# From Site Characterisation to Post-Injection: Lessons learned from the $CO_2$ Pilot Site at Ketzin (Germany)

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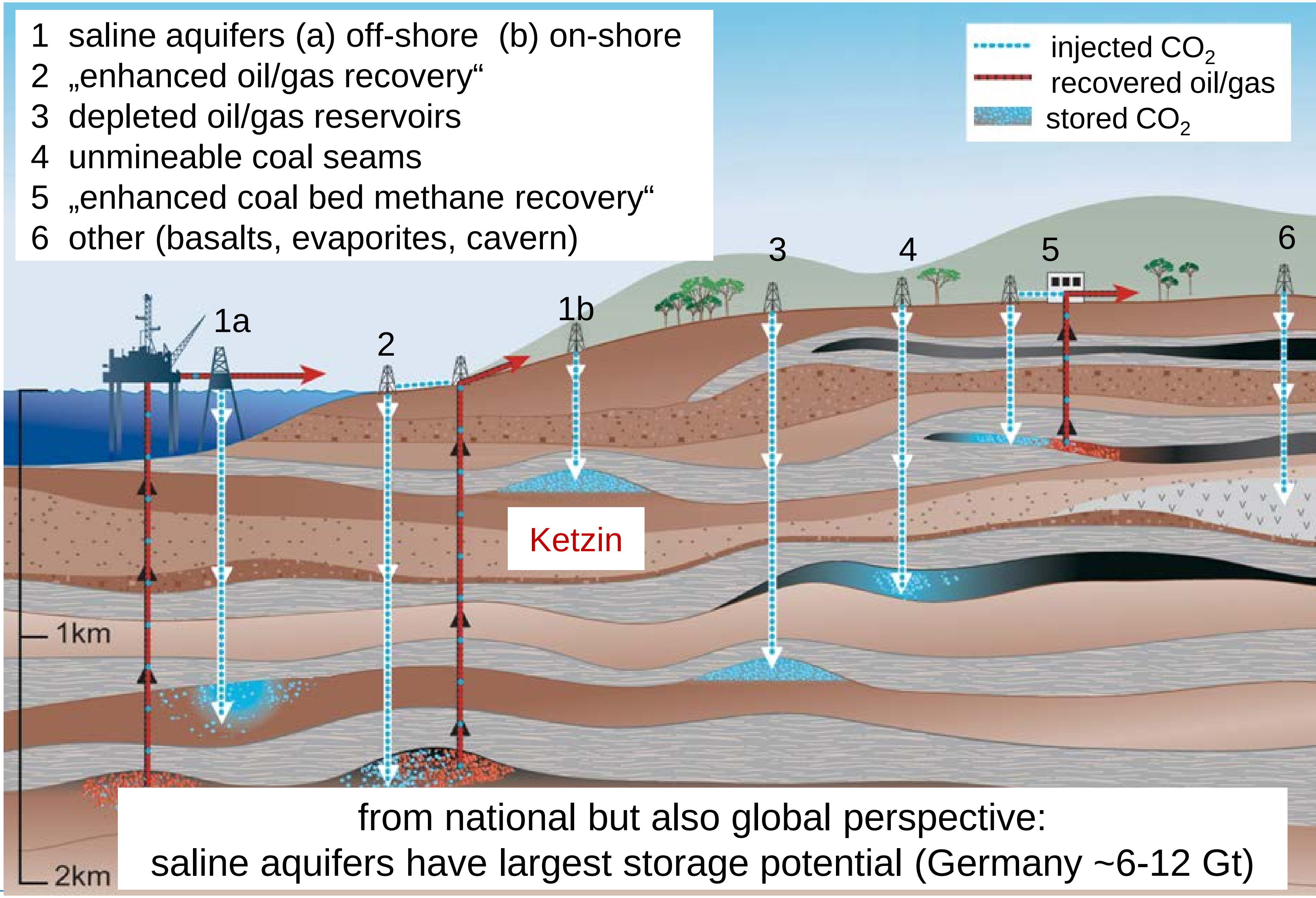
# Overview of the presentation

- Site characterisation
- Site development and operation
- Monitoring
- Dynamic modelling
- Public outreach
- Conclusion
- Combined Power-to-Gas $CO_2$-storage concept

# Different geological options for $CO_2$ storage

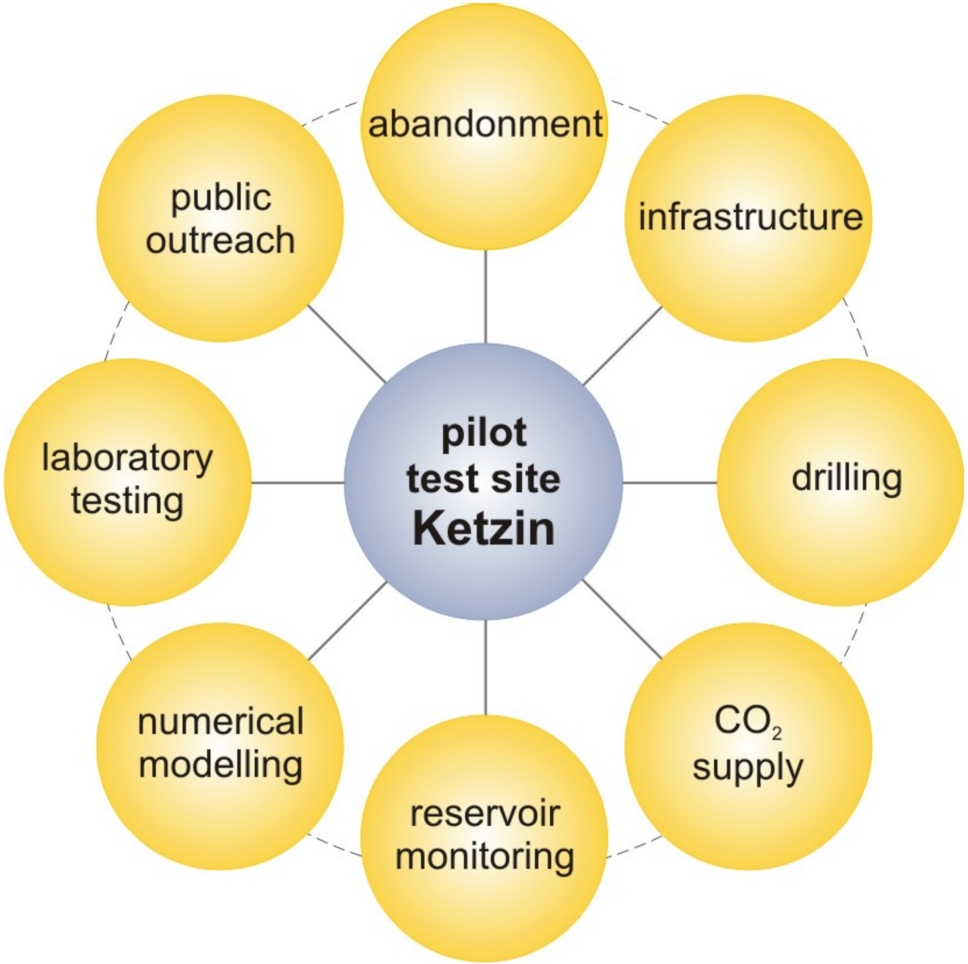
1 saline aquifers (a) off-shore (b) on-shore
2 „enhanced oil/gas recovery“
3 depleted oil/gas reservoirs
4 unmineable coal seams
5 „enhanced coal bed methane recovery“
6 other (basalts, evaporites, cavern)




from national but also global perspective:
saline aquifers have largest storage potential (Germany ~6-12 Gt)

*after IPCC (2005) – www.ipcc.ch*

# Today Ketzin covers all aspects of a $CO_2$ storage site




# Many project partners support the R&D activities at Ketzin since 2004

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FAU Friedrich-Alexander-Universität Erlangen-Nürnberg

Universität Stuttgart

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Uppsala Geophysics

GEUS

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KENT University of Kent at Canterbury

IEA Greenhouse Gas R&D Programme

brgm Géosciences pour une Terre durable

Verbundnetz Gas AG

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Mehr bewegen. OMV

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Forschungsprojekt CO2MAN Pilotstandort Ketzin

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# Characterisation – iterative and on-going

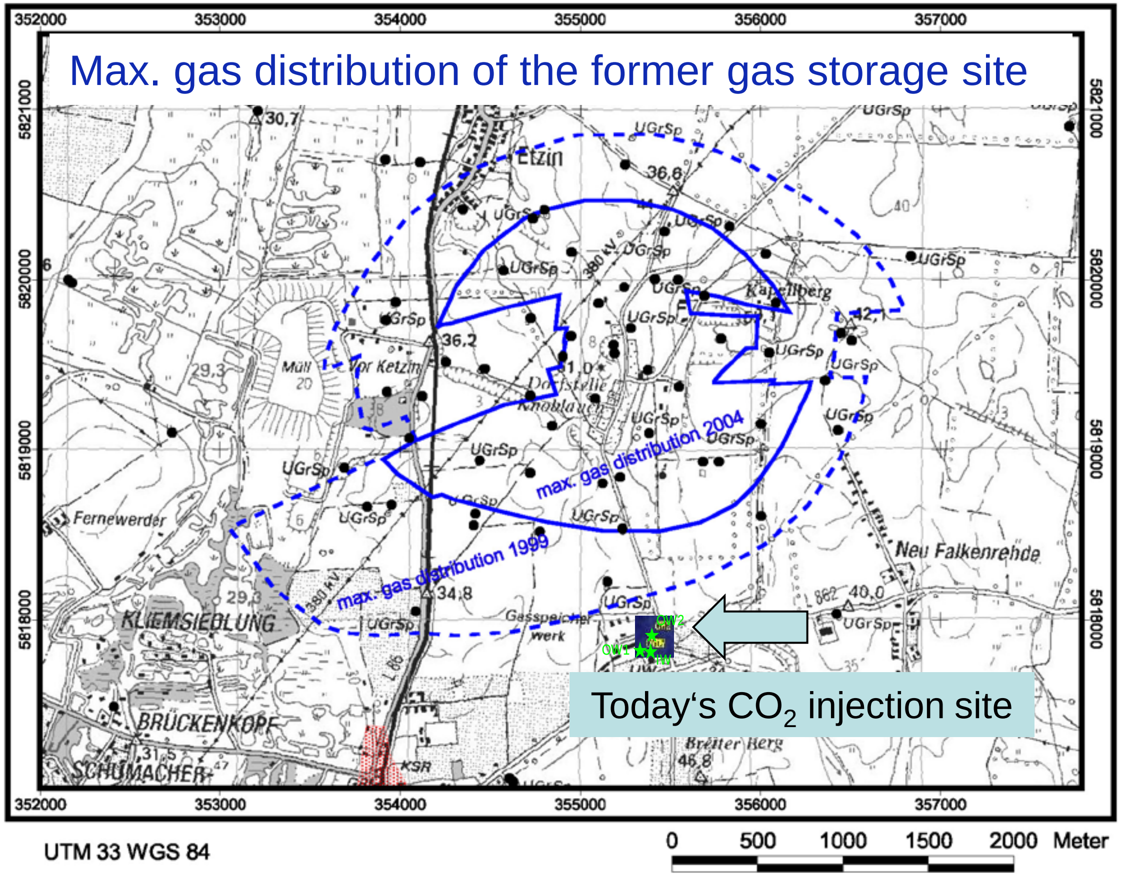
Aim: long-term storage of $CO_2$ without negative effects on humans and the environment

