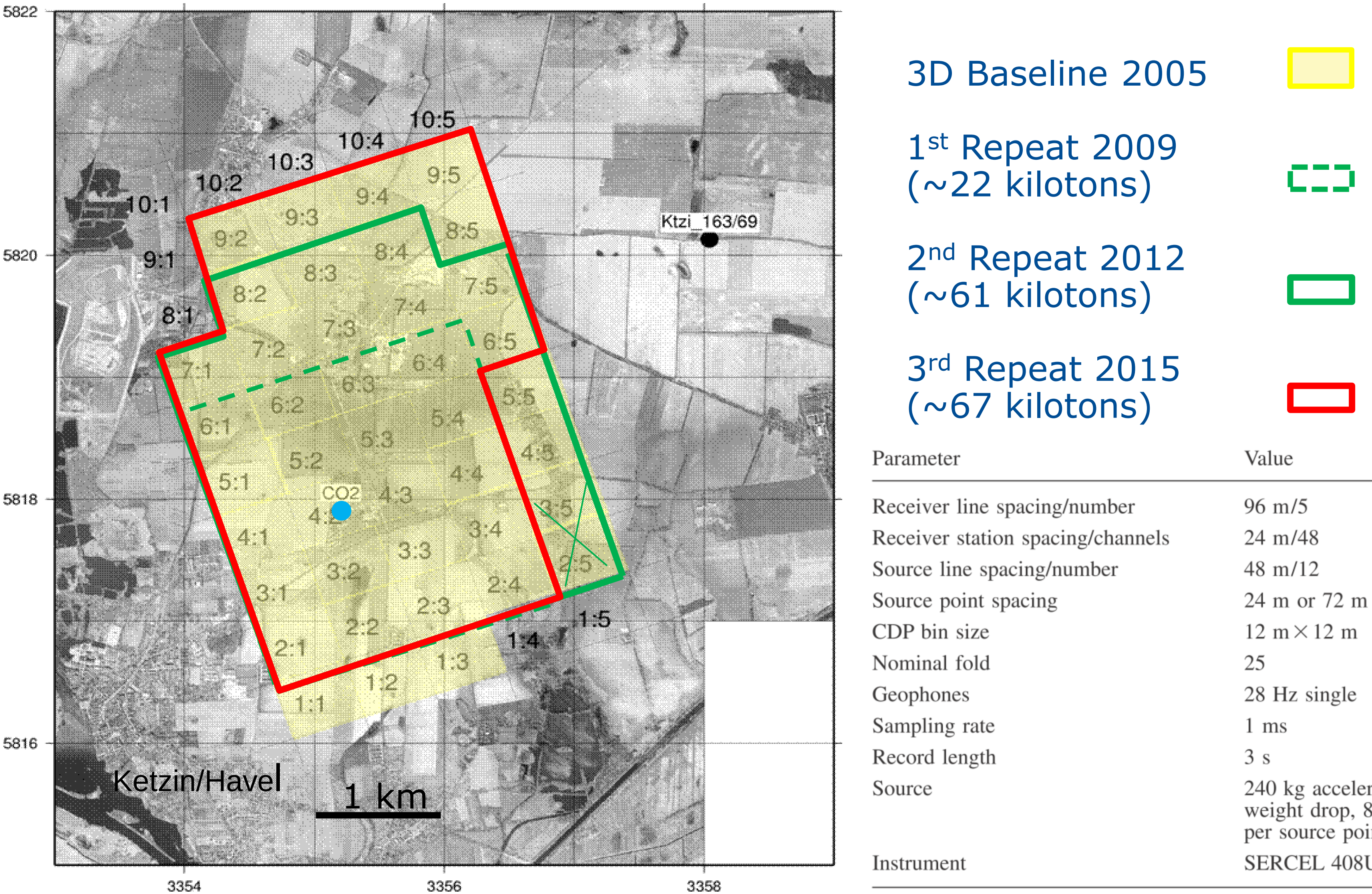
cross-hole (white circle)

Passive seismic methods

Geoelectric methods

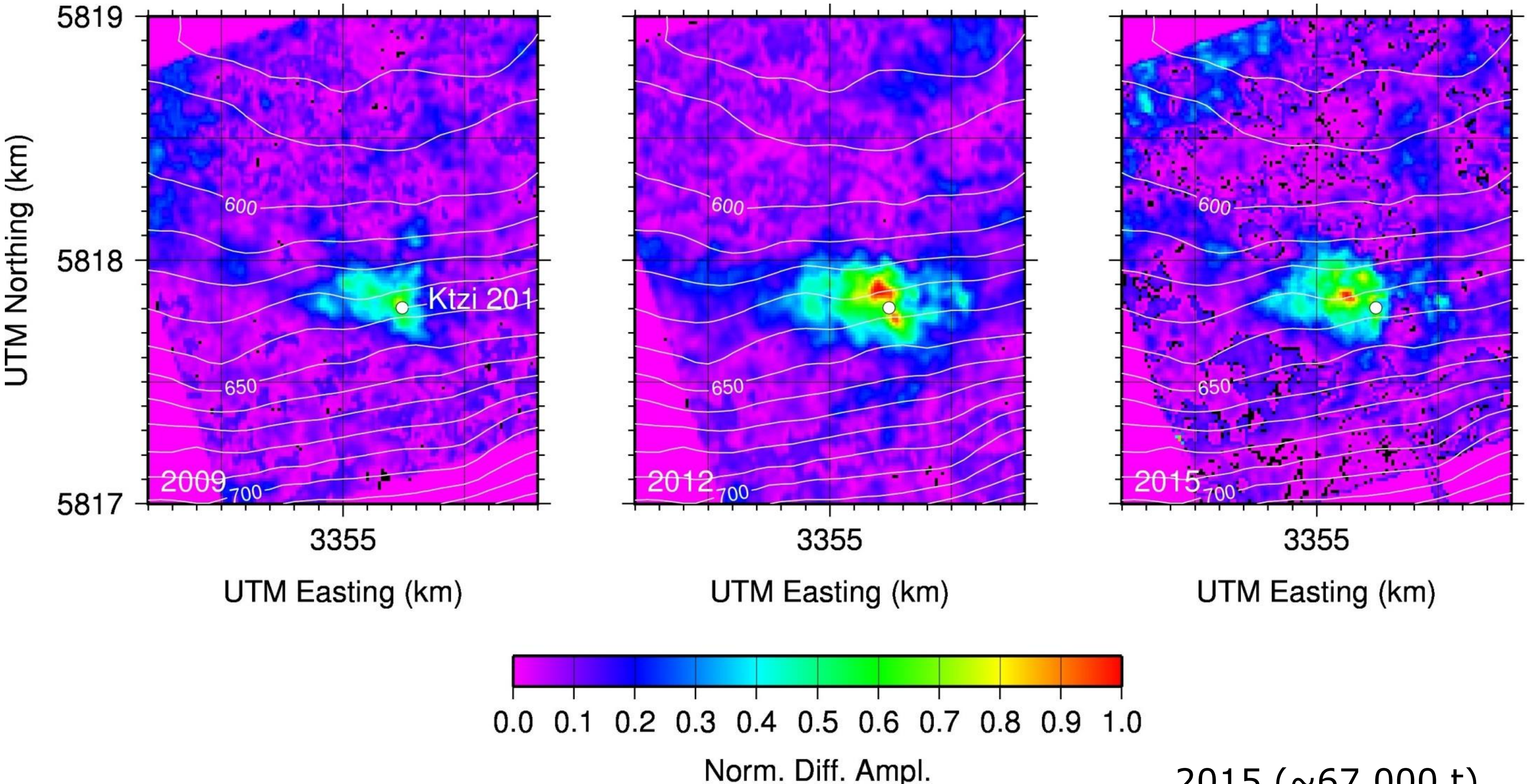
surface-downhole (yellow dots)
cross-hole (white circle)

4D seismic surveys at Ketzin



Parameter	Value
Receiver line spacing/number	96 m/5
Receiver station spacing/channels	24 m/48
Source line spacing/number	48 m/12
Source point spacing	24 m or 72 m
CDP bin size	12 m × 12 m
Nominal fold	25
Geophones	28 Hz single
Sampling rate	1 ms
Record length	3 s
Source	240 kg accelerated weight drop, 8–9 hits per source point
Instrument	SERCEL 408UL

Maps of time-lapse amplitudes in the storage layer showing stabilization of CO_2 plume



