Determination of thermodynamics in a CO_2 injection well using pressure and distributed temperature sensing

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CO2 REMOVE research monitoring verification
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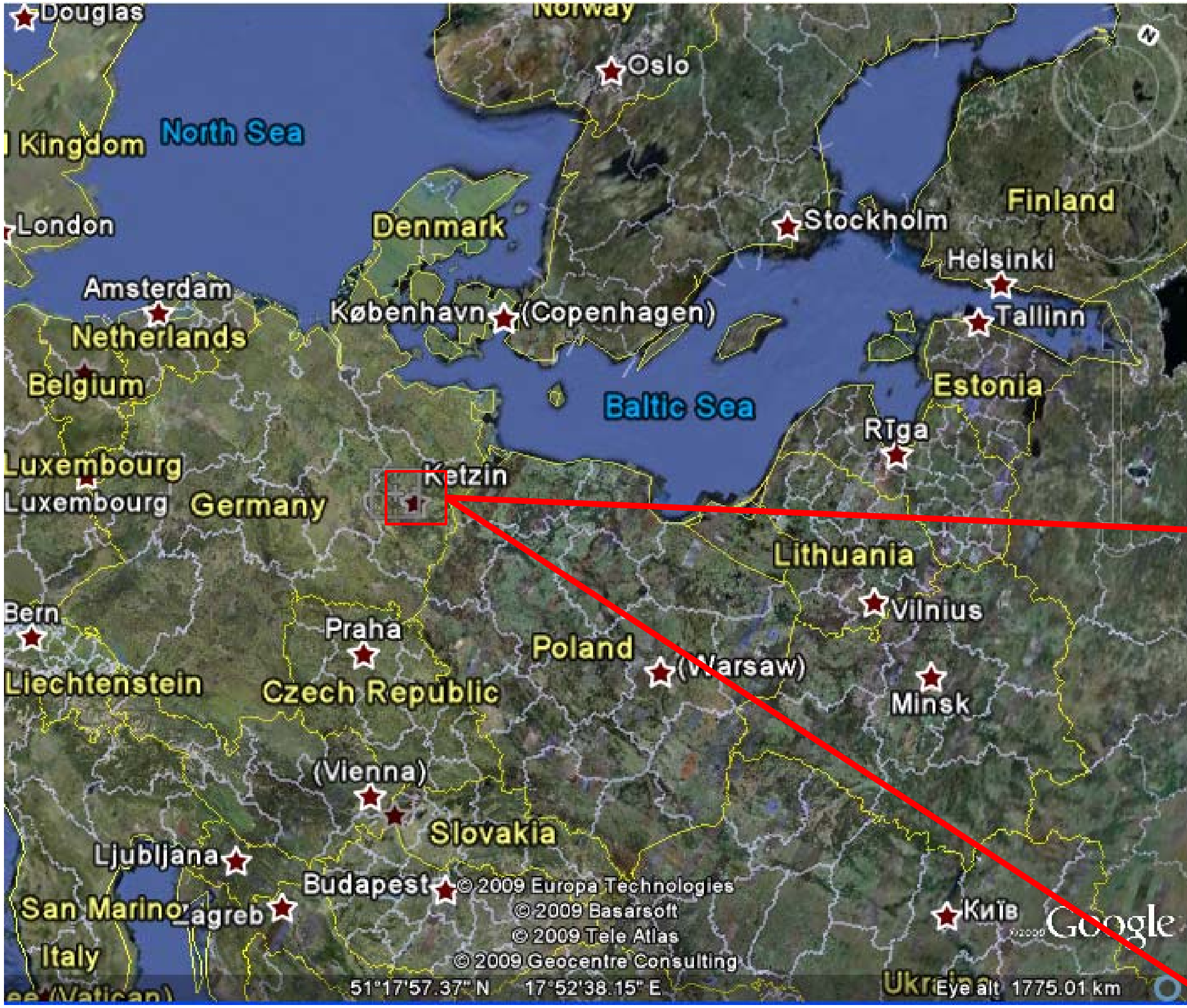
Introduction

- Injection of CO_2 into deep reservoir
  - Injection by means of a well
  - Use well installations as proxy for reservoir monitoring
  - At shallow depth may be gaseous or liquid
  - Phase transition should be avoided
  - Open thermodynamic system
    - Compression of CO_2
    - Frictional losses
    - Heat transfer
  - Two methods to calculate heat flux using DTS data

