CARMA – Carbon management in power generation (2009-2012)

Marco Mazzotti
ETH Zurich

Carbon Capture and Storage

Current status and future perspectives with focus to power generation

Ittigen, 31.08.2011

CARMA players

- M. Mazzotti, J.-P. Burg, D. Giardini, M. Siegrist, S. Wiemer, P. Jenny, A. Ruch, K. Evans, N. Deichmann, V. Visschers, B. Almqvist, M. Werner, S. Hariharan, A. Zappone, L. Wallquist, S. L'Orange, S. Dohle, M. Tyagi, L. Burlini (1962-2009), R. Pini (Stanford University)
- S. Hirschberg, P. Jansohn, I. Mantzaras, C. Bauer, K. Volkart, Y.-C. Lin,, Y. Ghermay, N. Weidmann, H. Turton
- F. Marechal, L. Tock, L. Girardin
  M. Dubius
- L. Diamond, P. Alt-Epping,
  G. Chevalier
- T. Griffin, D. Winkler, F. Bolanos
- W. Leu

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

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EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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n|w Fachhochschule Nordwestschweiz

geo form Geological Consulting and Studies Ltd.

Bundesamt für Energie BFE

FNSNF

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ALSTOM

CARMA key thrusts

Power plant → **CO_2 capture** → **CO_2 transportation** → **CO_2 storage**

- Assessing the role of CCS in future Swiss power generation.
  - CO_2 storage potential
  - Legislation
  - Public perception
  - Costs
  - Multi-criteria comparative evaluation
- Enhancing Swiss scientific and technical know-how in CCS.
  - Life cycle analysis
  - System integration
  - H_2-rich combustion
  - CO_2 storage modelling
  - Induced seismic risk
  - Mineralization

CARMA and the CCS value chain

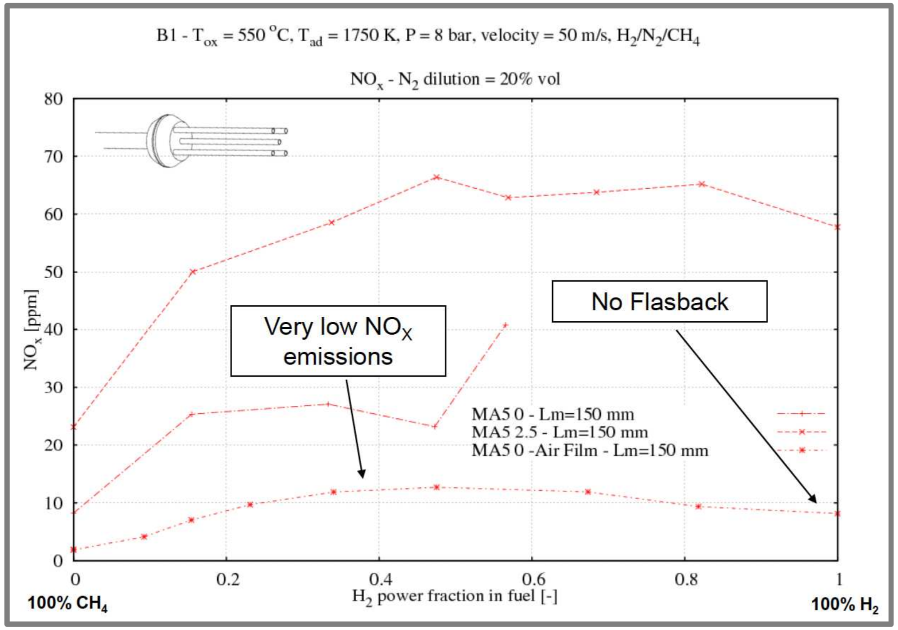
Power plant → **CO_2 capture** → **CO_2 transportation** → **CO_2 storage**

SP2: Pre-combustion capture (H_2 gas turbine), thermoenvironomic optimization

PAUL SCHERRER INSTITUT — **P. Jahnson, J. Mantzaras**

Fachhochschule Nordwestschweiz Hochschule für Technik — **T. Griffin**

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE — **F. Maréchal**



CARMA and the CCS value chain

Power plant → CO_2 capture → CO_2 transportation → CO_2 storage

SP3: Assessment of storage potential in Switzerland

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L. Diamond

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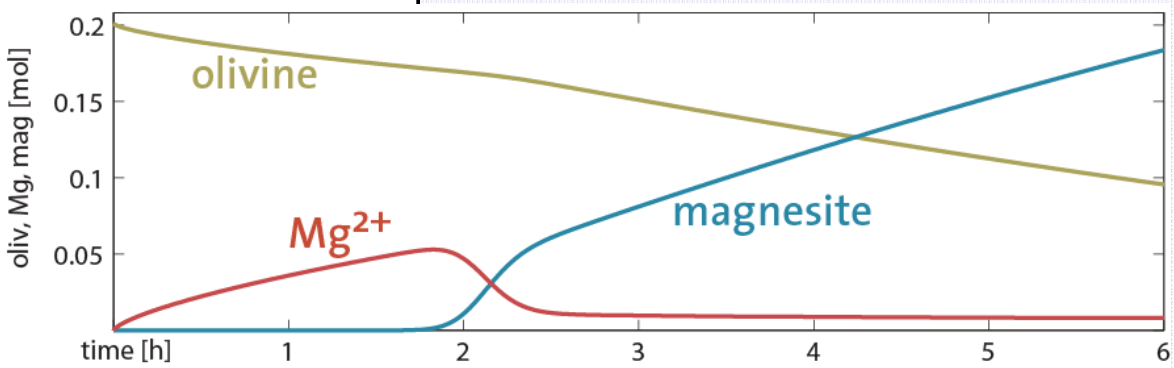
Swiss Federal Institute of Technology Zurich

J.-P. Burg
S. Wiemer

CARMA and the CCS value chain

Power plant → **CO_2 capture** → **CO_2 transportation** → **CO_2 storage**

SP4:
Mineral carbonation



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Swiss Federal Institute of Technology Zurich

M. Werner
M. Mazzotti

CARMA and the CCS value chain

Power plant → CO_2 capture → CO_2 transportation → CO_2 storage

SP1: Environmental and economic assessment

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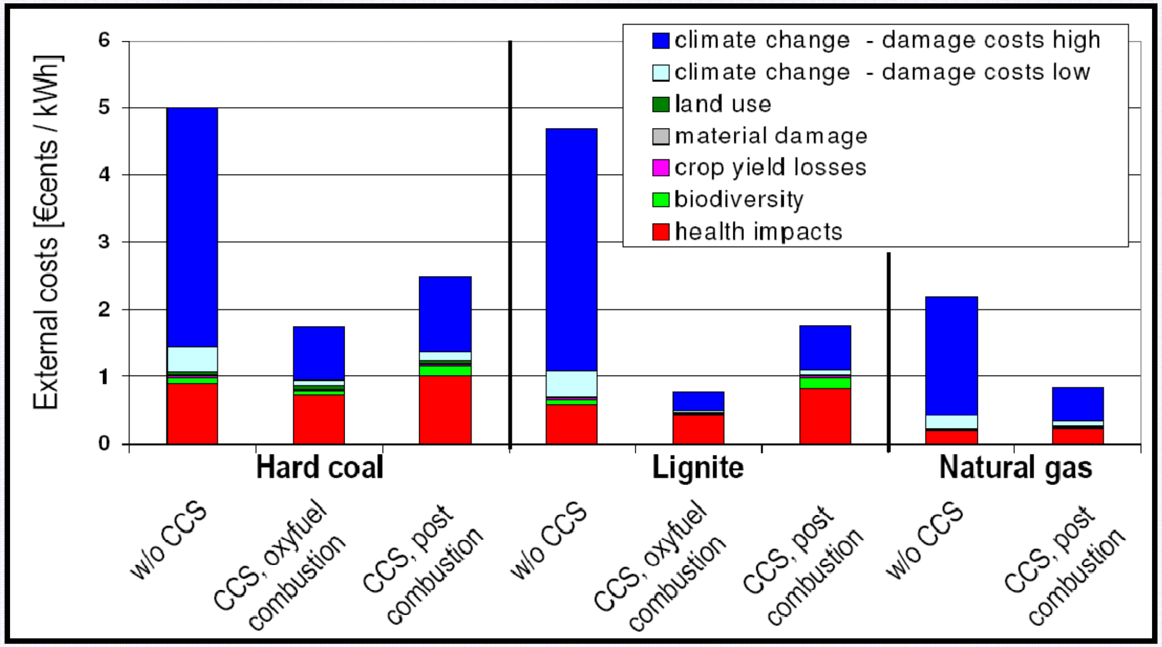
S. Hirschberg, C. Bauer



CARMA and the CCS value chain

Power plant → CO_2 capture → CO_2 transportation → CO_2 storage

SP5:
Public perception and legal aspects of CCS

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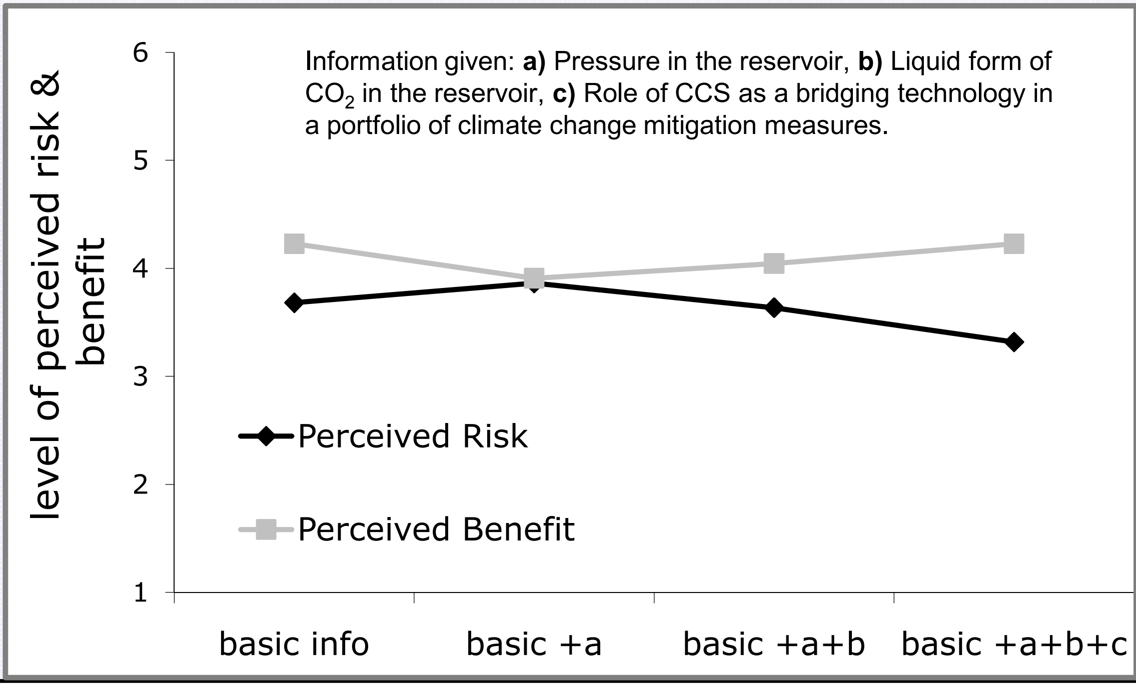
Swiss Federal Institute of Technology Zurich