Initial exploration to choose site

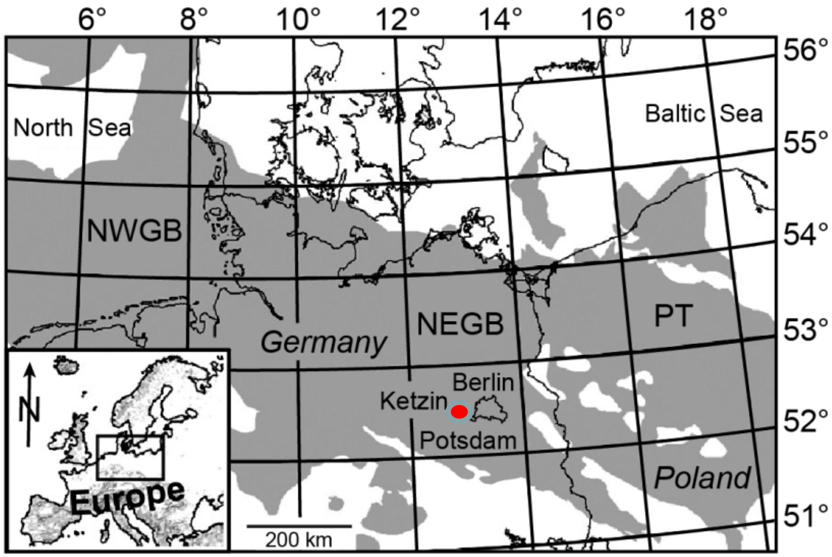
- Based on available data

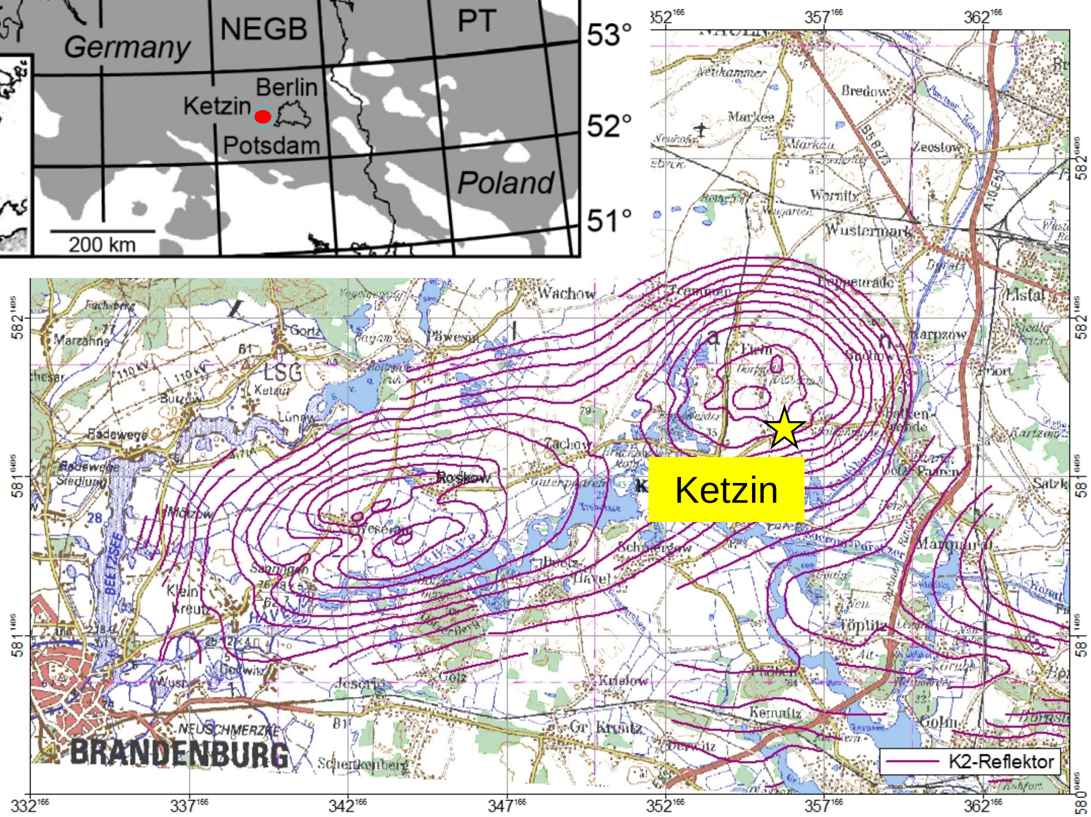
# Ketzin has a history in gas storage

- In 1960s facility for natural gas storage imported from Siberia installed.
- Natural gas was stored in sandstones at shallow depth (250 - 400 metres).
- Facility closed due to economical reasons in 2004.



# Local geology of the Ketzin pilot site




- located in the North German Basin
- double anticline above salt pillow

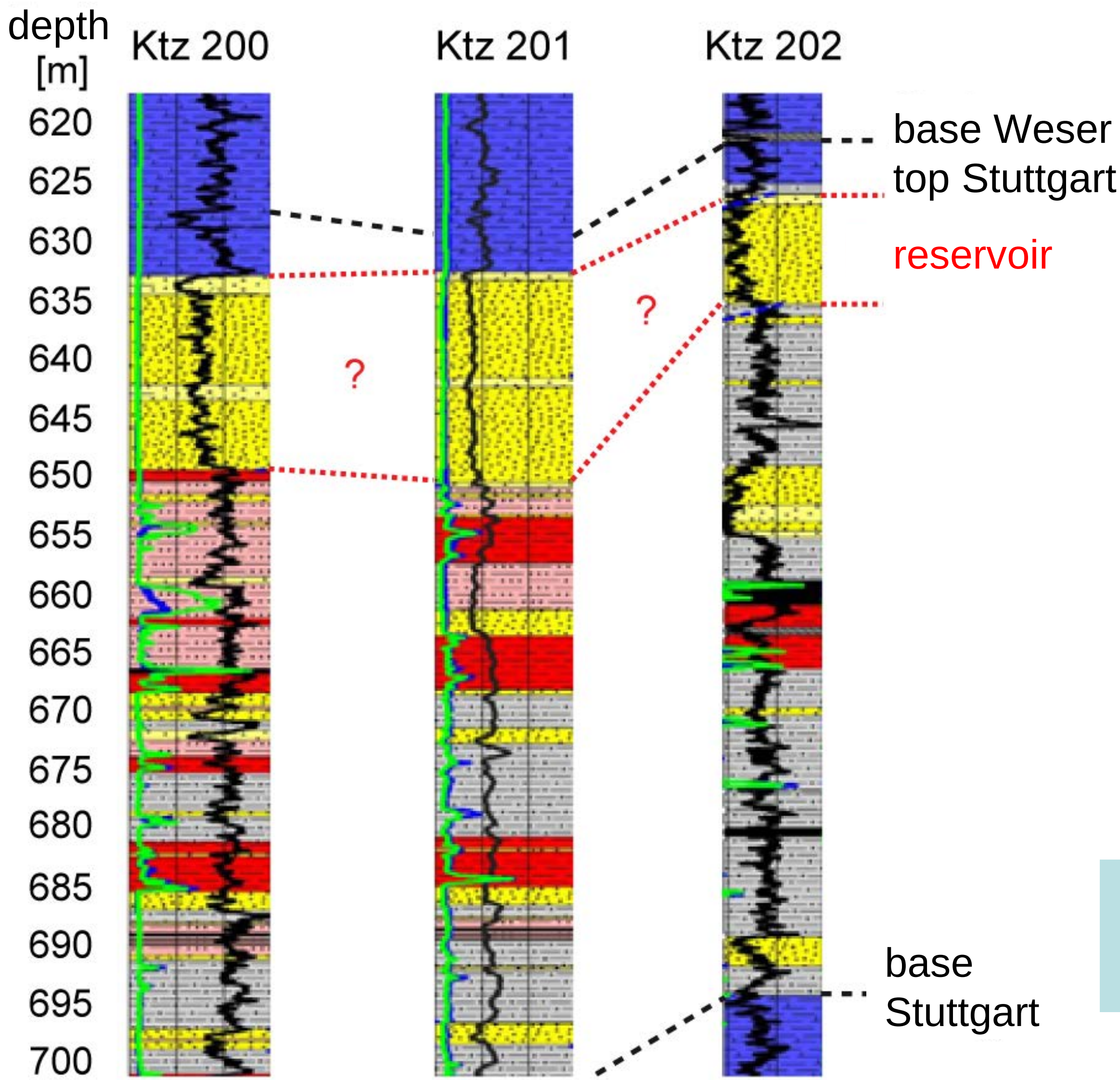
reservoir:

- sandstones of Upper Triassic Stuttgart Form.
- lateral and vertical heterogeneous
- 620 – 650 m depth

cap-rock:

- Upper Triassic shales
- >165 m

# Different rock types were characterized




cap rock:
mudstone (Weser formation)
porosity ~ 8 %, permeability ~ µD

reservoir:
sandstone (Stuttgart formation)
24 – 47 wt % quartz
13 – 20 wt % plagioclase
7 – 30 wt % clay minerals

porosity ~ 26%
permeability
laboratory: ∅ 300 – 400 mD
(but extreme variable)
hydraulic tests: 40 – 80 mD

fluvial system
extreme heterogeneous

Norden et al., (2010), SPE Reservoir Evaluation & Engineering, 13, 2, 179-192.
*Förster et al. (2006),* Environmental Geosciences, 13, 3, 145-161.

