Numerical Modelling of CO_2 Storage in Geological Formations with MUFTE-UG

Anozie Ebigbo, Andreas Kopp, Holger Class, Rainer Helmig

Universität Stuttgart

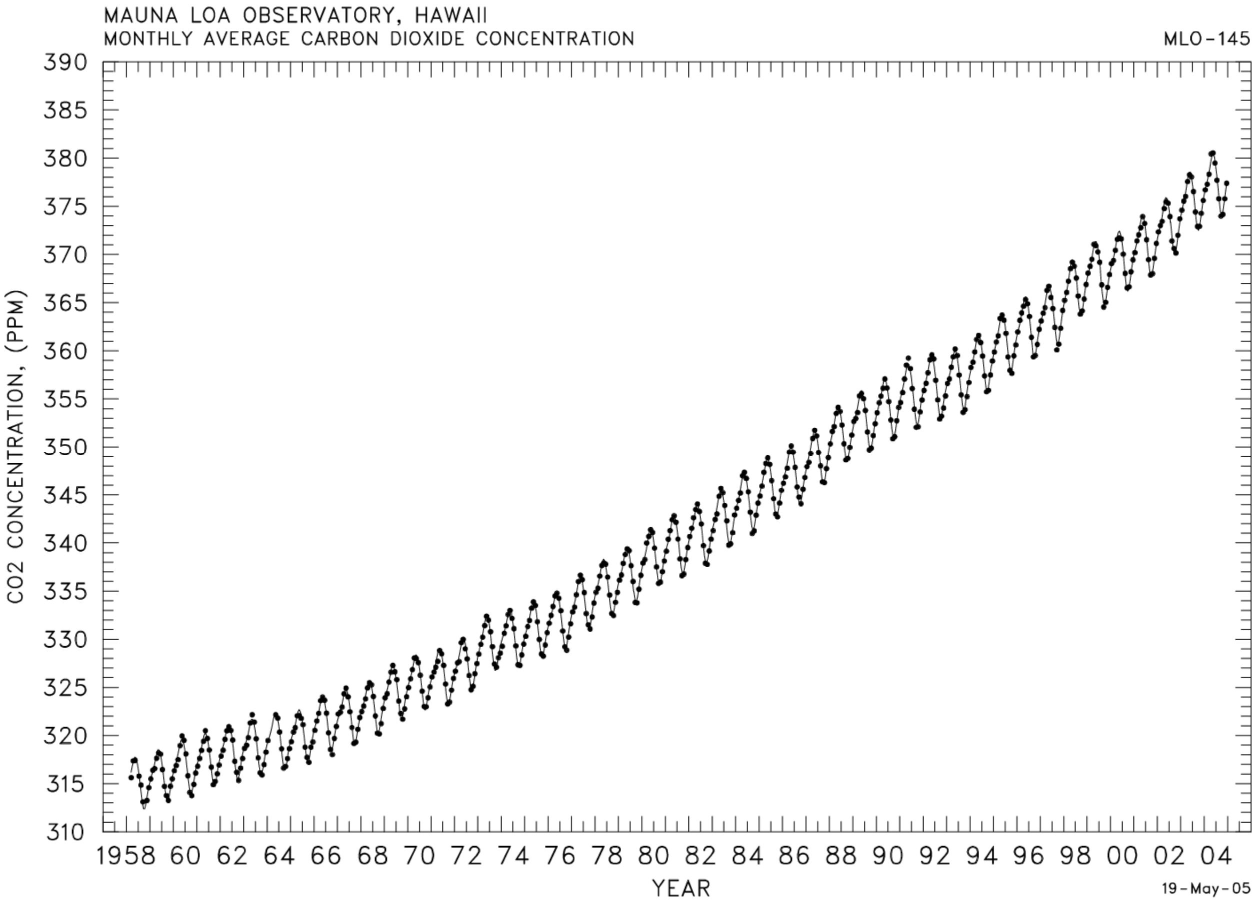
Wednesday, 14th March 2007

Outline

- Motivation
- Physical/mathematical and numerical model
- Simulations
  - Leakage
  - Storage in Depleted Gas Reservoirs
- Final remarks

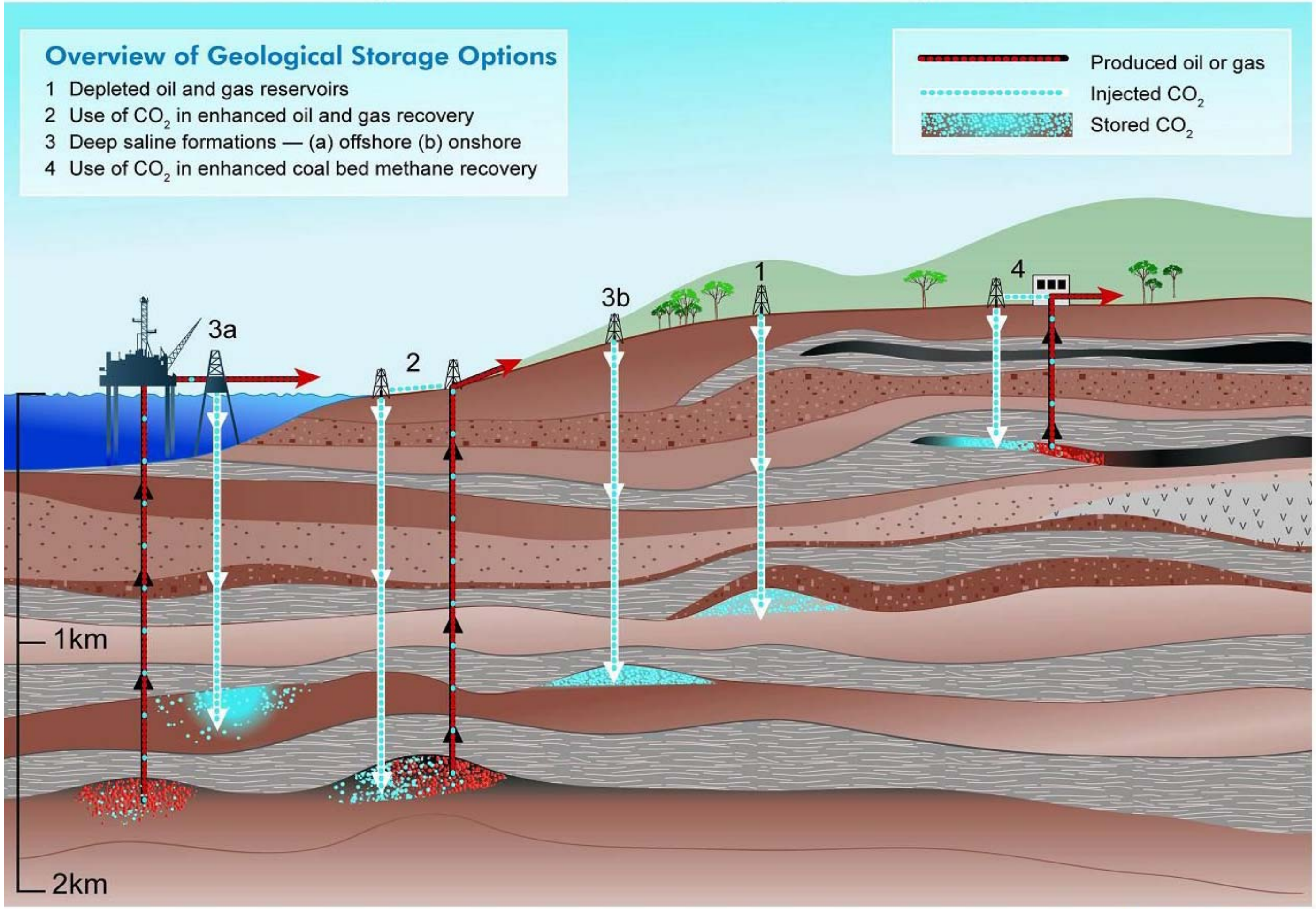
Atmospheric CO_2 Concentration

Increase in atmospheric CO_2 concentration is causing global climate change since CO_2 is a greenhouse gas.



