Steam-Air-Injection in fractured Bedrock: Experience and Lessons Learned from a CHC Contaminated Site

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Turning failure into success – What can we learn when remediation does not go as planned

Short History of the “Biswurm” Site

Former communal incineration plant for liquid organic waste (1960-1974)

- leaking storage and incineration ponds;
- spill of chlorinated and aromatic hydrocarbons (CHC, BTEX), mineral oils

- 2004: excavation of top soil (4 m bgs): 1600 kg CHC and 600 kg mineral oils etc. were removed
- 2006 – 2007: detailed site investigation → hydraulic containment P&T and SVE
- **2009 looking for alternative remediation options**

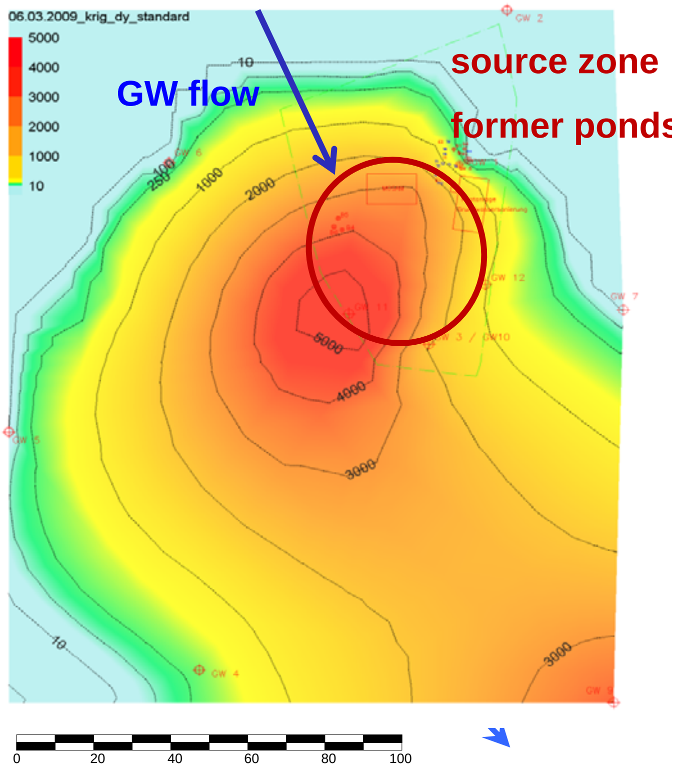
Extent of Contamination at Biswurm

➔ 2.900 m² surface area (source zone)
35 m thick sandstone formation affected

➔ CHC up to 40 mg/L in surface water,
1 mg/L in groundwater,
up to 4 g/m³ in soil vapor

➔ high contaminant potential in unsaturated zone and the groundwater fluctuation zone, “smaller” potential in saturated zone

➔ **pilot application** to investigate applicability of steam-air driven remediation



CHC (groundwater, µg/l): 06.03.2009

Steam distillation

Increasing temperature: 20°C → 80°C

and vapour pressure

- **Water: factor 20**
- **PCE: factor 15**
- **Xylene: factor 19**

Reduction of boiling point by steam distillation (azeotropic point):