# Site Development and Operation

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# Characterisation – iterative and on-going

Aim: long-term storage of $CO_2$ without negative effects on humans and the environment

Initial exploration to choose site

- Based on available data

Criteria fail, work stops

Detailed exploration and initial characterisation

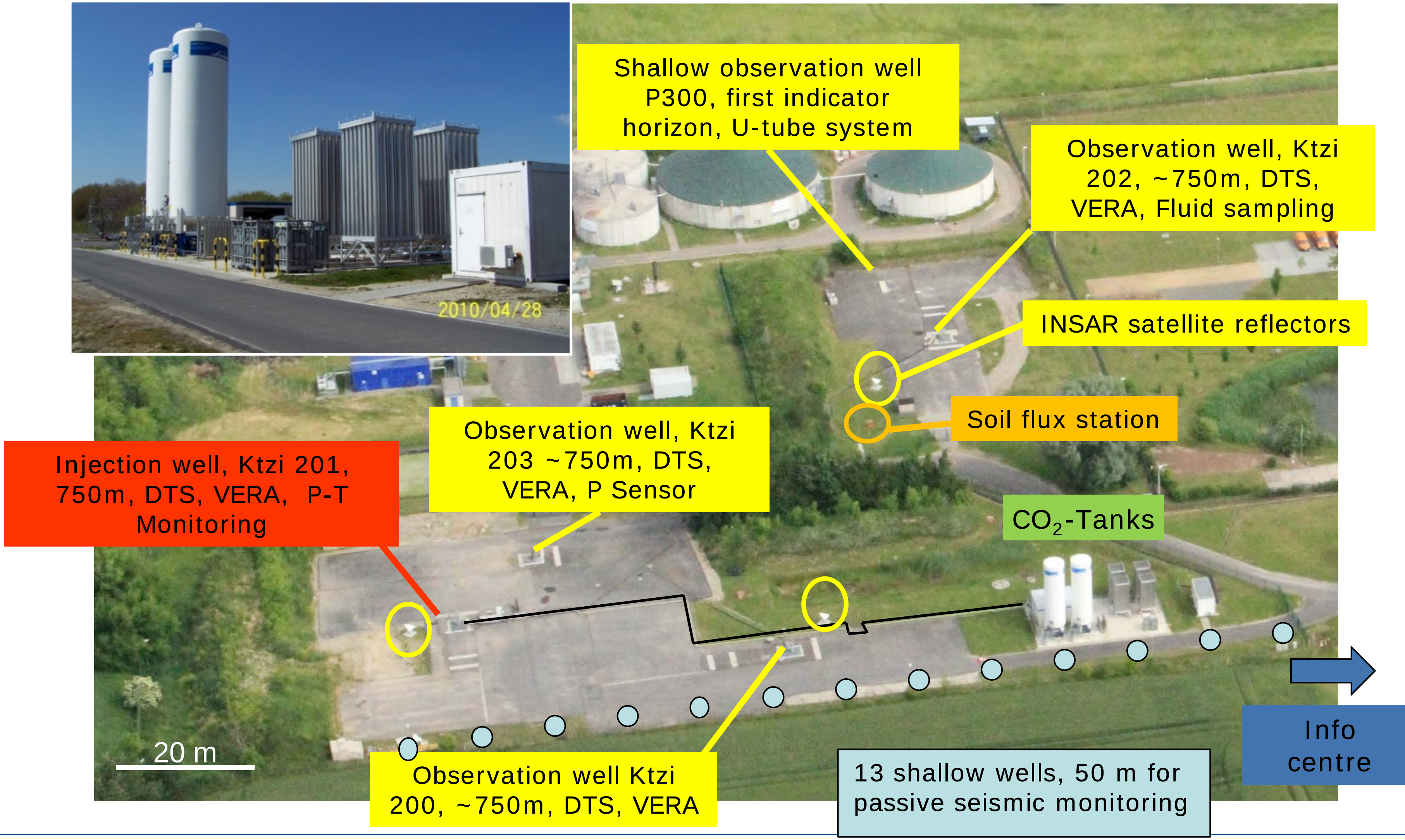
- New measurements to set up geological model and assess suitability of storage site

First comparison of models against field data

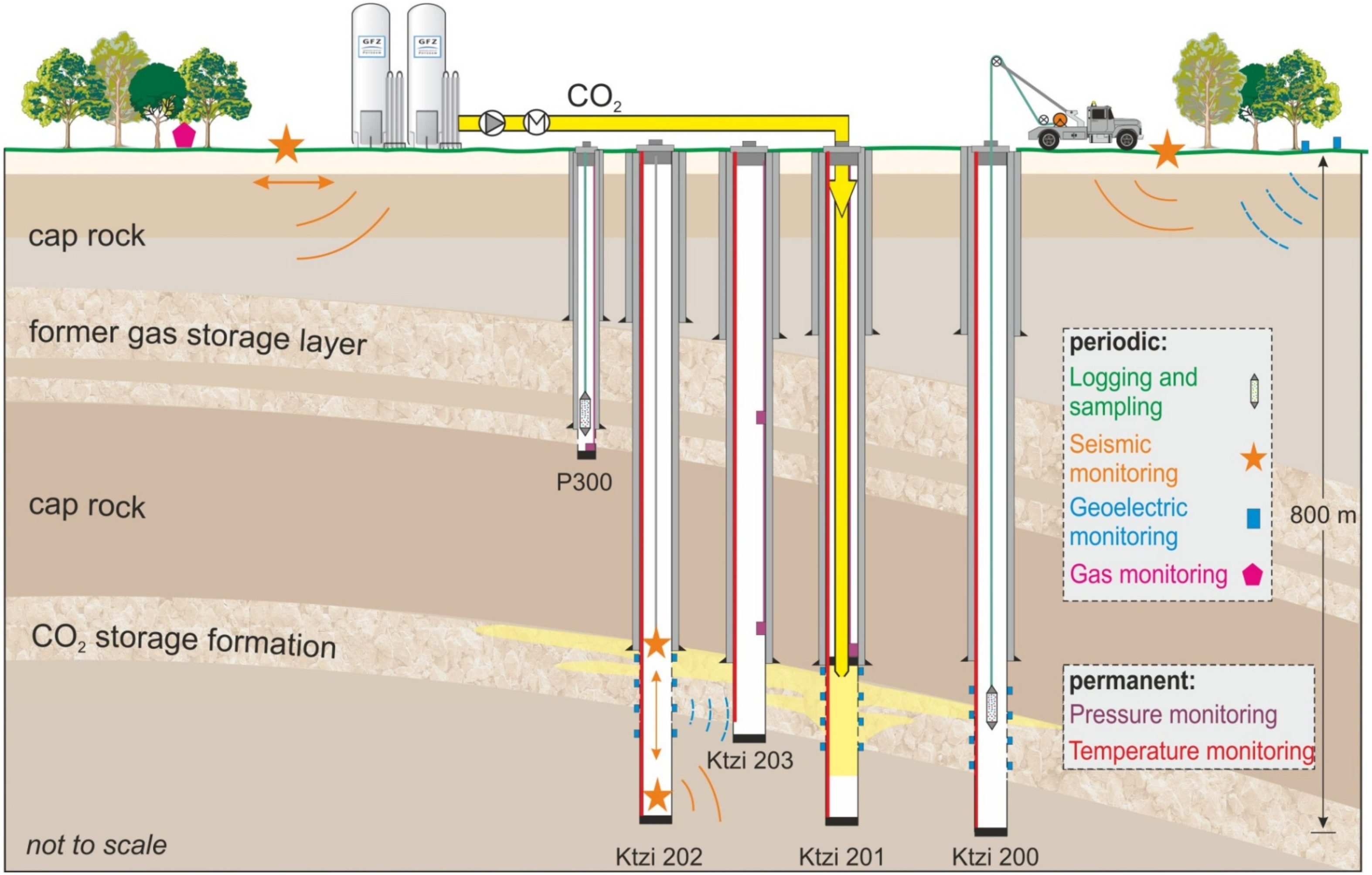
- hydraulic tests on site
- lab work e.g. for poro-perm parameters