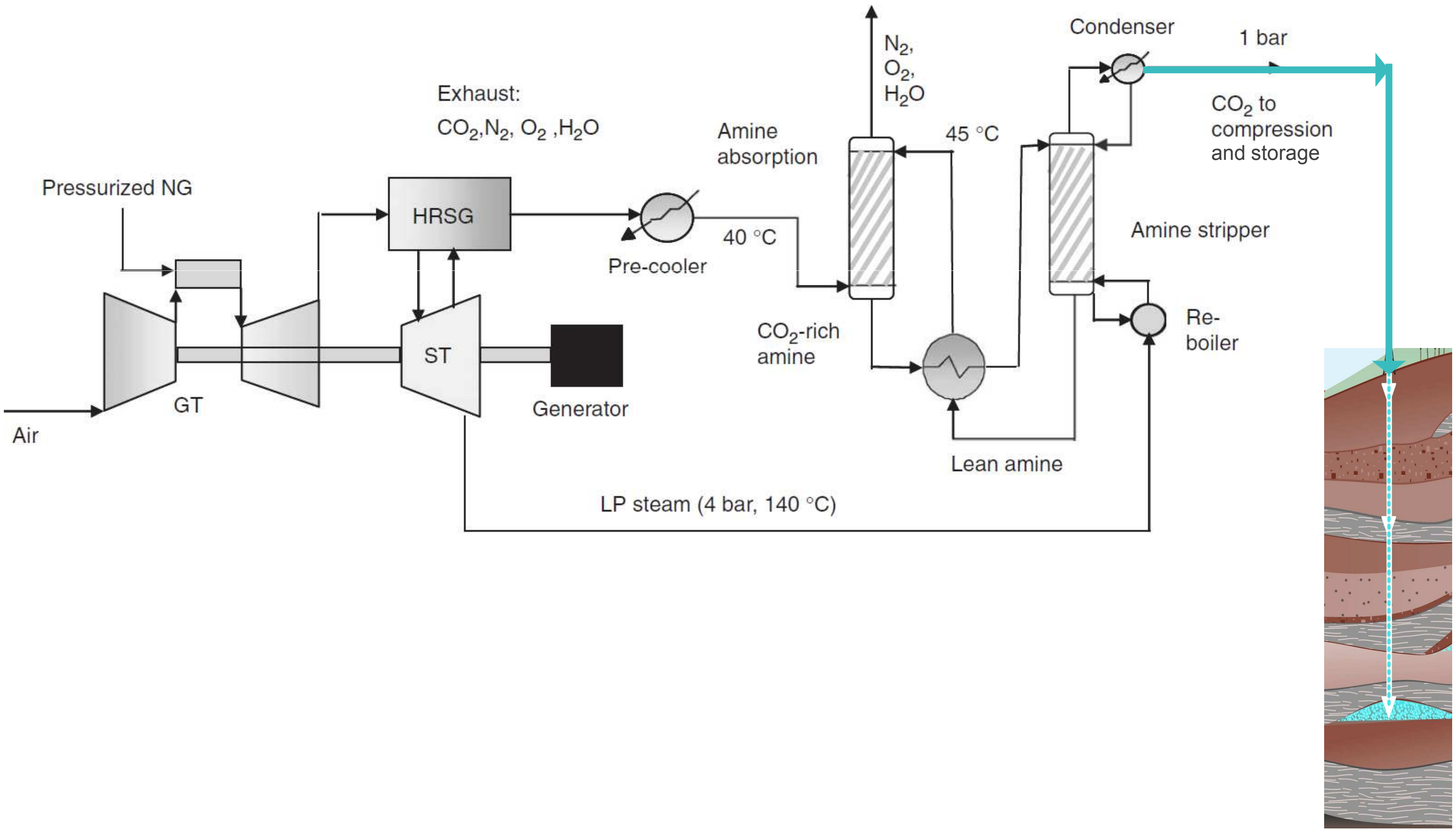
M. Siegrist
L. Wallquist



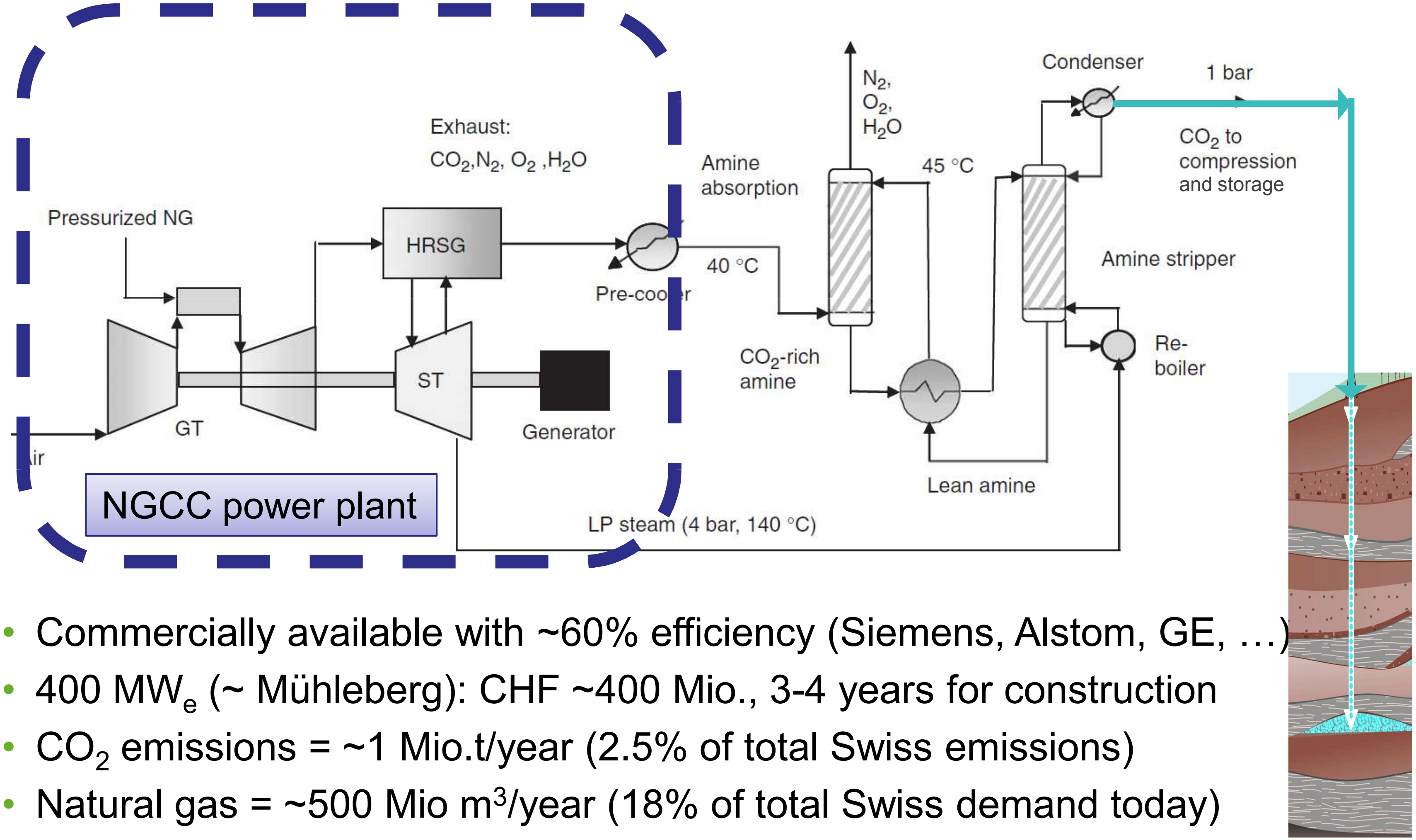
CCS status in a Swiss perspective

Power plant → CO_2 capture → CO_2 transportation → CO_2 storage

NGCC with CCS

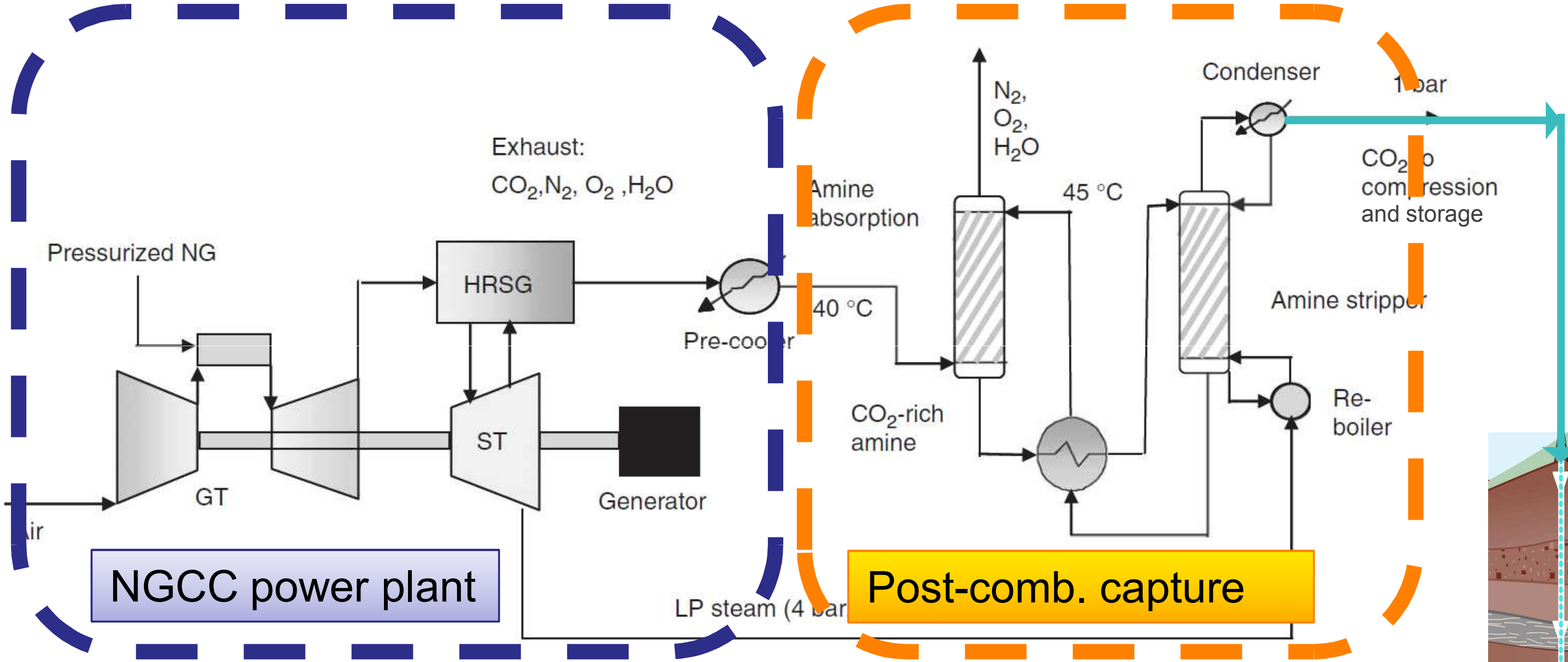


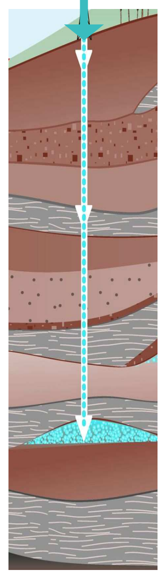
NGCC with CCS



- Commercially available with ~60% efficiency (Siemens, Alstom, GE, …)
- 400 MW_e (~ Mühleberg): CHF ~400 Mio., 3-4 years for construction
- CO_2 emissions = ~1 Mio.t/year (2.5% of total Swiss emissions)
- Natural gas = ~500 Mio m^3/year (18% of total Swiss demand today)