Keeling & Whorf, 2005

Geological Storage Options



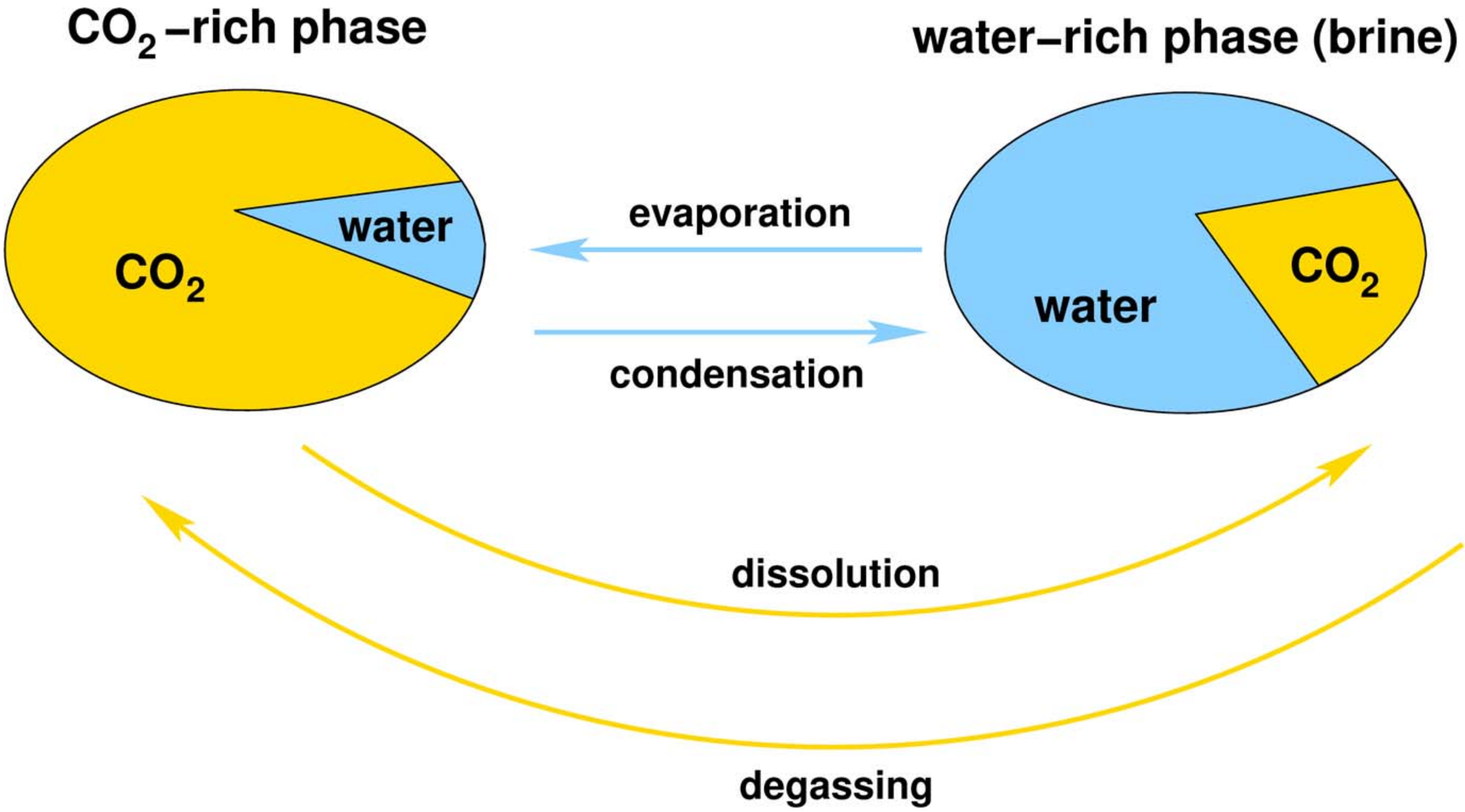
© Intergovernmental Panel on Climate Change (2006)

Model: Main Assumptions

General assumptions

- Slow velocities (Reynolds number < 1)
- Local thermodynamical equilibrium
- Rock matrix is rigid
  - porosity $\phi = f(\mathbf{x}),\ \phi \neq f(t)$
  - permeability $\mathbf{K} = f(\mathbf{x}),\ \mathbf{K} \neq f(t)$

Model Concept: Two-Phase Two-Component



CO_2–rich phase

water–rich phase (brine)

water

CO_2

evaporation

condensation

water

CO_2

dissolution

degassing

Model: Assumptions

- Two fluid phases: CO_2 and brine
- Salinity influences brine fluid properties but does not change with time $S = f(\mathbf{x}),\ S \neq f(t)$
- Only diffusion in the brine phase
- Multi-phase behaviour is taken into account by
    - Capillary pressure-saturation relationships $p_c = f(S_\alpha, \mathbf{x})$
    - Relative permeability-saturation relationship $k_{r\alpha} = f(S_\alpha, \mathbf{x})$
- No chemical reactions with rock matrix

Model: Mass Balance Equations

$$\underbrace{\phi \frac{\partial(\sum_\alpha \rho_\alpha X_\alpha^{\mathrm{C}} S_\alpha)}{\partial t}}_{\text{storage}}$$

$$- \underbrace{\sum_\alpha \nabla \cdot \left\{ \frac{k_{\mathrm{r}\alpha}}{\mu_\alpha} \rho_\alpha X_\alpha^{\mathrm{C}} \mathbf{K} (\nabla p_\alpha - \rho_\alpha \mathbf{g}) \right\}}_{\text{advective transport}}$$

$$- \underbrace{\nabla \cdot \left\{ D_{\mathrm{pm}}^{\mathrm{C}} \rho_{\mathrm{b}} \nabla X_{\mathrm{b}}^{\mathrm{C}} \right\}}_{\text{diffusive transport}}$$

$$- \underbrace{q^{\mathrm{C}}}_{\text{source/sink}} = 0 \qquad \mathrm{C} \in \{\mathrm{w}, \mathrm{CO2}\}, \ \alpha \in \{\mathrm{b}, \mathrm{CO2}\}$$

Two mass balance equations

for components CO_2 and water

Model: Energy Balance Equation

$$\underbrace{\phi \frac{\partial \left(\sum_\alpha \rho_\alpha u_\alpha S_\alpha\right)}{\partial t} + (1-\phi)\frac{\partial \rho_s c_s T}{\partial t}}_{\text{storage}}$$

$$-\underbrace{\nabla \cdot \left(\lambda_{\mathrm{pm}} \nabla T\right)}_{\text{heat conduction}}$$

$$-\underbrace{\sum_\alpha \nabla \cdot \left\{\frac{k_{\mathrm{r}\alpha}}{\mu_\alpha} \rho_\alpha h_\alpha \mathbf{K} \left(\nabla p_\alpha - \rho_\alpha \mathbf{g}\right)\right\}}_{\text{heat transport due to advection}}$$

$$-\underbrace{\sum_{\mathrm{C}} \nabla \cdot \left\{D^{\mathrm{C}}_{\mathrm{pm}} \rho_{\mathrm{b}} h^{\mathrm{C}}_{\mathrm{b}} \nabla X^{\mathrm{C}}_{\mathrm{b}}\right\}}_{\text{heat transport due to diffusion}} - \underbrace{q^h}_{\text{source/sink}} = 0$$

One energy balance equation,

assumption: local thermal

equilibrium

Numerical Model

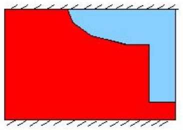
MUFTE-UG: **MU**lti-Phase **F**low **T**ransport and **E**nergy Model on **U**nstructured **G**rids

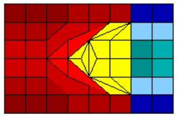
(Helmig et. al 1997, 1998)
(Bastian et. al 1997, 1998)

(S. Lang, K. Birken,
K. Johannsen et. al 1997)

Institute for Hydraulic Engineering (IWS)

- problem description
- constitutive relationships
- physical–mathematical models
- discretization methods
- numerical schemes
- refinement criteria
- physical interpretation

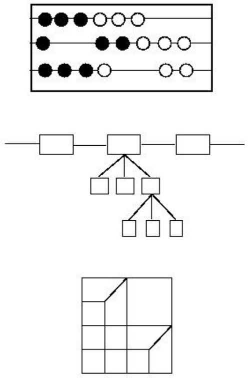




MUFTE (Helmig)

Interdisciplinary Center for Scientific Computing (IWR)

- multigrid data structures
- local grid refinement
- solvers (multigrid, etc)
- r,h,p–adaptive methods
- parallelization
- user interface
- graphic representation



UG (Wittum, Bastian)