Criteria fail, work stops

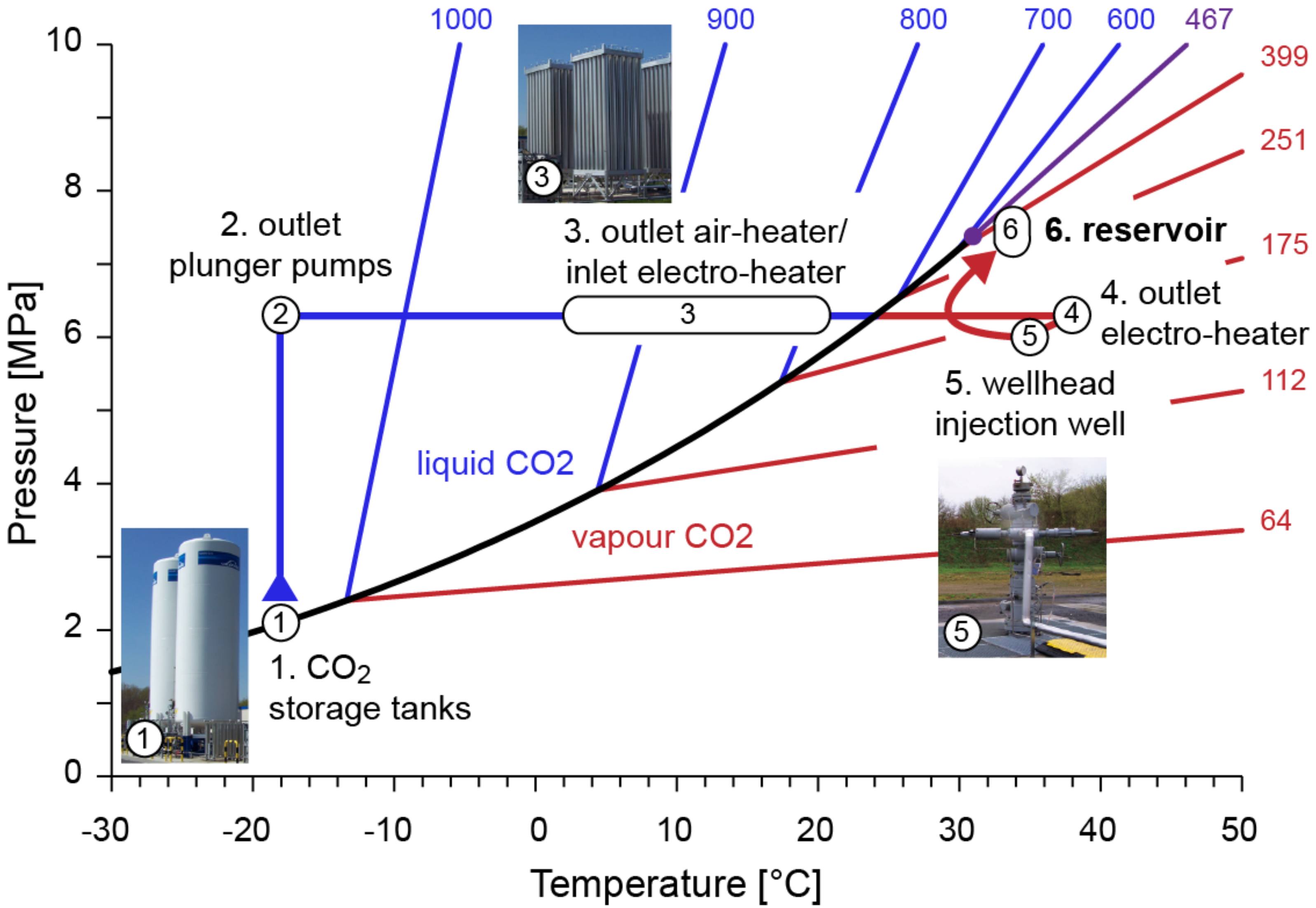
# The pilot site Ketzin



# A unique and interdisciplinary monitoring concept is applied and operated at Ketzin



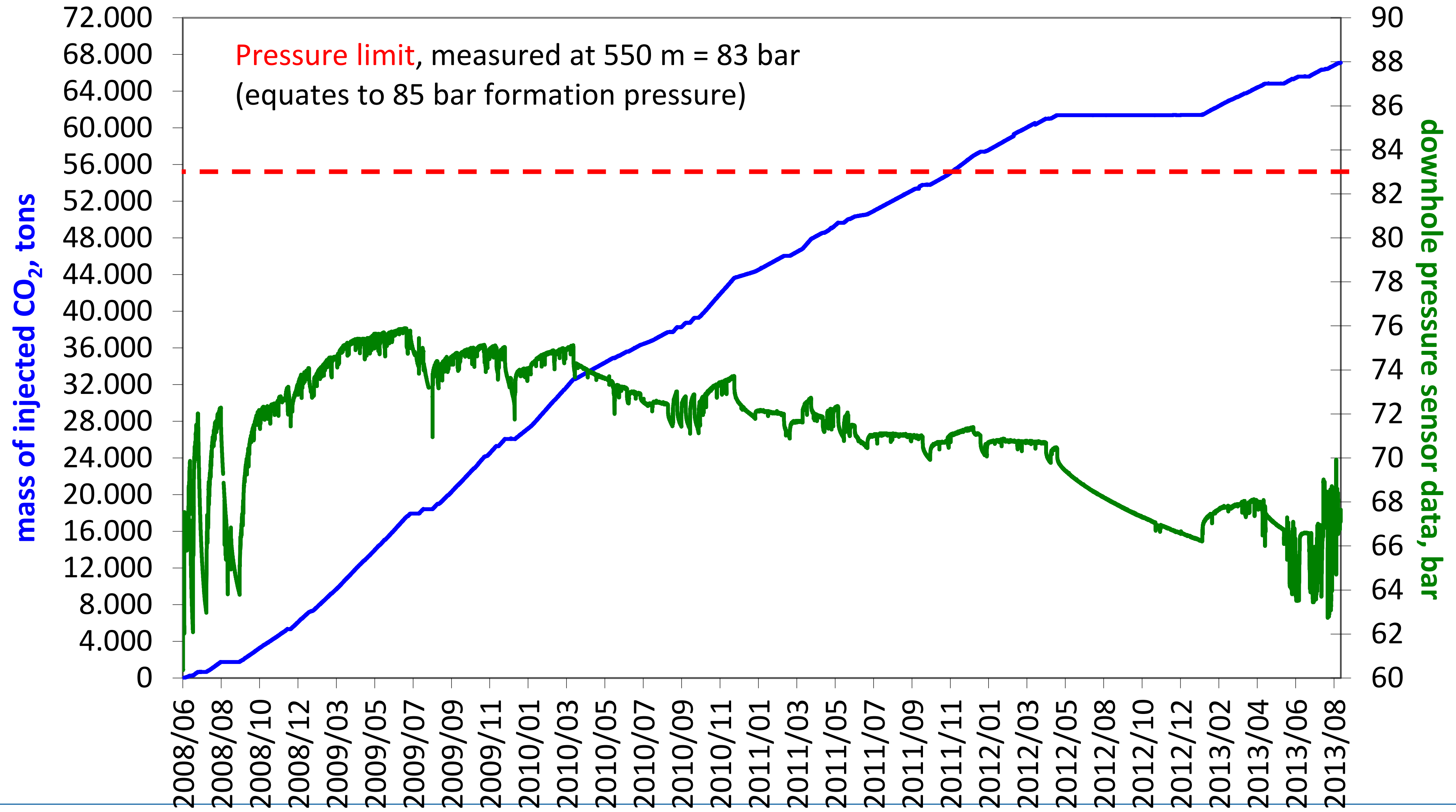
# Injection process at Ketzin



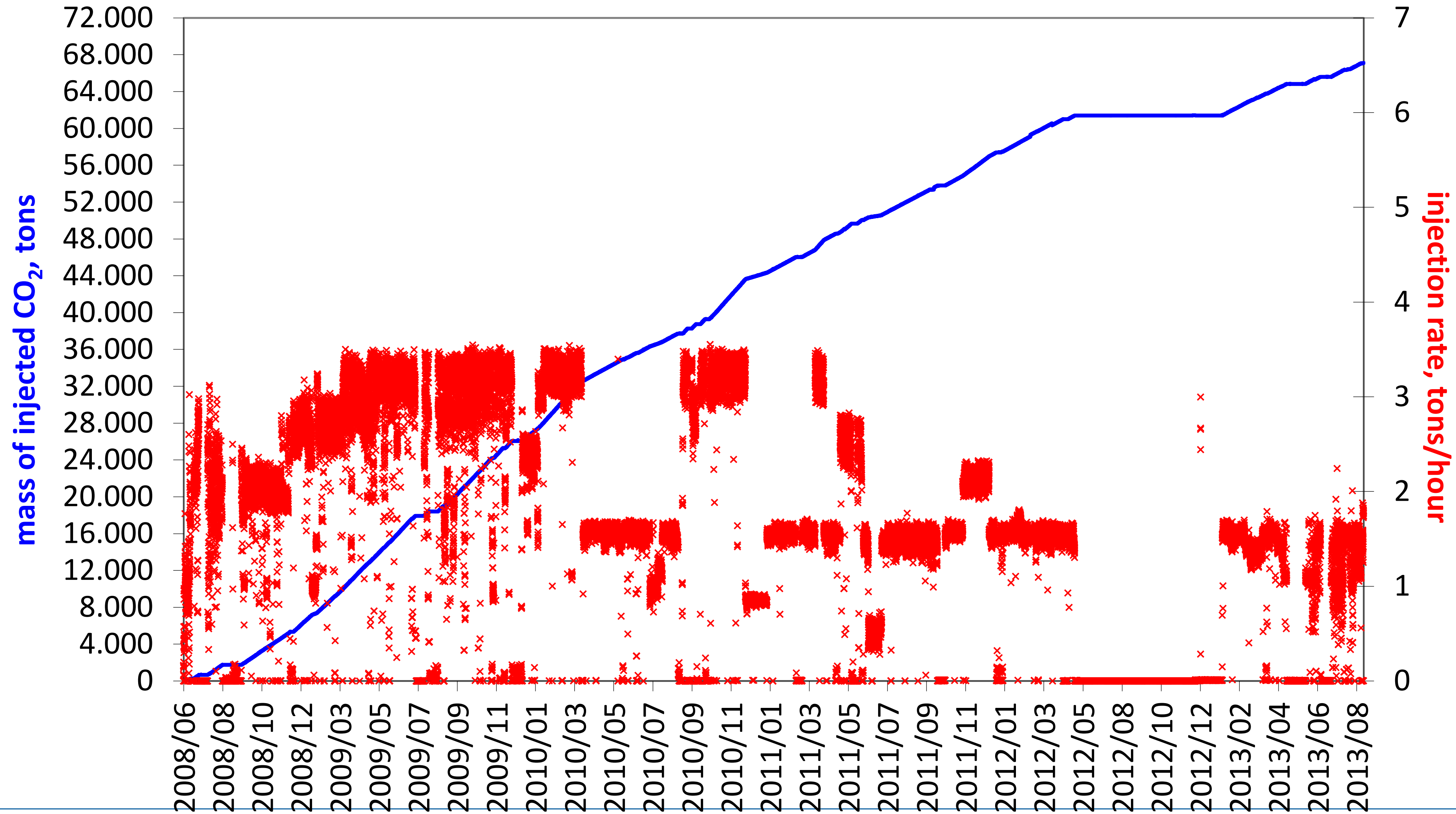
# The $CO_2$ injection ran safely and reliably

- **Start** of $CO_2$ injection: 30.06.2008
- **End** of $CO_2$ injection: 29.08.2013, $67*10^3$ t $CO_2$
- $CO_2$ sources and quality
  - Primary source: food-grade $CO_2$ (Linde), > 99.9%
  - Secondary source (1,515 t from May 05 to June 12, 2011): Schwarze Pumpe pilot plant (Vattenfall), > 99.7%
- Injection rates: 24 to 77 t/day (currently ~ 1 kt $CO_2$ /month)


# Formation pressure and injected mass of CO2



# Injection rates and injected mass of $CO_2$

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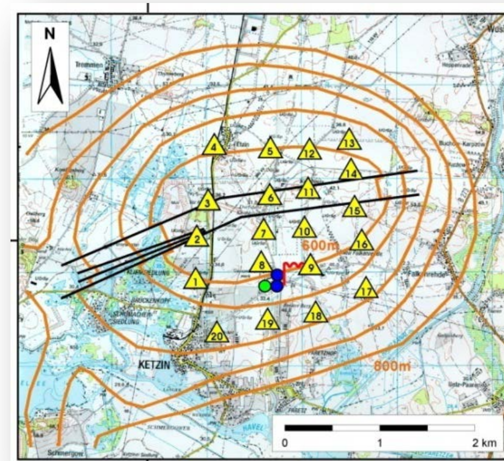
# Monitoring