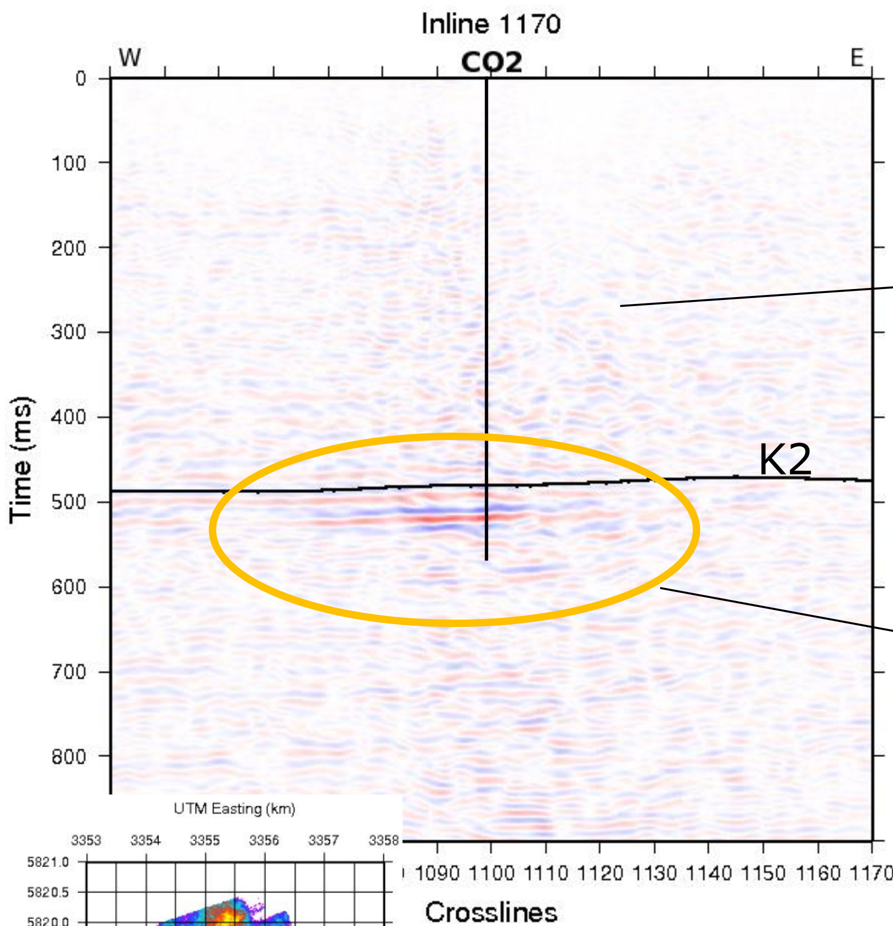
2009 (~23.000 t)

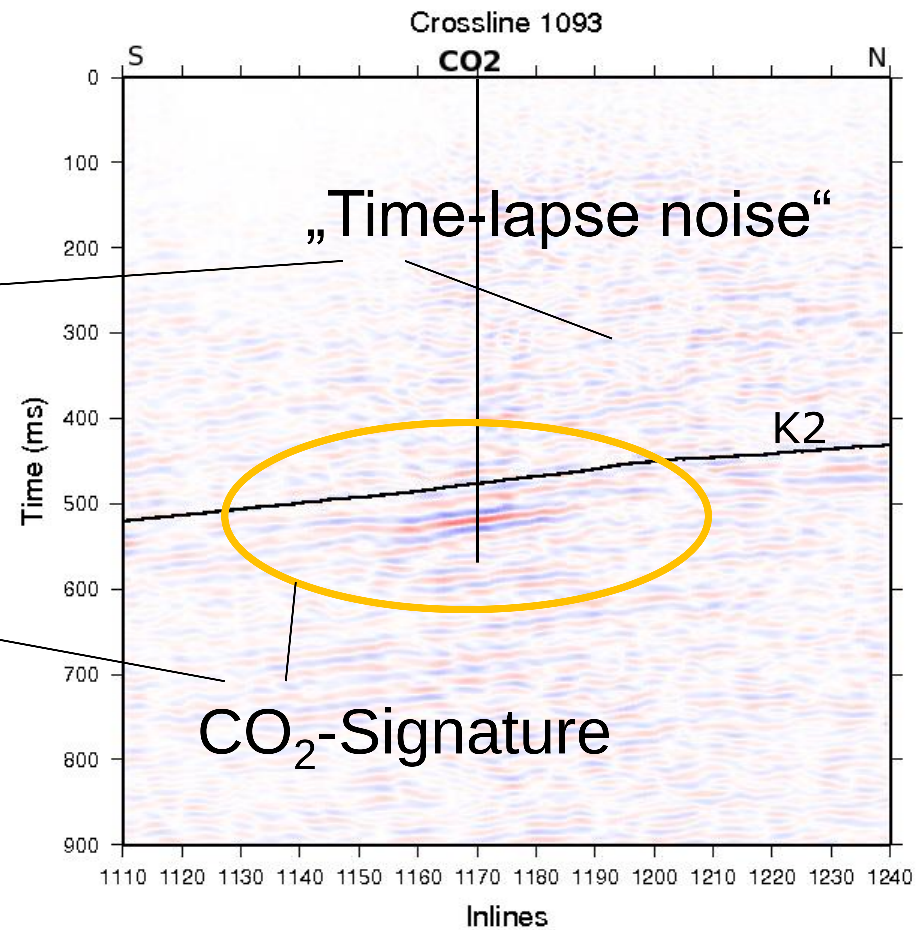
2012 (~61.000 t)

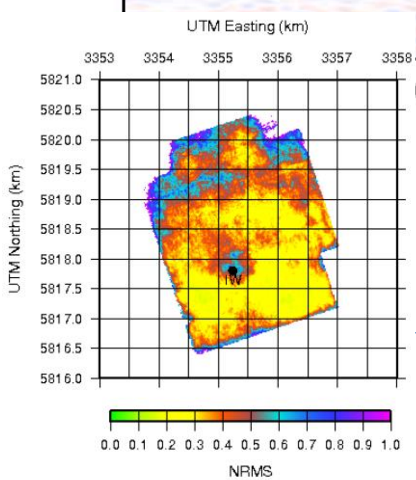
2015 (~67.000 t)
~ 2 years post-inj.

(Ivanova et al., 2012, Ivandic et al., 2015, Huang et al., 2016)

Sections of time-lapse amplitudes (2012-2005)







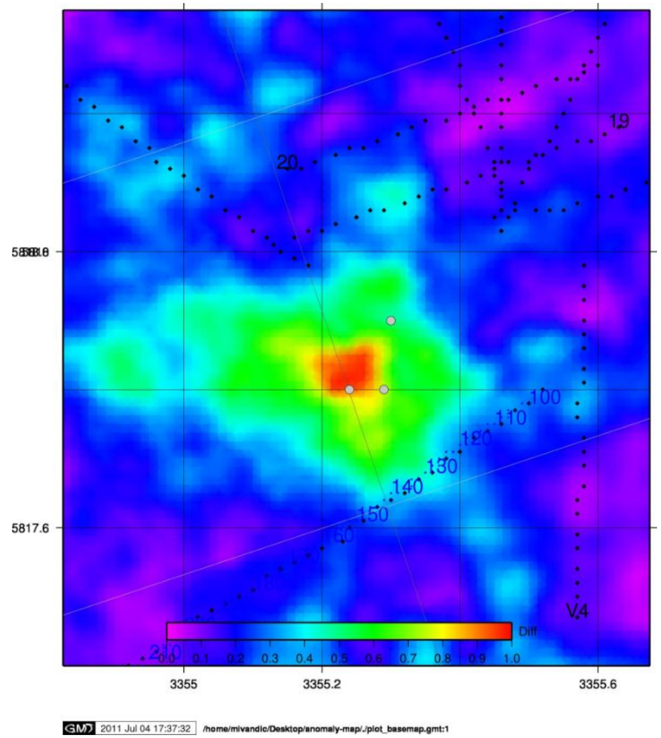
- Clear amplitude signature of the injected CO_2.
- Small NRMS (good repeatability).
- No indications of migration (leakage) to shallow layers.

HELMHOLTZ GEMEINSCHAFT

Sparse 3D geometry maps the CO_2 in the reservoir

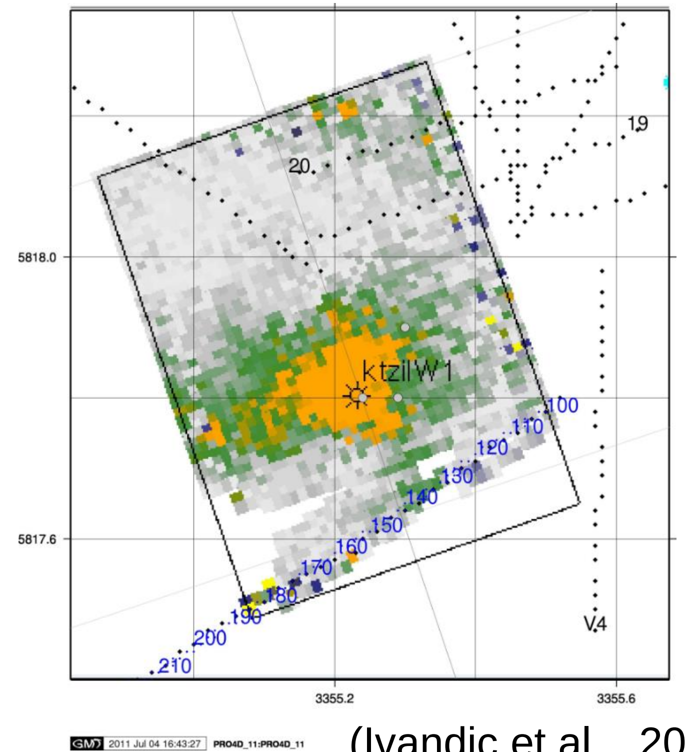
Difference amplitudes at Top Stuttgart

3D repeat Autumn 2009



(Juhlin et al. 2010 / Lueth et al., 2011)