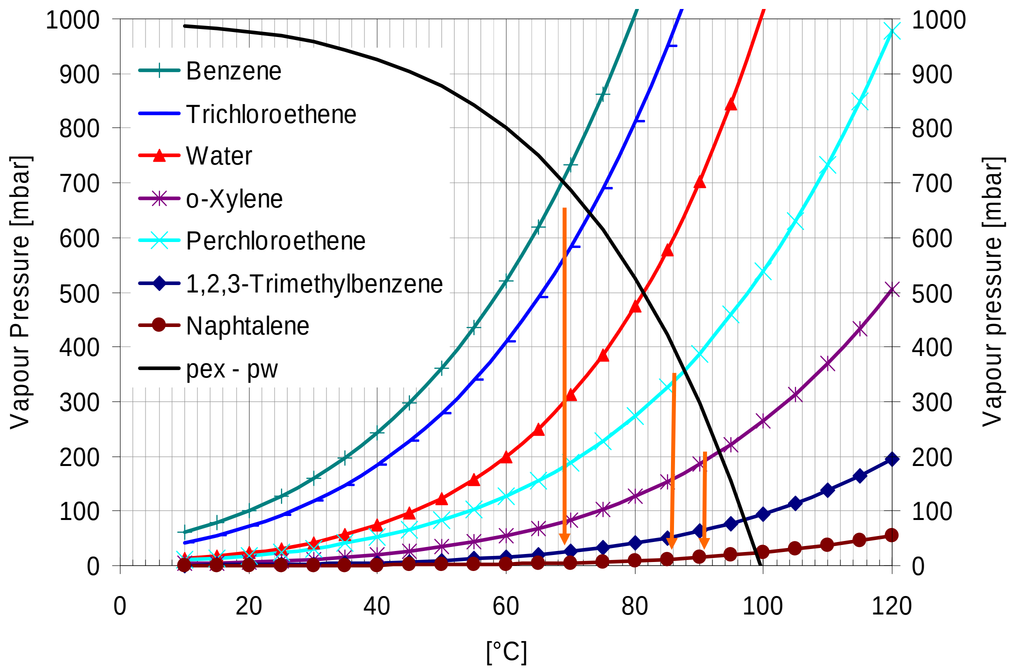
Benzene 80 → 69°C

TCE 87 → 74°C

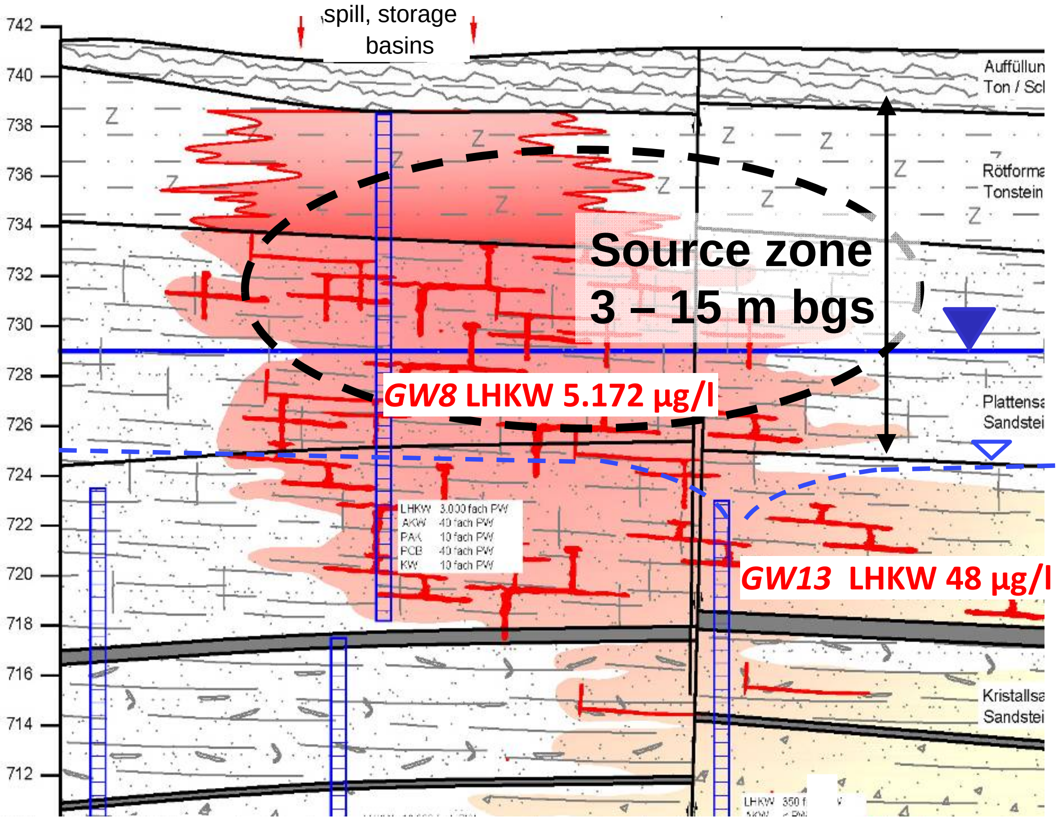
PCE 121 → 87°C

m-Xylene 144 → 93°C

Eutectic Temperature (boiling point of binary mixure), "steam distillation (McCabe-Thiele)"