Location of the Ketzin pilot site



~ 25 km west of Berlin

located in the North German Basin

only active national storage project

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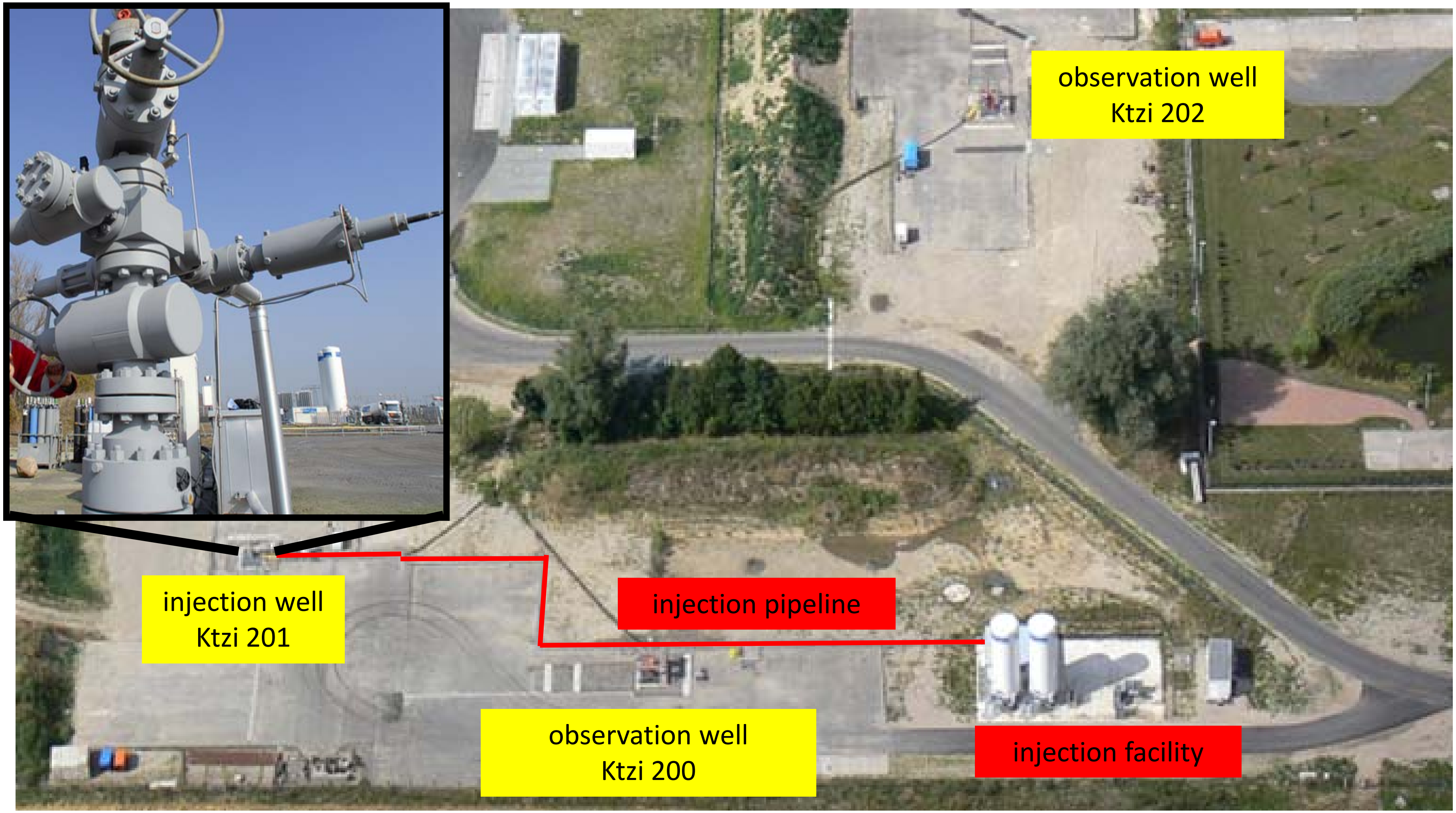
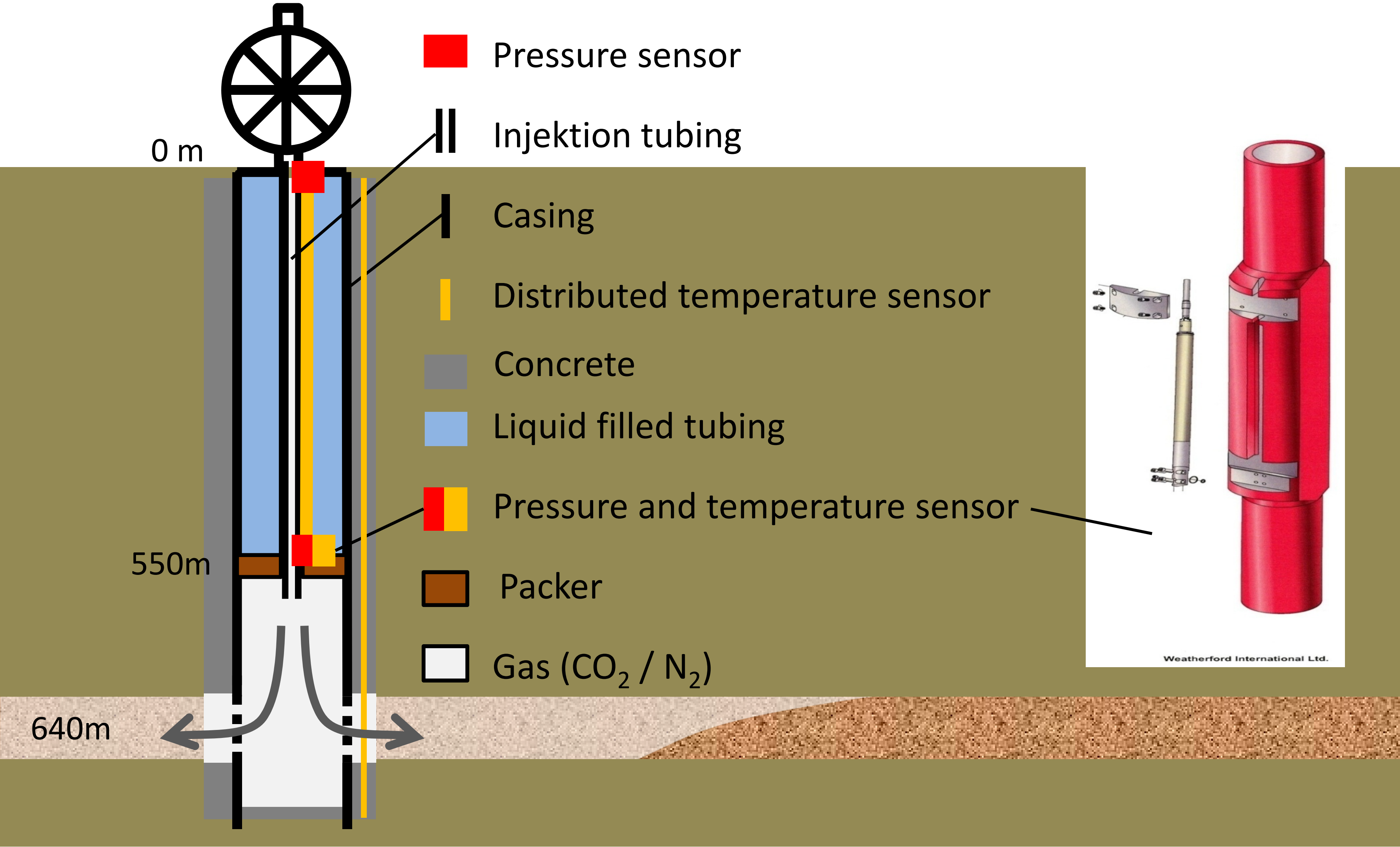
Aerial View of the Ketzin Pilot Site

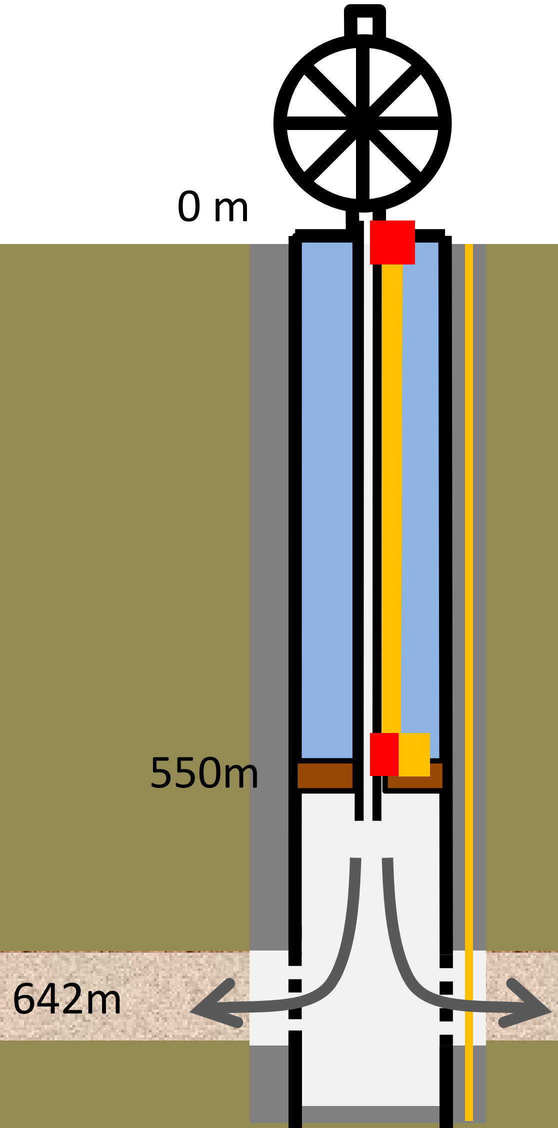


1 injection and 2 observation wells at distances of 50 and 112 m

Layout injection well Ktzi 201
(selection)