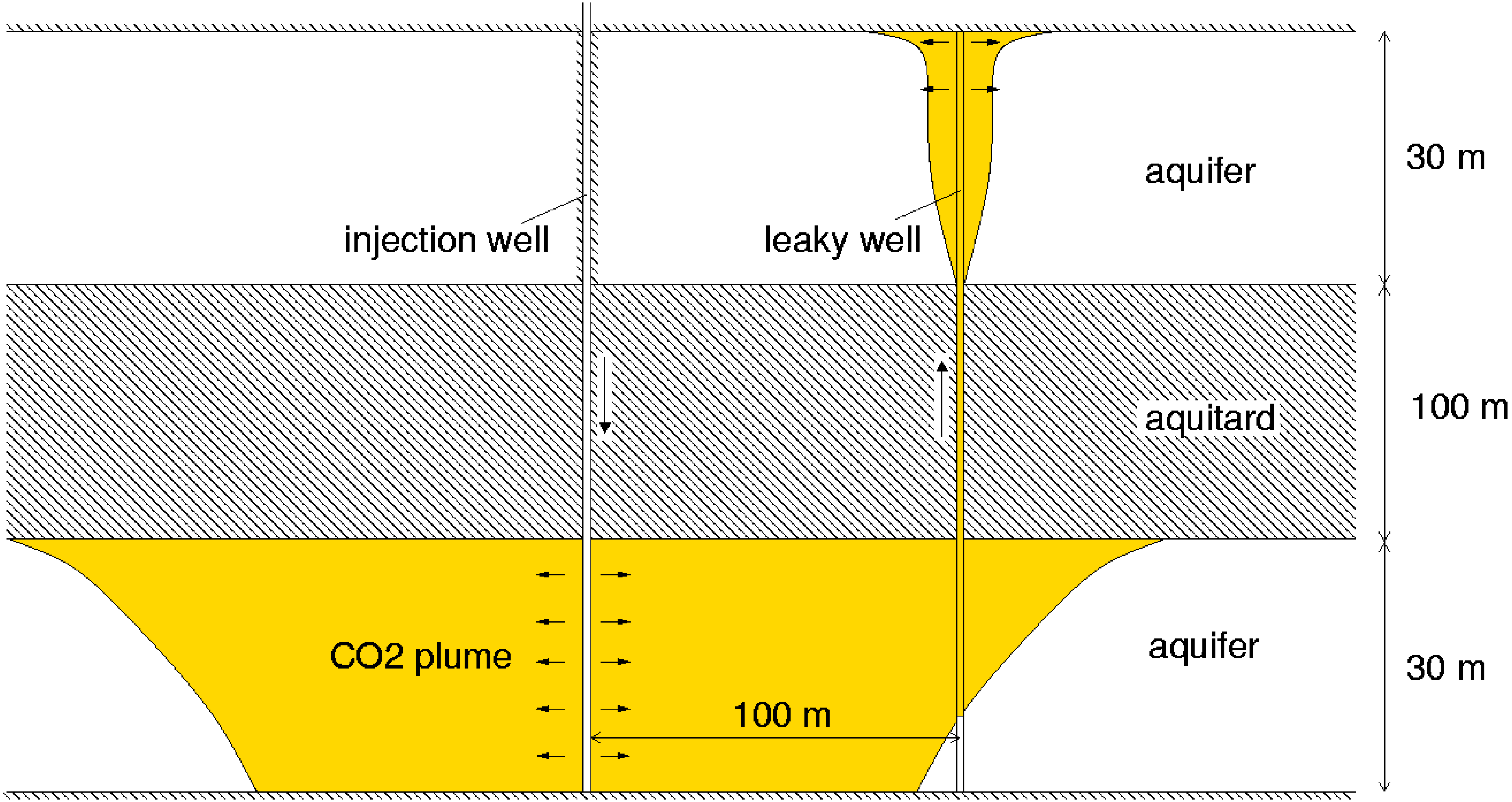
Numerical Model

- Time discretisation: fully implicit Euler scheme
- Space discretisation: Box-method, node-centered finite volume method (locally mass conservative, unstructured grid)
- Linearisation: Newton-Raphson method
- Several linear solvers are provided by UG

- Class & Helmig, 2003 (AWR)
- Class et al., 2003 (AWR)

Leakage Simulations

Plume Evolution and CO_2 Leakage



Leakage scenario as described by J.M. Nordbotten et al., 2005

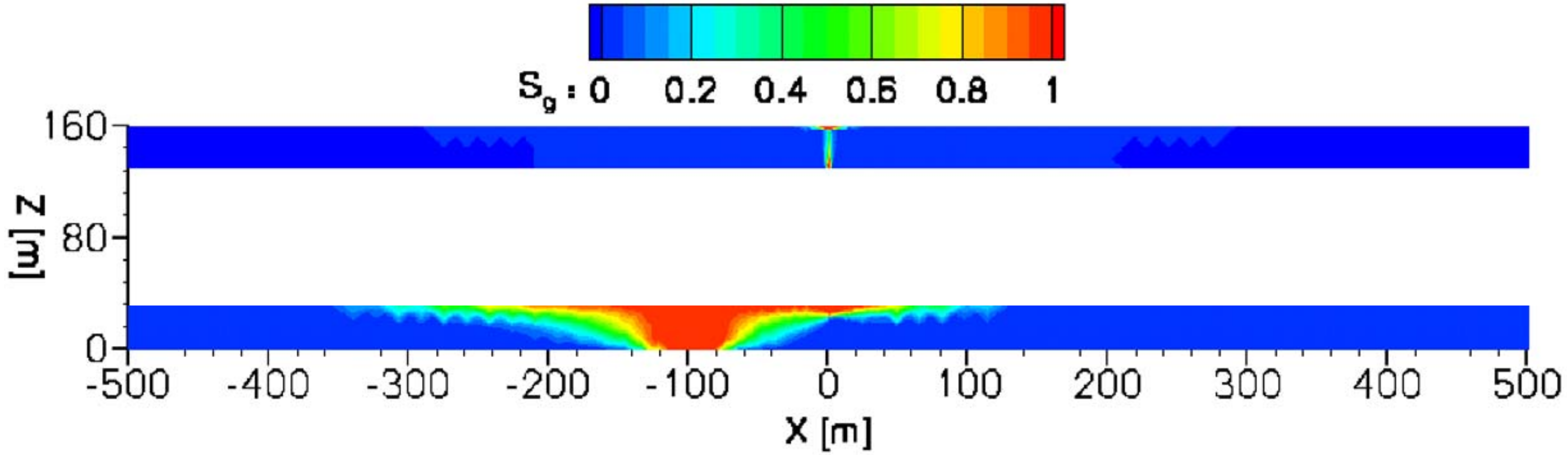
Plume Evolution and CO_2 Leakage

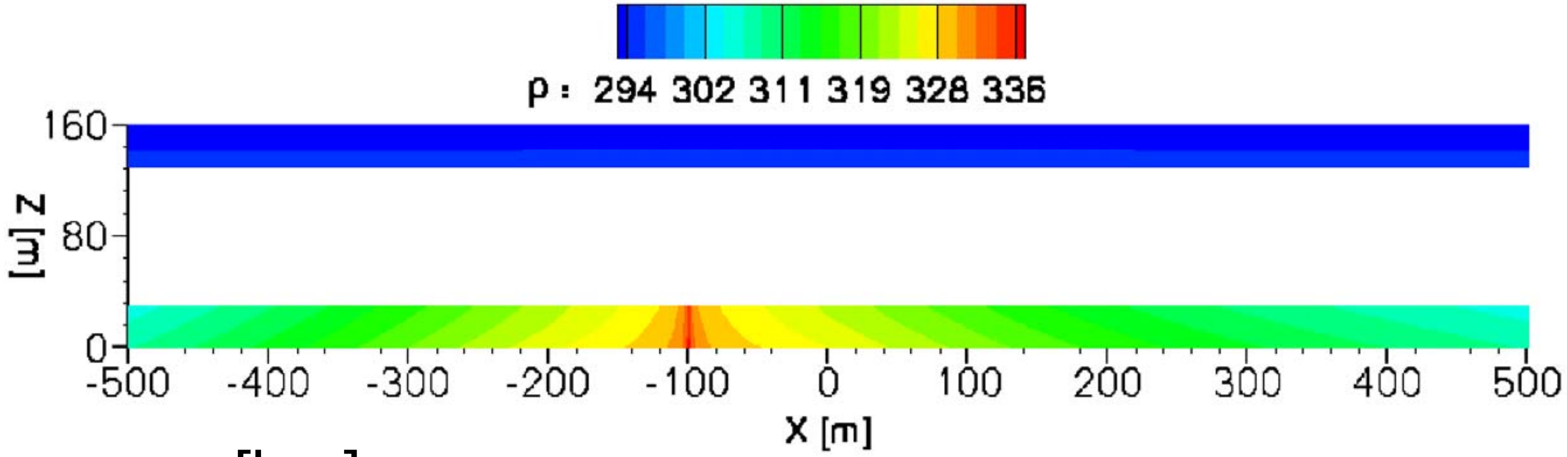
Problem description:

- Domain dimensions: 1000 m x 1000 m x 160 m
- Depth: 2840 m - 3000 m
- Assumption of constant fluid properties (densities and viscosities)
- Injection rate: 8.87 kg/s (1600 m^3/d)
- Mesh: 65 985 nodes with tetrahedra of varying sizes

Plume Evolution and CO_2 Leakage (Results1)