Geology and Contamination

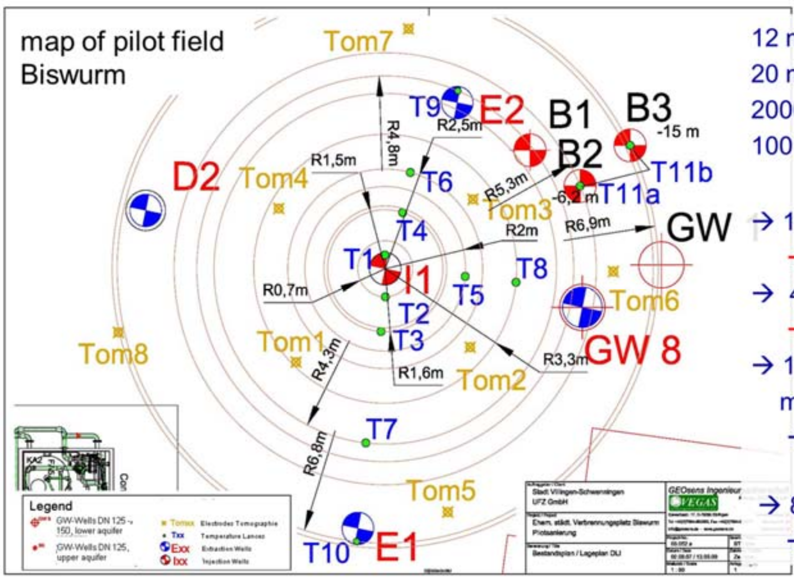


complex fractured bedrock aquifer

- unsaturated zone „Röt“ formation = claystone
- upper platy sandstone aquifer mudstone basis (21 m bgs.)
- lower siliceous sandstone aquifer
- granite basis (37 m bgs.)

Pilot Field Biswurm in 2009

- Applicability of steam-air injection to remediate the claystone and upper platy sandstone
- Increase of mass extraction by a factor of 2 to 5 as compared to „cold“ soil vapour extraction



12 m in diameter,
20 m thickness,
2000 m³ fractured rock
100 kW injection power

→ 1 injection well
→ I1
→ 4 extraction wells
→ E1, E2, D2, GW8
→ 11 temperature measurement lances
→ T1 - T11
117 Pt100 sensors
→ 8 geo-electrical probes
→ (Tom1-8)

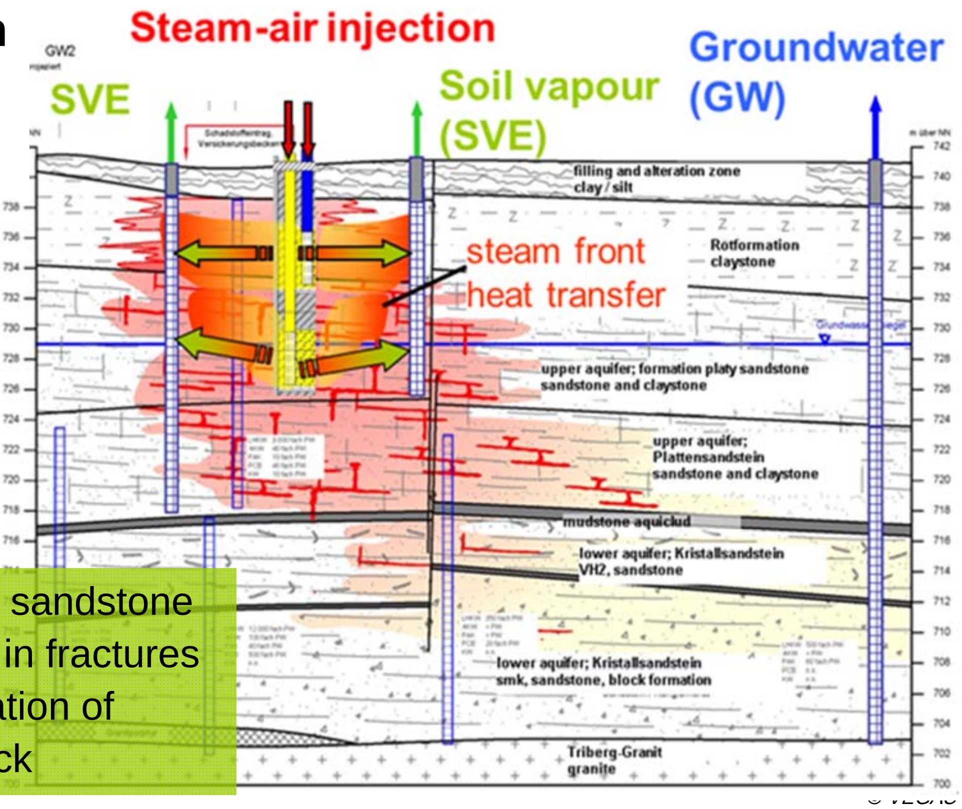
- For the upper aquifer and for the unsaturated zone a steam expansion of more than 10 m in diameter was confirmed
- **Total mass removal of 500 kg CHC during 3 months from 1,500 m³ bedrock**

Remediation Concept (I)