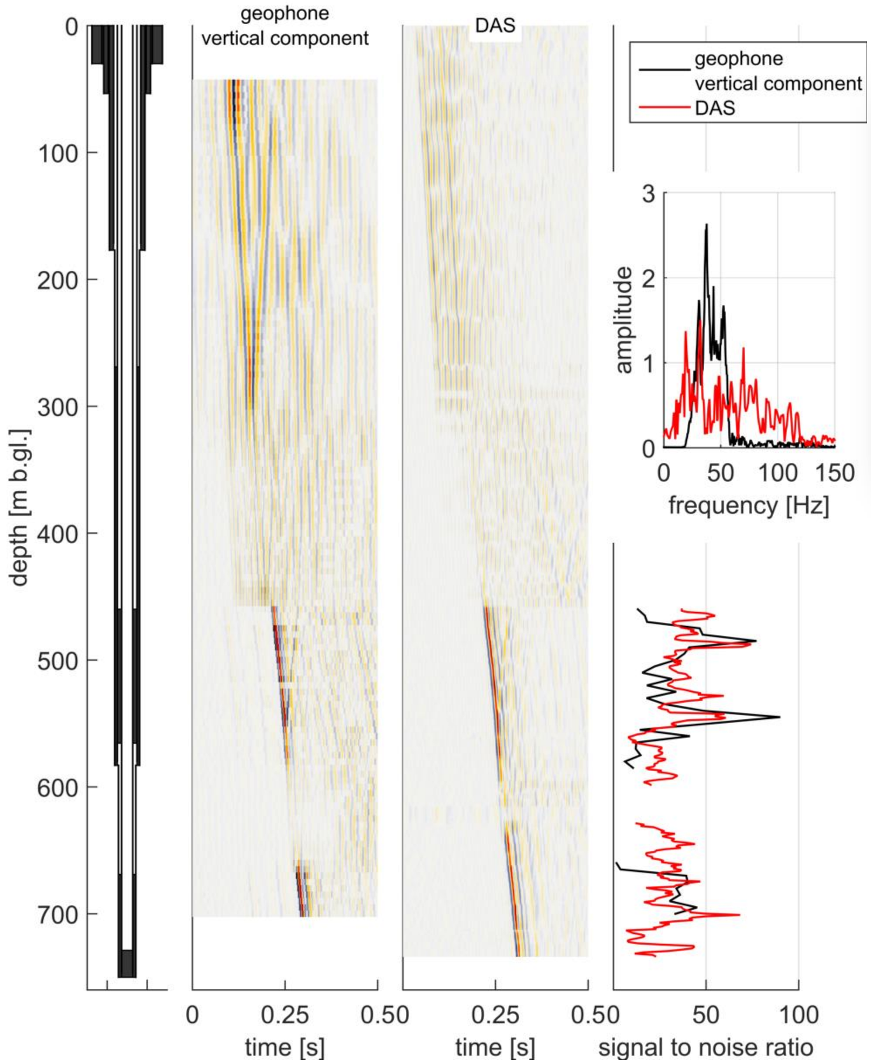
Star lines repeat survey, Februar 2011



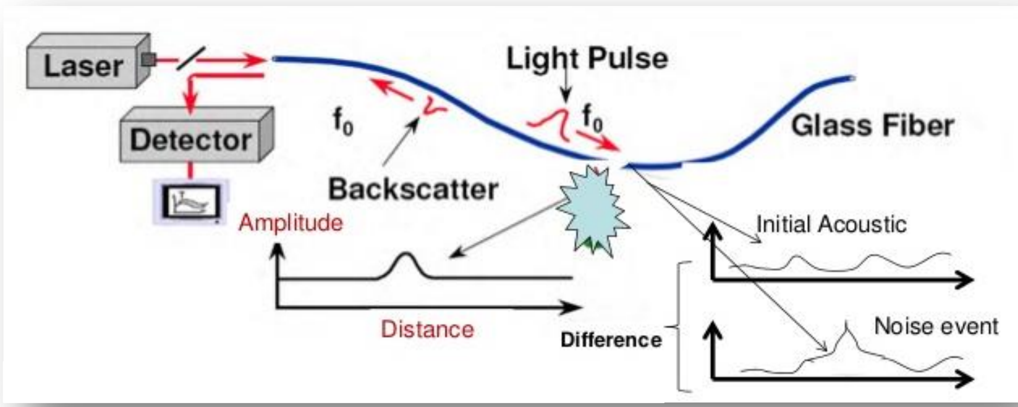
(Ivandic et al., 2011)

- Consistent results with the 3D seismic time-lapse studies achieved
- Lower operational and cost effort than for the conventional 3D surveying
- Preferential migration of the CO_2 towards the WNW direction is indicated

Test 3c-geophon vs. distributed acoustic sensing (DAS)



Sensing principle of DAS



(Source: D. Dria, SPE Lecturer Prog., 2012)

Conventional VSP survey:
3c-geophones and VIBSIST source
Spatial sampling: 5 m

DAS survey:
Fiber cable and VIBRO source 7- 120Hz.
Spatial sampling: 1 m

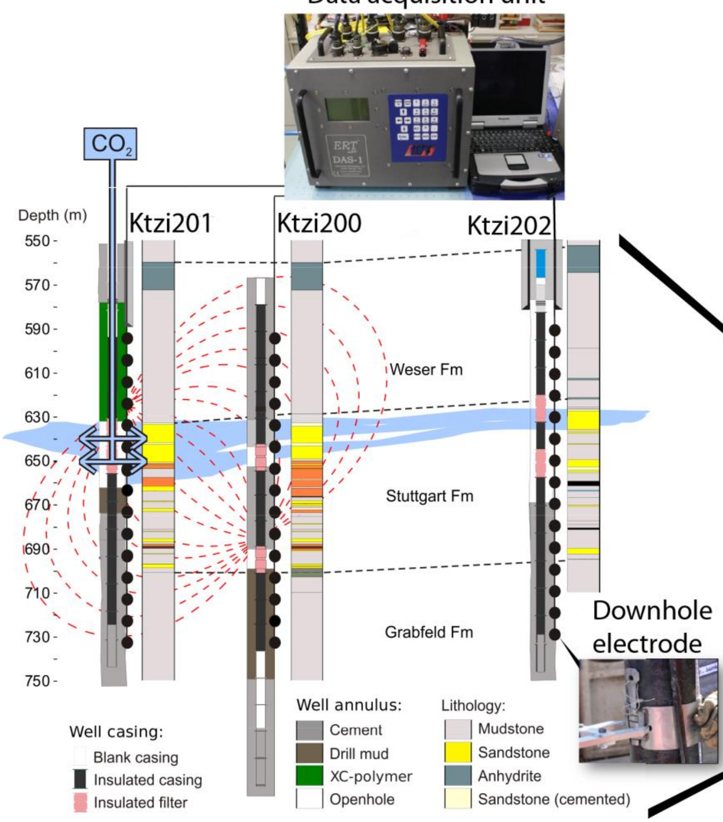
Comparable SNR

(Reinsch et al. 2015, World Geothermal Congress)

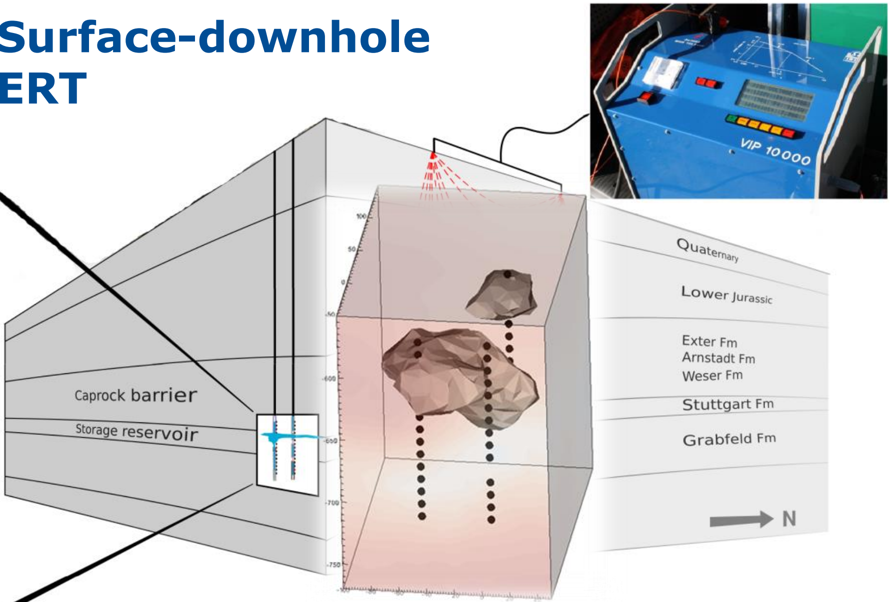
Geoelectric monitoring concept at Ketzin

Crosshole ERT

Resistivity measurements are sensitive to changing pore fluids.