Saturation

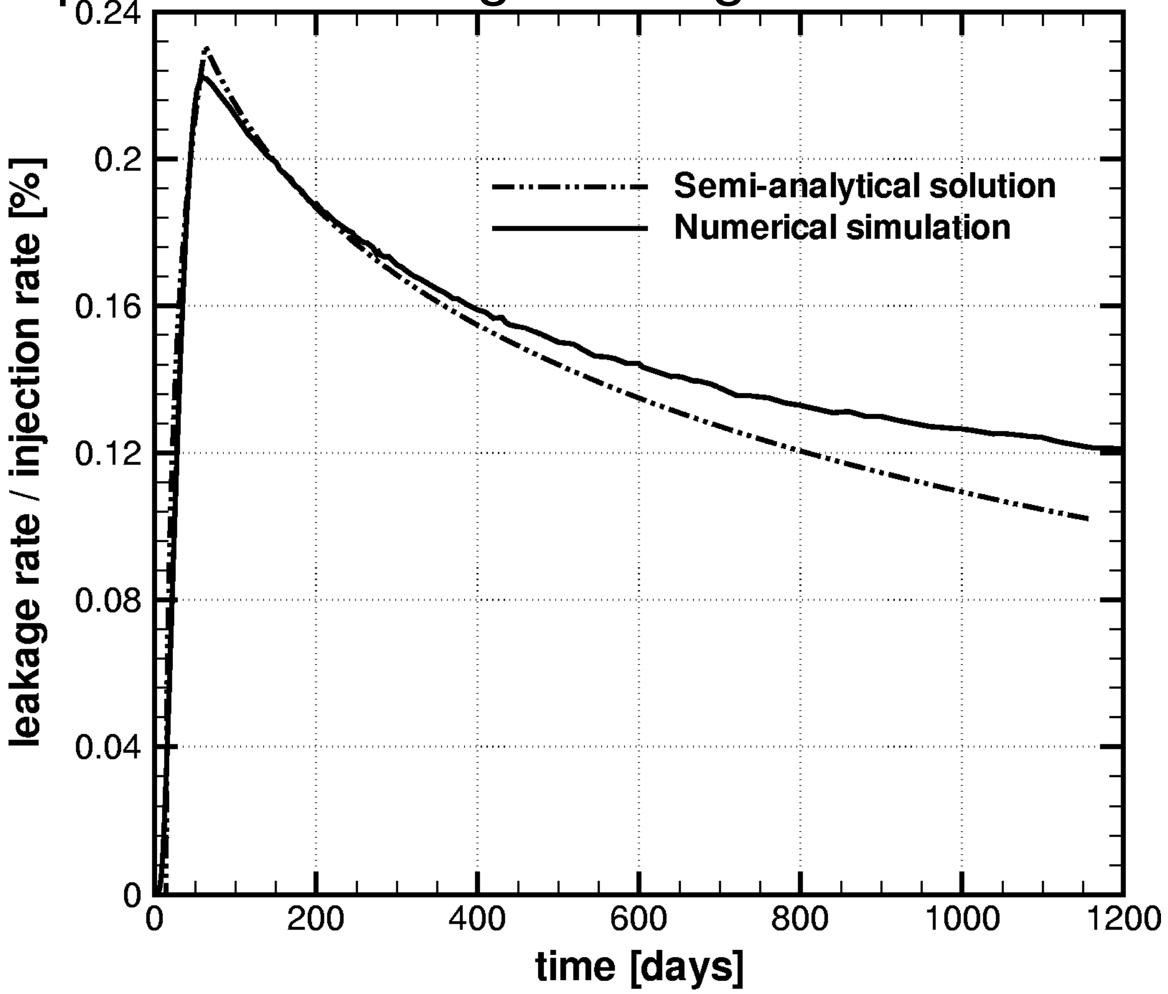




Pressure [bar]

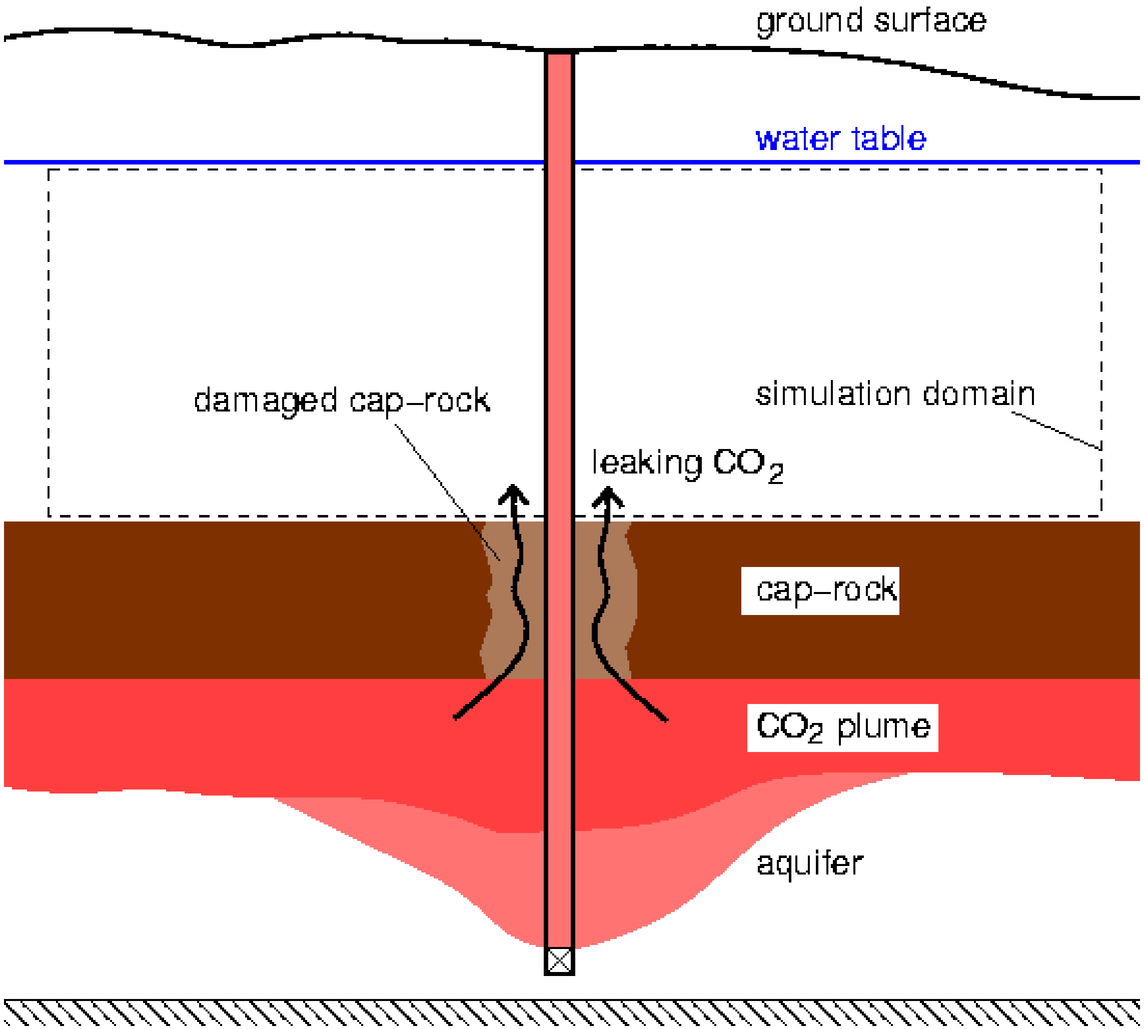
Plume Evolution and CO_2 Leakage (Results2)

Comparison: Leakage through abandoned well

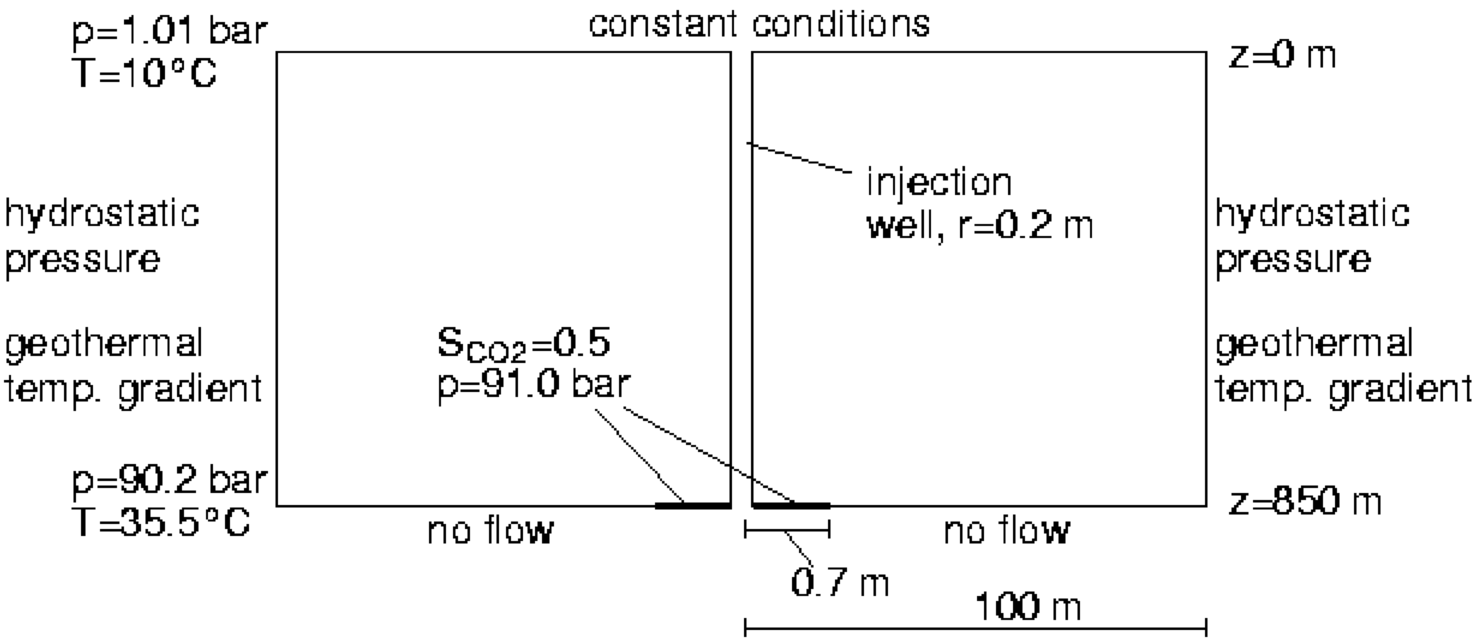


Ebigbo et al., 2006 (Computational Geosciences)