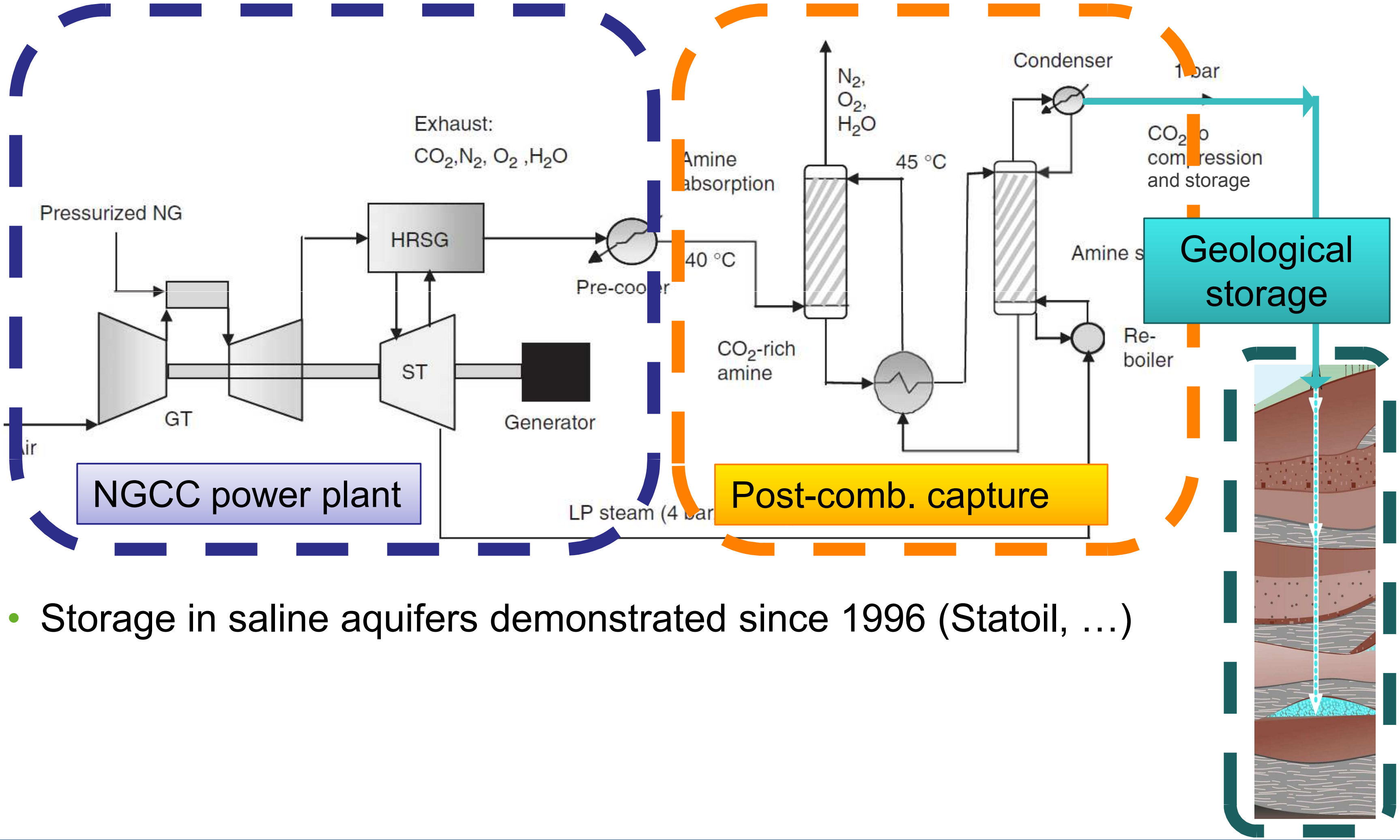
NGCC with CCS





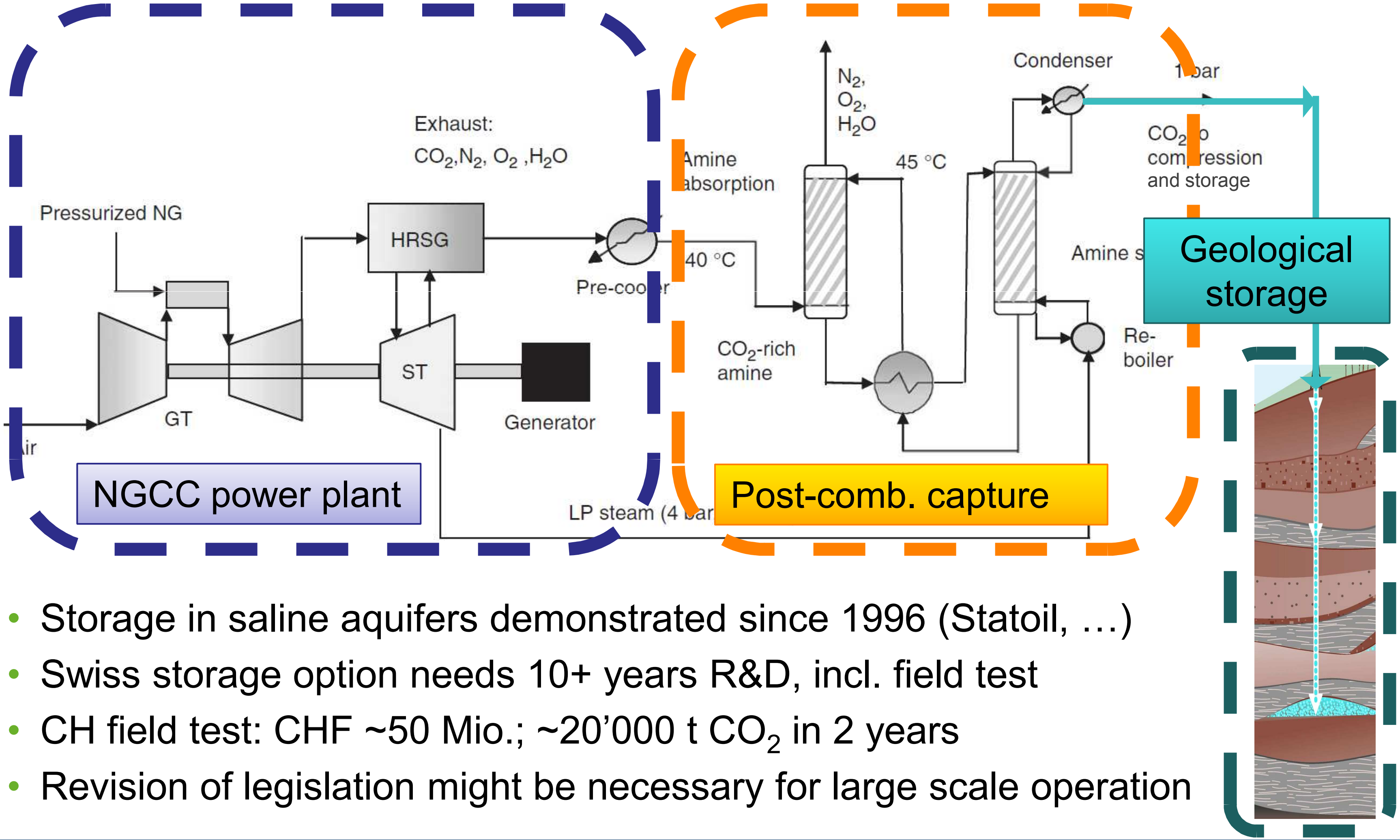
- Demonstrated process (MHI, Aker, Alstom, Sulzer, …)
- Retrofit: CHF ~400 Mio.; electricity cost: + 50%
- Capture rate: 90%; efficiency penalty: - 8%
- CO_2 emissions = ~0.15 Mio. t/year; NG = ~600 Mio. m^3/year

NGCC with CCS



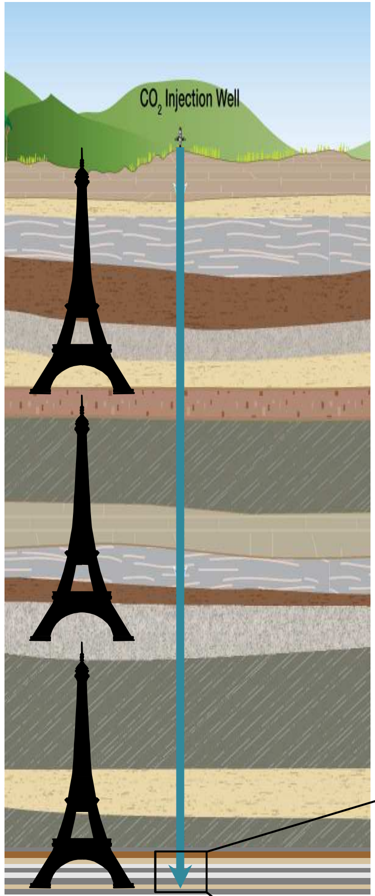
- Storage in saline aquifers demonstrated since 1996 (Statoil, …)

NGCC with CCS



- Storage in saline aquifers demonstrated since 1996 (Statoil, …)
- Swiss storage option needs 10+ years R&D, incl. field test
- CH field test: CHF ~50 Mio.; ~20’000 t CO_2 in 2 years
- Revision of legislation might be necessary for large scale operation

CO_2 storage in saline aquifers



Saline aquifer, min. 800 m deep

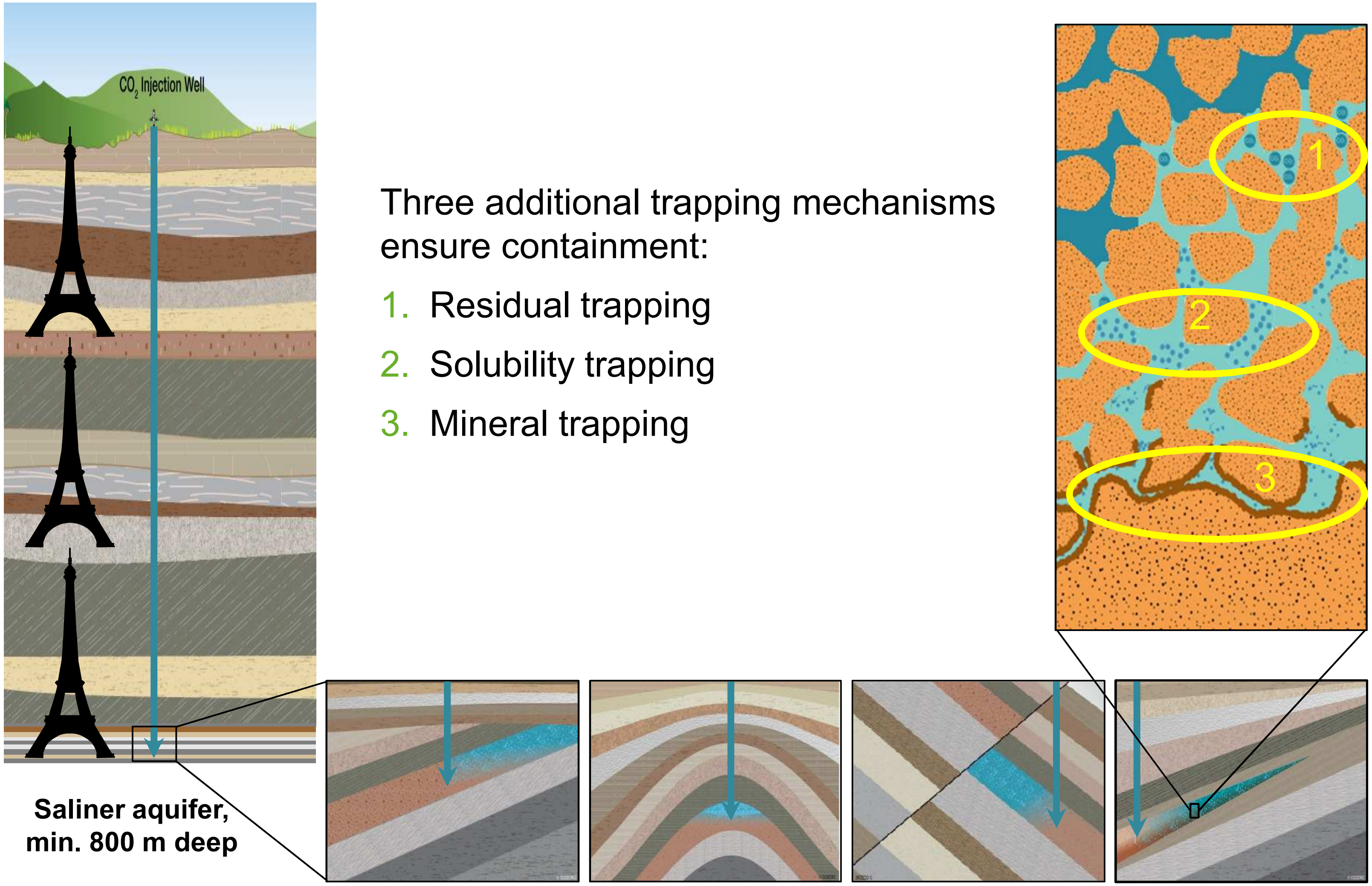
- Dense (impermeable) and porous (permeable) geologic formations alternate
- Porous formations in greater depth are saturated with brine (= **saline aquifer**)

- CO_2 is injected into the saline aquifer and replaces the brine locally.
- CO_2 at this depth and pressure is liquid, but positively buoyant in the brine.
- The CO_2 is trapped under a suitable geologic formaltion (= **caprock**).

CO_2 storage in saline aquifers

Three additional trapping mechanisms ensure containment:

1. Residual trapping
2. Solubility trapping
3. Mineral trapping



Saliner aquifer, min. 800 m deep

CCS status in a Swiss perspective

Power plant → **CO_2 capture** → **CO_2 transportation** → **CO_2 storage**

NGCC technology

- Commercial
- Well established

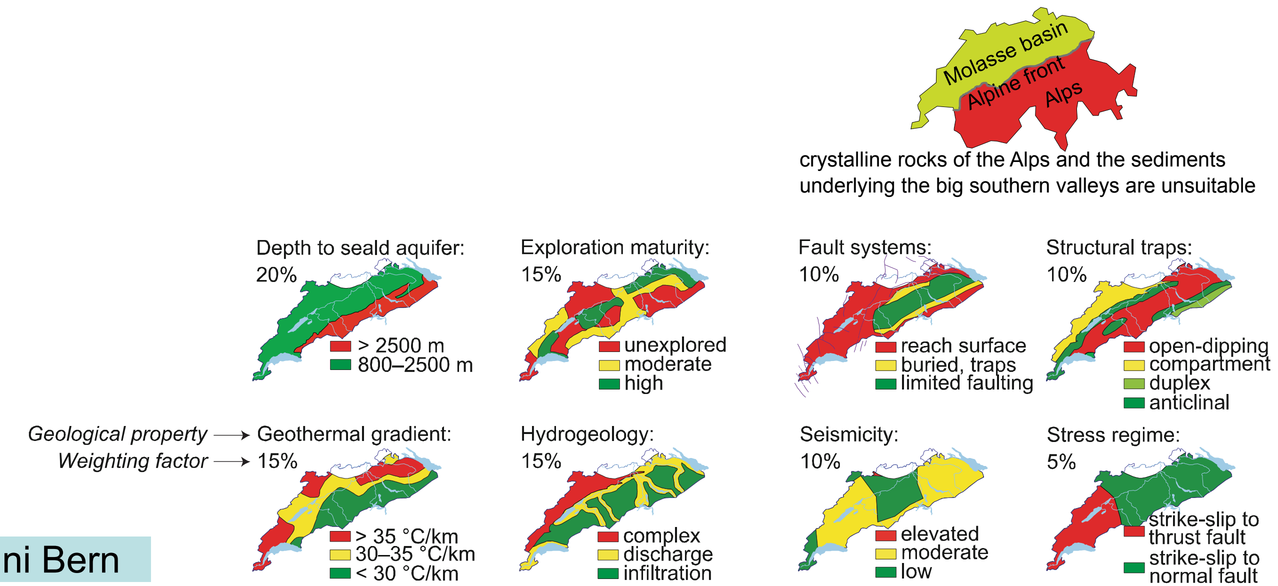
Amine-based processes and **Chilled Ammonia** Process

