Geothermal fluid and reservoir properties in the Upper Rhine Graben

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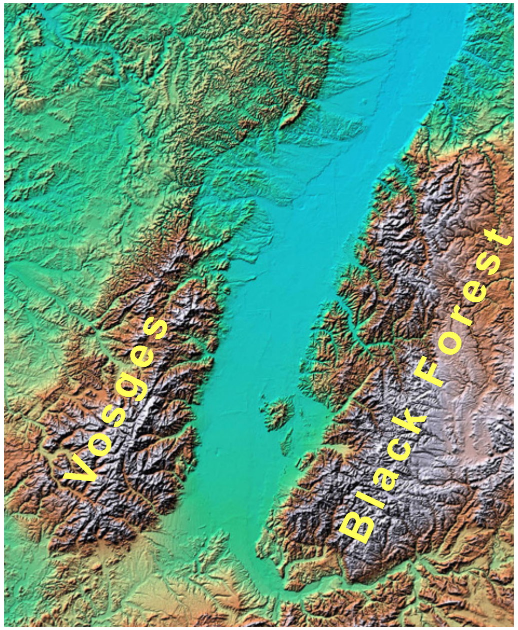
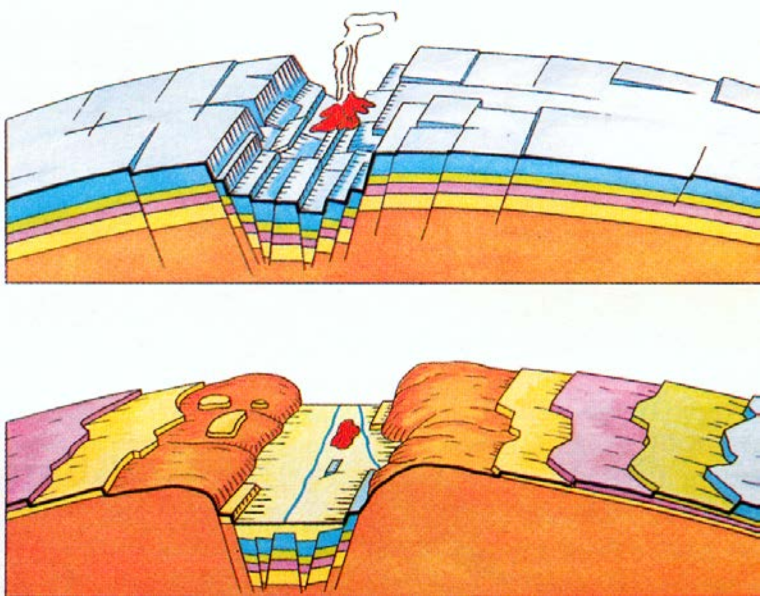
Geological situation of the Upper Rhine Graben





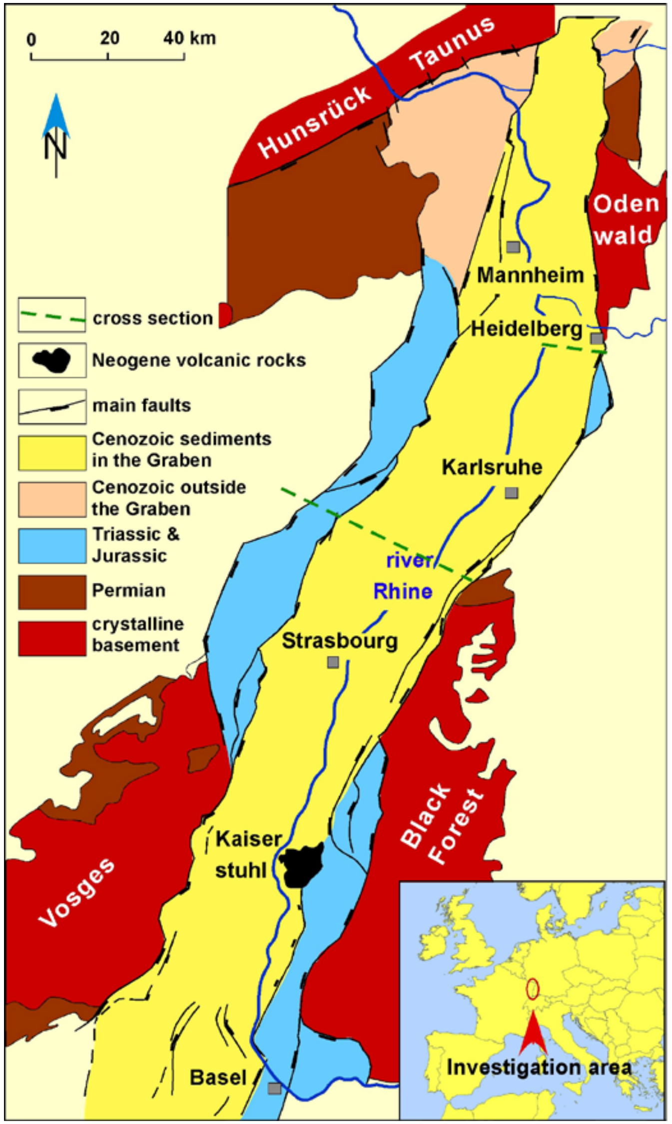
During Early Cenozoic and Late Eocene:

- Subsidence of Upper Rhine Graben
- Uplift of Black Forest and Vosges mountains as Rift flanks

Uplift (several km) caused erosion on both flanks of the Graben, exhuming gneisses and granites. The former sedimentary cover is conserved within the Graben. The deeply burried sediments include several aquifers containing hot water.