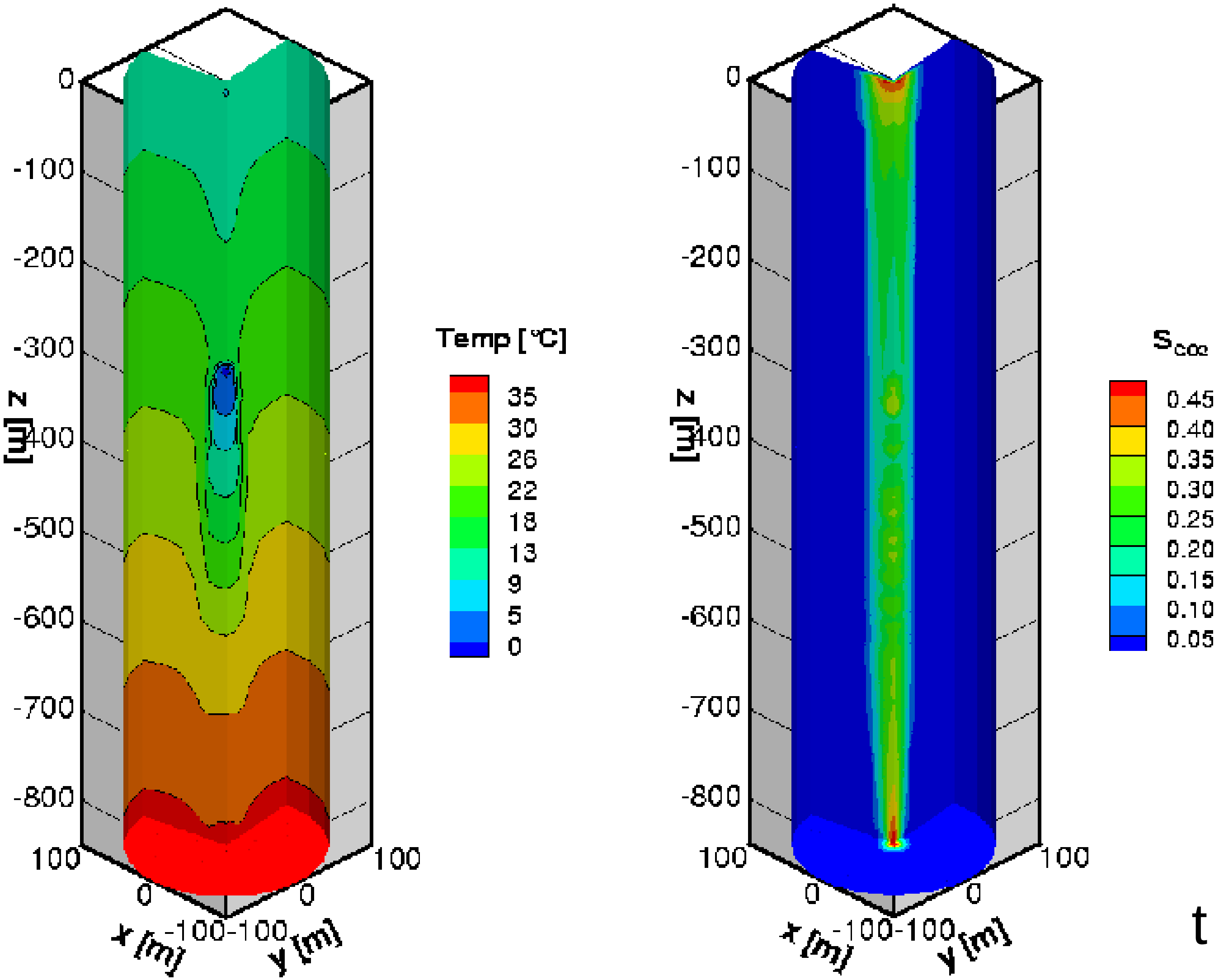
Leakage to the Surface(1)



Leakage to the Surface(2)

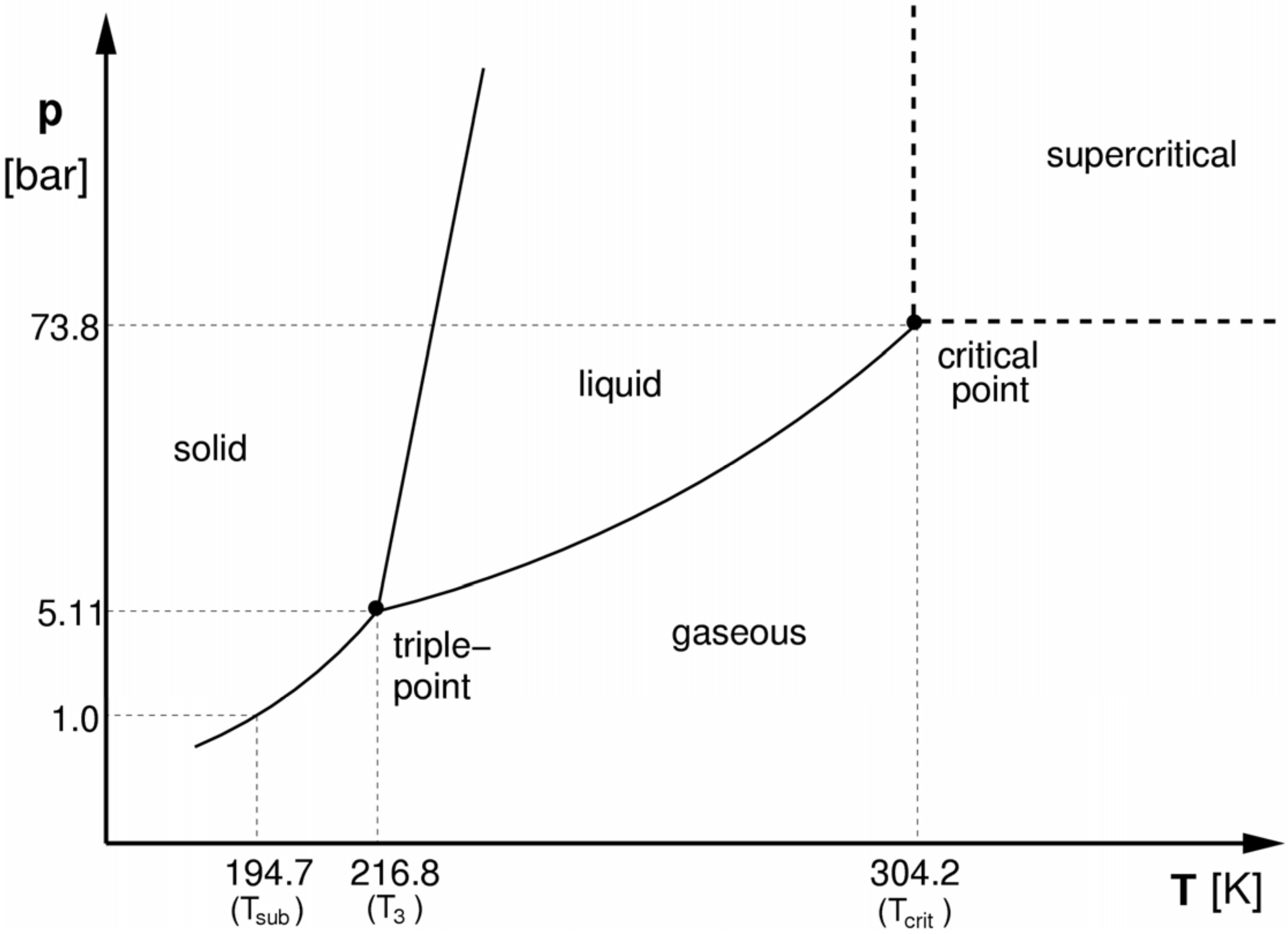


Leakage to the Surface(3)

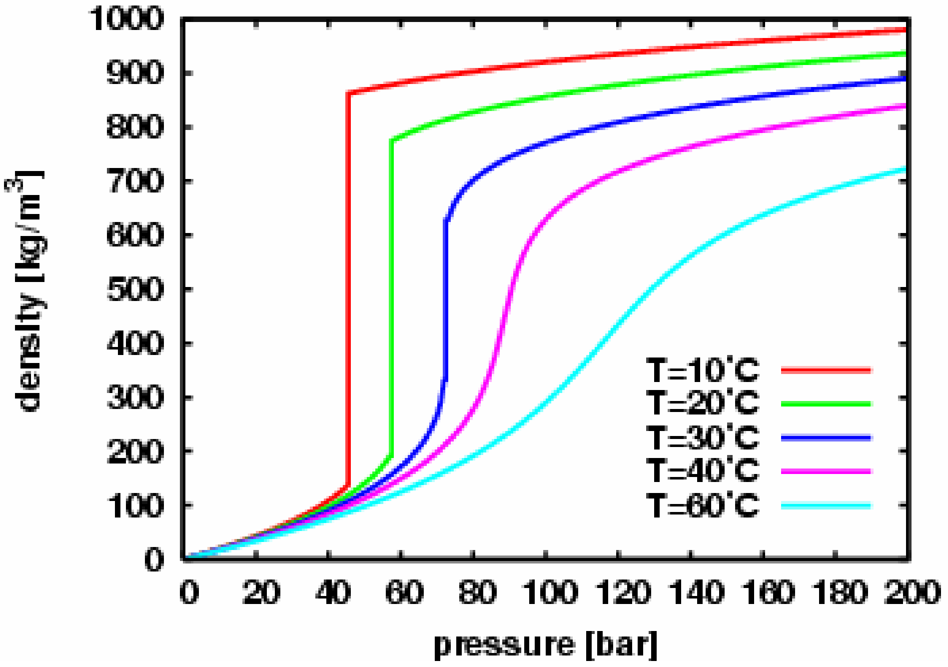


t = 4.3 yrs.