- Semi-commercial

- Pipeline CO_2 transport in USA
- Transport of NG worldwide

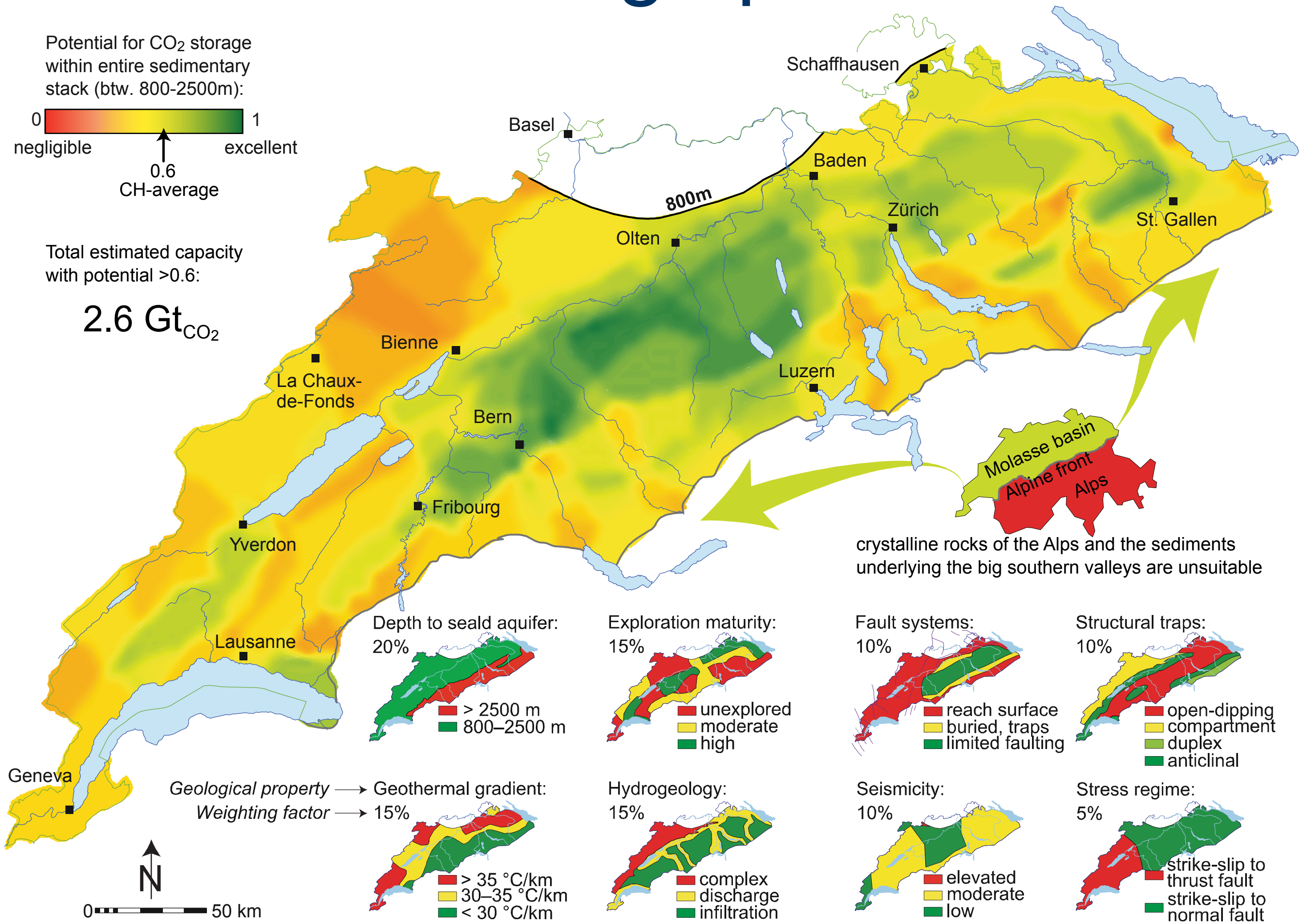
- Characterization of the Swiss sub-surface
- Public acceptance
- Regulatory issues

Estimated storage potential in CH



Diamond et al., Uni Bern

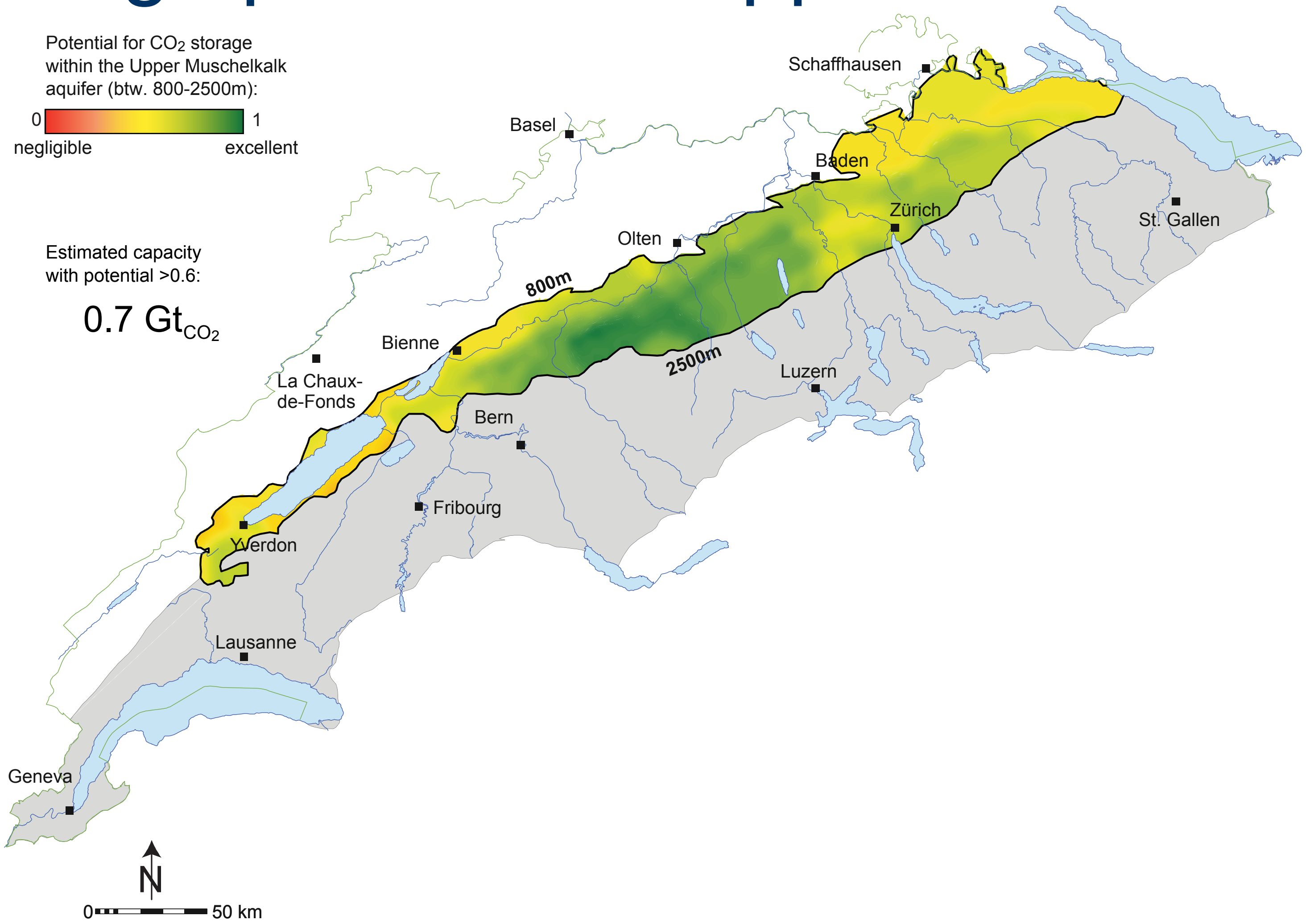
Estimated storage potential in CH



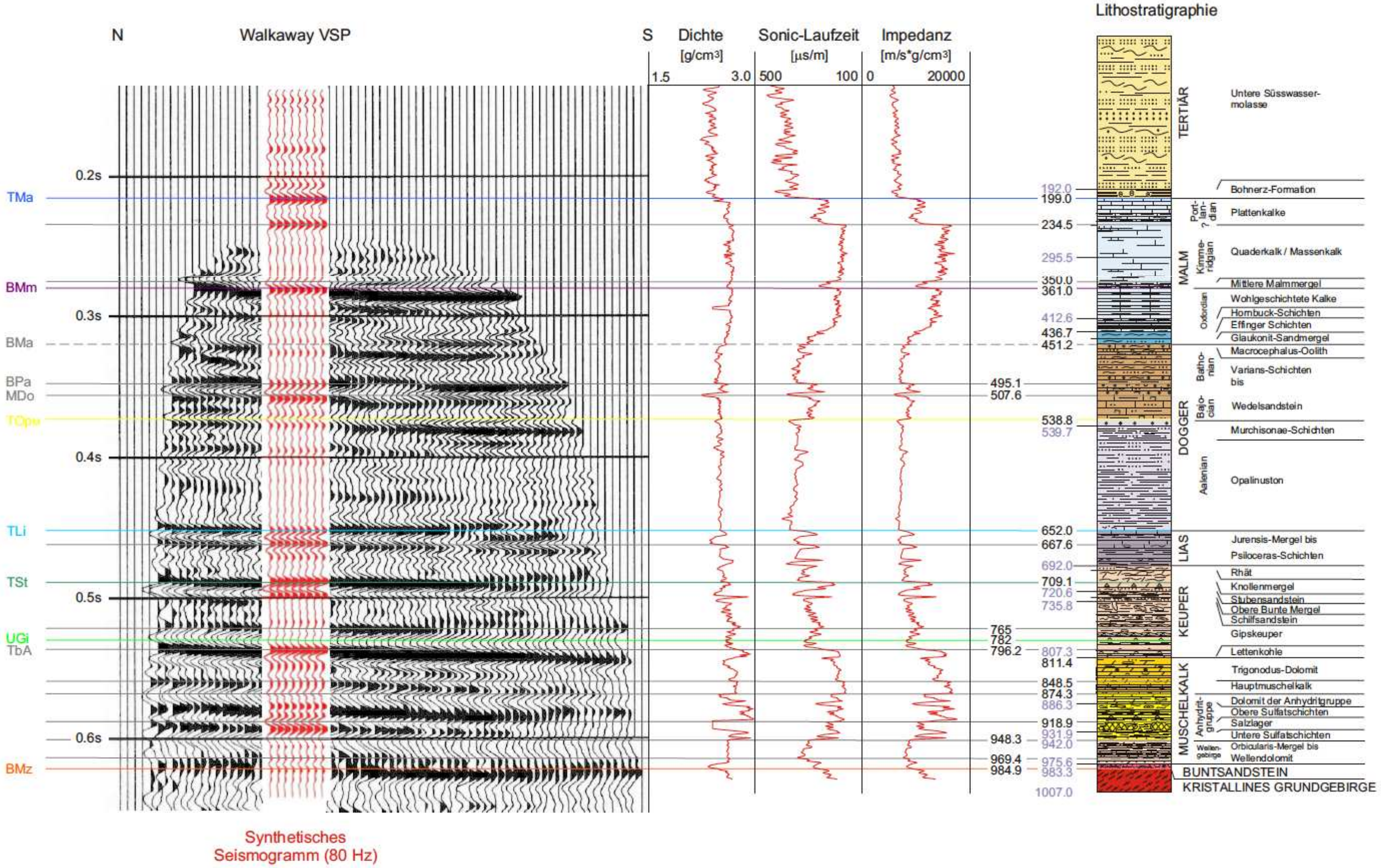
CO_2 geological storage in Switzerland

- Potential structures for test site
- Conflicts of use
- Prediction of CO_2 migration
- Risk of induced seismicity
- Field test

Storage potential in Upper Muschelkalk



Available geological log data



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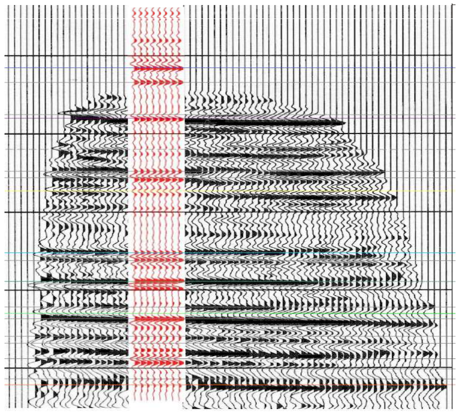
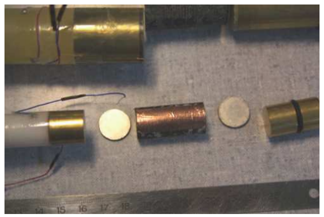
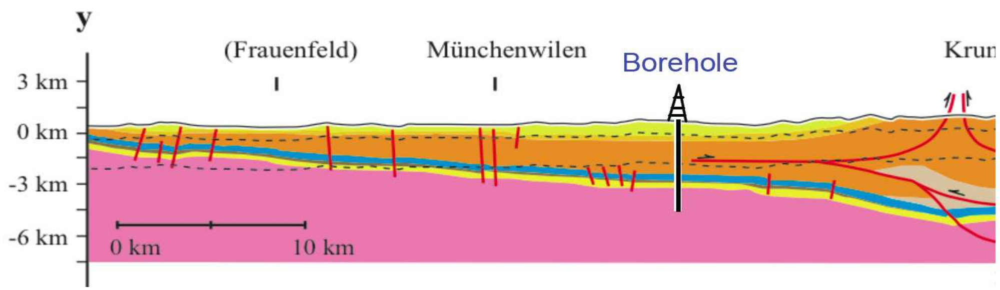
From borehole to reservoir scale