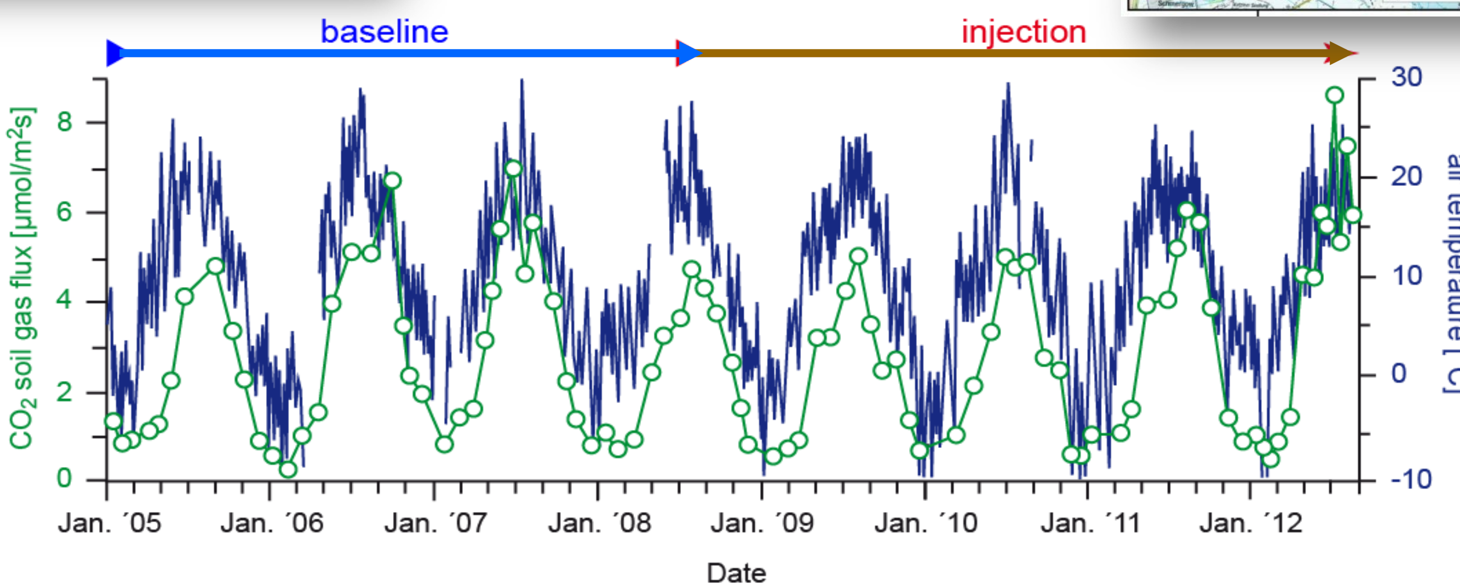





# $CO_2$ flux and temperature show typical seasonal variations

Monthly soil flux measurements
at 20 sampling locations

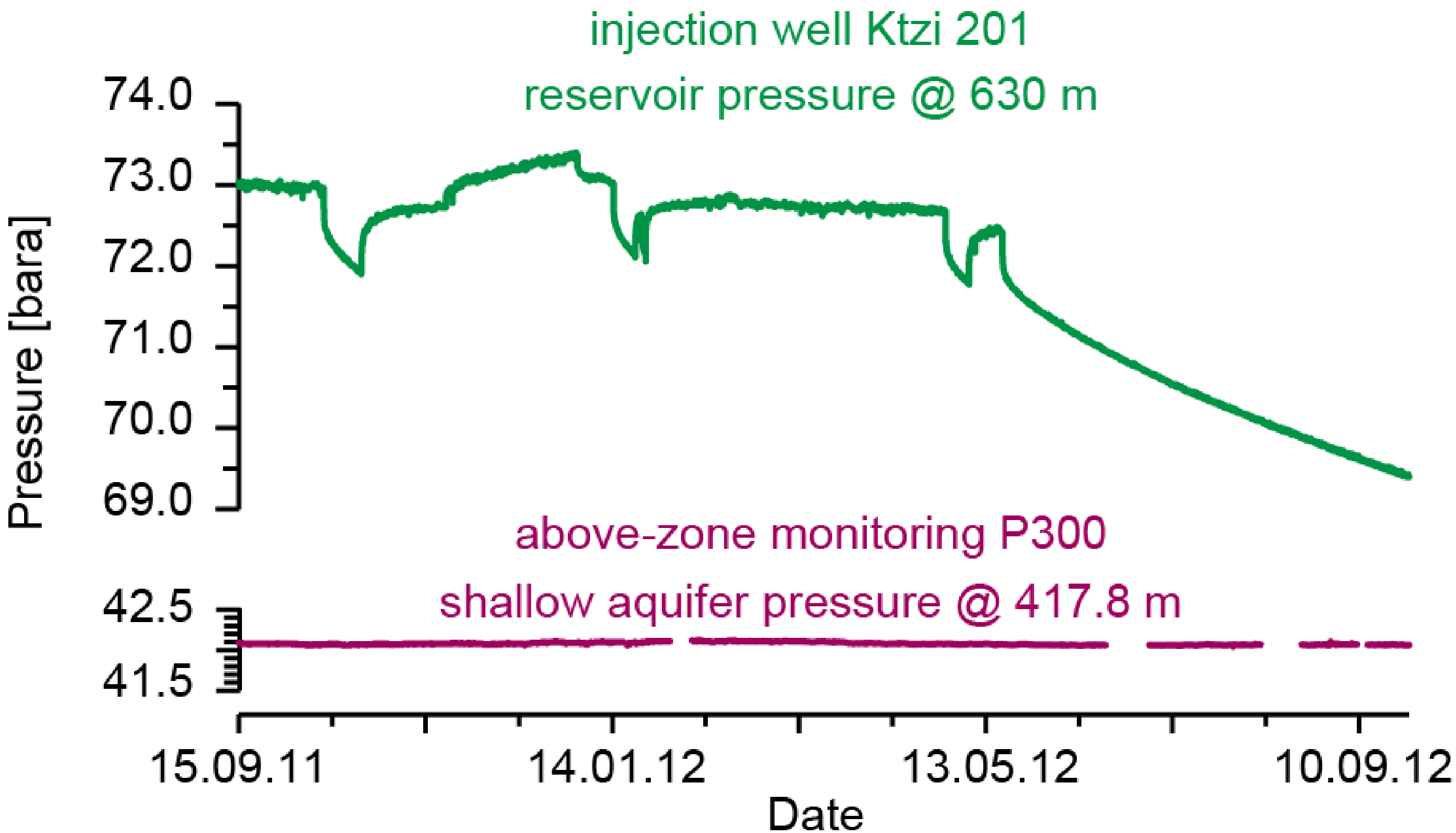




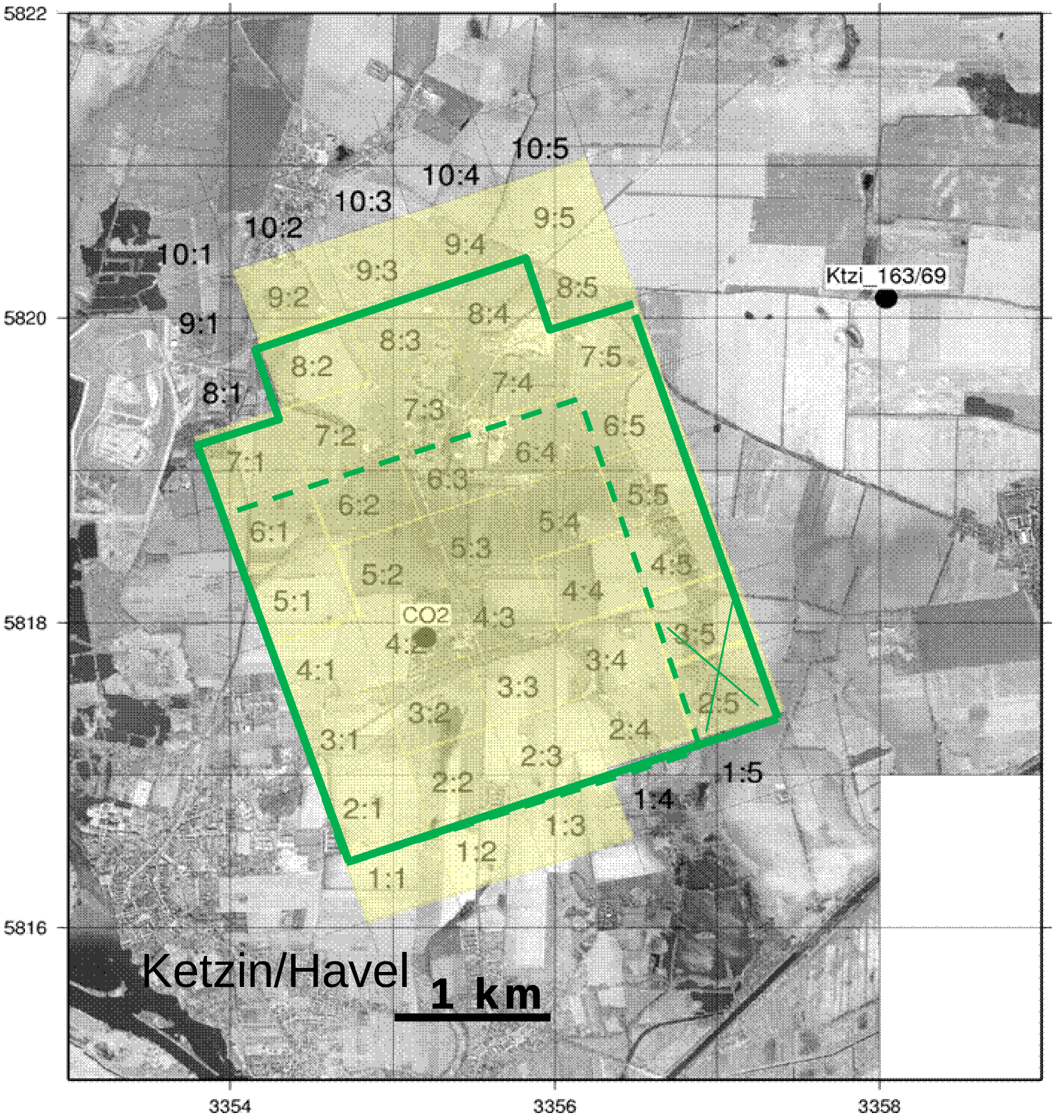
Zimmer, M.; Pilz, P.; Erzinger, J. (2011): Long-term surface carbon dioxide flux monitoring at the Ketzin carbon dioxide storage test site. Environmental Geosciences, 18, 2, 119-130.
| EDOC: 17229 | 10.1306/eg.11181010017 |

# Above-zone pressure monitoring P300




- no hints to any leakage
- no hints to any hydraulic connectivity through cap-rock

# Second 3D seismic repeat evaluated



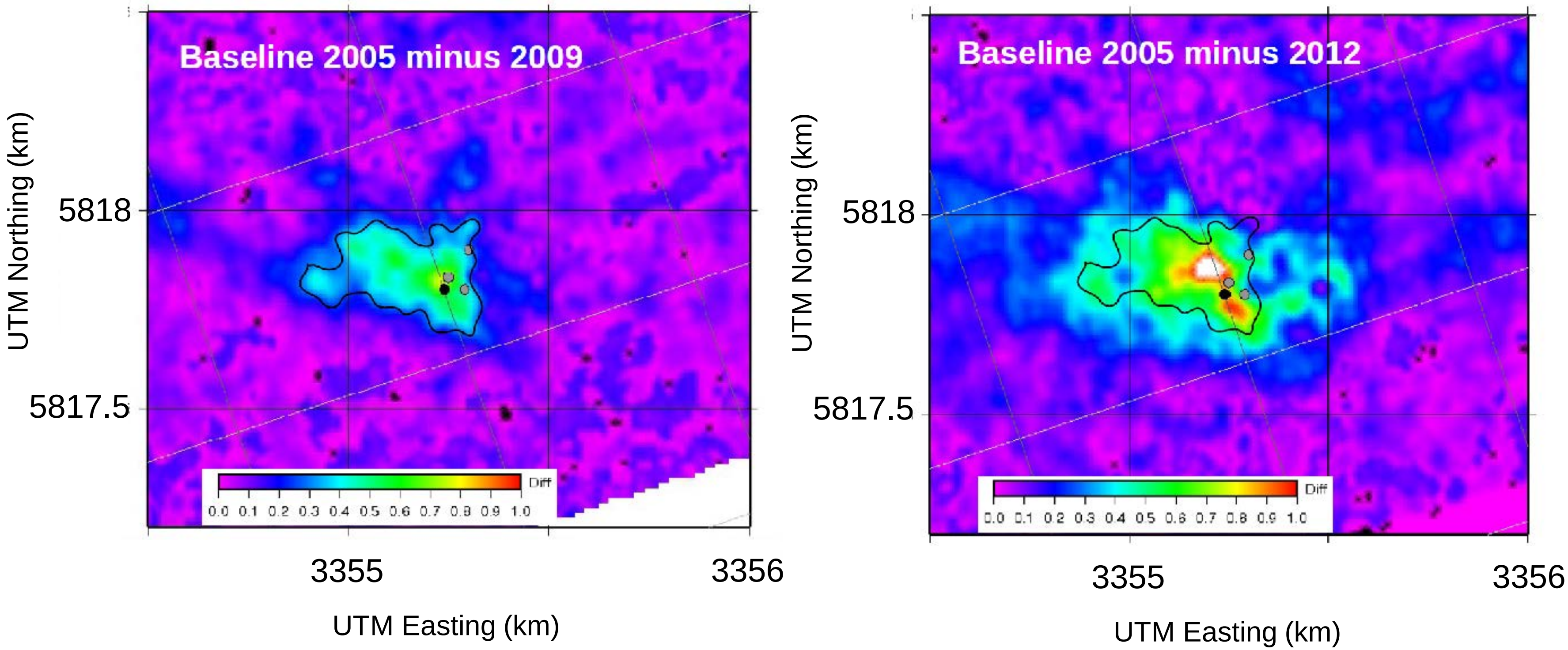

**3D Baseline 2005:**
41 Templates
~12 km$^2$

**3D Repeat 2009:**
20 Templates
(~22 kilotons injected)

***3D Repeat 2012:***
*31 Templates*
*(~61 kilotons injected)*
*Survey performed from September to November 2012*

1 Template:
5 lines, 240 geophones
12 lines, 180 shotpoints

# Time-lapse seismic wave amplitudes at top Stuttgart indicate lateral extent of detected $CO_2$




Normalized time-lapse amplitudes:

Baseline – 2009; 22 kt $CO_2$ | Baseline – 2012; 61 kt $CO_2$

Areal extension:

**~8 hectares** | **~15 hectares**

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Lueth et al., 2013

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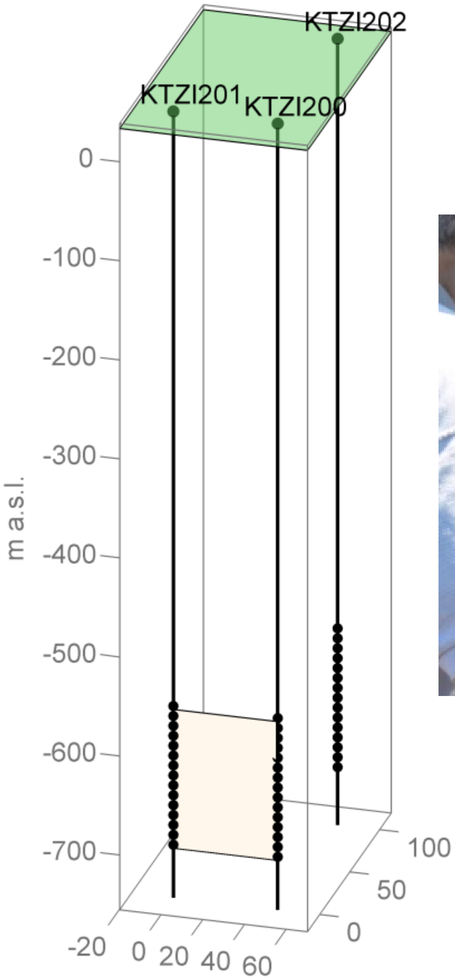
# Set-up of the Vertical Resistivity Array (VERA)

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Schmidt-Hattenberger, C.; Bergmann, P.; Kießling, D.; Krüger, K.; Rücker, C.; Schütt, H. (2011): Application of a Vertical Electrical Resistivity Array (VERA) for Monitoring CO2 Migration at the Ketzin Test Site: First Performance Evaluation. Energy Procedia, 4, 3363-3370. doi: 10.1016/j.egypro.2011.02.258 |

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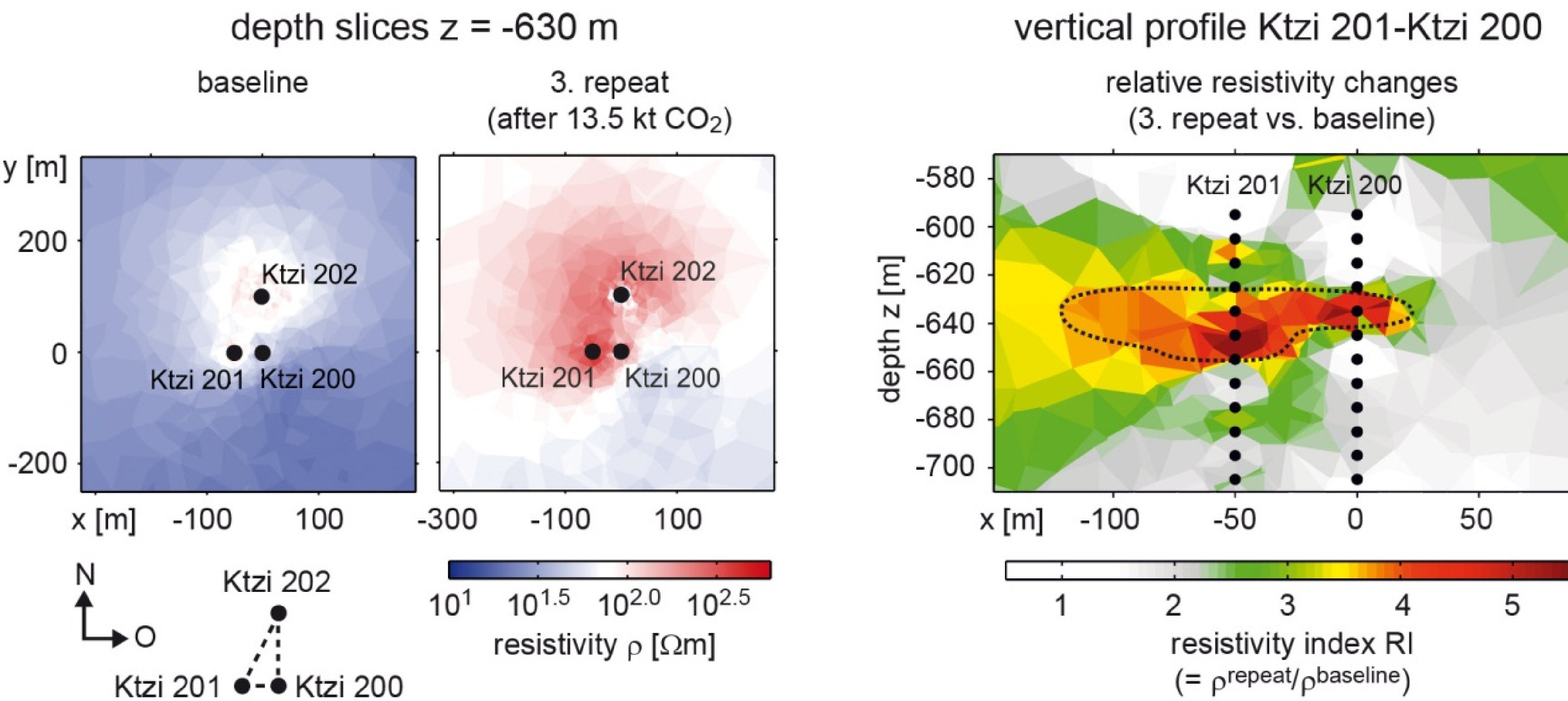
# Geoelectrical measurements show resistivity increase at reservoir level

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Bergmann, P.; Schmidt-Hattenberger, C.; Kiessling, D.; Rücker, C.; Labitzke, T.; Henninges, J.; Baumann, G.; Schütt, H. (2012): Surface-downhole electrical resistivity tomography applied to monitoring of the CO2 storage Ketzin (Germany). Geophysics, 77, 6, B 253-B 267. doi: 10.1190/GEO2011-0515.1


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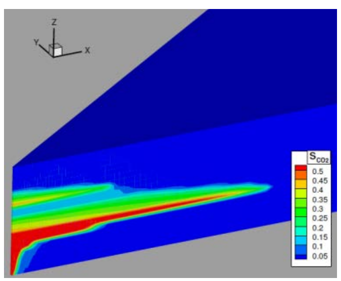
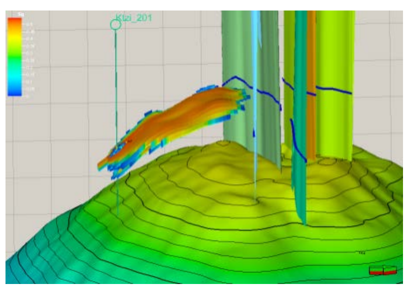
# Modelling and simulation started before injection and accompany entire operation

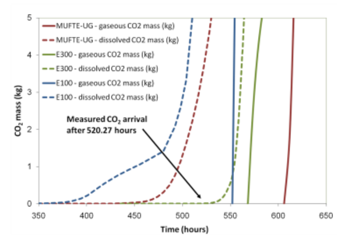
Project schedule → Risk assessment → Process understanding → Prediction



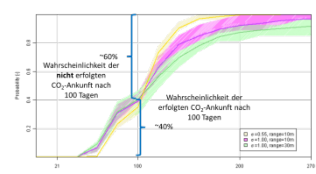
Bielinski (2007)
Kopp et al. (2008)



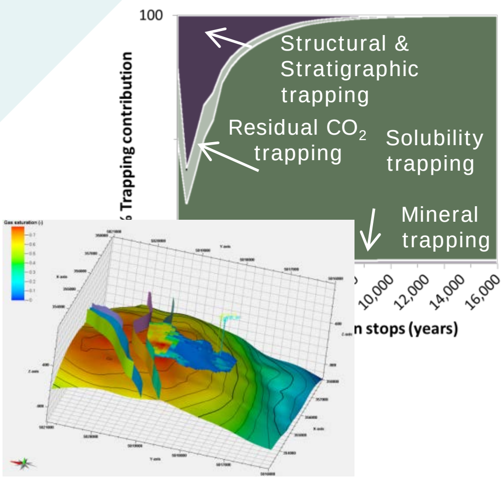
Frykman (2008)




Kempka et al. (2010)

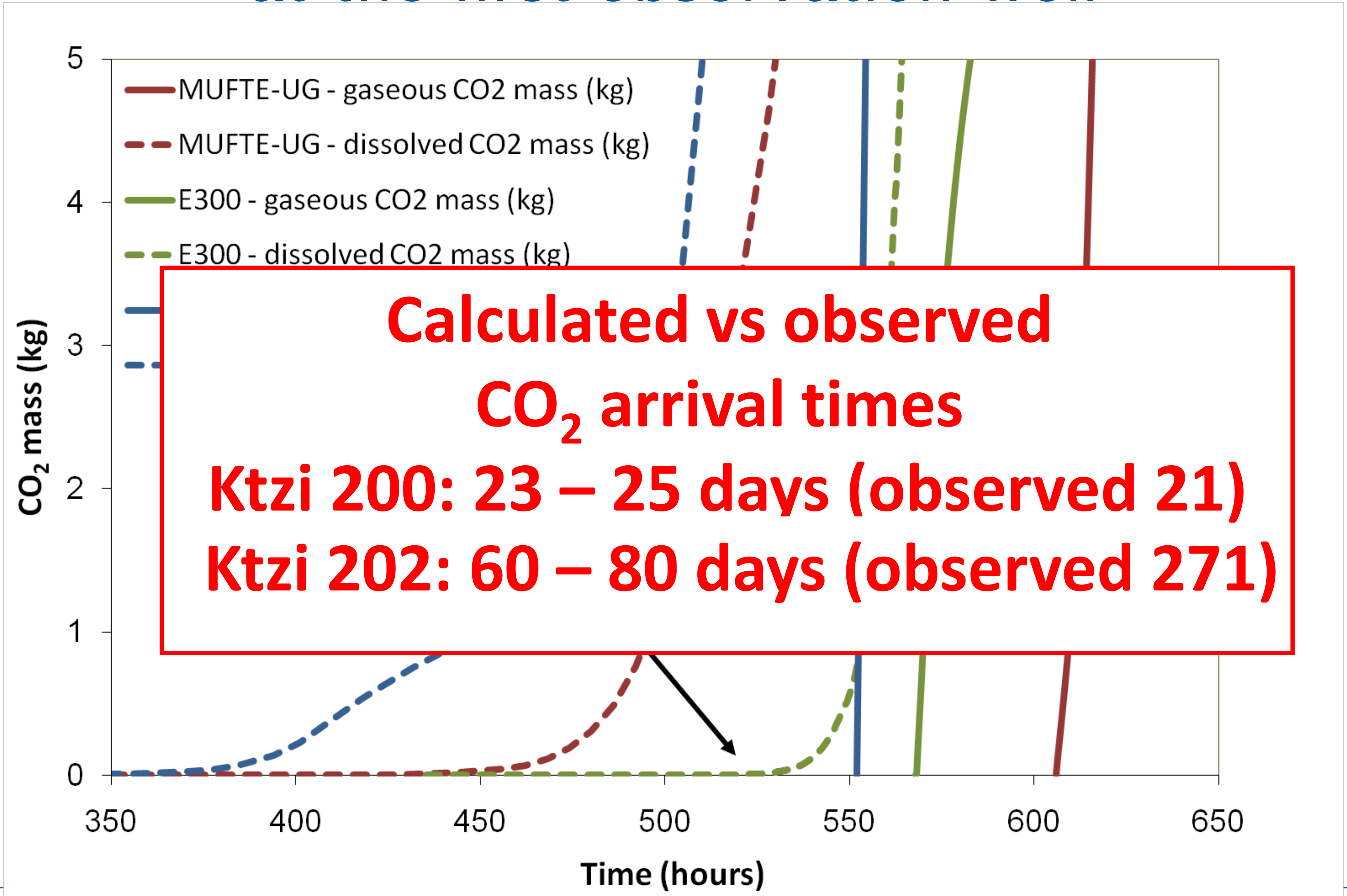


Lengler et al. (2010)