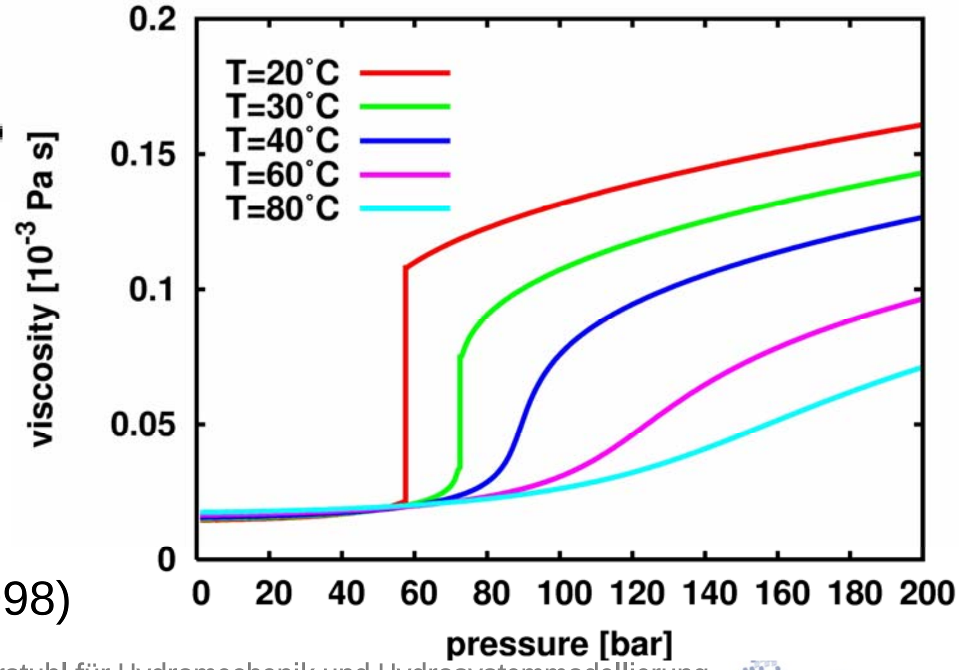
CO_2 Phase Diagram



Model: Density of CO_2



(Span & Wagner, 1996)



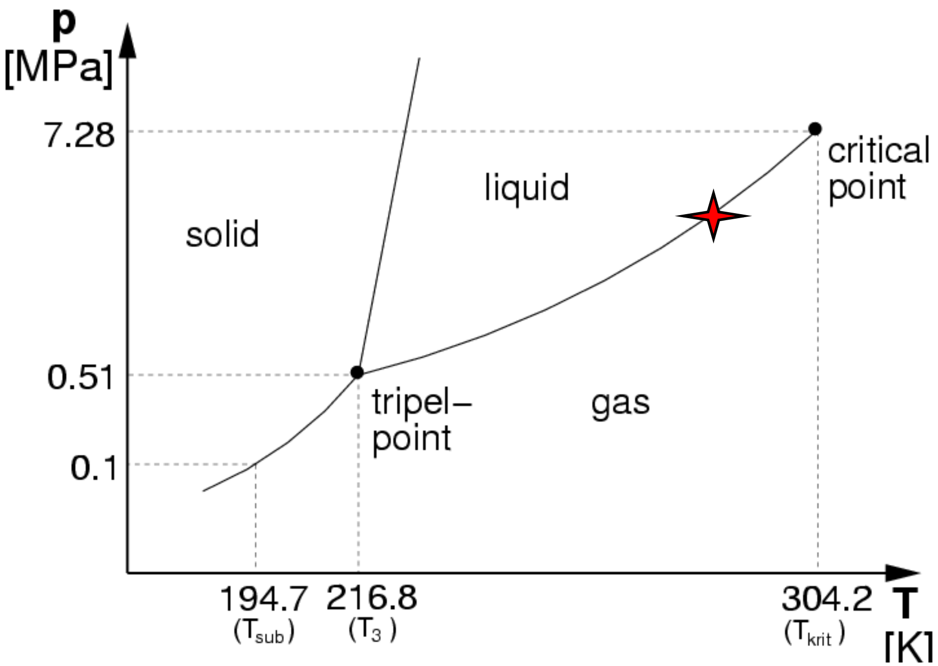
(Fenghour et al, 1998)

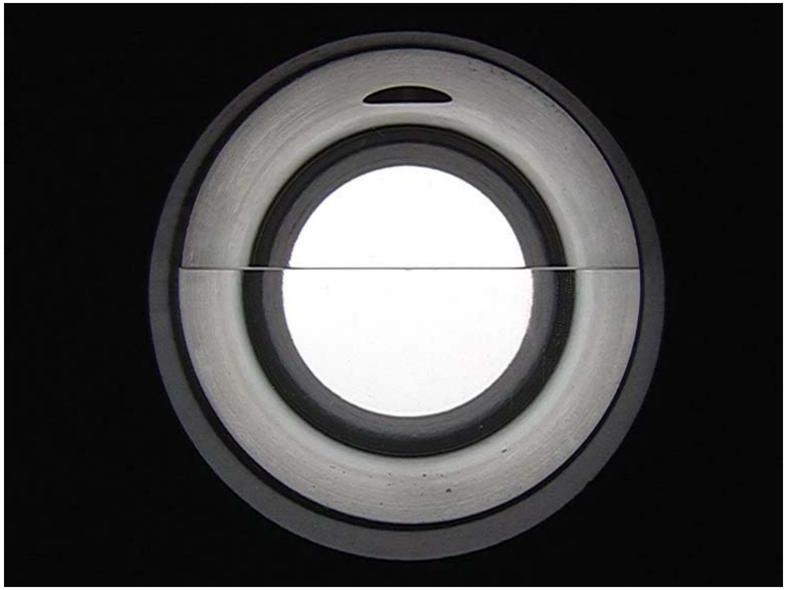
Simple Experiment Showing the Different CO_2 States of Aggregation