Design of remediation based on pilot application

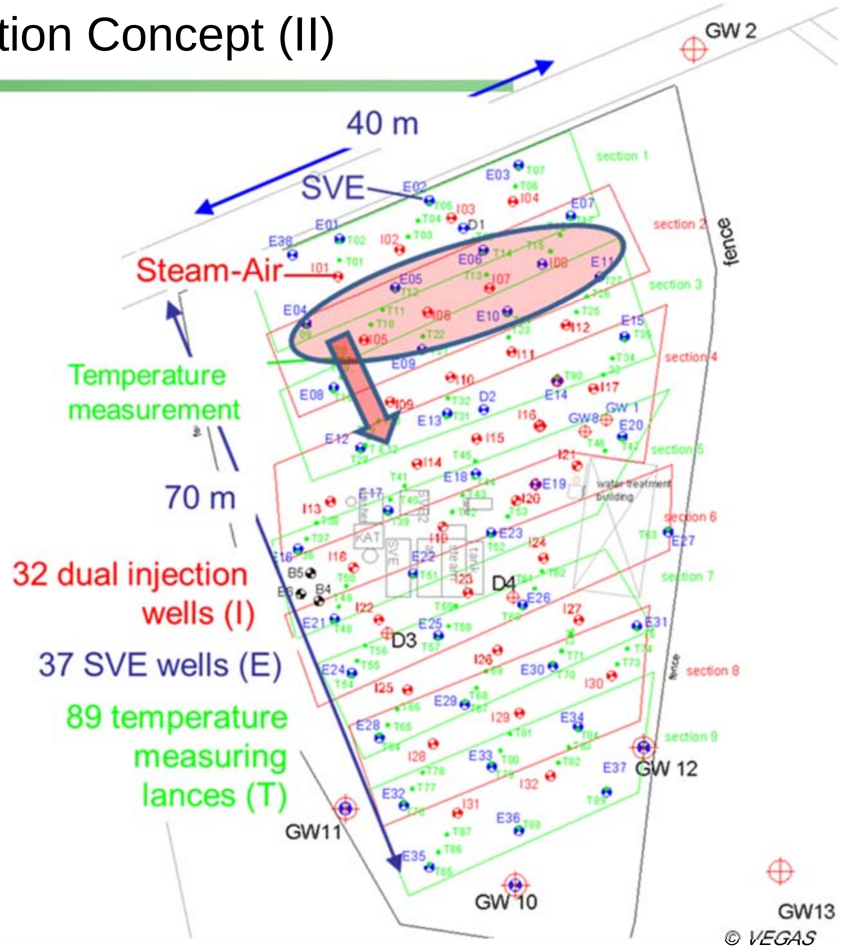
Steam-air injection
two injection levels:
- sandstone and claystone (4 – 8 m bgs.)
- sandstone, upper aquifer (11 – 15 m bgs.)

➢ **Heating** of claystone and sandstone by steam-air propagation in fractures
➢ **Desorption** and evaporation of contaminants from bedrock



Remediation Concept (II)

- **9 treatment sections**
  each 4 or 5 injection wells
  to treat 4.000 m³ of bedrock
- **Steam-air injection** with
  350 – 450 kW heating power
  ➔ *steam expansion phase*
  6 weeks at 550 kg/h steam-air flux
  ➔ *CHC desorption phase*
  8 weeks at 450 kg/h steam-air flux
- Groundwater containment at southern border



Design and Reality of the Remediation

Remediation design based on pilot application

➔ **thermally enhanced remediation section by section**

- **Steam-air injection**
  3 - 4 months each section (33 month)
  → **6 weeks** steam-air expansion (heating)
  → **+ 8 weeks** removal time (evaporation & desorption)

- **Cooling phase**
  one week each section (2,5 months)
- **January 2015**
  end and remediation control