Implications of instrumentation



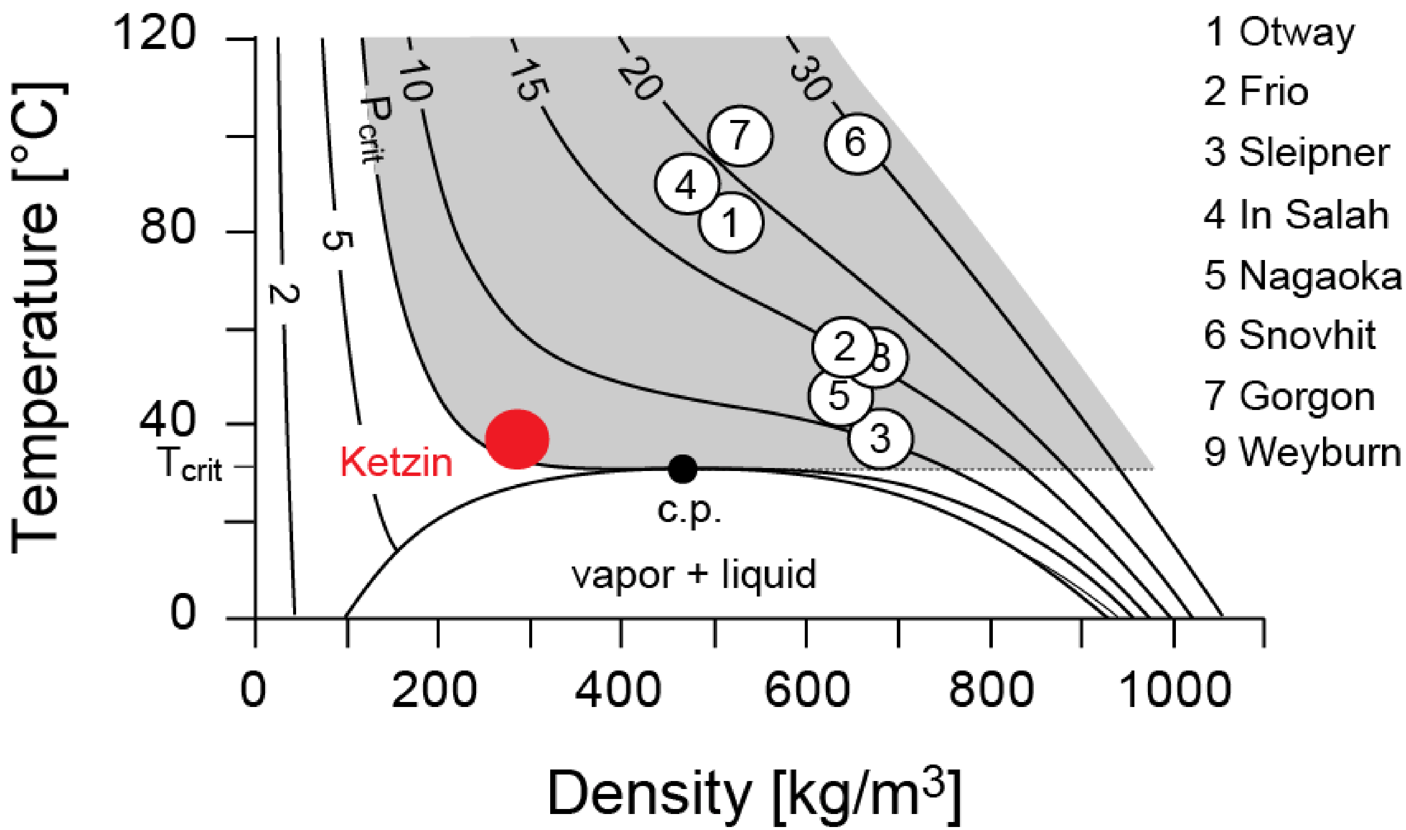
- Instrumentation is attached to injection tubing
  - Direct observation of injection
  - Continous data (interval ~5min)
- Pressure observation at 0 und 550 m
  - Reservoir pressure not known
    - Static pressure of gas column
    - Friction losses

Calculation of phase state

- Gibbs Phase Rule
  - F (Degrees of freddom)=N (Components)–P (Phases) +2
  - F=2, N=1, P=1
- State variables:
  - Temperatur e (continuous)
  - Pressure (point information)
- Temperature defines one degree of freedom(known),
- Pressure is chosen for second degree of freedom (unknown)

⇒ Stepwise iterative calculation of pressure and density allows to determine the remaining degree of freedom and to define the phase state

Temperature and pressure conditions



comparably low pressure and density

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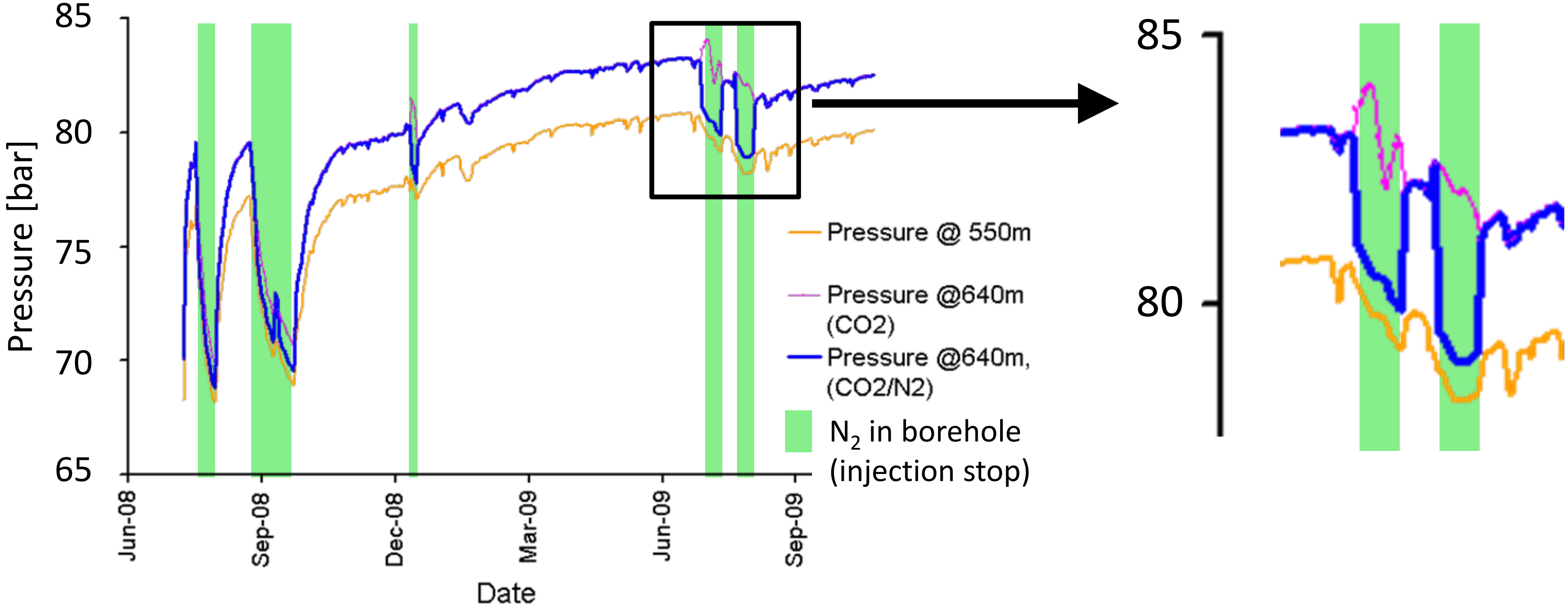
Pressure correction



- Sensor at 550m, reservoir at ~640 m
- Temperature proxy from 550m
- ~2.4 bar difference during injeciton
- ~0.6 bar difference during injeciton stop

=> Reservoir reacts more dynamic than raw data suggests

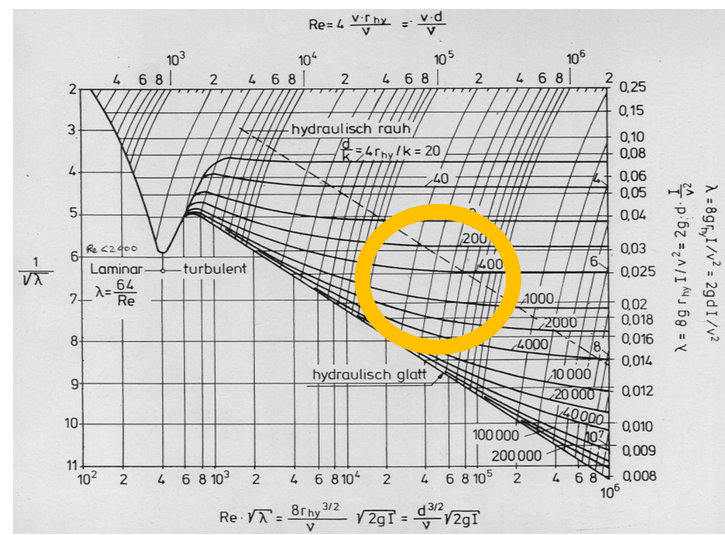
Friction losses

- Gas friction and turbulent losses at walls of injection tubing
- Determination with Darcy-Weisbach equation
  - constant pressure (stepwise)
  - Newton Fluid

$$\Delta p = \lambda \frac{L}{D} \frac{v^2 \rho}{2}$$

  - λ nonlinear from Colebrook–White equation (or Moody Diagram)