Geophysical response → Petro-physics → Geological setting



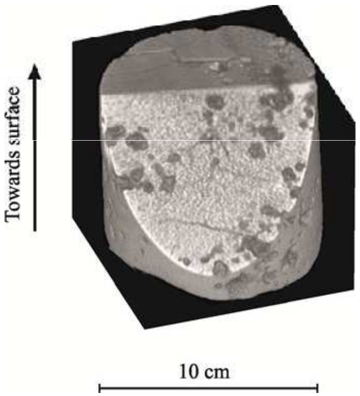


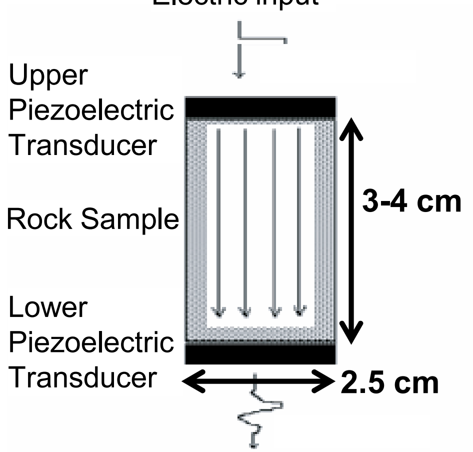


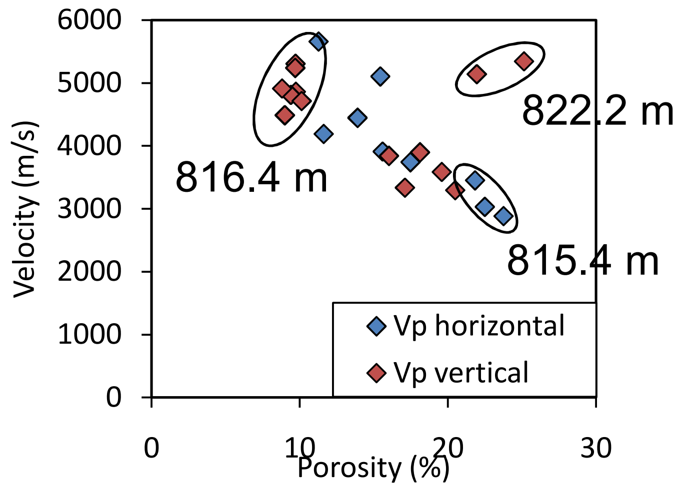
- Porosity → Storage capacity
- Permeability → CO_2 injectivity

Physical Properties: Ultrasound velocities

CT scan



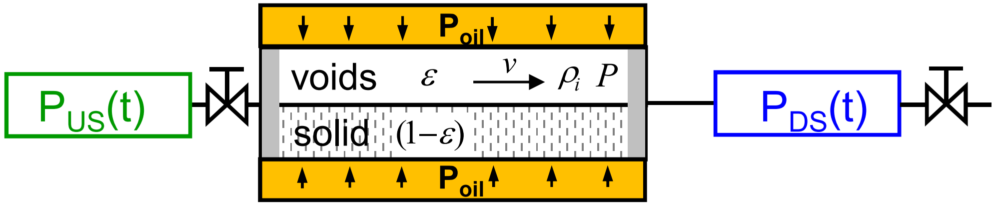




Knowing the ultrasound velocity, reflected shock waves from geological surveys can be matched to formation interfaces.
Ultrasound velocities could also be correllated with permeability, and have been used to observe the CO_2 plume after injection in Ketzin.

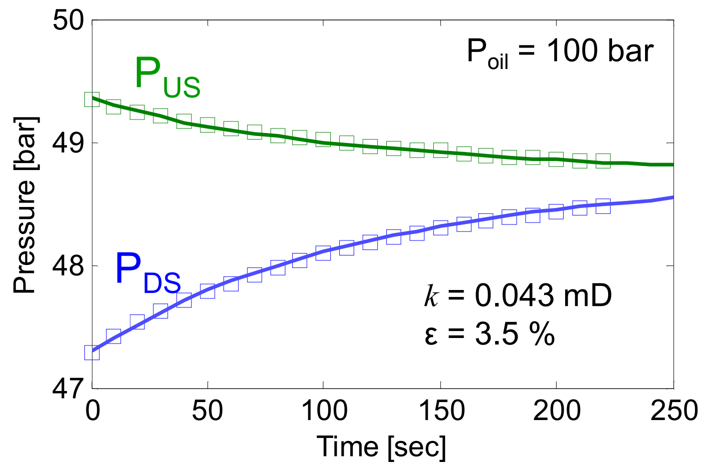
Physical Properties: Permeability

Permeability measurements by transient step method



Working conditions:
P < 300 bar, P_{oil} < 1000 bar, T < 100 °C

Pressure equilization in transient step



Mass balance

$$\boxed{\frac{\partial(\varepsilon c_i)}{\partial t} + \frac{\partial(u c_i)}{\partial z} = 0}$$

Boundary conditions

$$\frac{\partial c_i^{US}}{\partial t} = -\frac{A}{V_{US}} u\big|_0 \, c_i^{US}$$

$$\frac{\partial c_i^{DS}}{\partial t} = \frac{A}{V_{DS}} u\big|_L \, c_i\big|_L$$

Velocity (Darcy) and permeability

$$u = -\frac{k}{\mu}\left[\frac{\partial P}{\partial z}\right] \qquad \frac{k}{k_0} = \left(\frac{\varepsilon}{\varepsilon_0}\right)^3 = \exp\left[\frac{-C_1(P_c - P)}{K\varepsilon_0}\right]$$

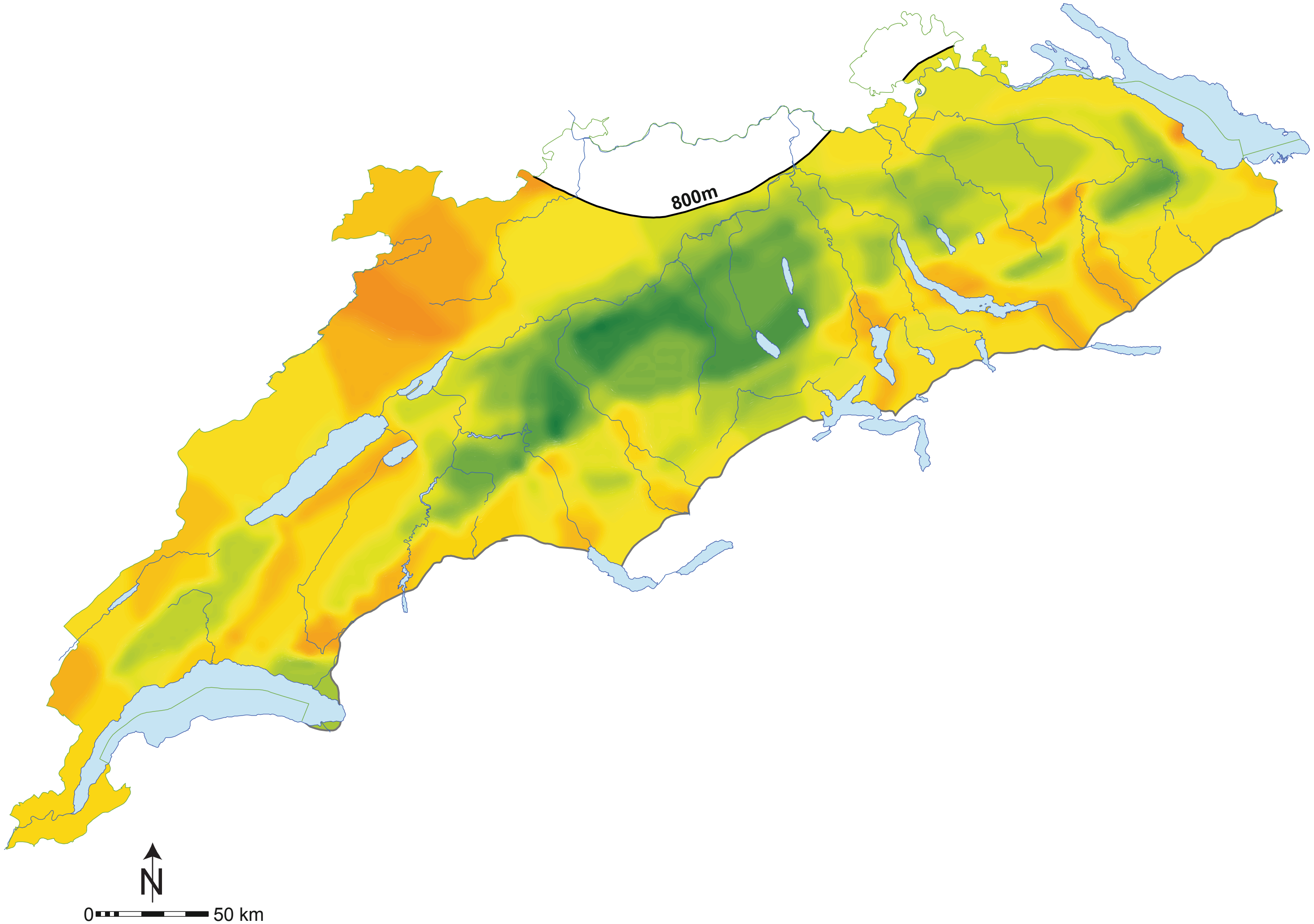
EOS

$$\boxed{P = P(\underline{y}, \rho, T)}$$

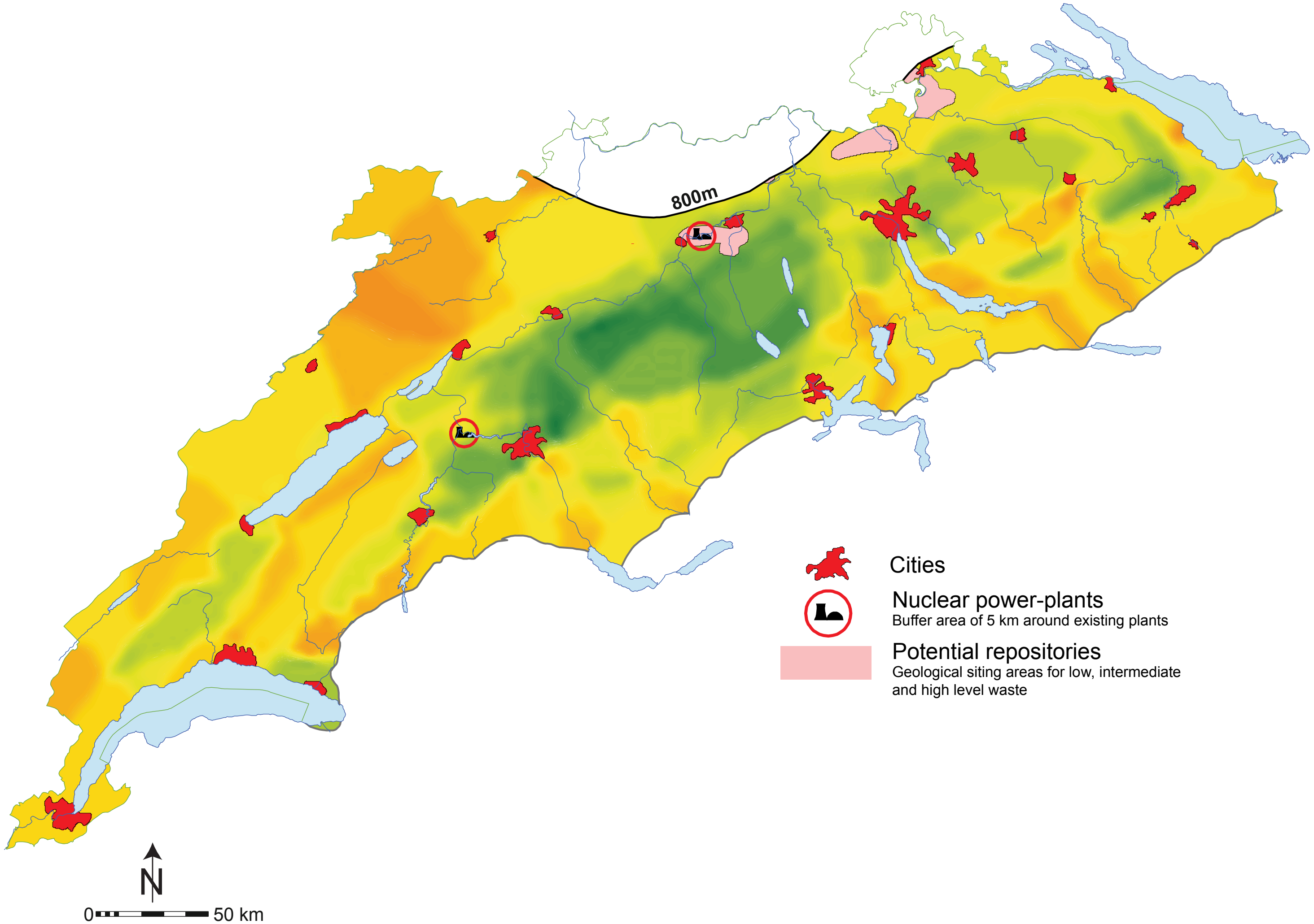
CO_2 geological storage in Switzerland

- Potential structures for test site
- Conflicts of use
- Prediction of CO_2 migration
- Risk of induced seismicity
- Field test