.. but real life is different

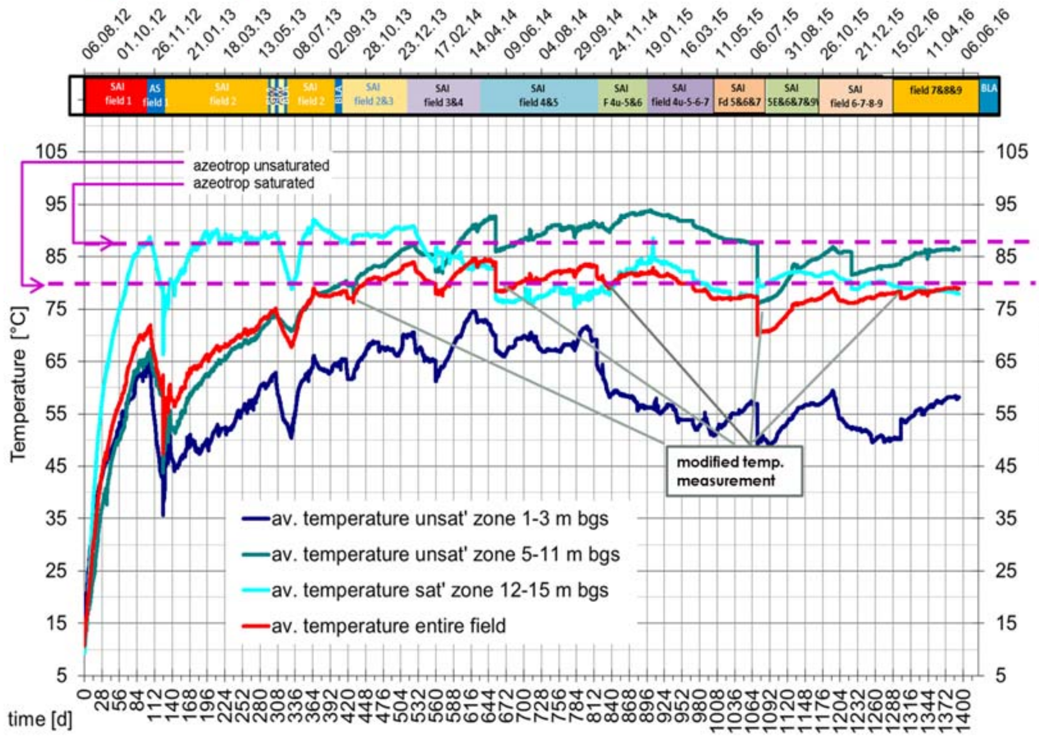
➔ time of desorption is significantly longer
➔ simultaneous remediation of two or more sections

- **Steam-air injection**
  4 - 6 months each section (> 45 month)
  → **5 weeks** heating time of claystone (200 kW)
  → **+ 11 – 13 weeks** evaporation time of claystone and sandstone (300 kW)
  → **9 weeks** desorption phase of platy sandstone (150 kW)
- **Cooling phase** → in total 6 months
- **August 2016** (estimated)
  end and remediation control

Impressions of Remediation

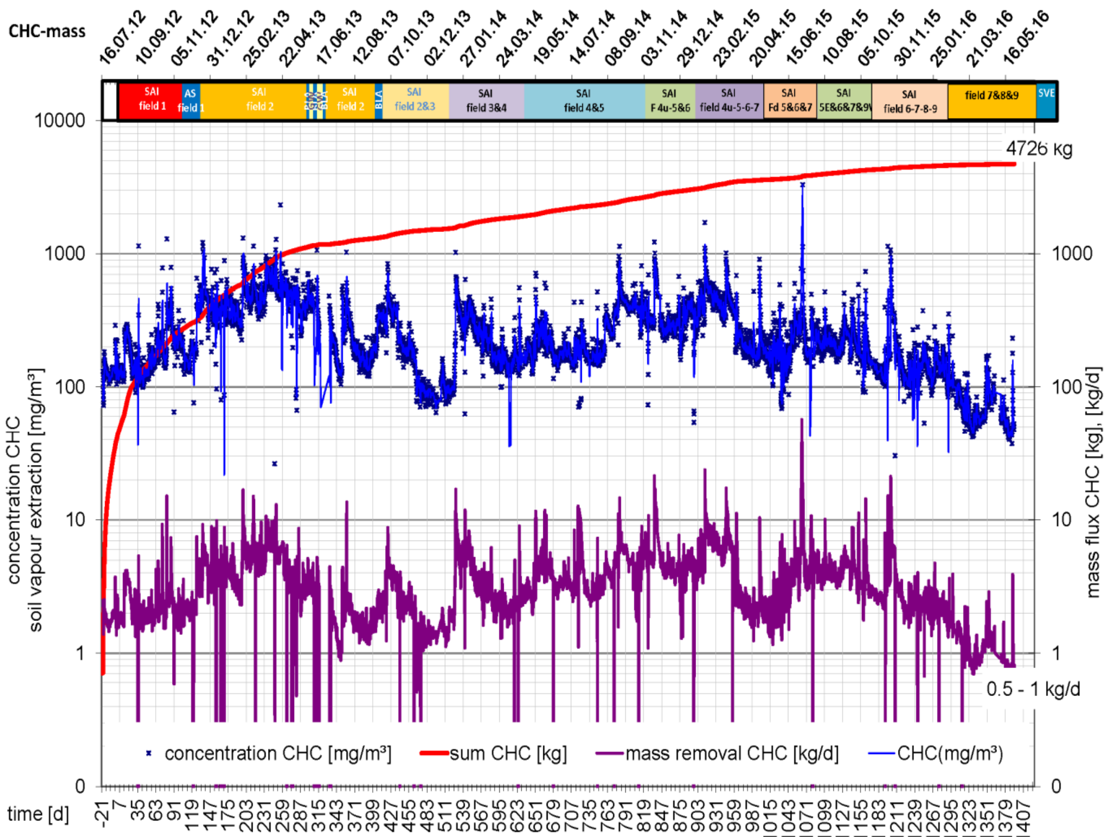
Temperature Development

Target temperature in the unsaturated zone > 80°C
Target temperature in the saturated zone > 88°C