Surface-downhole ERT

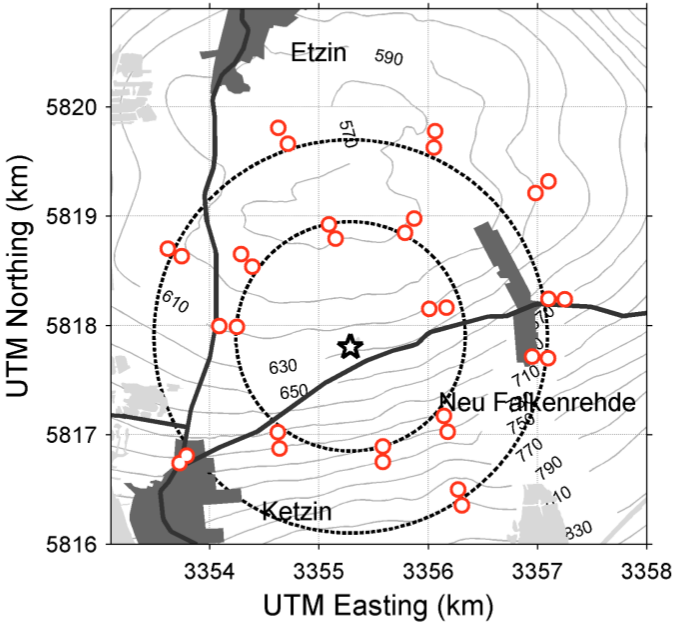


(ERT: Electrical Resistivity Tomography)

Displacement of saline formation water due to injected CO_2 increases the electrical resistivity ρ.

Large-scale geoelectric surveys at Ketzin

Acquisition geometry of the Surface-downhole electrical resistivity tomography (SD-ERT) surveys



Baseline 1	**Oct 2007**	**0 tons CO_2**
Baseline 2	**April 2008**	**0 tons CO_2**
Repeat 1	**July 2008**	**~0.6 kilotons CO_2**
Repeat 2	**Nov 2008**	**~4.5 kilotons CO_2**
Repeat 3	**April 2009**	**~13.7 kilotons CO_2**
Repeat 4	**April 2011**	**~47 kilotons CO2**
Repeat 5	**April 2012**	**~60 kilotons CO2**

Electric power source TSQ4 (I_{max} = 11 A, U_{max} = 3.3 kV)

Texan-125 data logger

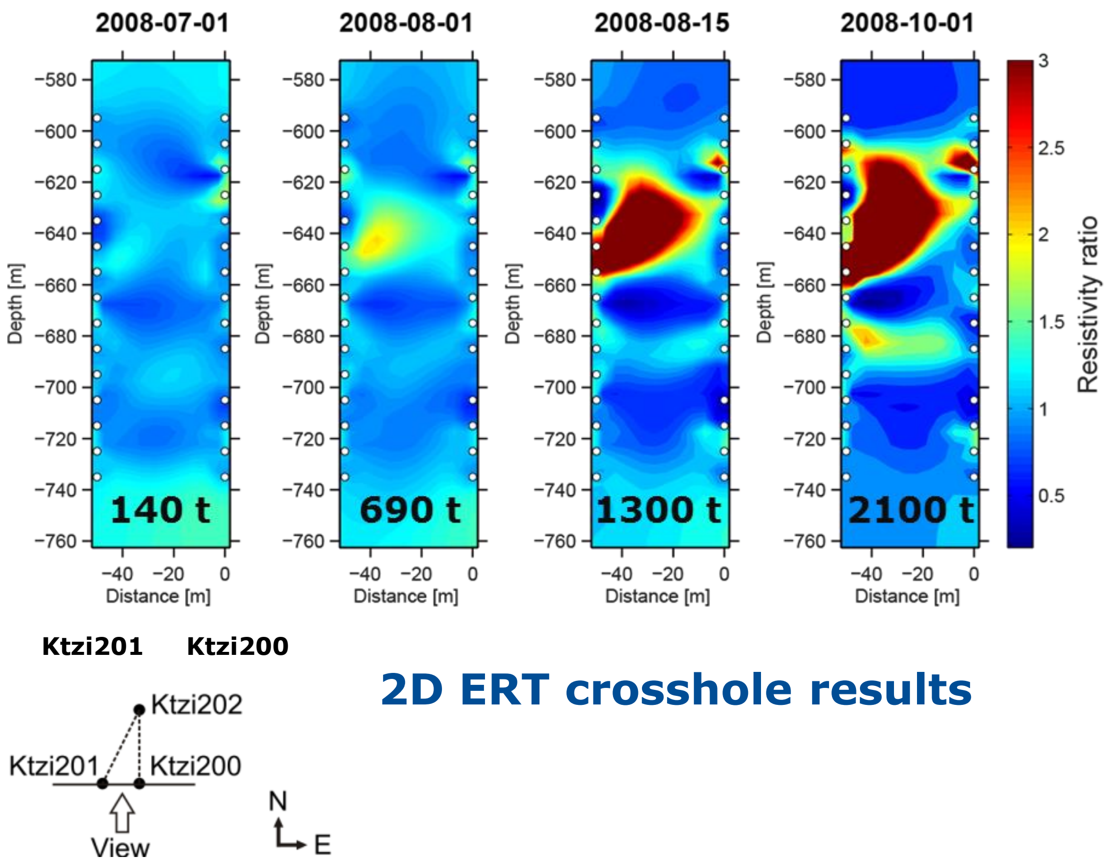
UNIVERSITÄT LEIPZIG

Institute of Geophysics and Geology

Borehole electrode

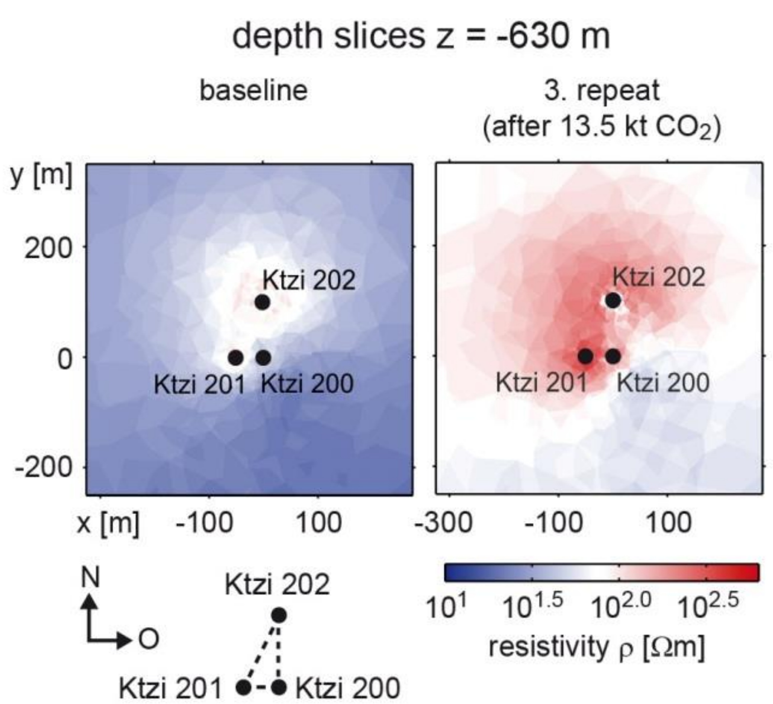
Surface electrode ensemble for current injection

ERT measurements show resistivity increase and give tomographic information



2D ERT crosshole results

Surface-downhole measurements



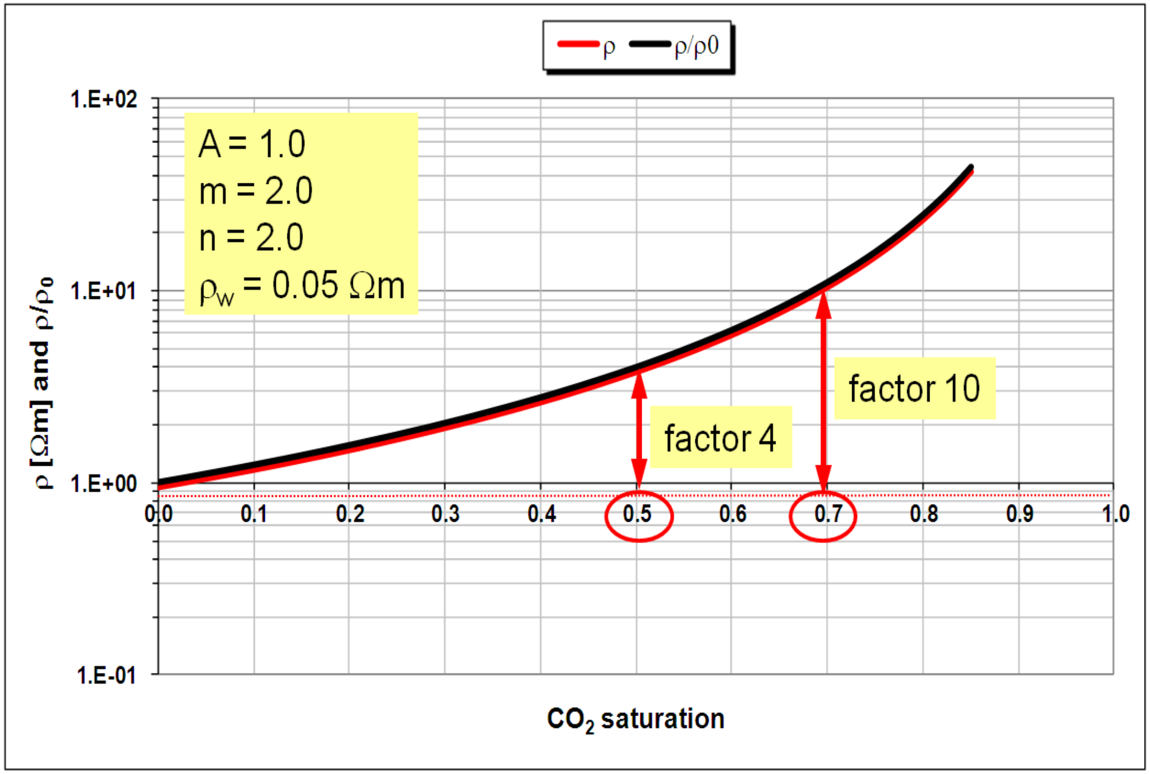
- Settlement of the CO_2 related transient effects in the near-wellbore area after ~6 months.