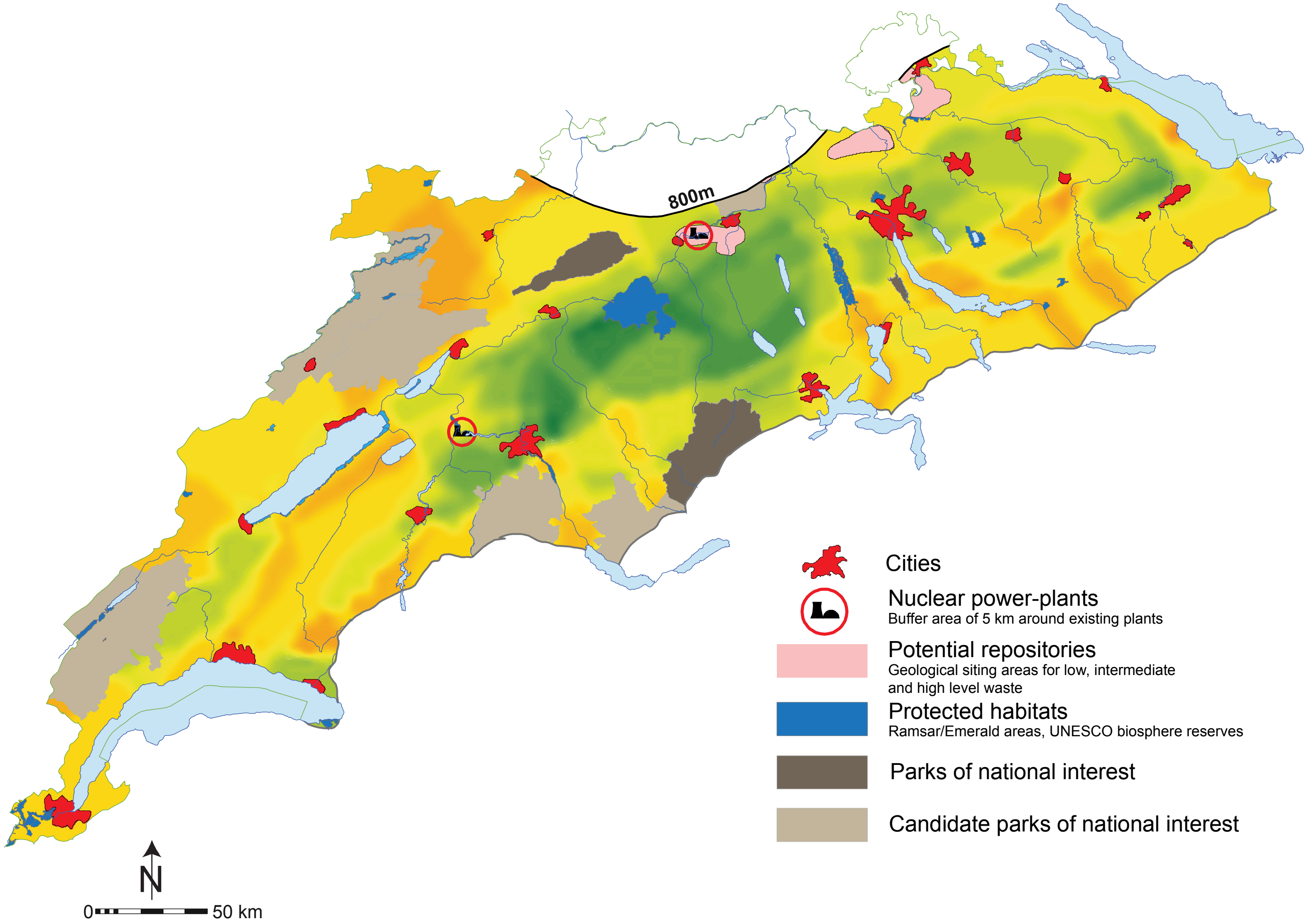
Local restrictions



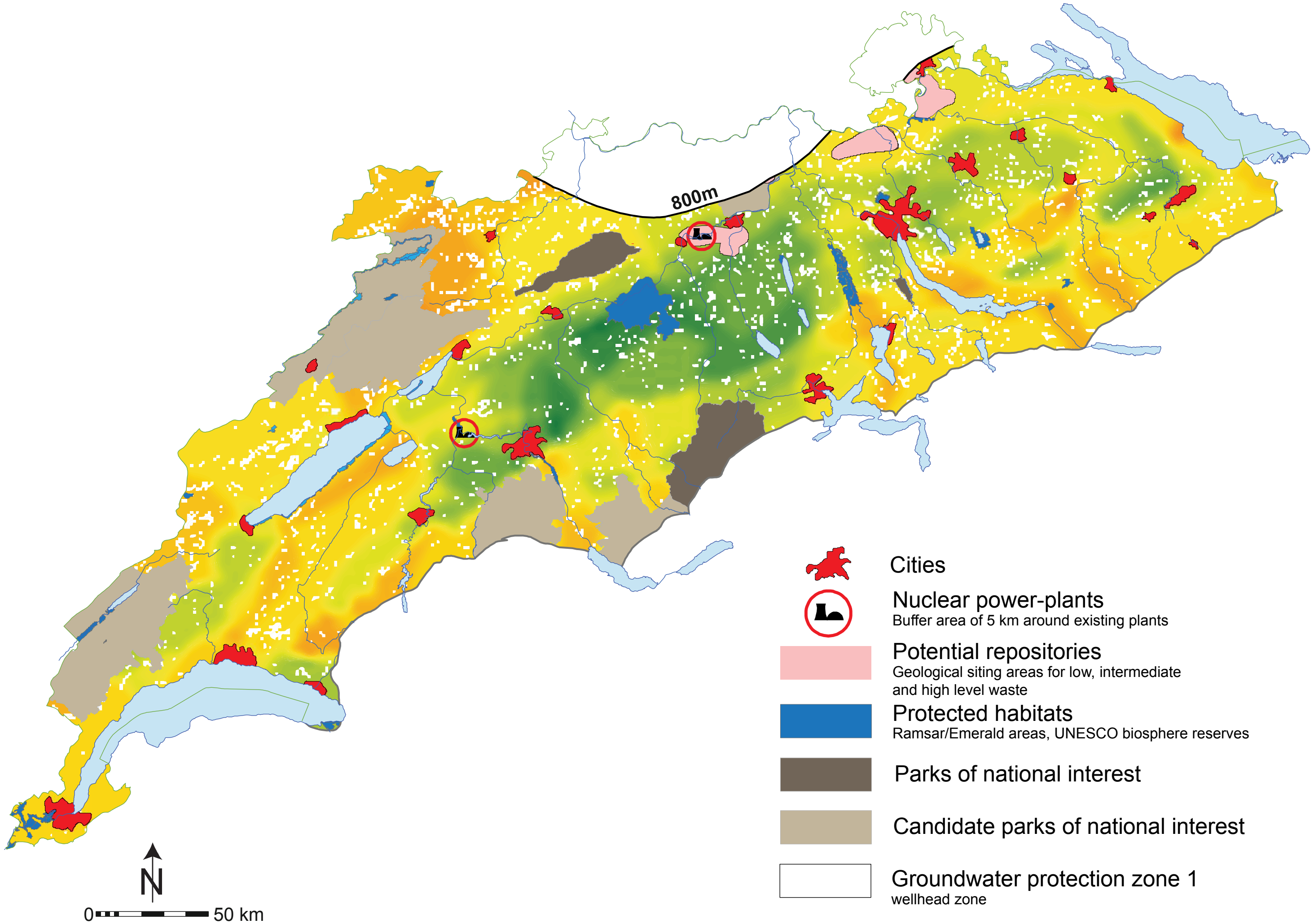
Local restrictions



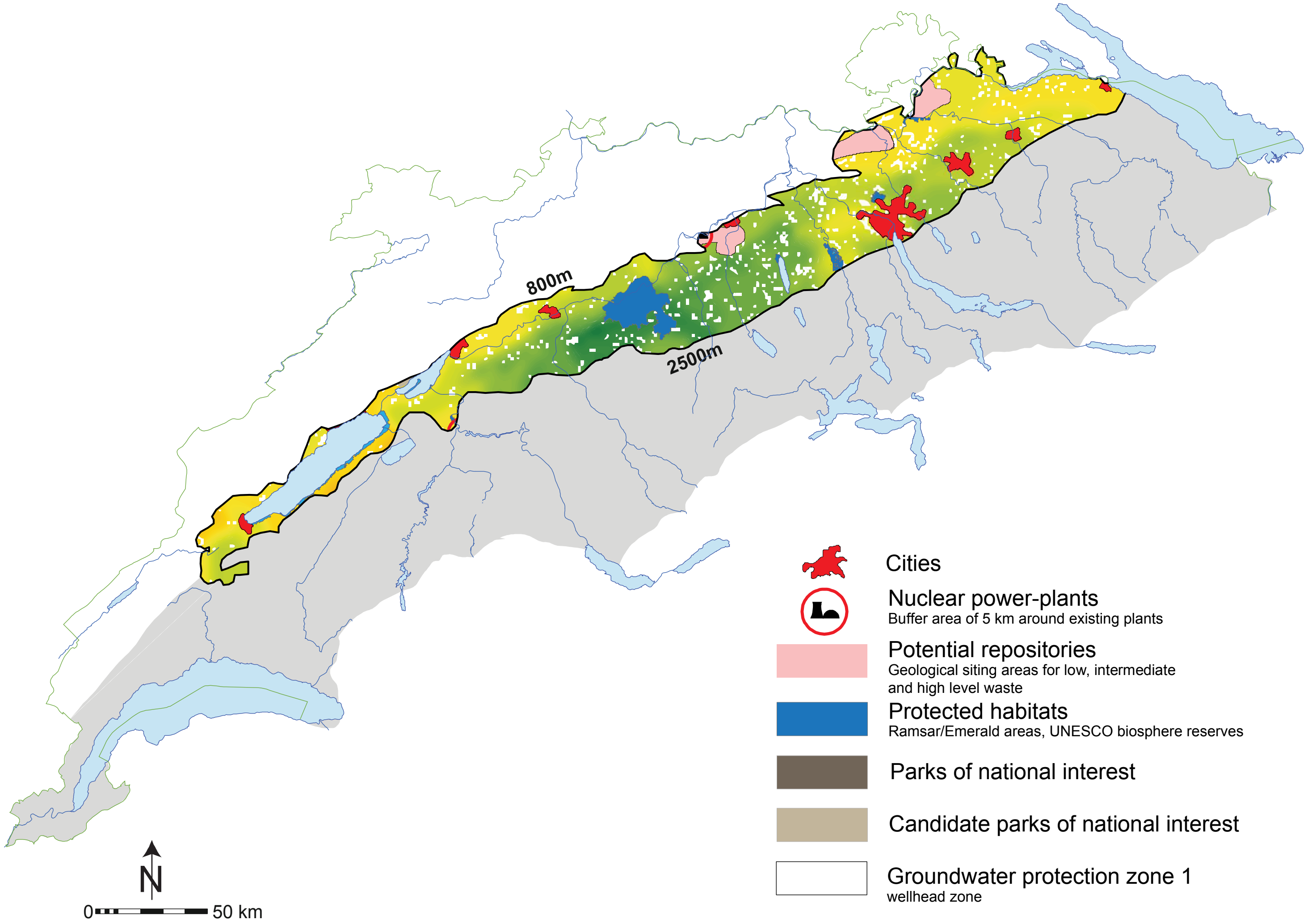
Local restrictions



Local restrictions



Local restrictions

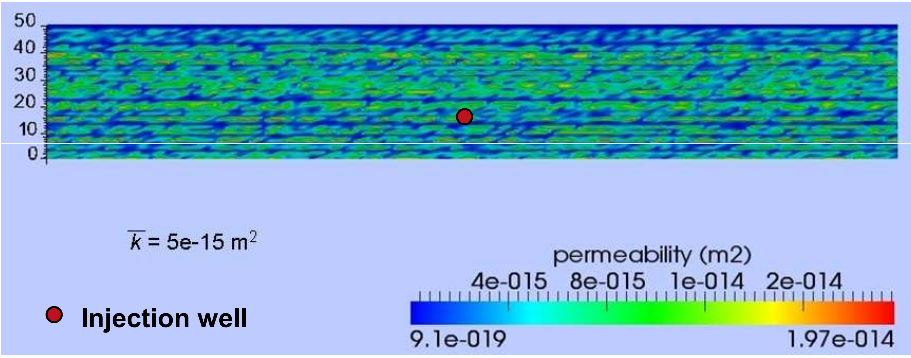


CO_2 geological storage in Switzerland

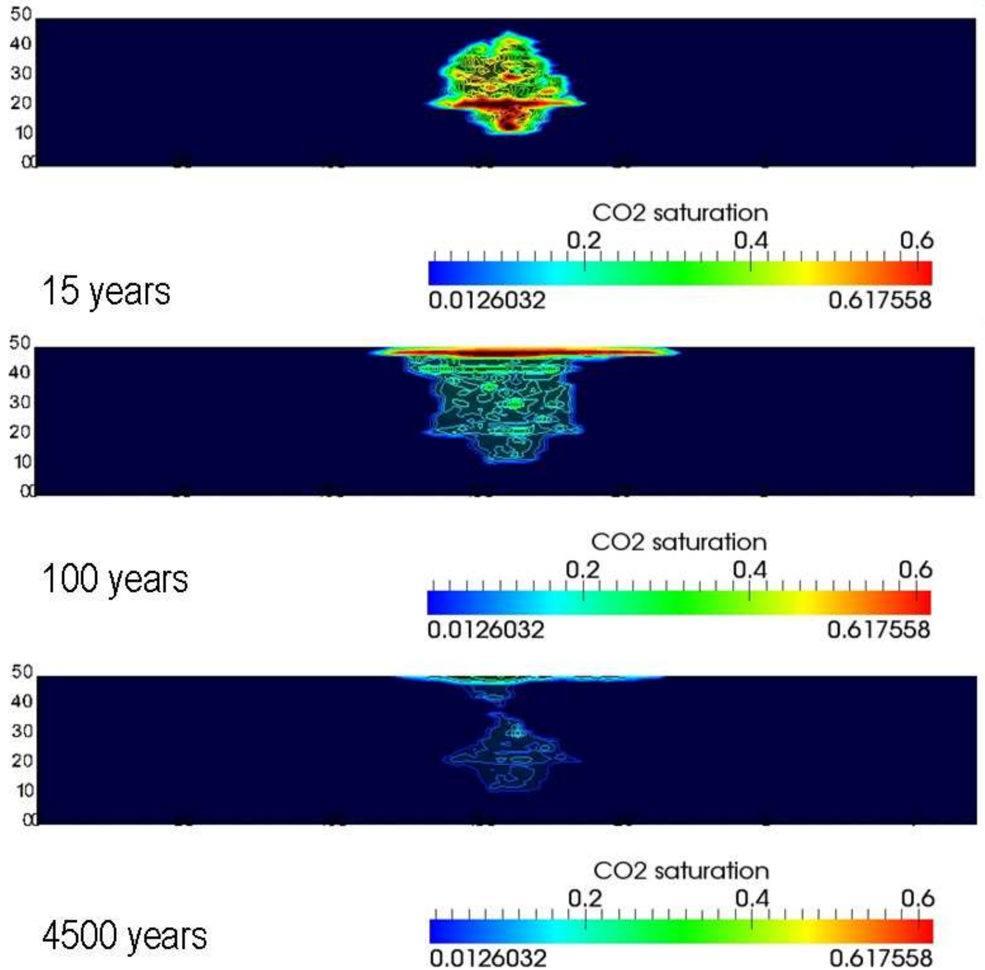
- Potential structures for test site
- Conflicts of use
- Prediction of CO_2 migration
- Risk of induced seismicity
- Field test