Moody Diagram



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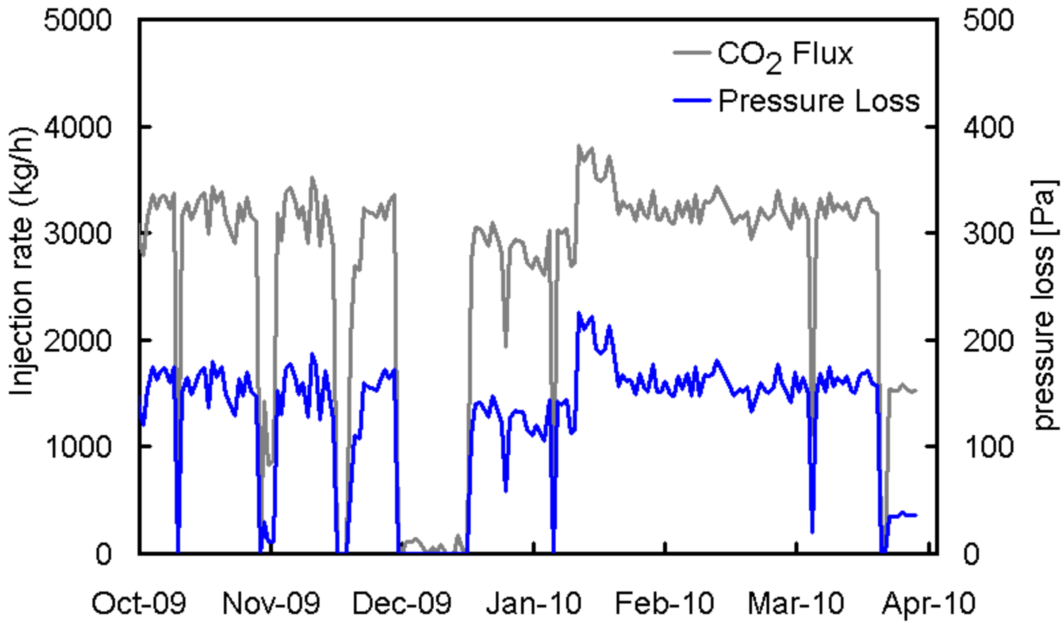
Friction losses - Results



- Injection rate principal factor of influence
- Maximum losses of 235 Pa (0.00235 Bar)
  - negligible
- May become relevant for higher injection rates (proportional v^2)

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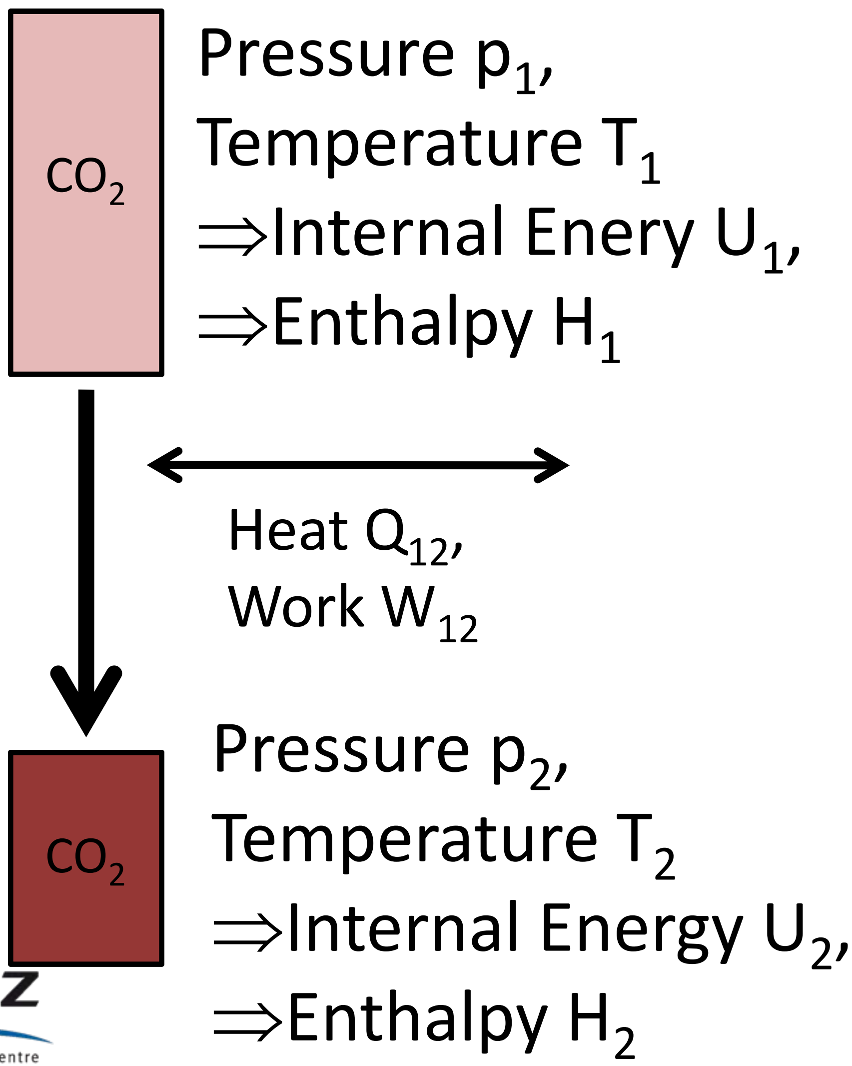
Thermodynamics

- Thermodynamics affected by
  - Electrical heating of gas flux
  - Heat transfer Borehole-subsurface
  - Geothermal impact
  - Subsurface temperature increase due to heat flux

⇒Highly coupled system

- Distributed temperature data (DTS) allows significant simplification
  - Direct calculation of heat flux independent of coupled processes

Thermodynamics



- Polytrophic process phase transition
- Nonideal gas
- Energy balance:

$$\frac{\mathrm{d}E_{\mathrm{sys}}}{\mathrm{d}t} = \sum \dot{Q}_{\mathrm{i}} + \sum \dot{W}_{\mathrm{t,j}} + \sum \dot{m}_{\mathrm{e}} \cdot \left(h_{\mathrm{e}} + g \cdot z_{\mathrm{e}} + \frac{1}{2} c_{\mathrm{e}}^2 \right) - \sum_a \dot{m}_{\mathrm{a}} \cdot \left(h_{\mathrm{a}} + g \cdot z_{\mathrm{a}} + \frac{1}{2} c_{\mathrm{a}}^2 \right)$$

Simplification of energy balance

- General heat balance

$$\frac{\mathrm{d}E_{\mathrm{sys}}}{\mathrm{d}t} = \sum_i \dot{Q}_{\mathrm{i}} + \sum_j \dot{W}_{\mathrm{t,j}} + \sum_e \dot{m}_{\mathrm{e}} \cdot \left(h_{\mathrm{e}} + g \cdot z_{\mathrm{e}} + \frac{1}{2} c_{\mathrm{e}}^2 \right) - \sum_a \dot{m}_{\mathrm{a}} \cdot \left(h_{\mathrm{a}} + g \cdot z_{\mathrm{a}} + \frac{1}{2} c_{\mathrm{a}}^2 \right)$$

- Where $h=u+w_{1,2}$
- Steady state process
- Kinetic energy negligible
- Potential energy not relevant