Bergmann et al. (2012)

Petrophysical relation between resistivity & saturation

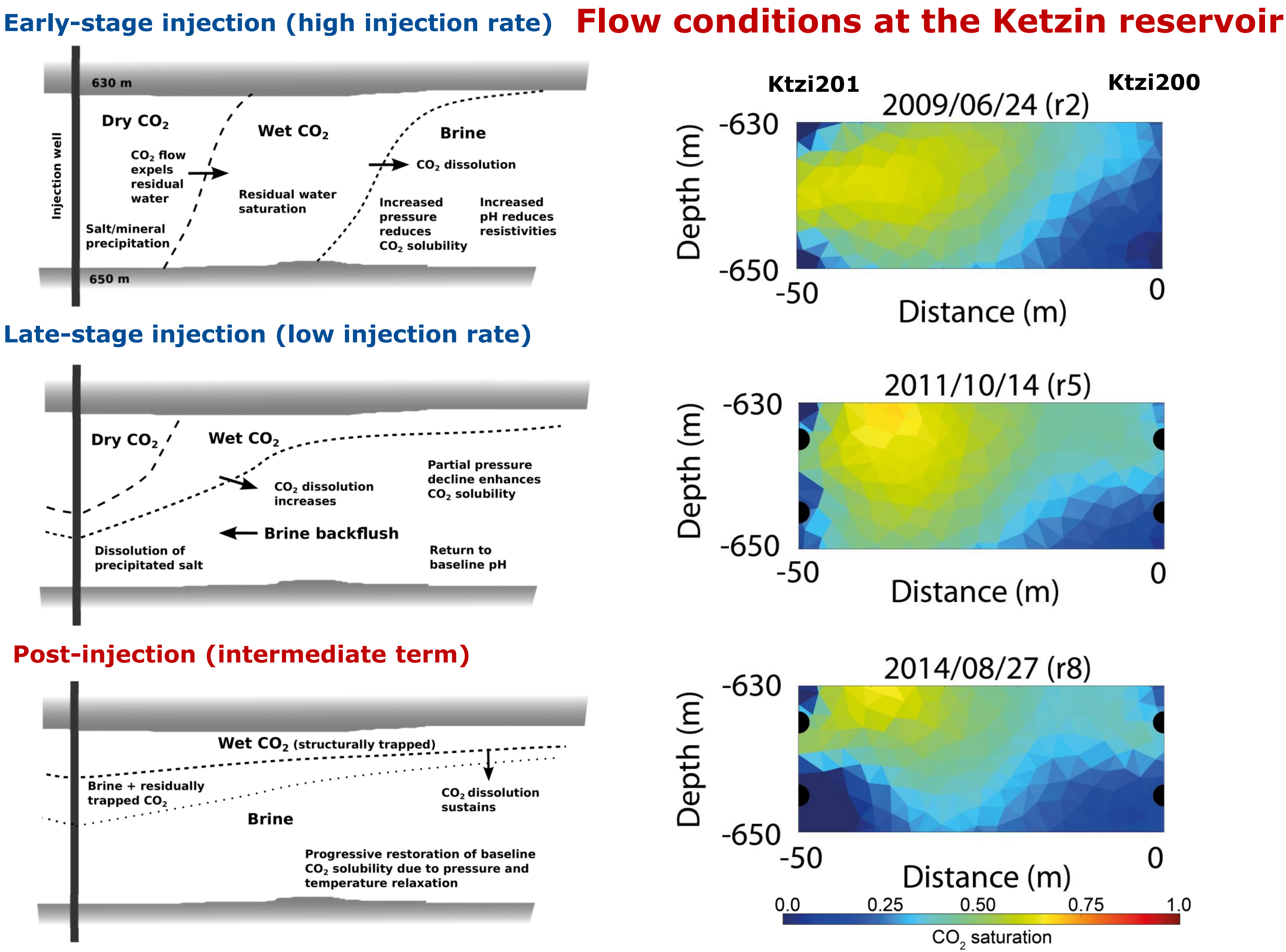
The changes of resistivity in dependance of the pore fluid can be expressed by Archie´s law (1942):

$$\rho = A\, \rho_W\, \phi^{-m}\, S_W^{-n} \quad ;\ \text{with} \quad S_{CO2} = 1 - S_W$$



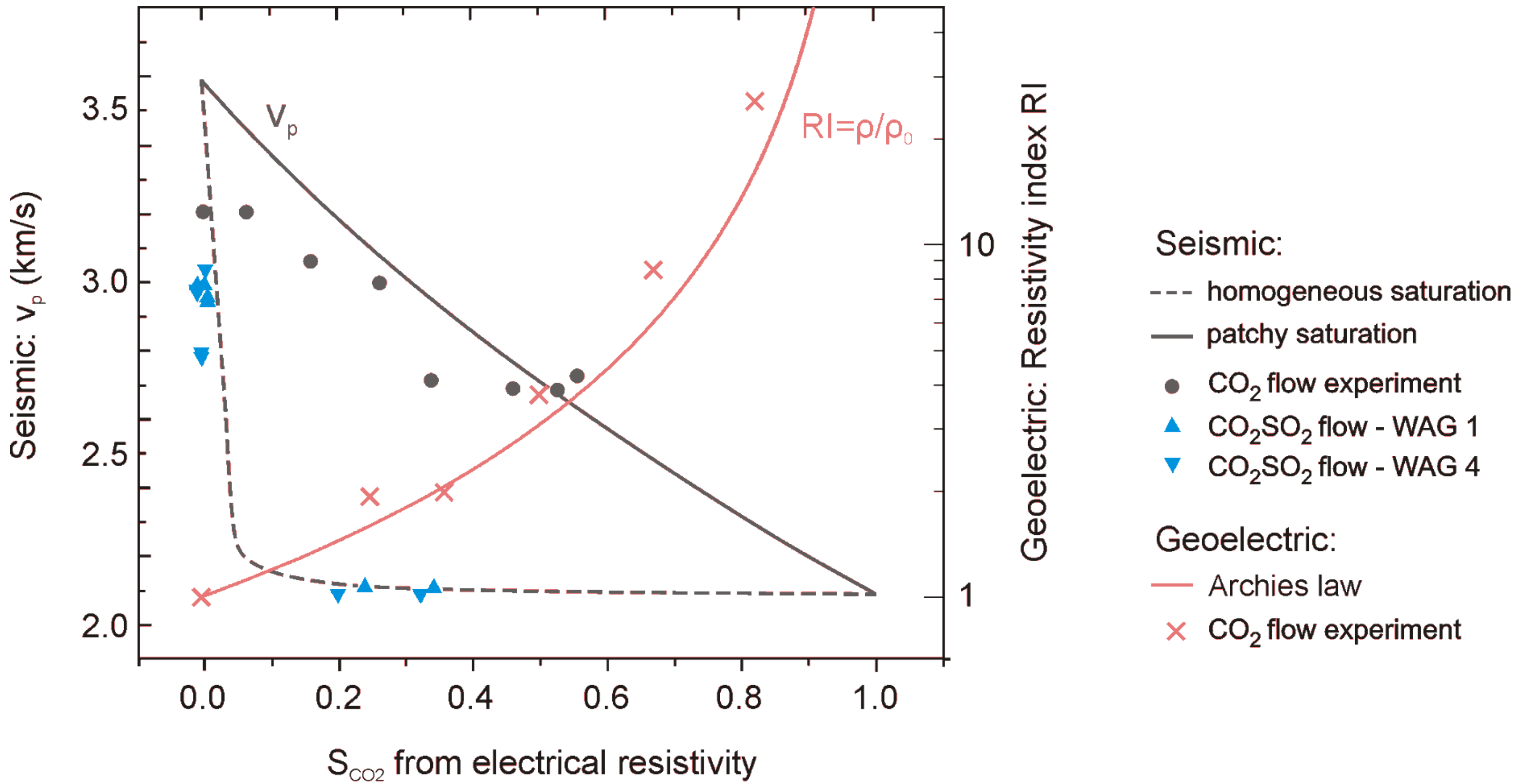
Expected changes for the Ketzin test site:

- Salt content of formation fluid: ~ 230 g/l
- Reservoir temperature: ~36 °C (from T-logs)
- Resistivity of 20% Sole @ 36°C: 0.05 Ωm
- Average porosity: 23 %
- Archie parameter:
- A = 1; m=2, n = 2