Kempka & Kühn (2012),
Klein et al. (2012)

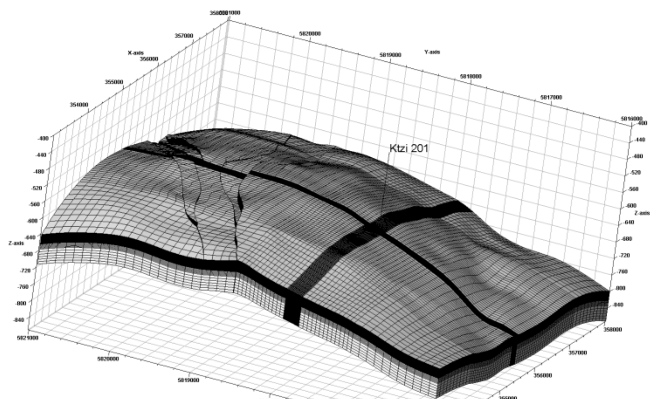
# Successful history matching only for arrival time at the first observation well

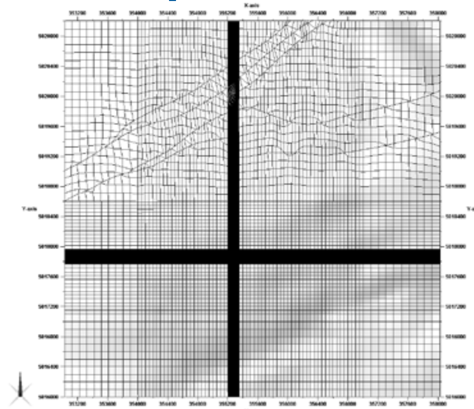


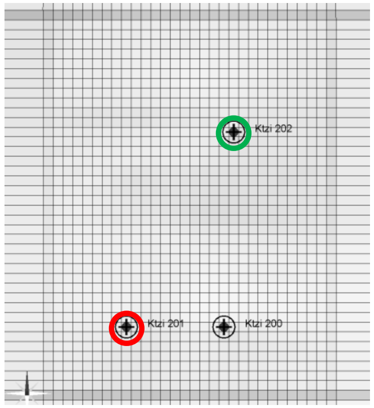


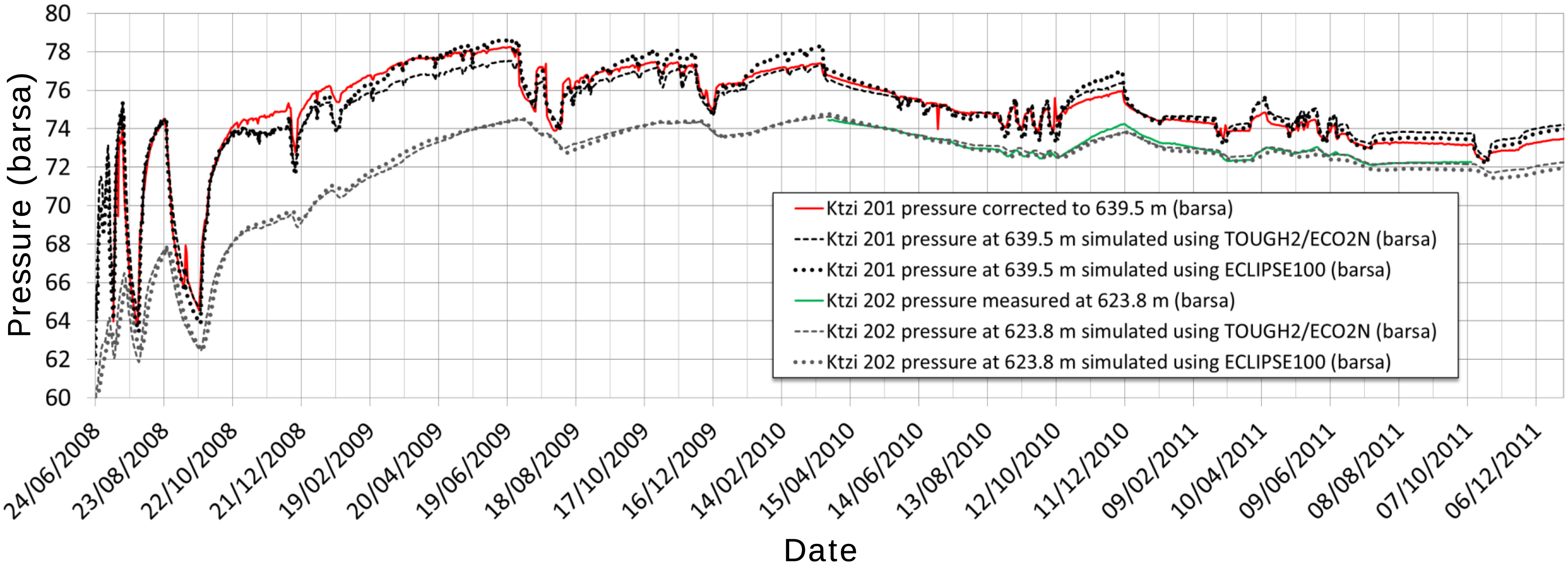

Kempka, T.; Kühn, M.; Class, H.; Frykman, P.; Kopp, A.; Nielsen, C. M.; Probst, P. (2010): Modelling of CO2 arrival time at Ketzin – Part I. Int. J. Greenh Gas Con, 4, 6, 1007-1015. | EDOC:15131 | 10.1016/j.ijggc.2010.07.005 |

# Dynamic fluid flow models show a good agreement with Ketzin pilot site observations



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Kempka T, Kühn M (2013 online first): Numerical simulations of $CO_2$ arrival times and reservoir pressure coincide with observations from the Ketzin pilot site, Germany. Environmental Earth Sciences. doi:10.1007/s12665-013-2614-6

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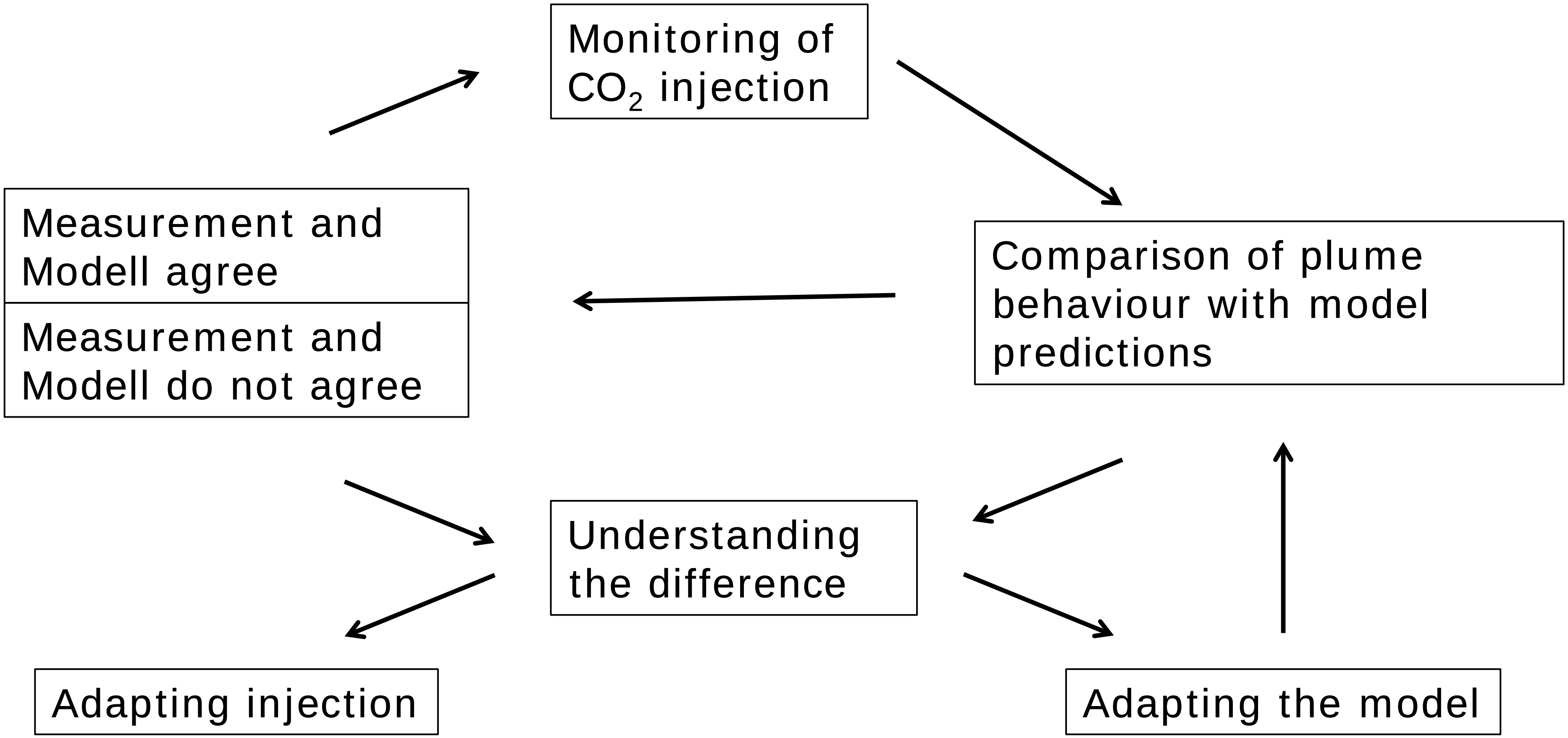
# Characterisation – iterative and on-going

Aim: long-term storage of $CO_2$ without negative effects on humans and the environment