Experiment by Prof. Borm

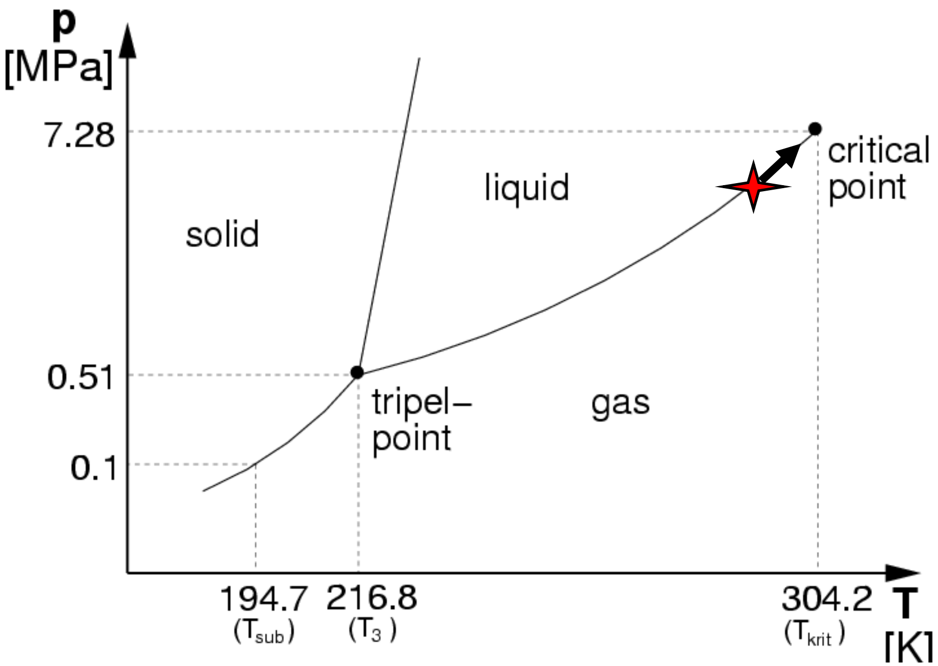
Geoforschungszentrum Potsdam

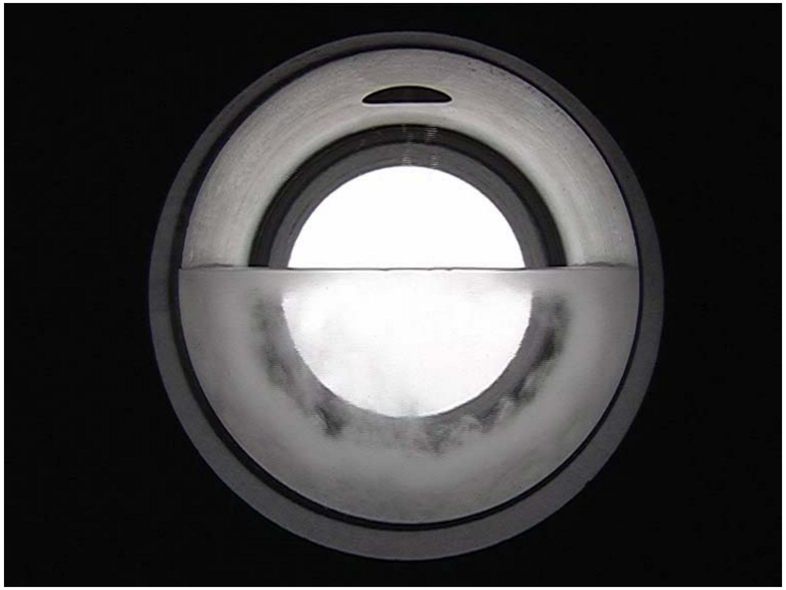
2-phase State – Initial Condition



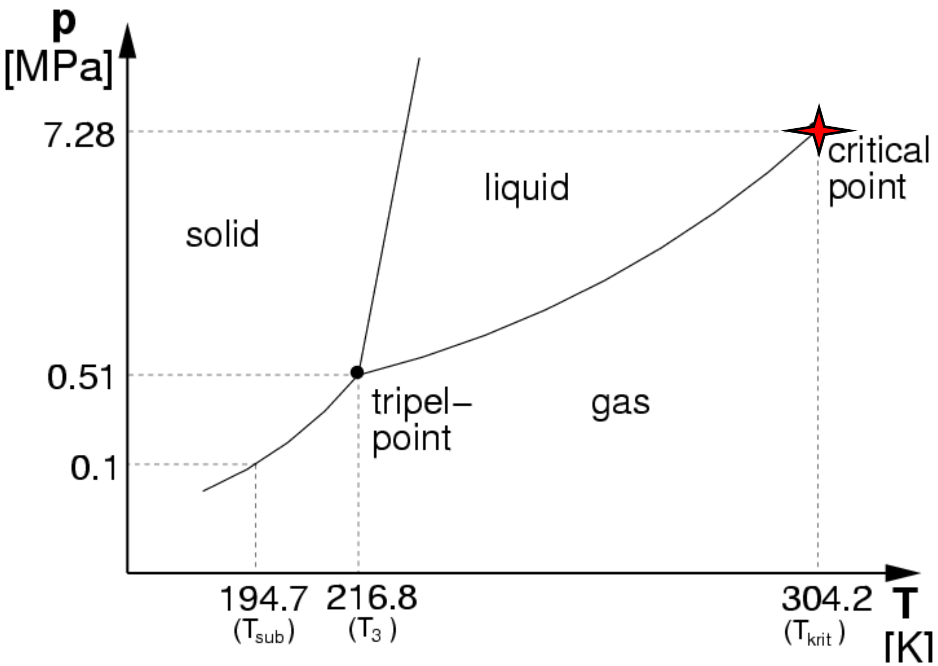


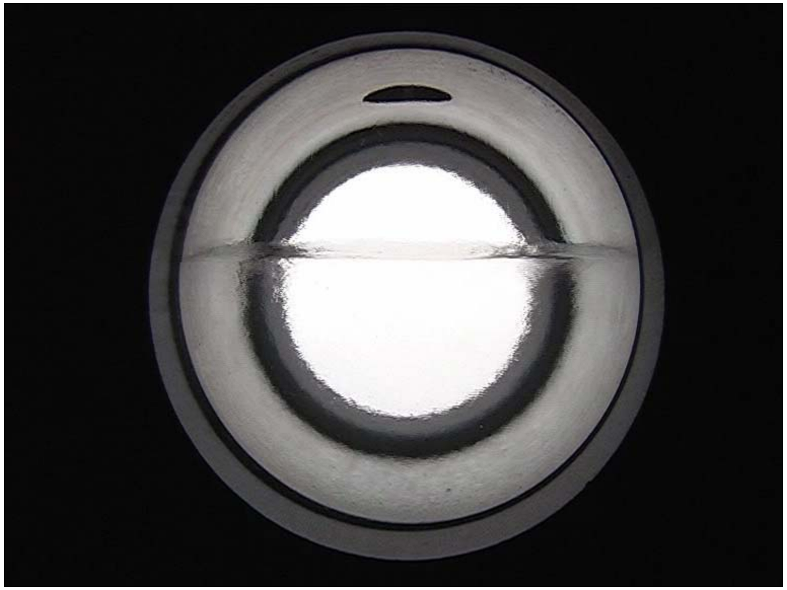
2-phase State – Heating up



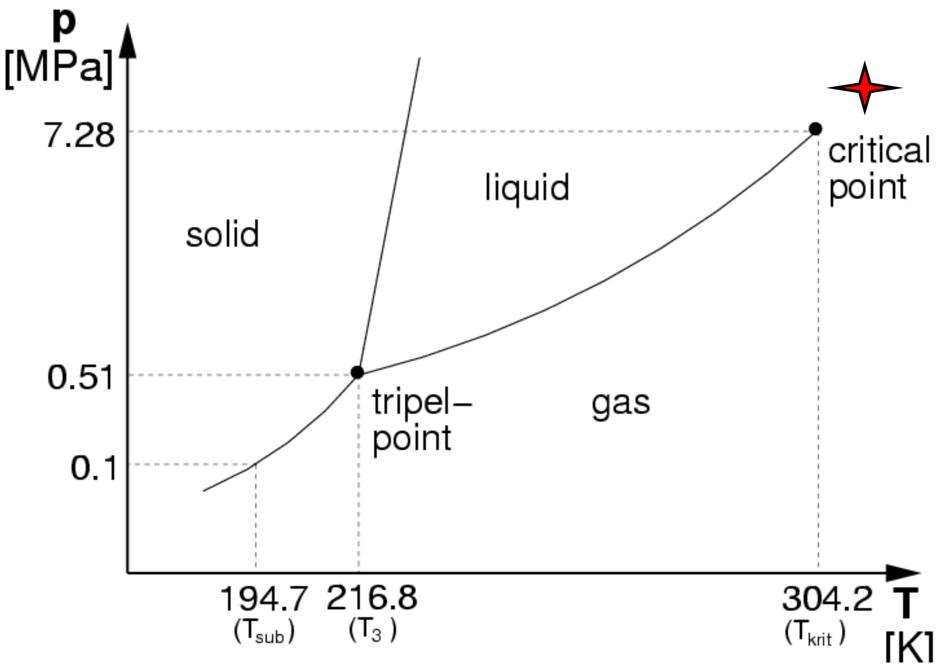


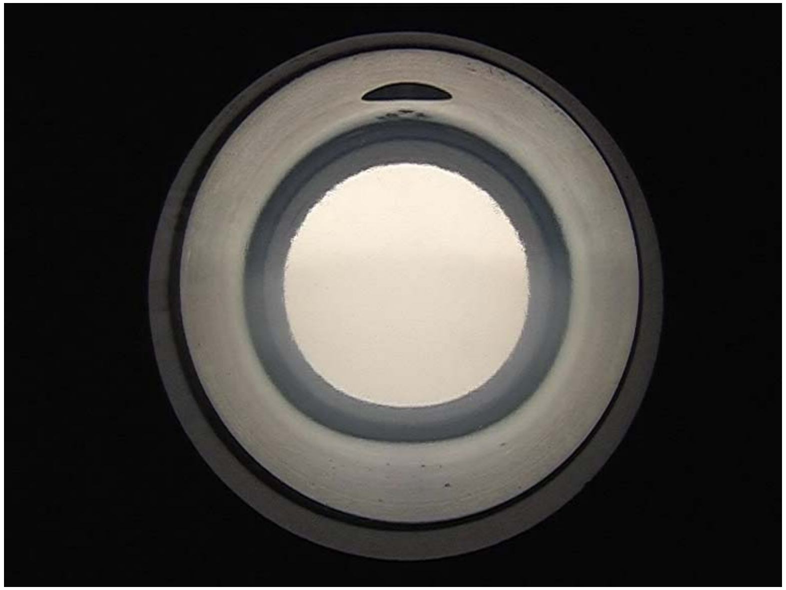
Critical Point – Meniscus separating phases disappears





Supercritical State





CO_2 Storage and Enhanced Gas Recovery

CH_4

Depleted gas reservoir

CO_2

<u>Simple 2D-Simulation</u>

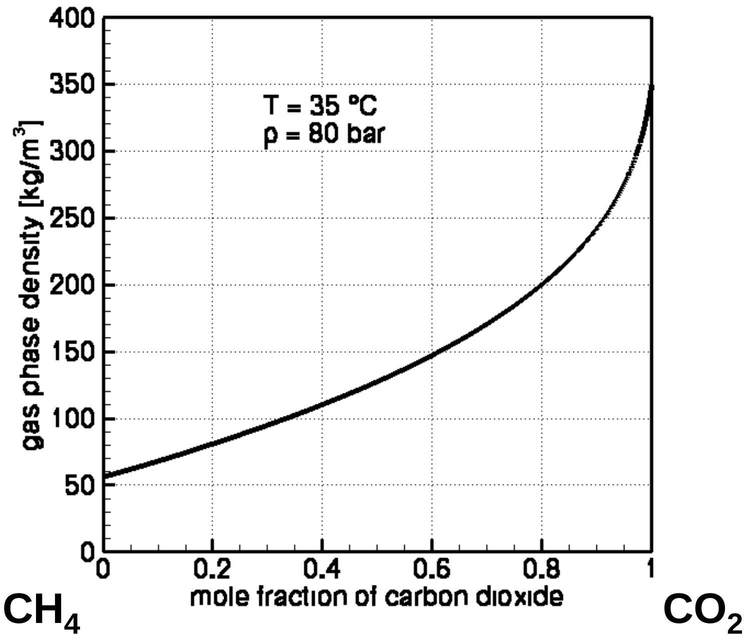
Depleted reservoir pressure: ~40 bar

Reservoir permeability: 50 mD
Reservoir porosity: 0.23

Domain dimensions: 300m x 30m

Water saturation: 0.1 (immobile)