- Dewatering leads to a target temperature of 80°C
- Until end of dewatering process (section 3) temperature in saturated zone > 88°C
- Pre-heating of claystone results in temperatures > 90°C → increase of evaporation process

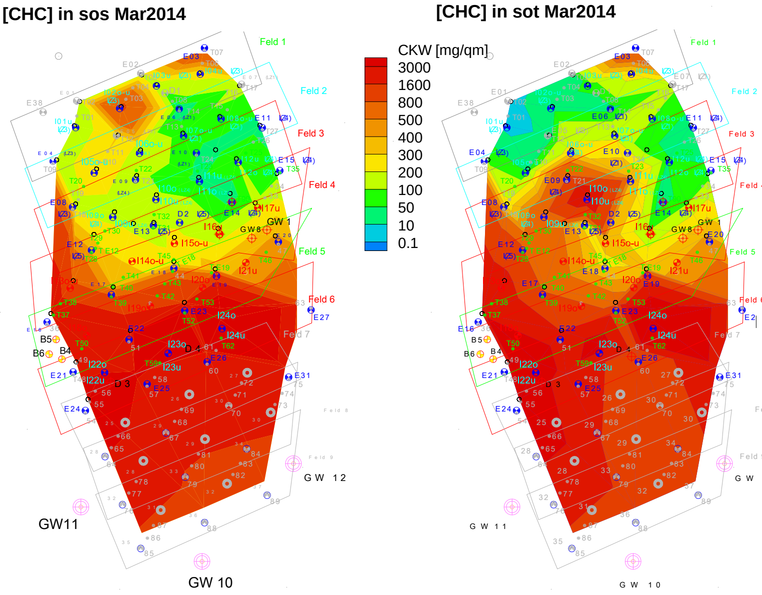
Summary after 30 months



after 1.400 days of steam-air injection
→ removal of 4.726 kg CHC

Mass removal up to 20 kg CHC per day, average 3.5 kg CHC per day

Spatial Contaminant Distribution (I)

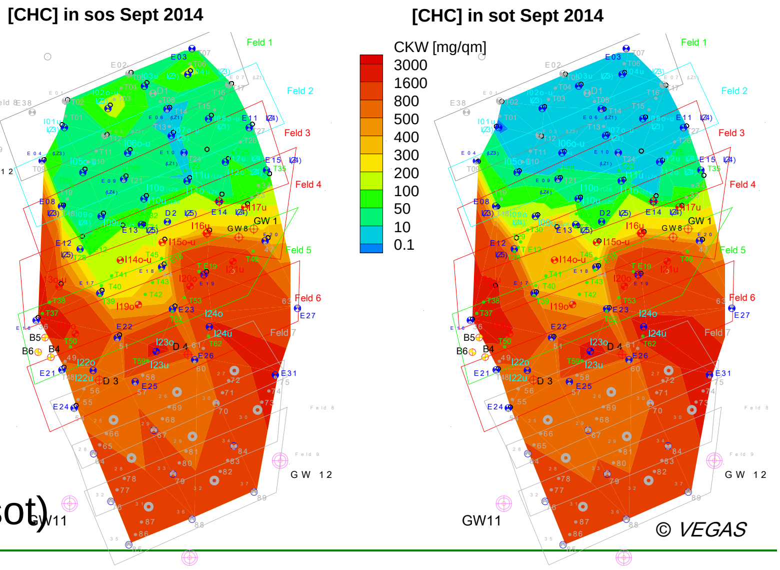


Water and heat storage in fractures and bedrock increased duration of mass removal and desorption