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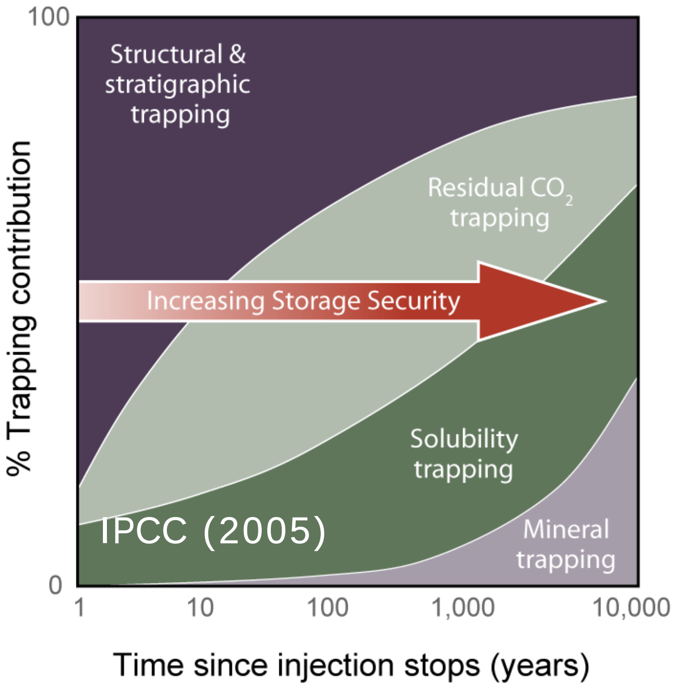
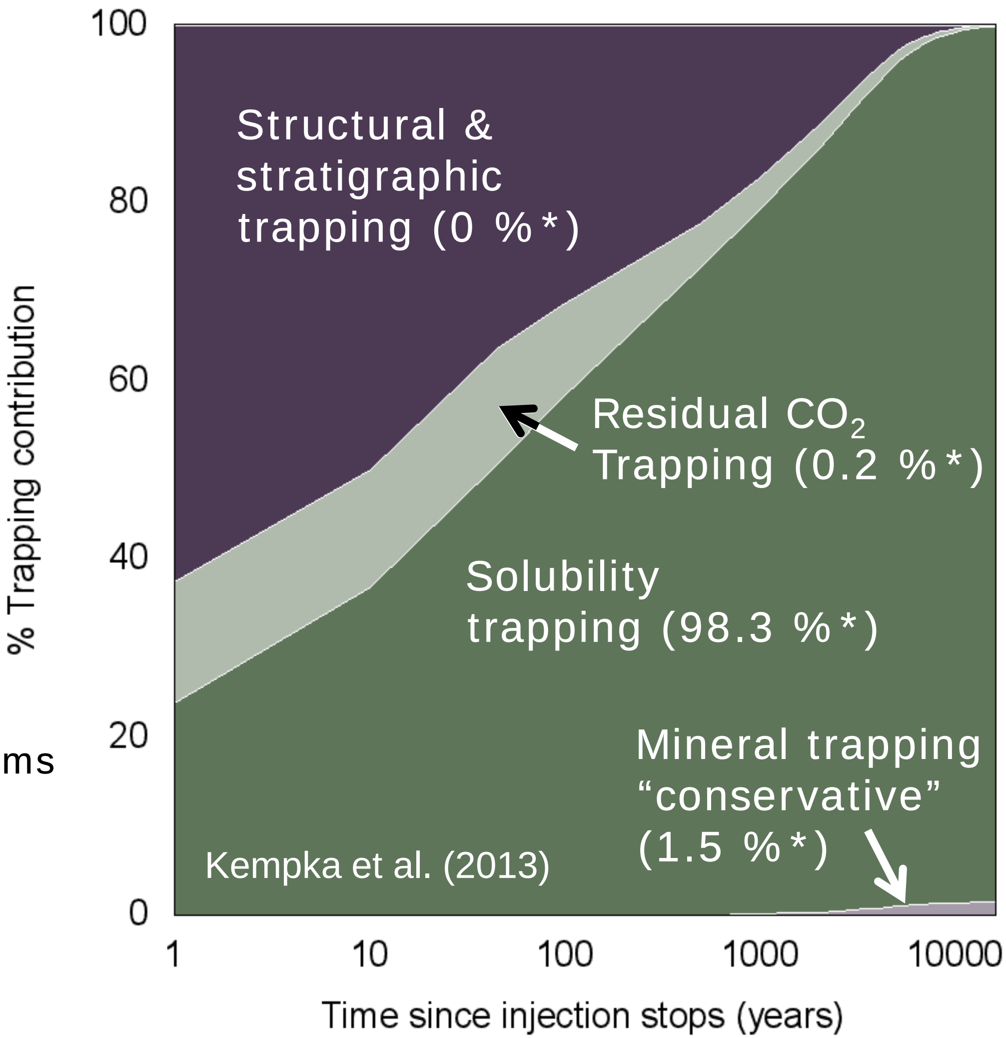
# $CO_2$ trapping is dominated by the solubility trapping mechanism at the Ketzin pilot site




*Contribution of $CO_2$ trapping mechanisms after 16,000 years of simulation ("best-case" mineral trapping is 30 %)

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Kempka T, Klein E, De Lucia M, Tillner E, Kühn M (2013) Assessment of Long-term $CO_2$ Trapping Mechanisms at the Ketzin Pilot Site (Germany) by Coupled Numerical Modelling. Energy Procedia, 37:5419-5426. doi:10.1016/j.egypro.2013.06.460

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# Public outreach

Don’t ask what it costs to get acceptance, ask what it costs not! to get it. (N.P. Christensen)

- Transparent information about the Ketzin project, the monitoring concept and results from the very beginning
- Engagement on community level – presenting results at the district council, on Wednesday everybody is welcome at the test site, annual open house for the locals
- Extension of visitor centre (1000 visits/year), set-up of new website (www.co2ketzin.de), further press relations
- Extensive publishing of scientific results




# The way forward at Ketzin

The planned project (2014-2018) will:

- for the first time ever **close the whole life-time cycle** of a $CO_2$ storage site at pilot scale,
- expand knowledge on **post-injection** monitoring and site behaviour, and
- provide first-hand experiences on **site abandonment** and **transfer of liability**

by:

- **R&D work** on long-term well integrity, well abandonment strategies, post-injection monitoring and
- continued **profound and factual information policy**

# Lessons learned from the Ketzin pilot site

- Ketzin project demonstrates successful $CO_2$ storage in a saline aquifer on a research scale – scientific base for a demo-scale project has been achieved.
- Storing $CO_2$ in the subsurface is a lifelong learning-process: predicting -> storing -> comparing ->understanding.
- Down hole temperature and pressure are very important parameters for the daily operation.
- Geophysical and geochemical methods used were able to detect the $CO_2$ plume and gave valuable input for the models
- Transparency towards the regulator and the public are of highest important – building up confidence!




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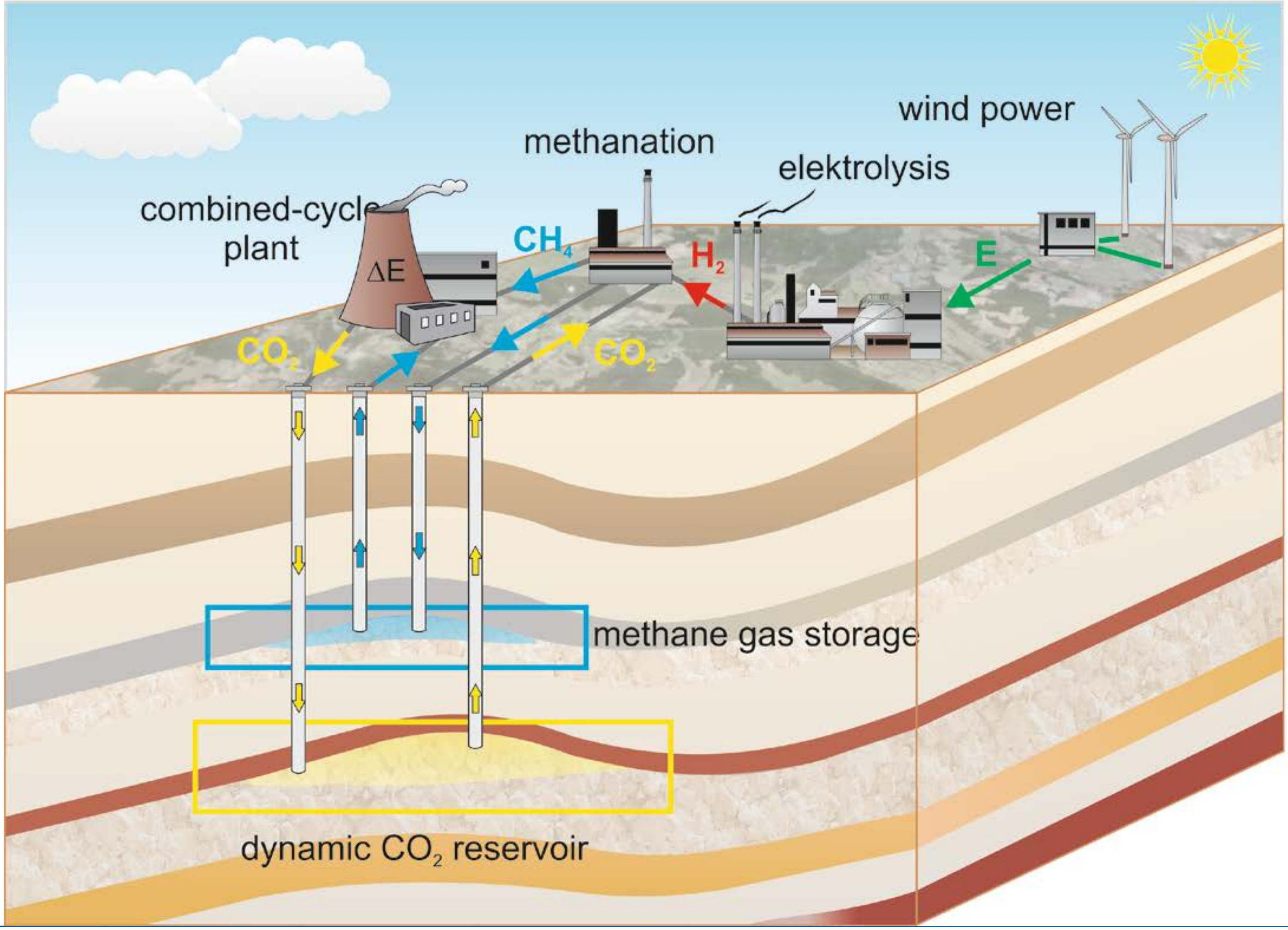
# The coupled Power-to-Gas $CO_2$-storage concept



# Case study for the city of Potsdam (Germany) supports the concept

- Due to a rapid increase of wind turbines and photovoltaic in the German energy generating system, energy is produced which cannot be used at the time of generation.
- By using excess electricity to run electrolysers $H_2$ is produced which can subsequently be used to produce $CH_4$ for which an infrastructure exists.
- The cycle wind energy –> $H_2$ –> $CH_4$ –> electricity has an overall efficiency of 33%.
- If the power generating unit is equipped with a capture unit and the $CO_2$ of the combustion of $CH_4$ is stored and reproduced when needed a closed carbon cycle is established which produces approx. 80% less $CO_2$. This cycle has an overall efficiency of 28%.
- To provide enough $CH_4$ from wind energy, fuelling the transformation of $CO_2$, to produce 300 GWh – 30% of the annual electricity consumption of a German city – the annual full load of approx. 510 wind turbines is needed.



Streibel, M.; Nakaten, N.; Kempka, T.; Kühn, M. (2013): Analysis of an Integrated Carbon Cycle for Storage of renewables. Energy Procedia, 40, 202-211.