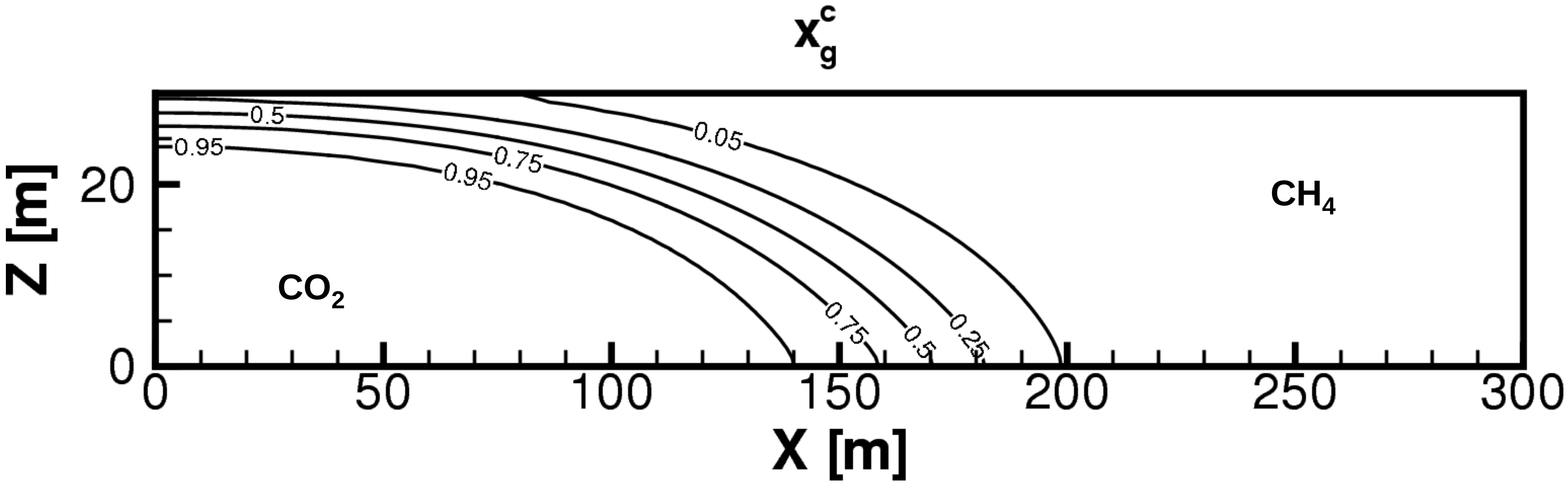
Constant CO_2 injection.



(Duan et al, 1992)

2D-Simulation Results (CSEGR)

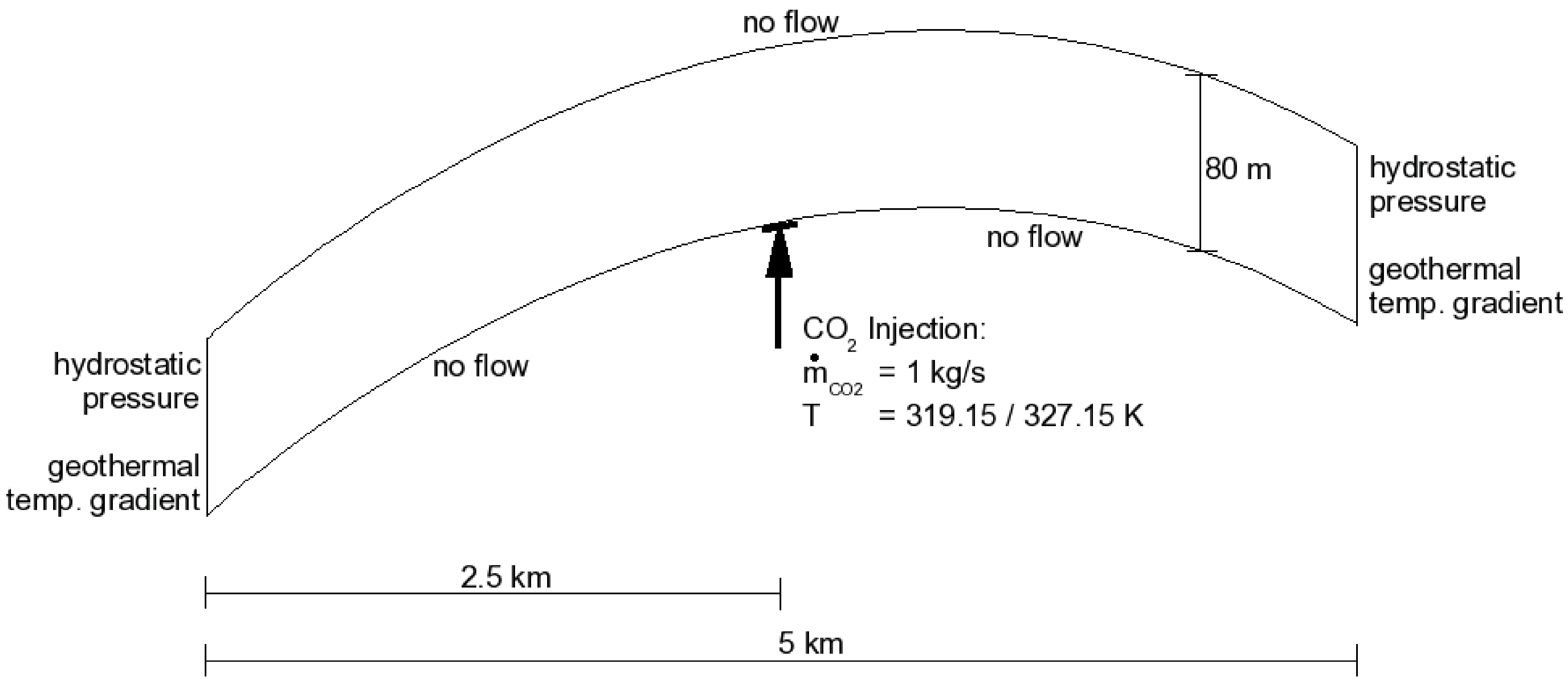
Mole fraction of CO_2 in the gas phase (t=200 days)



discretisation length, h = 1m

Field Application(1)

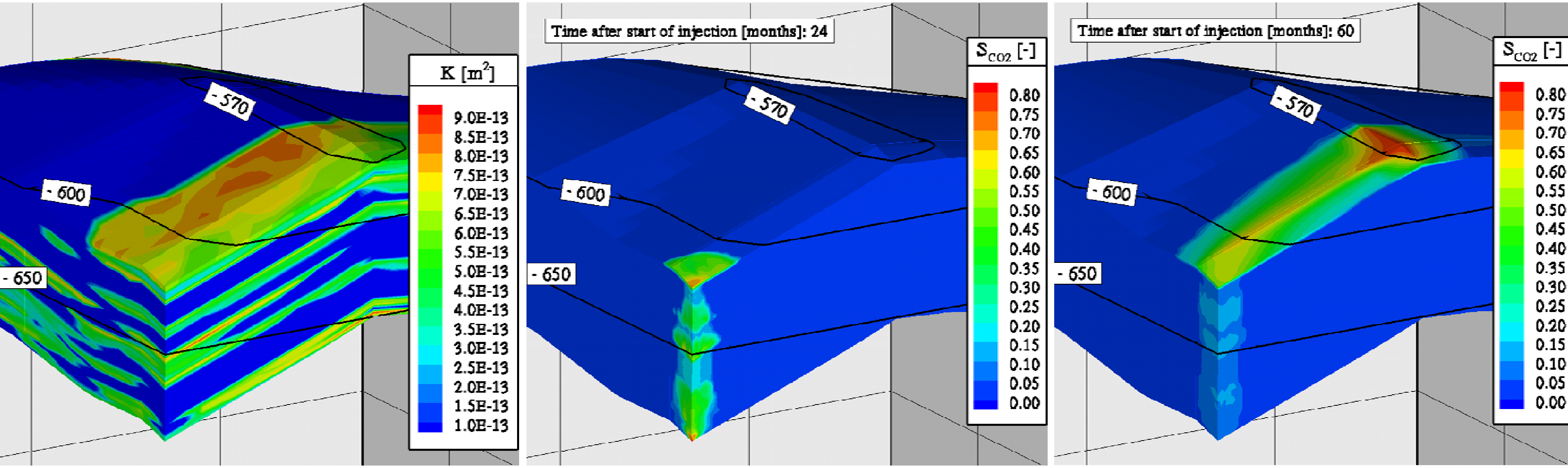
Within the EU R&D project - CO_2SINK



Andreas Kopp

Field Application(2)

Simulation of injection of a limited amount of CO_2 using a geostatistical realisation of the permeability distribution.



Andreas Kopp

Final Remarks

- A model has been set up to simulate processes which occur during CO_2 geosequestration.
- Comparison with semi-analytical solution of leakage scenario to test model reliability.
- Simulation of enhanced gas recovery.

- Questions:
  - What are the capillary pressures and relative permeabilities for the CO_2-brine system?
  - How do other components (e.g. salt, non-pure CO_2) influence the behaviour of the processes?

Thanks for your attention.