Early-stage injection (high injection rate)
Flow conditions at the Ketzin reservoir
630 m
Injection well
Dry CO2
Wet CO2
Brine
CO2 flow expels residual water
Residual water saturation
CO2 dissolution
Increased pressure reduces CO2 solubility
Increased pH reduces resistivities
Salt/mineral precipitation
650 m
Late-stage injection (low injection rate)
Dry CO2
Wet CO2
CO2 dissolution increases
Partial pressure decline enhances CO2 solubility
Brine backflush
Dissolution of precipitated salt
Return to baseline pH
Post-injection (intermediate term)
Wet CO2 (structurally trapped)
Brine + residually trapped CO2
CO2 dissolution sustains
Brine
Progressive restoration of baseline CO2 solubility due to pressure and temperature relaxation
Ktzi201
Ktzi200
2009/06/24 (r2)
2011/10/14 (r5)
2014/08/27 (r8)
Depth (m)
-630
-650
-50
0
Distance (m)
0.0
0.25
0.50
0.75
1.0
CO2 saturation

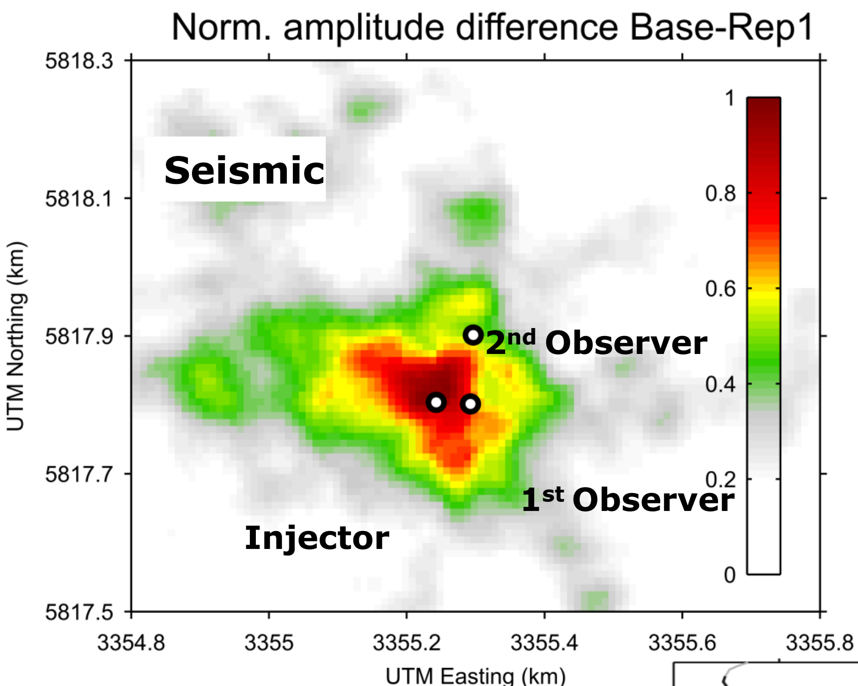
Petrophysical sensitivities motivate multi-method monitoring

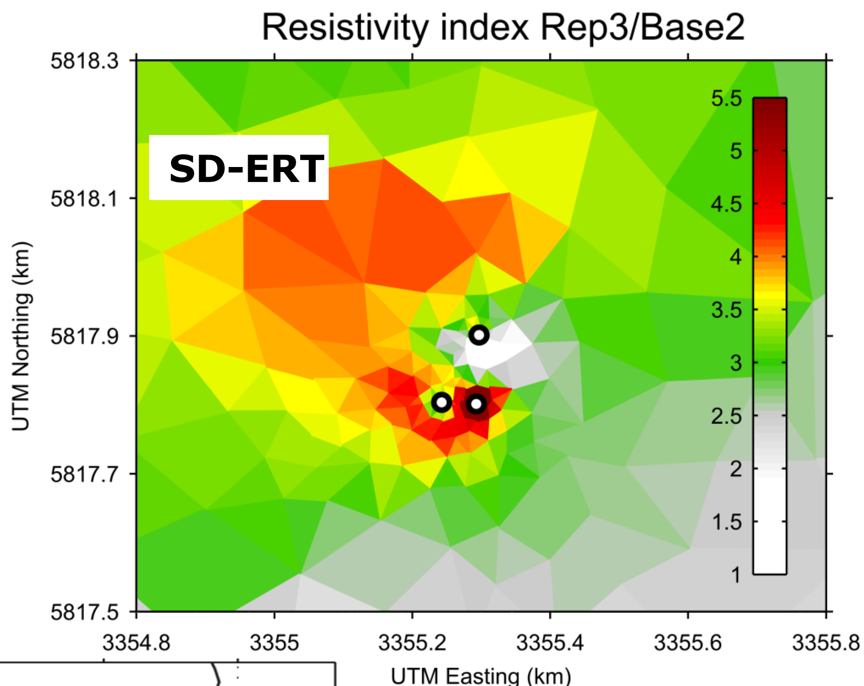


Compiled and redrawn after Kummerow and Spangenberg (2011)