➔ mass removal during time without heating

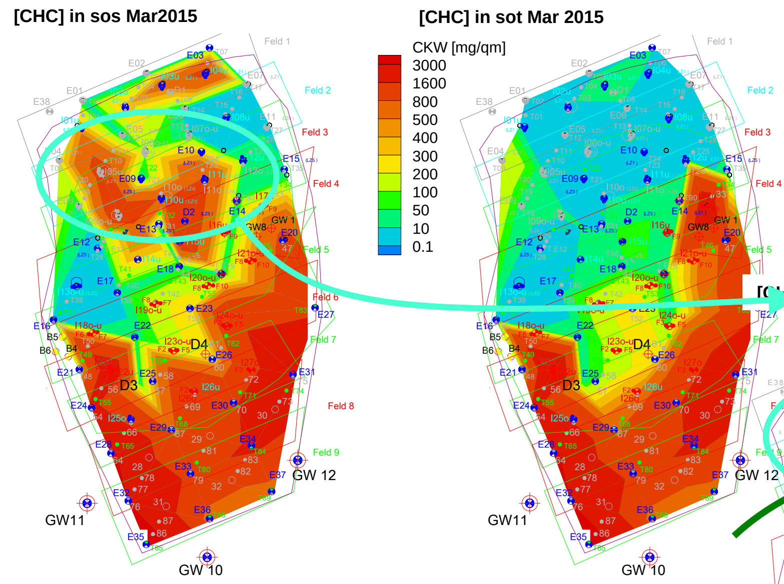
➔ extension of SVE capacities

CHC in soil vapour
platy sandstone (sos)



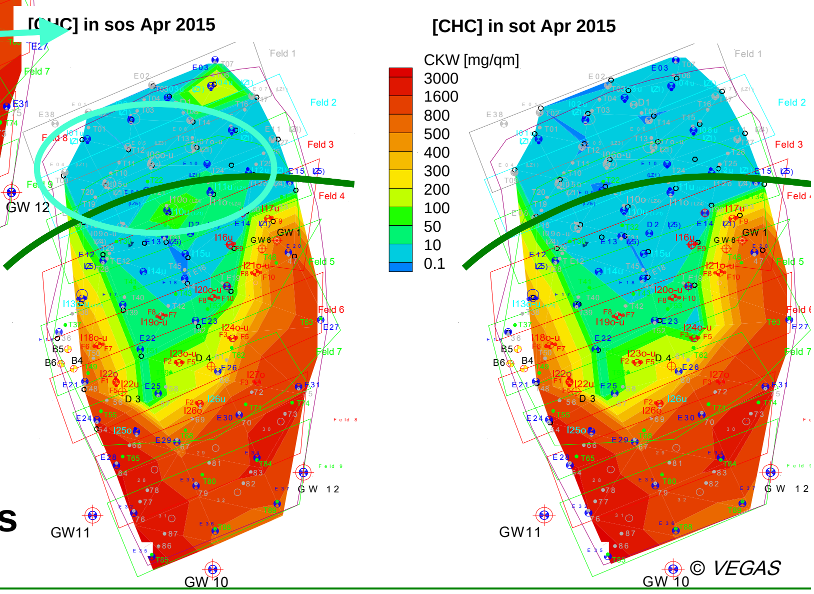
CHC in soil vapour
claystone-sandstone (sot)

Spatial Contaminant Distribution (II)



Rebound effects in sandstone bedrock (sos)