$\Rightarrow$ $q_{1,2}=u_2-u_1+w_{1,2}$ or $q_{1,2}=T_m*\Delta S$

where

Extraction von U (internal energy) form EOS

Calculation of $w_{1,2}$ (work) from

=> all state variables are known

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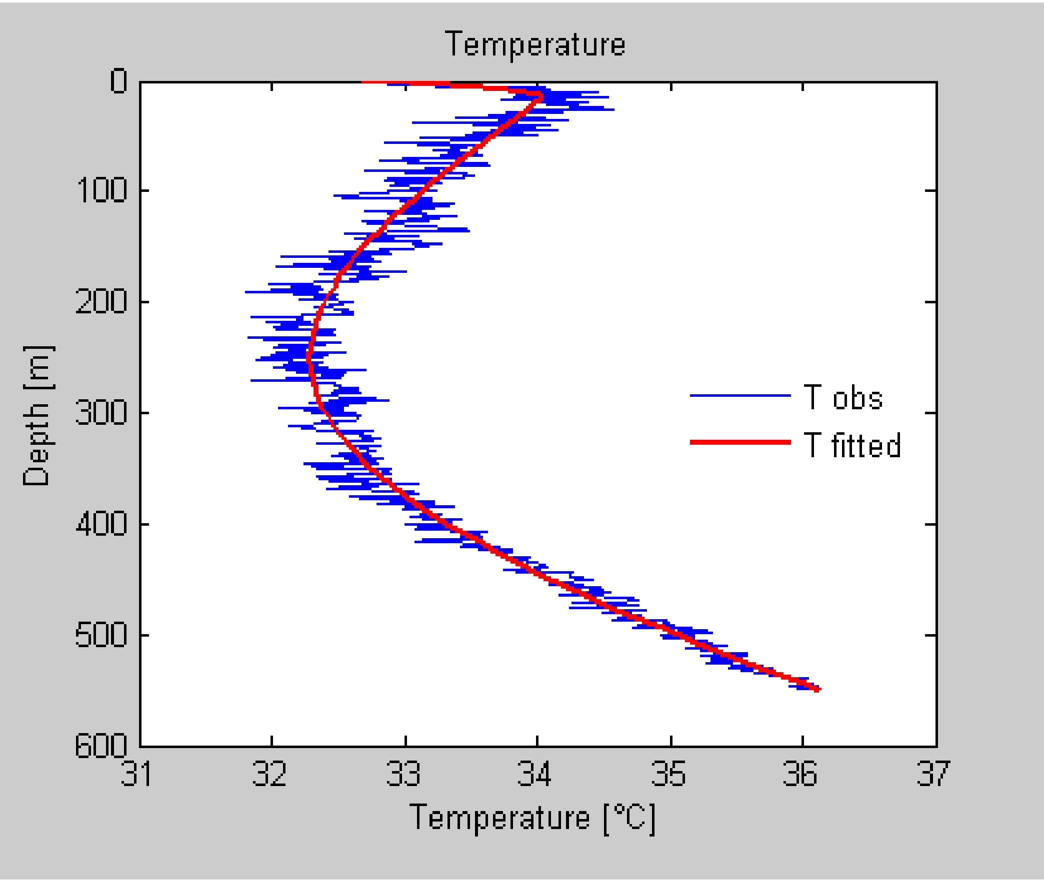
DTS raw data



- Problem: Noise in raw data
- Smoothing necessary
  - 2 polynoms with secondary condition
  - Atmospheric impact near ground surface

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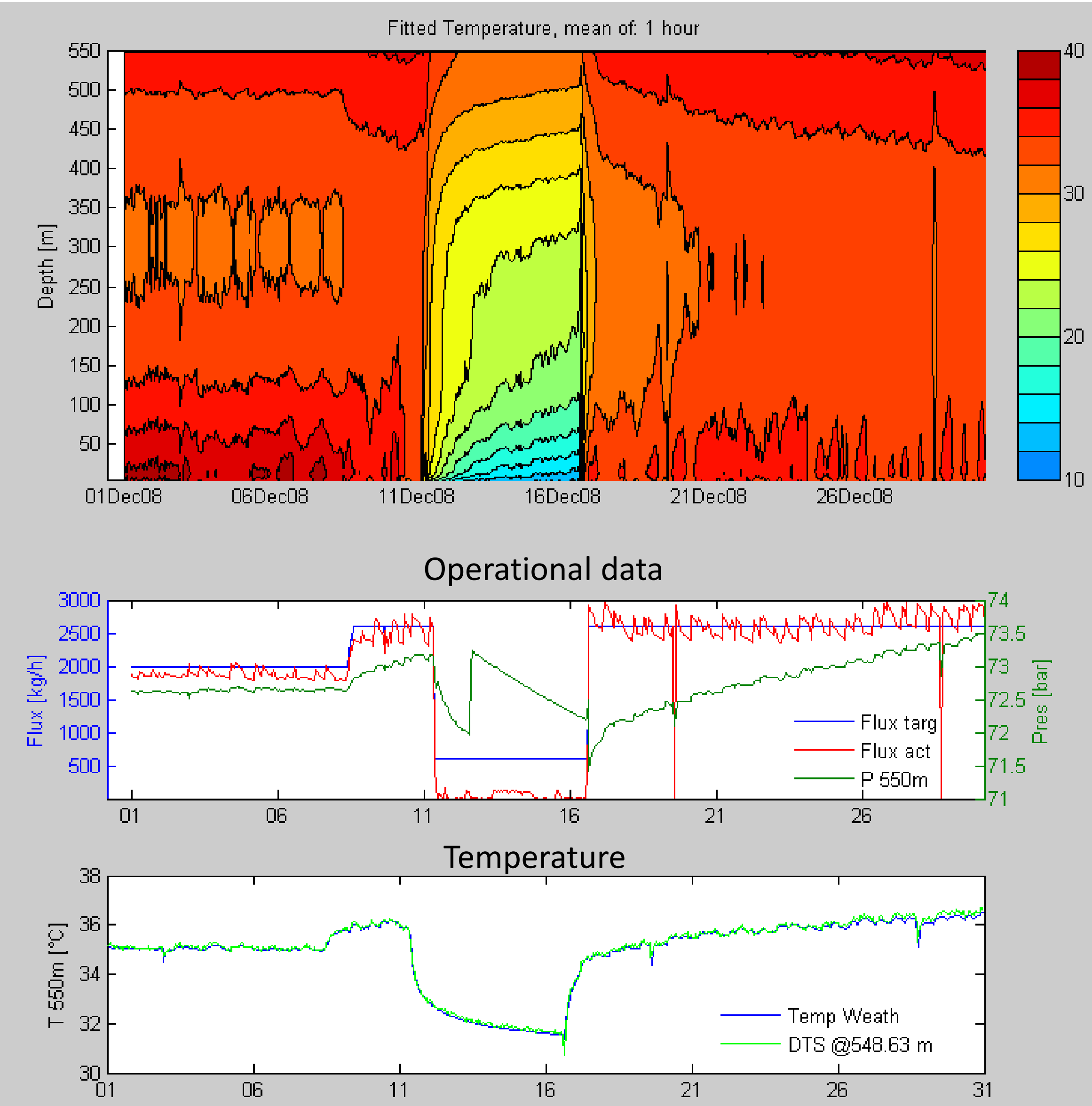
Raw data