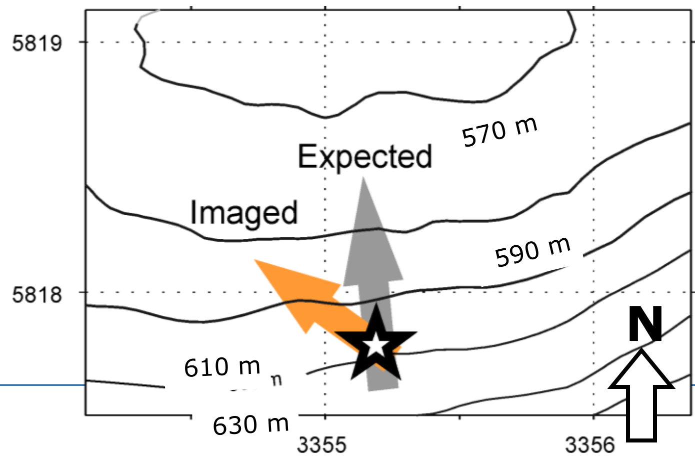
The time-lapse responses vis-à-vis

Comparison 3D seismic with structural constrained geoelectric results





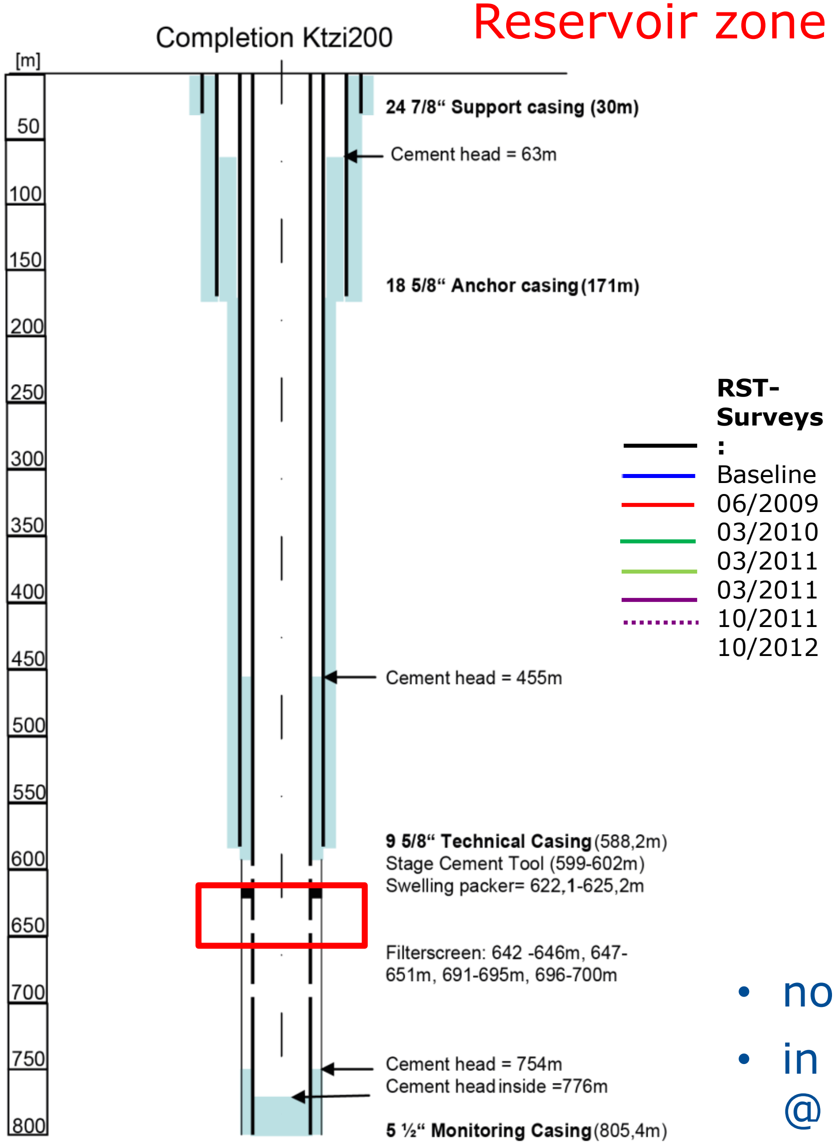
22 kt CO_2

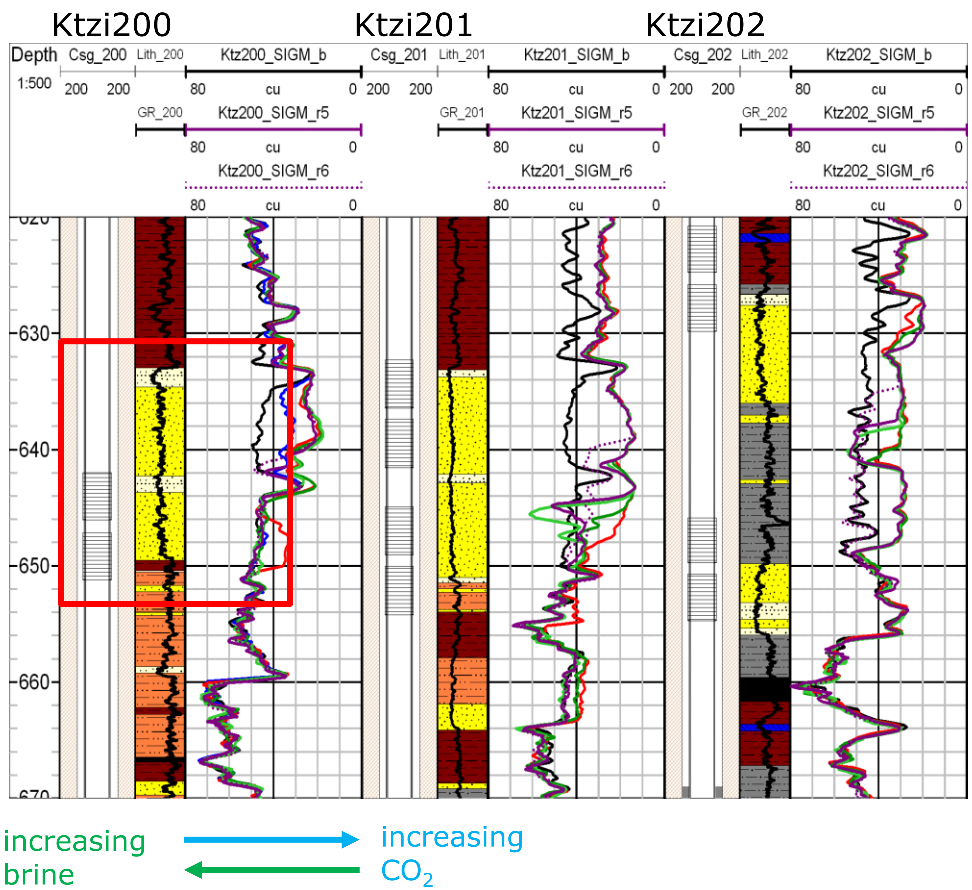


13,5 kt CO_2

Reservoir Saturation Tool (RST) measurements

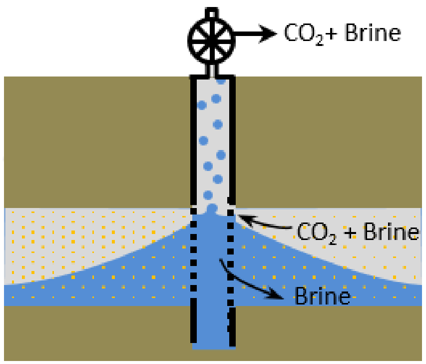
Reservoir zone

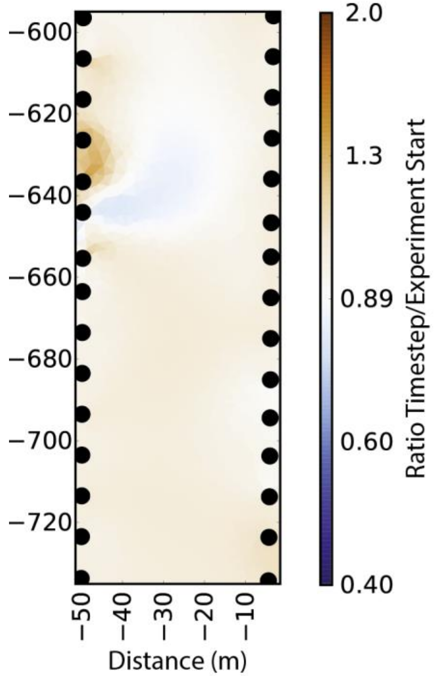




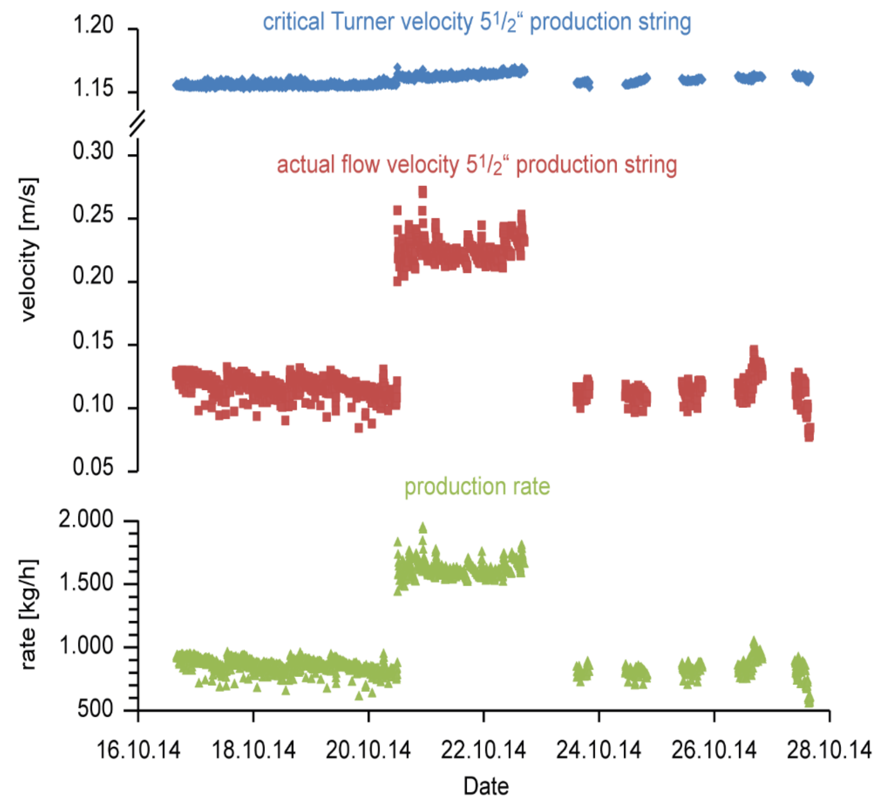
- no CO_2 in the caprock and in the substratum
- in the uncemented parts of borehole annulus @ Ktzi201 and Ktzi202 CO_2 has been detected

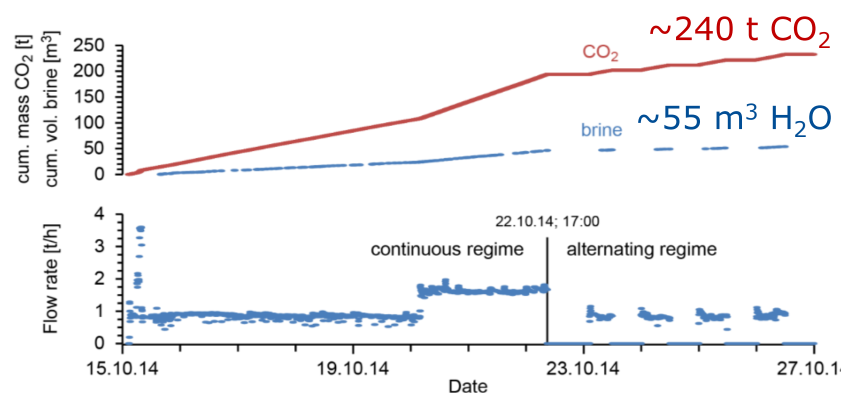
CO_2 back production from the reservoir





October 22, 2014
Back Production



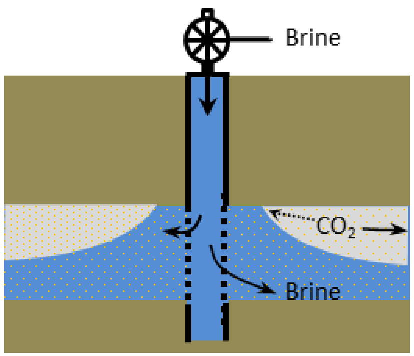


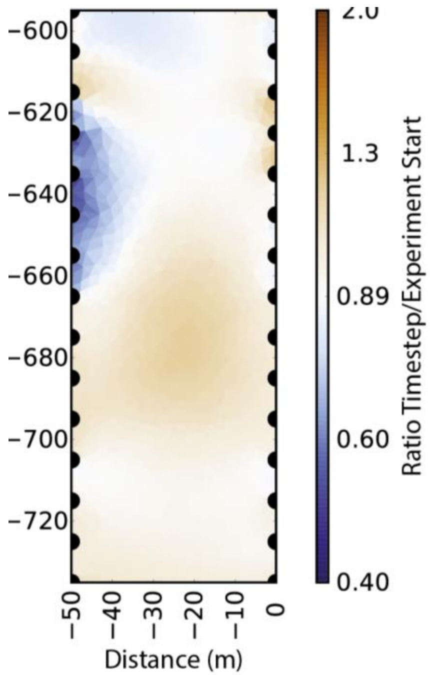
Production of **240 t CO_2/55 t formation water**

Flow rates were high enough to exceed the minimum (critical) velocity for fluid entrainment.