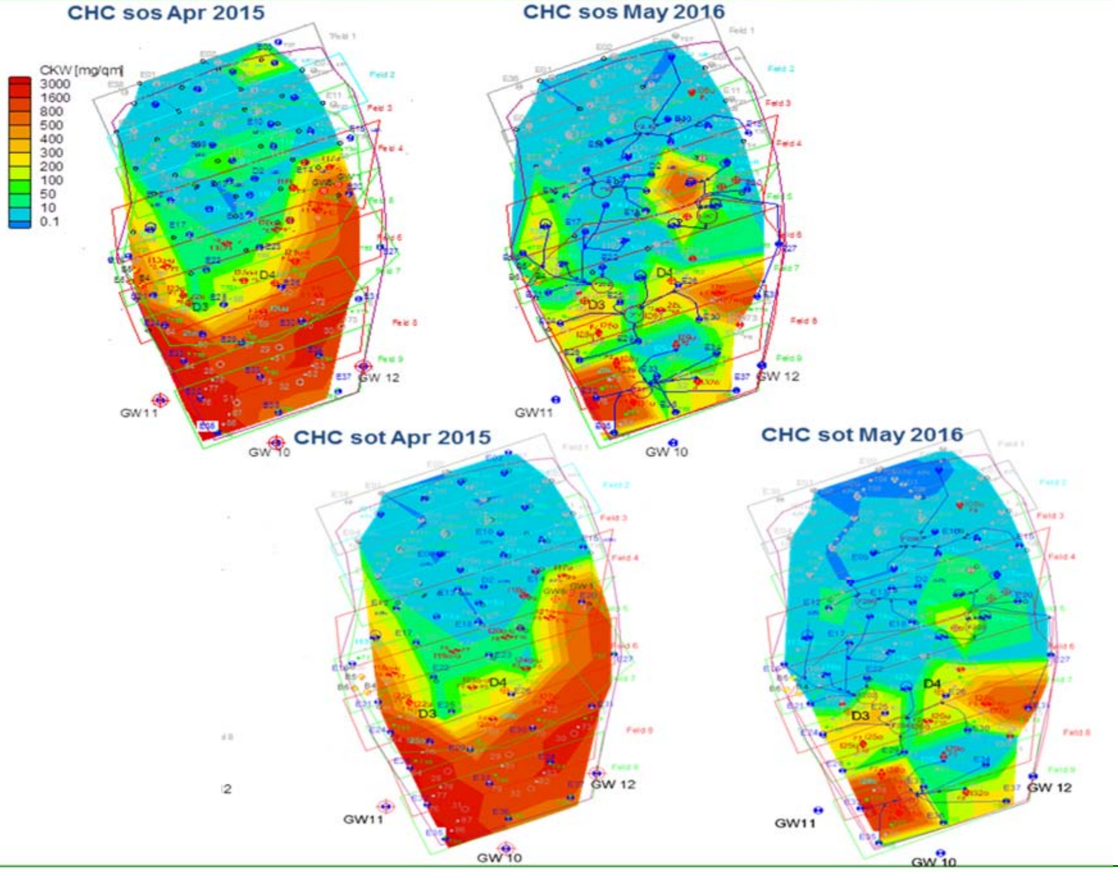
➔ Investigation of overlapping effects



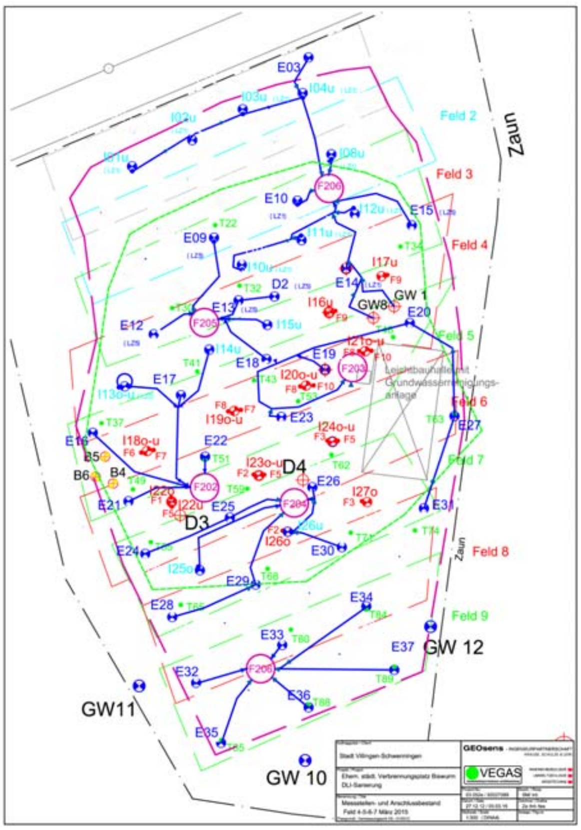
Underpressure belt and steam-air off during sampling in April 2015

➔ contaminant spreading in fractures

Spatial Contaminant Distribution (II)



Limits of Application - Lessons Learned -



Conductive heating of bedrock takes 40% more time as estimated

➔ remediation time will be 20 – 25% longer

- **simultaneous injection in 2 sections**
- **SVE from 5 sections**

➔ energy consumption optimized

Steam-air propagation in fractures is hard to control

- **SVE from 40 SVE-wells instead of 10 wells**

➔ mass flux of SVE at least 1.5 x injection rate

Heat storage capacity results in long-term desorption capacity

➔ extending cooling phase

Summary after 44 months

- Fractured bedrock is challenging in flux and control
  ➔ spreading of evaporated contaminants in fractures
- Heat transport and contaminant removal differs from pilot trial
  ➔ uncertainty requires additional resources (+ 30 %)
- Target temperatures exceeded
- CHC removal by SVE is dominant: 5,000 kg CHC
  200 kg CHC by groundwater containment
- Remediation procedure requires time by time adaption of mass removal (SVE system)
- Additional time required 48 months instead of 33 months

Lessons Learned

- Flux and control spreading of evaporated contaminants in fractures is difficult and sometimes surprising
- Intensive online monitoring and prompt data analysis is required
- Adjustment and optimization of the remediation based on the monitoring data has to be made
- Heat transport and contaminant removal differs from the pilot trial, this requires additional measures and resources
- Remediation procedure requires several times a flexible and quick adaption of the SVE system
- Intensive and trustfully communication between all partners involved is crucial

➔ **Remediation of fractured bedrock by steam-air injection can be very successful but requires:**

(1) an effective monitoring and control (online monitoring) and short "reaction time" for managing the system

(2) flexibility of the parties involved (consultant, remediation company, site owner, regulator)

(3) and maybe financial resources

Acknowledgements

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