Injection into a heterogeneous aquifer

Model domain and permeability distribution



Injection rate: 630 t/yr
Injection period: 30 years
Salinity (NaCl): 1 molal



Plume migration and solubility trapping

P. Alt-Epping, Uni Bern

CO_2 geological storage in Switzerland

- Potential structures for test site
- Conflicts of use
- Prediction of CO_2 migration
- Risk of induced seismicity
- Field test

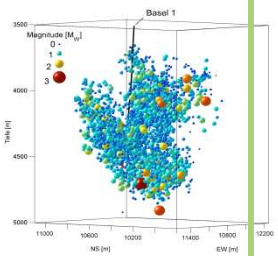
Risk of induced seismicity

- Best practice guideline for the assessment of injection induced seismicity
- Iterative assessment as project proceeds

Planning phase

Drilling

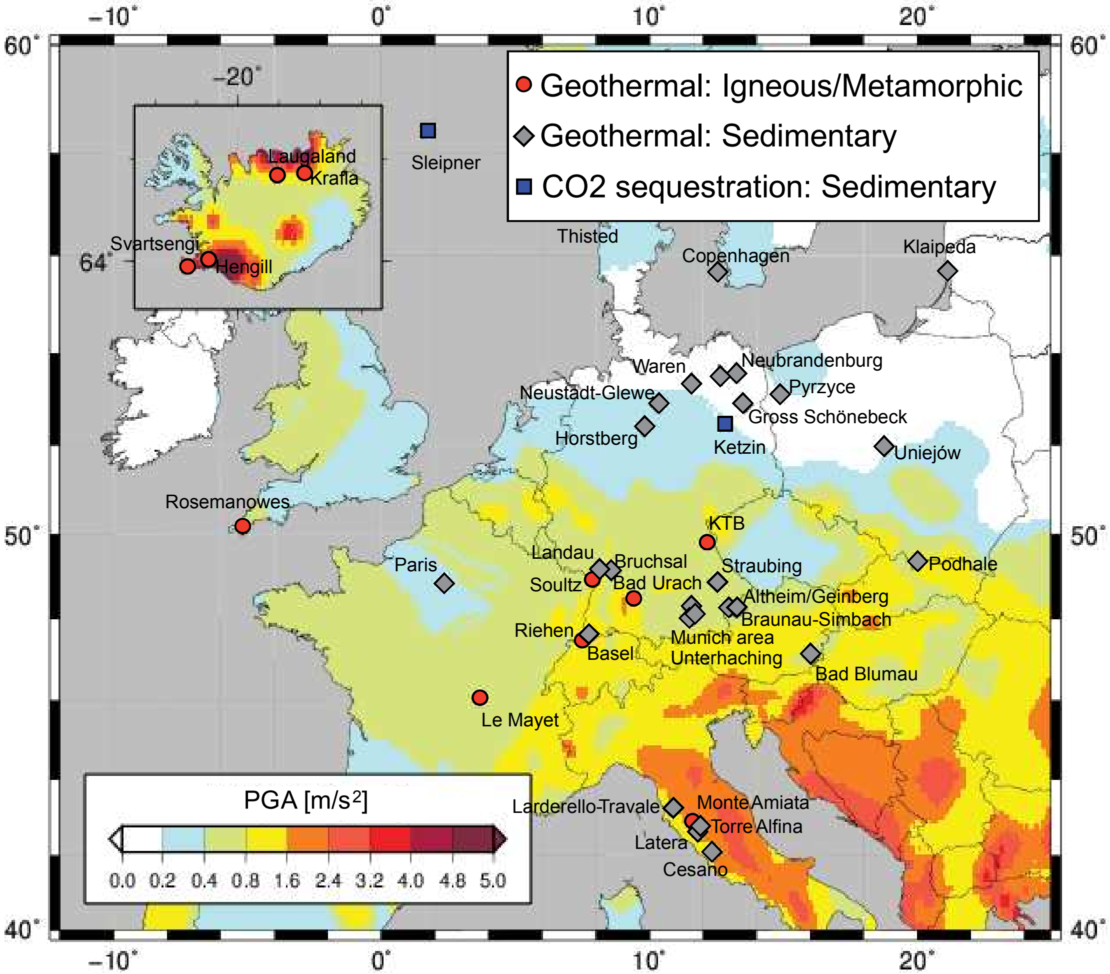
Hydraulic testing

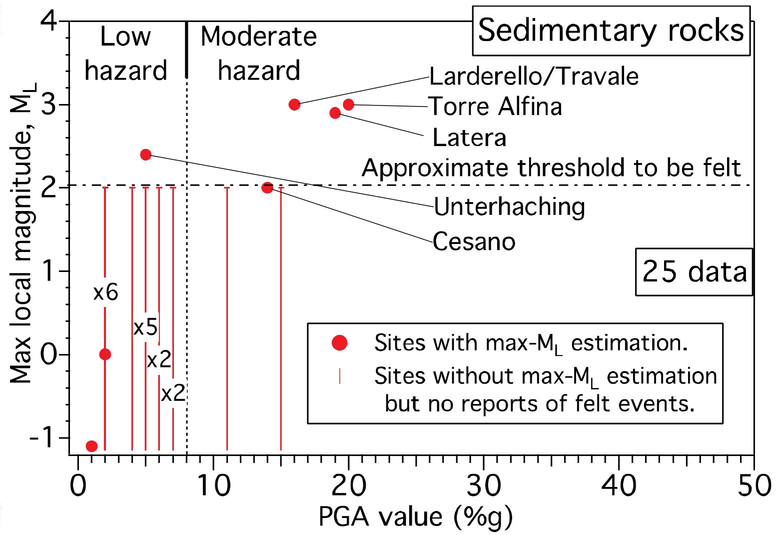


Injection

Post-injection

Database of injection induced seismicity





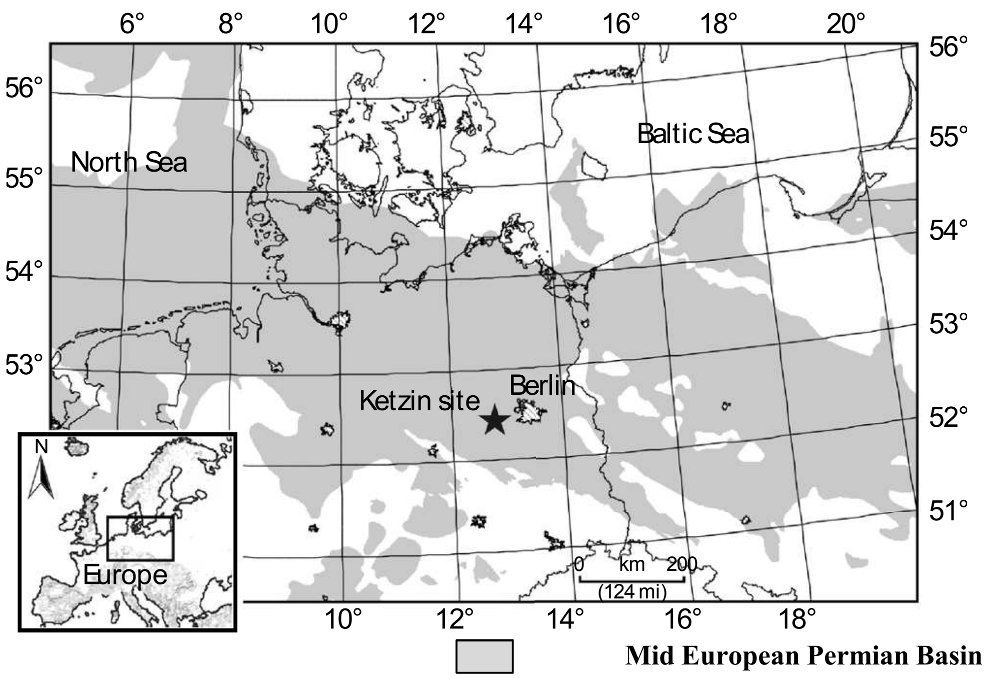
Background seismic activity was quantified by the peak ground acceleration (PGA).
Induced seismic activity was quantified by the maximum local magnitude (ML) .

K. Evans, A. Zappone, ETH Zürich

CO_2 geological storage in Switzerland

- Potential structures for test site
- Conflicts of use
- Prediction of CO_2 migration
- Risk of induced seismicity
- Field test

Location Ketzin



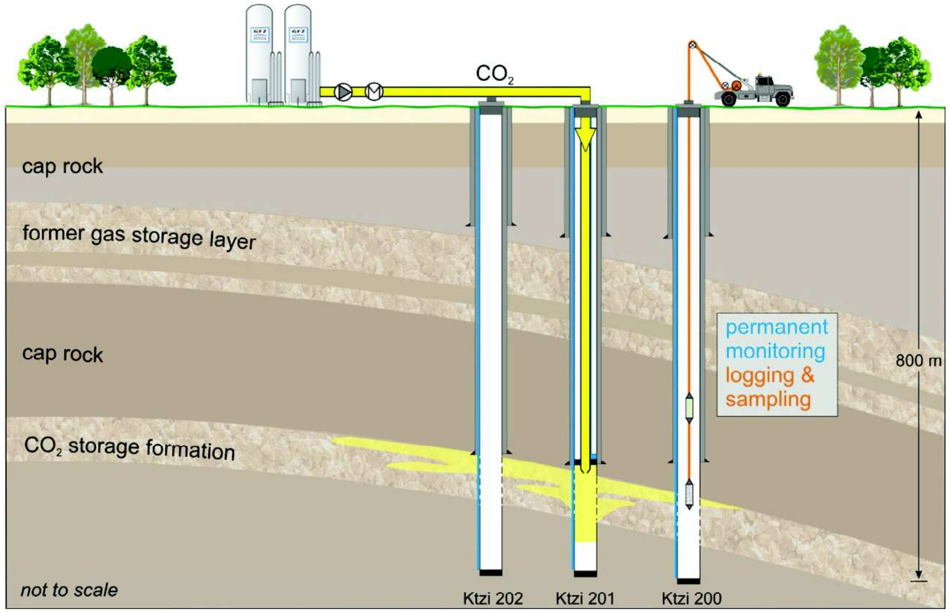
Lokhorst (1998), NW European Gas Atlas

- ~6500 inhabitants
- Bundesland Brandenburg
- Former NG storage site
- Research project!
  - < 100,000 t
  - Investigative approach
- Geo-Forschungszentrum Potsdam as project coordinator + partners
  - CO_2 transport and pre-injection: Linde
  - Site operation: VNG (gas utility company)
- Geology:
  - Saline aquifer
  - Multi-barrier system
- Test site operation: 2008 - 2015

Reservoir monitoring at the Ketzin pilot

- Project covers all aspects of CCS storage operation
- Focus on reservoir monitoring
- Testing of different techniques for monitoring the CO_2 plume in the reservoir

- Reservoir conditions
  - Injection depth: ~ 630 m
  - Formation temperature: 35°C
  - Injection pressure: 72 bar