Stimulation of formation water is seen, together with the ascending CO2 .

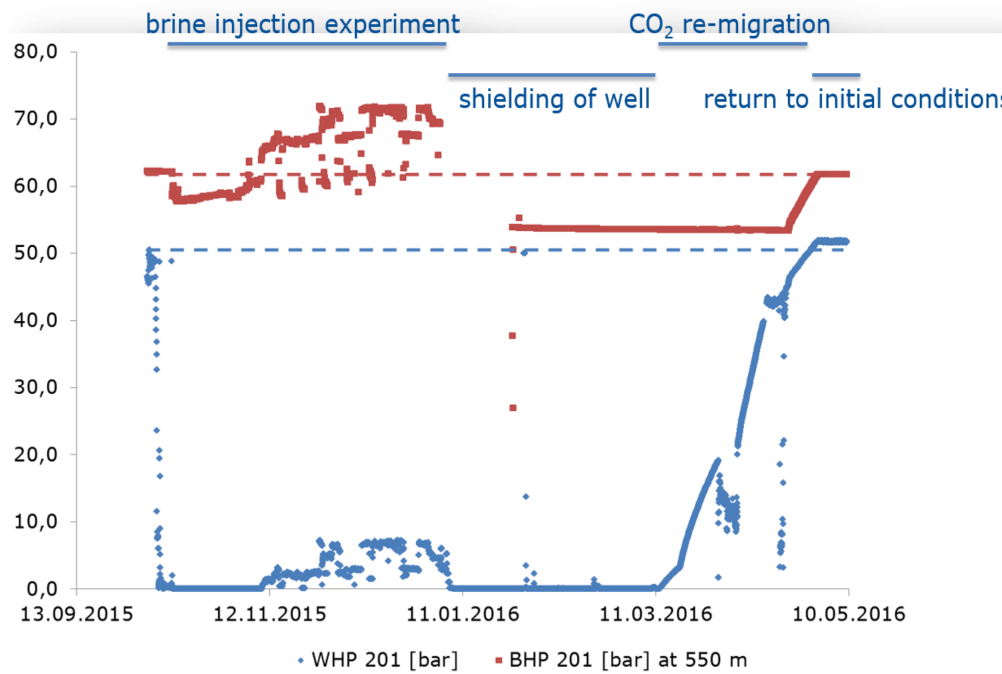
Brine injection as remediation measure





November 15, 2015

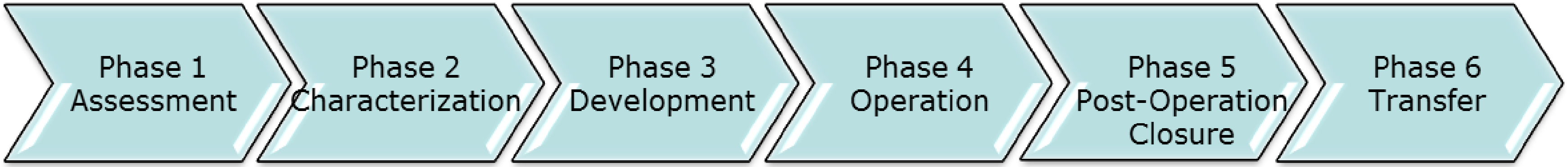
Brine Injection



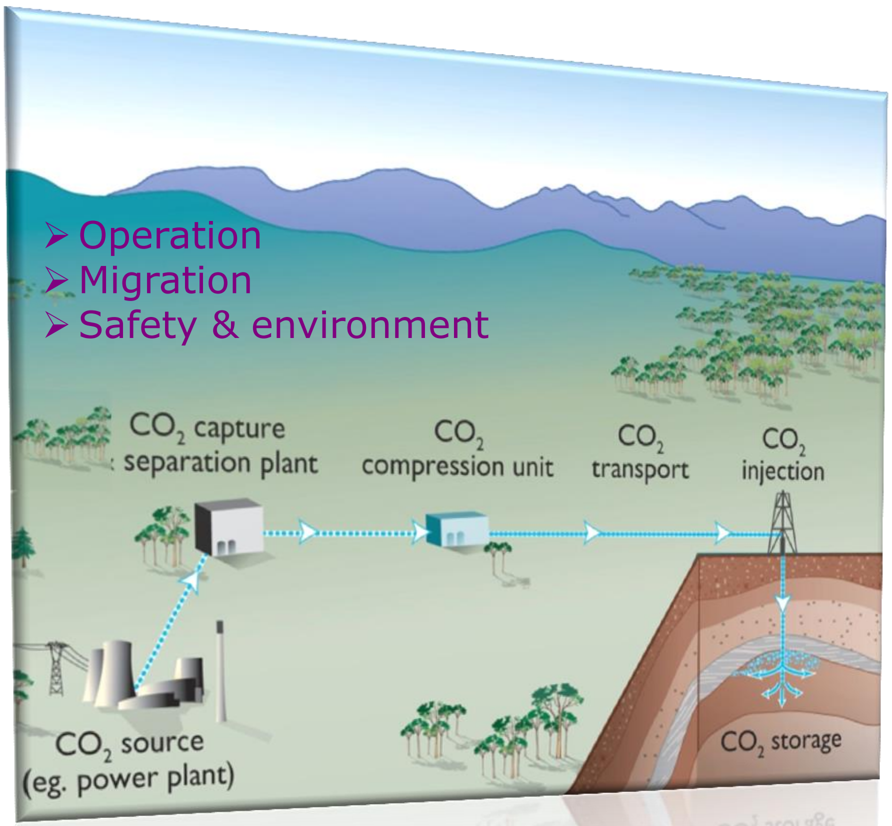
Injection of **2,884 t brine,** imaging of CO_2 displacement by brine.

Zero well-head pressure maintained for two months → enables shielding a „leaking" well and provides additional time for well remediation work.

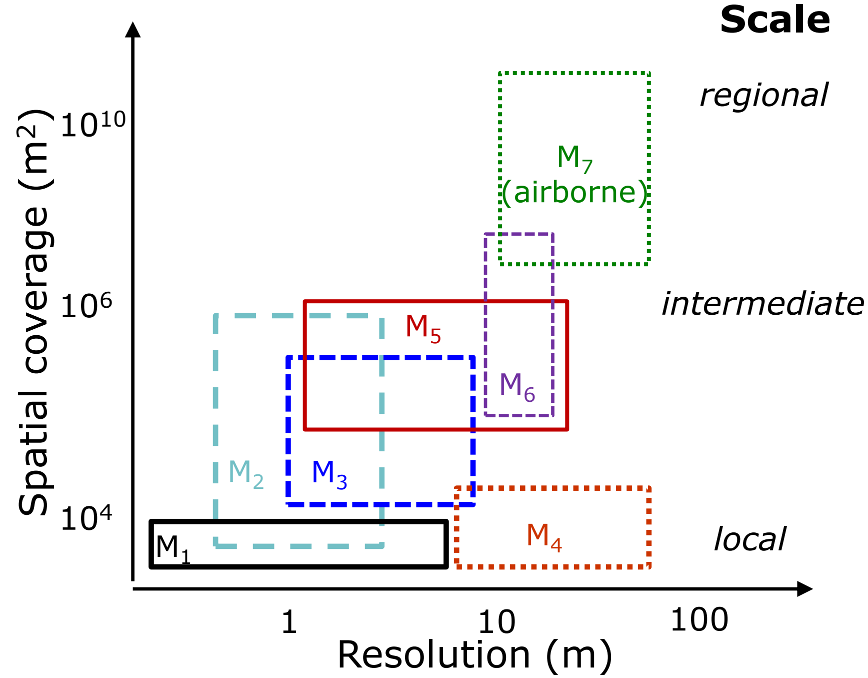
Monitoring accompanies the whole life-cycle of a CO_2 storage site



Source : Guidance Document GD3 to the 2009/31/EU CCS Directive



Monitoring by multi-disciplinary methods M_N



Conclusion

The multi-disciplinary reservoir monitoring concept …

- **… is capable of detecting small amounts of CO_2, e.g. clear signature at ~ 500 tons.**
- **… can image regular injection operations as well as reservoir processes related to pore fluid contrasts, i.e. CO_2 migration, CO_2 venting or brine injection as flow diversion measures.**
- **… can accompany all phases of the storage reservoir at various scales as demanded by regulatory frameworks.**
- **… provide a data base for coupled/joint data evaluation, and therefore, improved reservoir interpretation.**

Due to its long life-time and comprehensive data harvest, the monitoring investment was worthwhile and profitable from the scientific point of view!

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Ketzin publication archive → http://www.co2ketzin.de/en/publications/

Many project partners support the R&D activities at Ketzin since 2004, e.g.

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