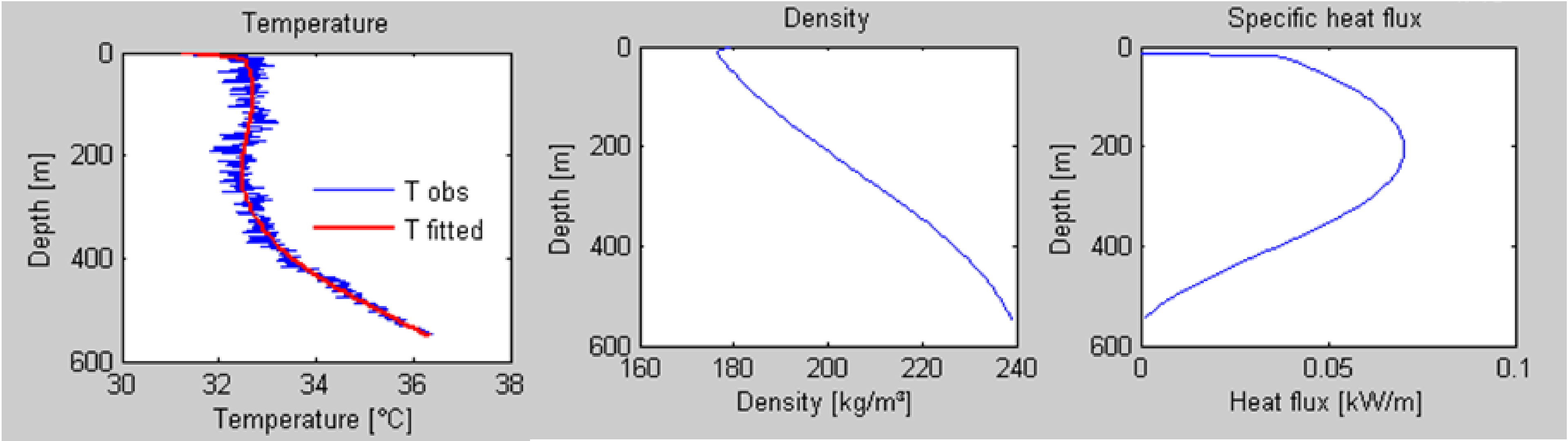


Example Dec. 2008

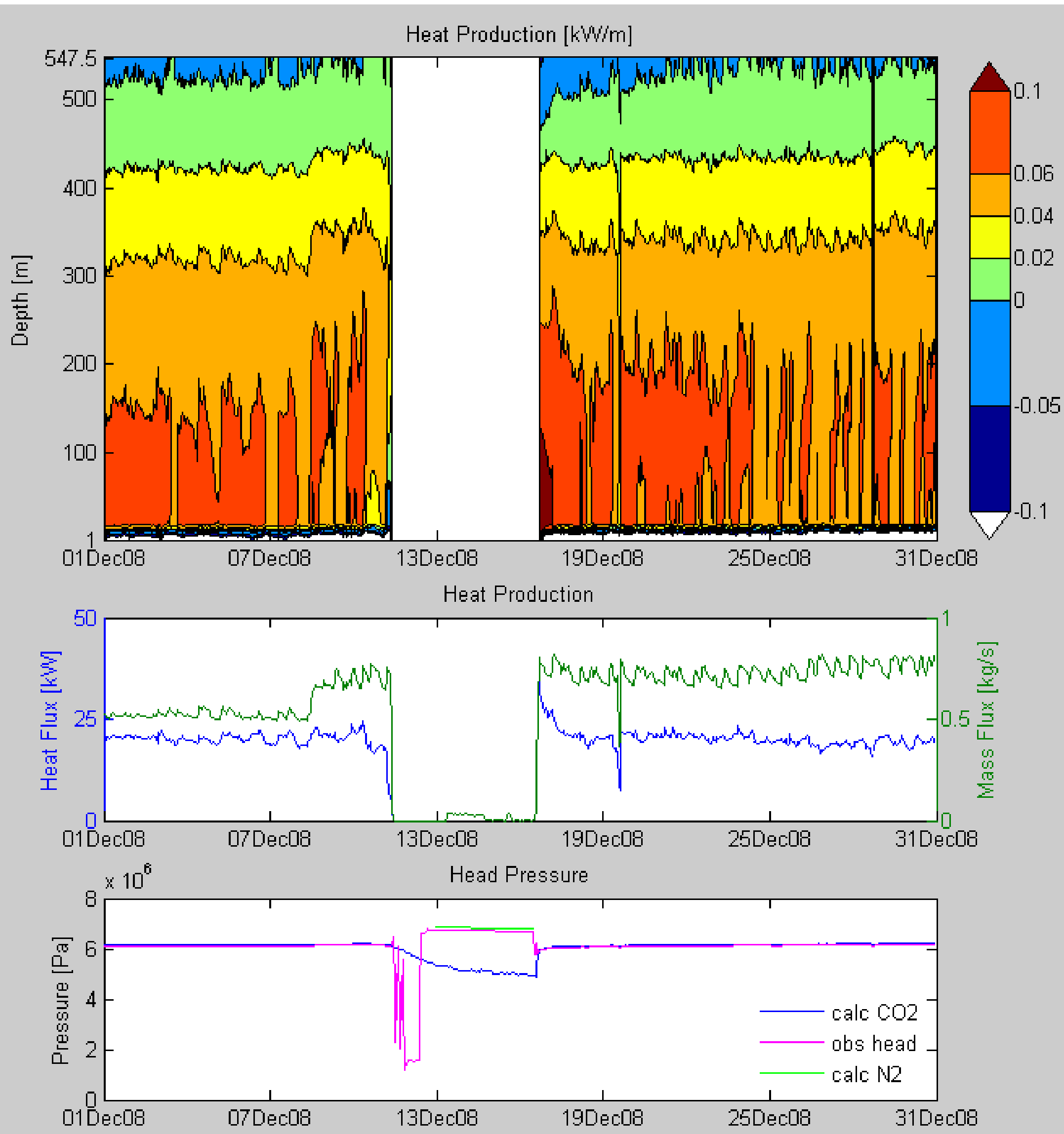
- During injection lowest Temperature at 300m
- 11. Dez.:
  - Injection stop
- 12. Dez.:
  - N_2 in well
- 16. Dez.:
  - Injection CO_2
- Very good match between DTS and reference sensor (Weatherford)

Derived profiles

- e.g. 10. Dec. 2008 16h
- Phase state calculated from 550m upwards
  - Calculated pressure 0.5 bar lower compared to observed values (ca. 5%) within device accuracy
  - Distance to condensation
  - Potential for reducing electrical heating



Heat production



- Calculation only for single phase operation
- Heat loss to the subsurface
- Calculated heat absorption close to 550 m ->not correct
- Highest heat loss
  - bei ca. 100 m
  - after injection restart
- Independent of injection rate (first approximation)
- Negative heat flux not correct