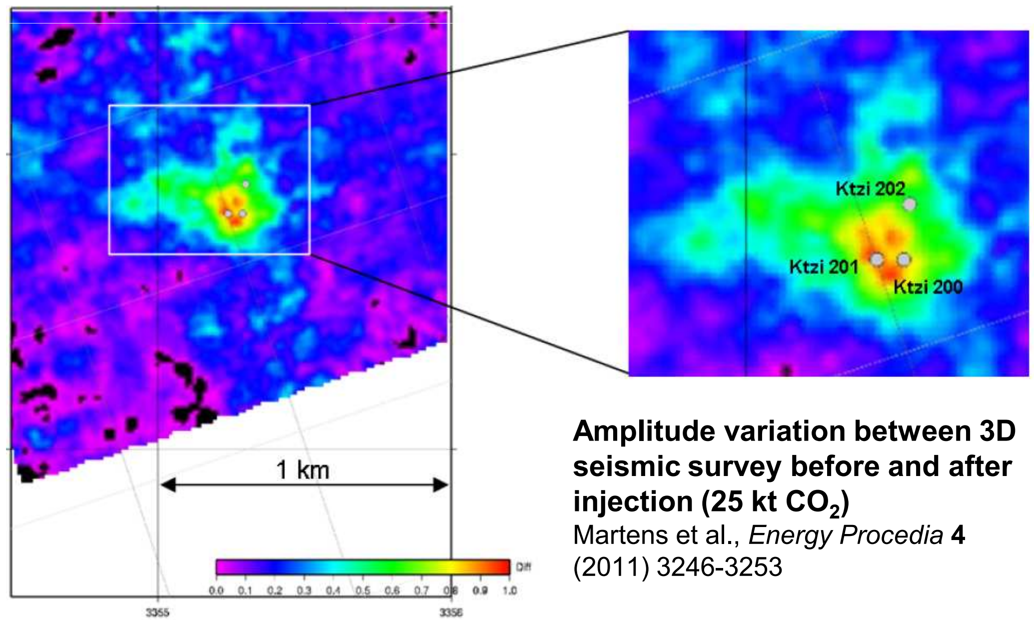


Martens et al., *Energy Procedia* **4** (2011) 3246-3253

Reservoir monitoring at the Ketzin pilot

- Project covers all aspects of CCS storage operation
- Focus on reservoir monitoring
- Testing of different techniques for monitoring the CO_2 plume in the reservoir

- Seismic monitoring:
  - Applied methods
    - 2D and 3D surface surveys
    - Cross-hole tomography between observation wells
    - Surface-downhole observations
  - Localization of the CO_2 through
    - Reduction of seismic velocity
    - Increase of reflectivity

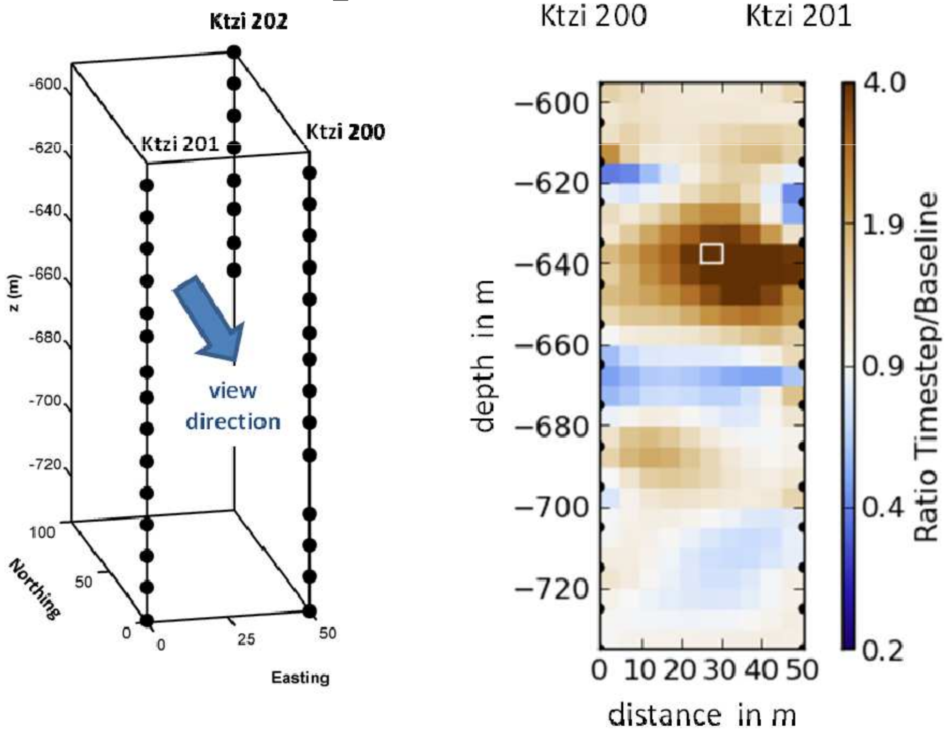


Amplitude variation between 3D seismic survey before and after injection (25 kt CO_2)
Martens et al., *Energy Procedia* **4** (2011) 3246-3253

Reservoir monitoring at the Ketzin pilot

- Project covers all aspects of CCS storage operation
- Focus on reservoir monitoring
- Testing of different techniques for monitoring the CO_2 plume in the reservoir

- Geoelectric monitoring
  - Applied methods
    - Vertical electric resistivity array (VERA)
    - Downhole electrical resistivity tomography (ERT)
  - Localization of the CO_2 through
    - Increase of electrical resistivity



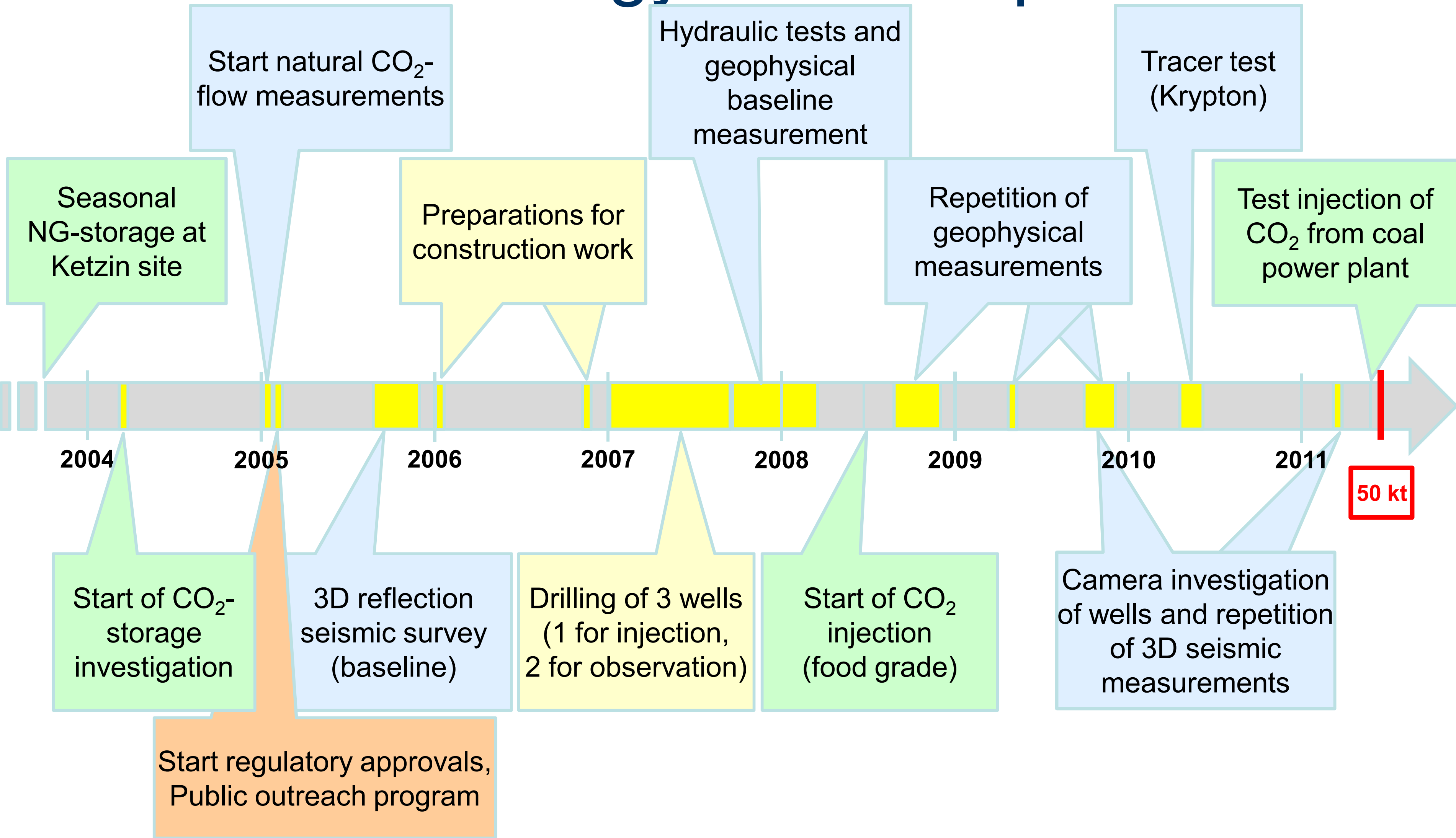
Resistivity ratio after/before CO_2 injection (5 kt CO_2)
Martens et al. *Energy Procedia* **4** (2011) 3246-3253

Public acceptance of Ketzin pilot

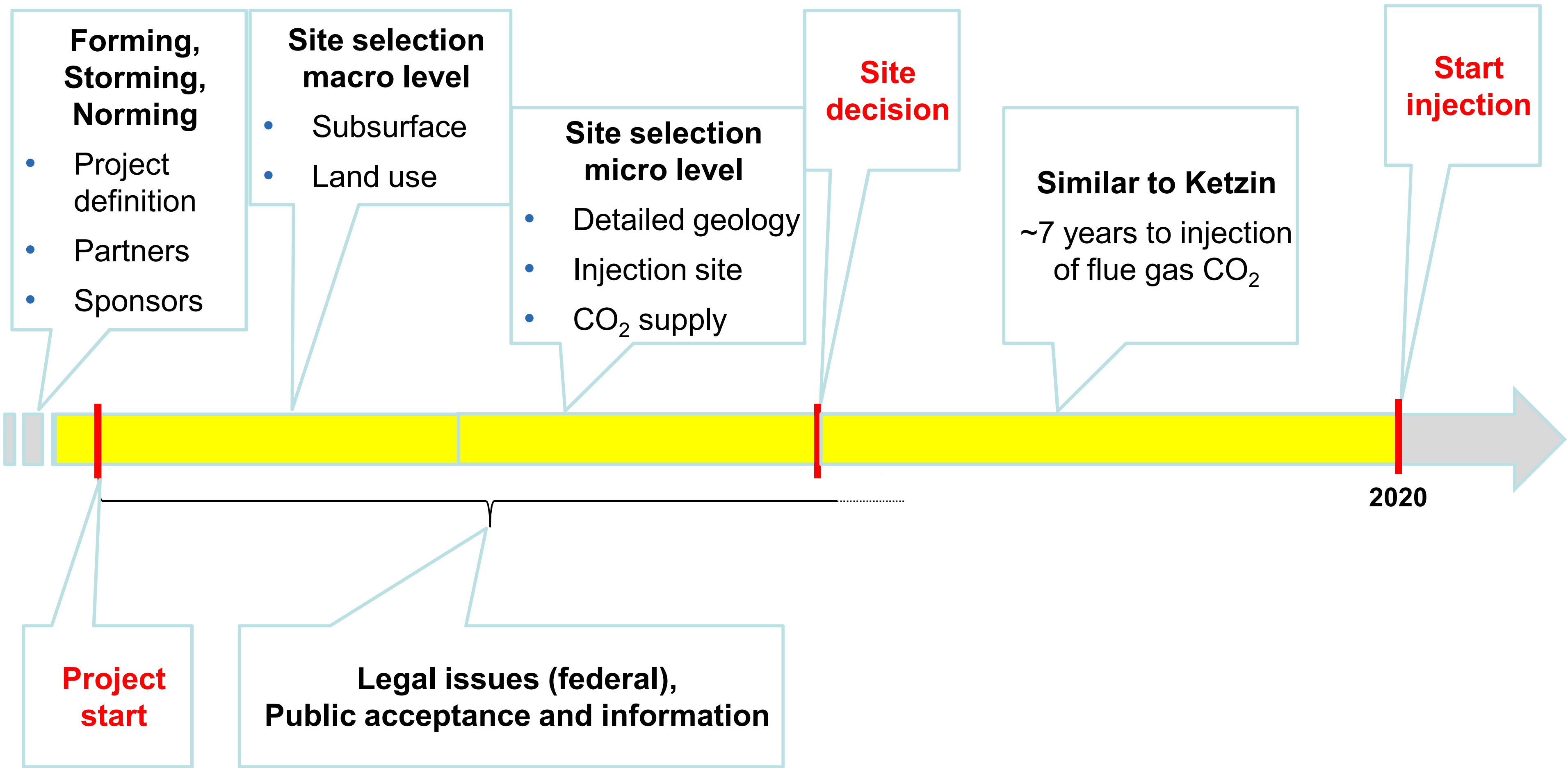
- Forward relation to major and council of Ketzin
- Neighbors and journalists informed ahead of all planned operations
- Priority for local requests and local press
- Benefits of publicity for Ketzin communicated through local authorities
- Visitors center and guided tours on-site
- Website: www.co2ketzin.de
- Injection of food grade CO_2 to favor acceptance
- Generally accepting attitudes in local community (NG-storage)

Würdemann et al., *Int. J. Greenh. Gas Con.* **4** (2010) 938-951
Martens, Academic Research Strategy Meeting, Edinburgh (2010)

Chronology of Ketzin pilot



Comparison to the Swiss case



CARMA key thrusts (2009-2012)

- Assessing the role of CCS in future Swiss power generation.
- Enhancing Swiss scientific and technical know-how in CCS.

2013-25: NCCR GeoEnergy

Leading to CCS field test in Switzerland www.carma.ethz.ch