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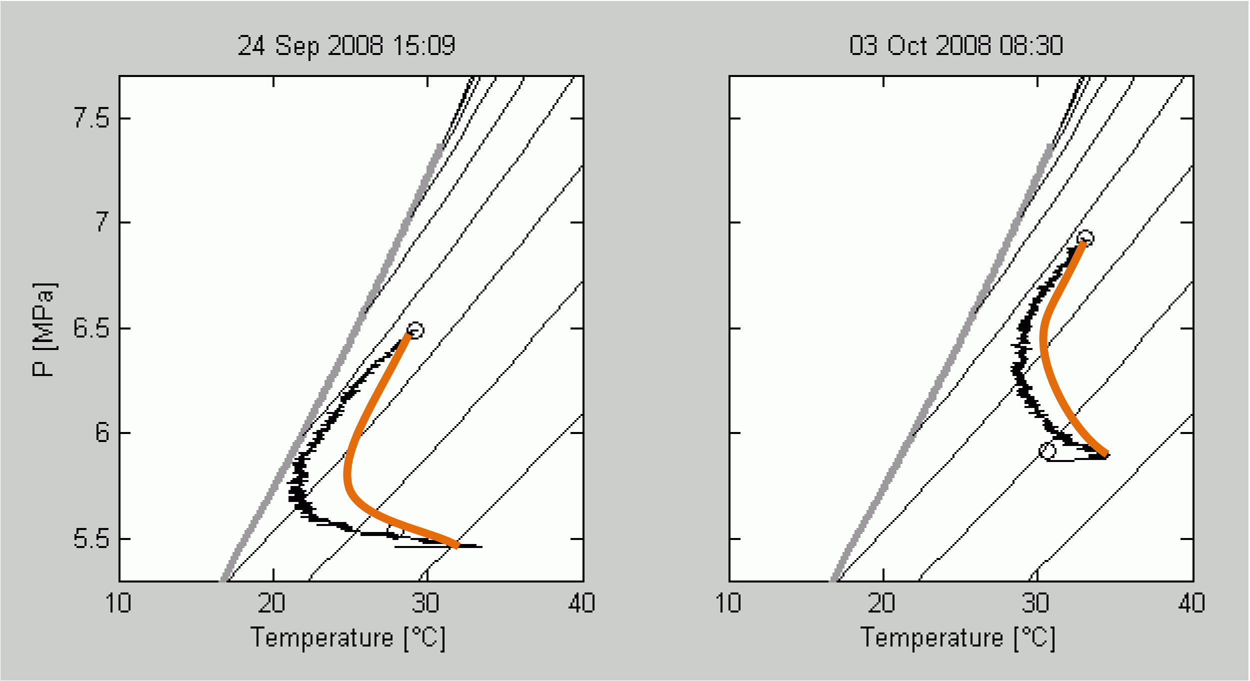
Analysis of heat exchange

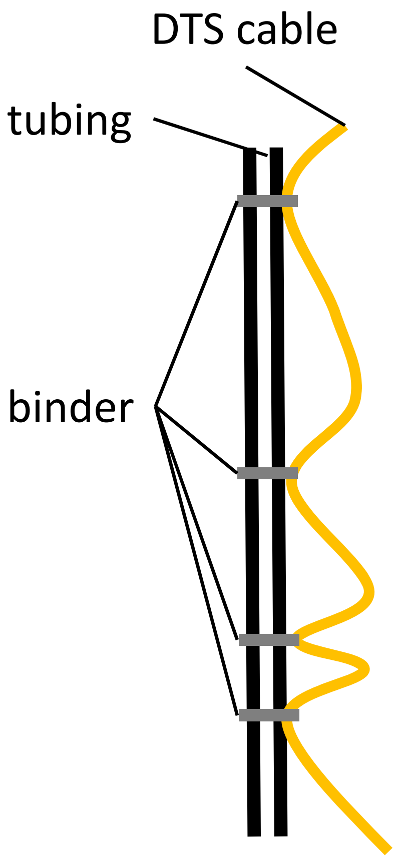
- After restart
- Quasi steady state



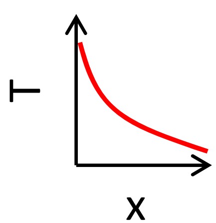
- Isentopes (gas)
- Condensation line
- Simulated phase state
- Postulated phase state with strictly positive heat flux

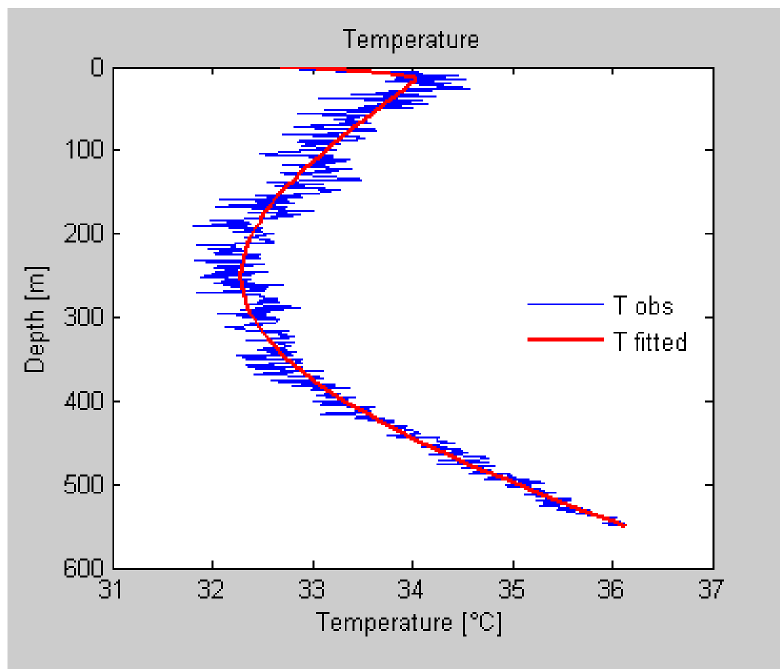
- Ca. 4 °C distance to condensation

Observe heat flux with spatial temperature differences

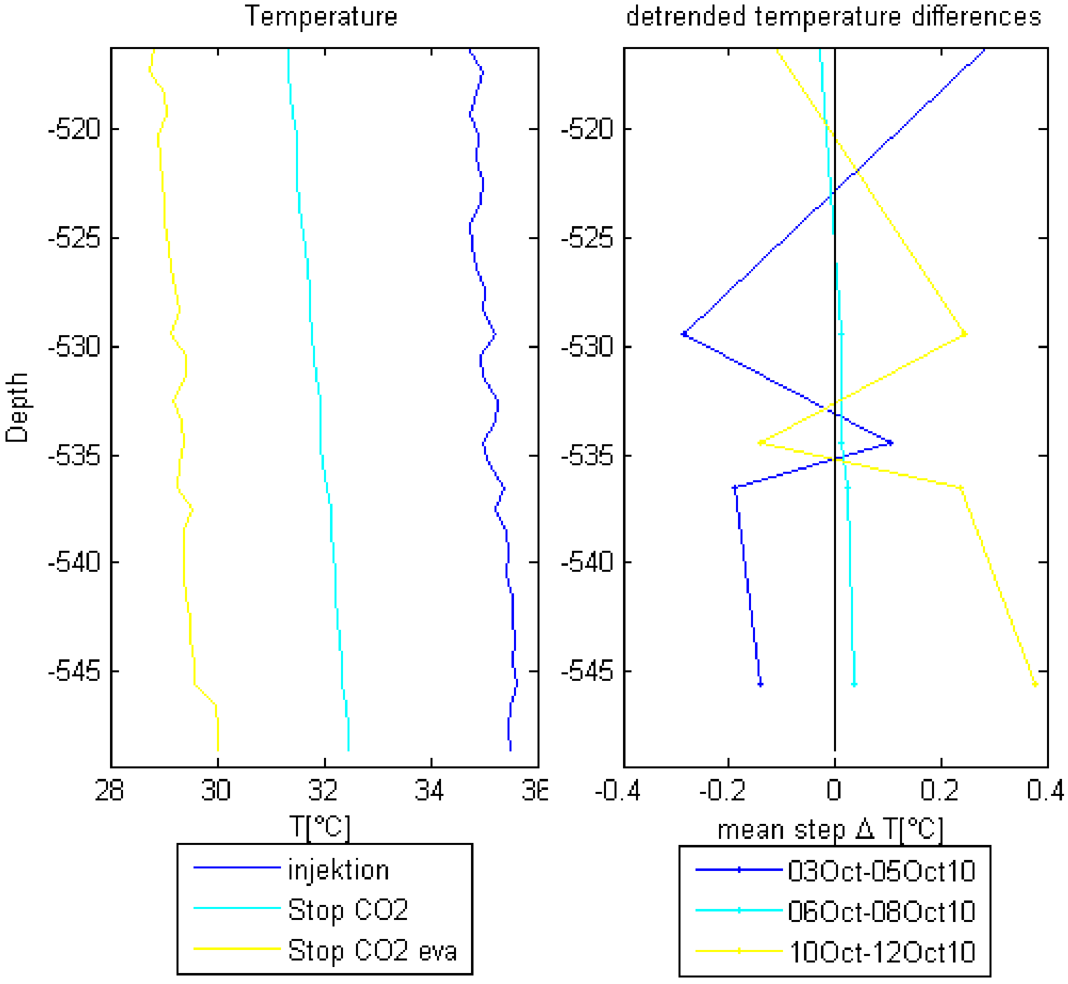


- Radial temperature gradient due to heat flux
- DTS cable has different distances to injeciton tubing
- Temperature differences occur which are proportional to the heat flux



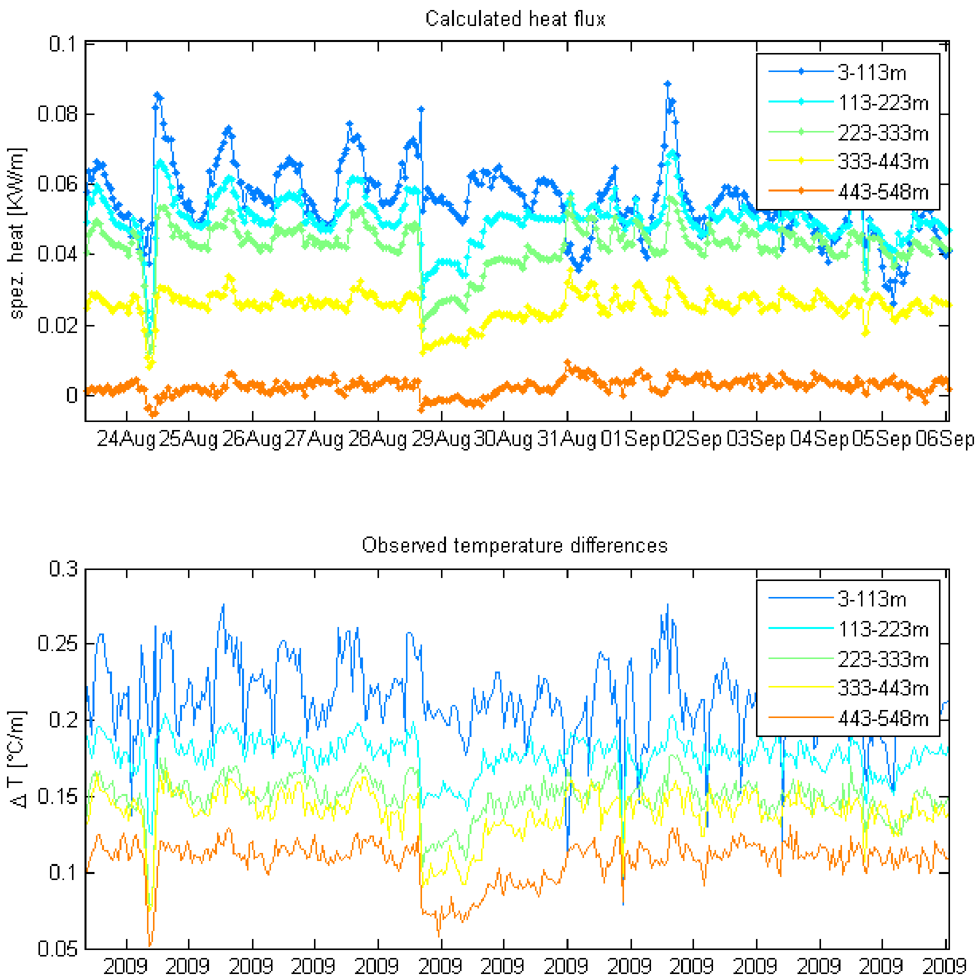


Observed differences



- 3 heat flux conditions
  - Positive
  - Neutral
  - Negative
- Only evaluate points with highest differences
- Long time means
- Temperature differences invert
- Applicable also for multi phase conditions

Comparison heat flux methods



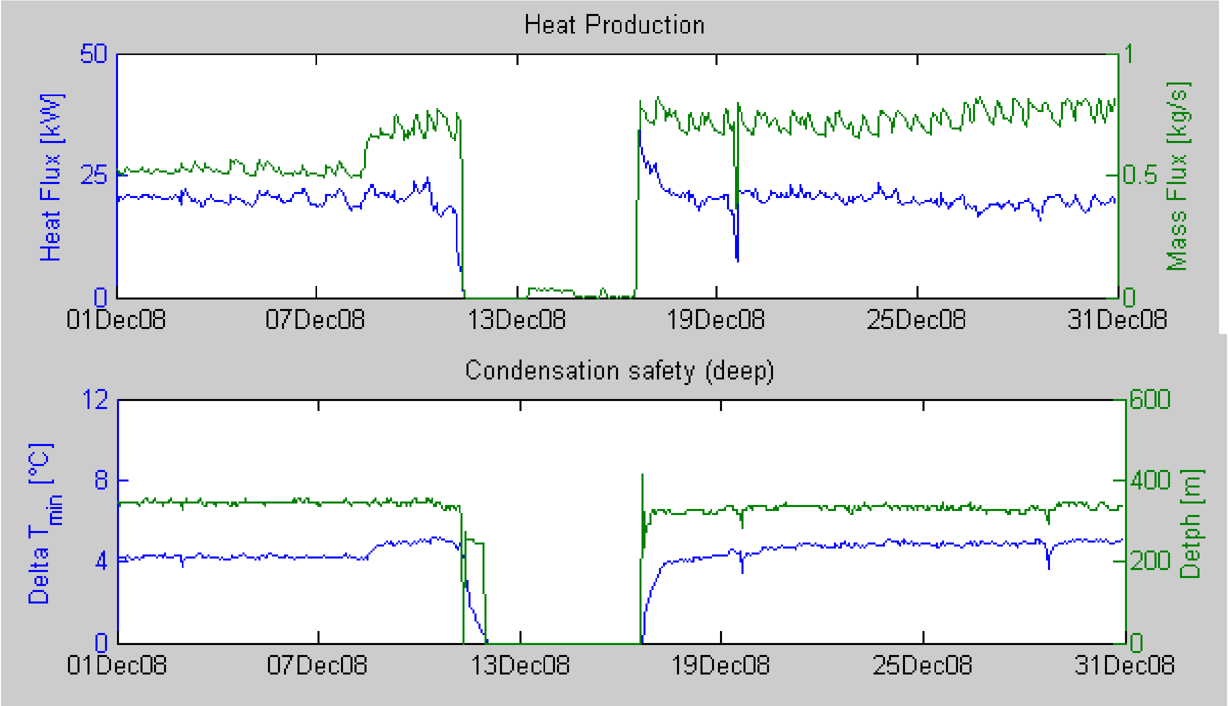
- Good temporal correlation
- Fair depth trend
- Direct correlation not possible

Comparison calculated heat flux vs. temperature differences

- Conclusions:
- High accuracy necessary
  - Only applicable for a mean of high numbers
- Allows monitoring during injection stop two phase conditions
- Comparison to calculated heat flux
  - Dynamic very similar
  - Depth dependence similar
  - Absolute value differs
  - Better results for higher depth

Application

- Tool for minimisation of heating
  - Minimum distance to condensation 4°C in 350 m depth
- Soure term for heat flux calculations in subsurface
  - Consequences for fluid flux
  - Thermally induced stress



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Conclusions

- DTS data from injection string
  - Pressure correction to reservoir
  - Nonlinear behavior in well
  - Determination of heat flux
    - Heat flux depends only slightly on mass flux
  - Determination of phase state and pressure during injetion
    - Detection of condensation
- Probems
  - Calculated negative heat flux for deepest 50 m (wrong)
  - Regression between two heat flux methods poor
    - But temporal behaviour coincides
- Application
  - Operational optimisation
  - Themal modelling of subsurface