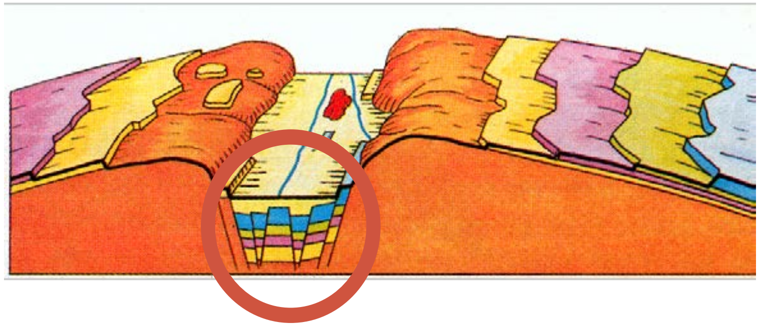
Additionally there are thick Tertiary and Quaternary sediments, formed during the subsidence of the Graben.

Complex hydrogeological situation in the Graben



- Broken layers, partly with hydraulic connection, partly without
- Alternation between depression areas & elevated regions (horst – graben – structure)
- Hydraulic behavior of faults unknown
- There are extensional as well as compressive faults
- Main faults show vertical displacements of several 1,000 meters
- Thickness of the individual layers not constant.

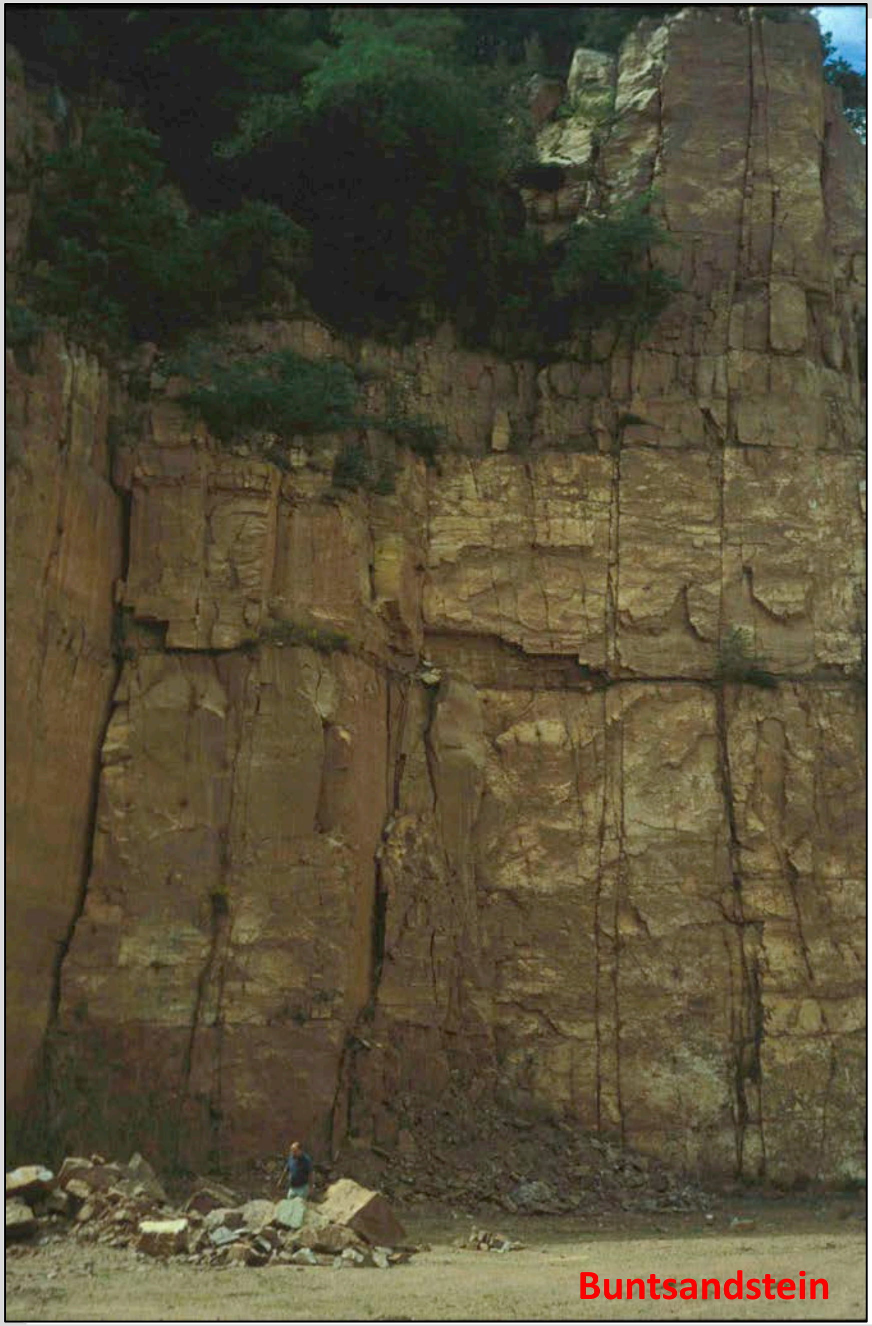
Hydrogeology



- Thickness of the individual layers not constant
  - Hauptrogenstein decreases from S to N, 120 m to 0 m (Strasbourg)
  - Upper Muschelkalk (60-85 m)
  - Buntsandstein increases from S to N, 60 m to 550 m
- Temperature is very high in depression zones, like the Heidelberg area, and quite low in more elevated regions

There are <u>4 major thermal aquifers</u> within the Upper Rhine Rift, primary targets of potential geothermal reservoirs:

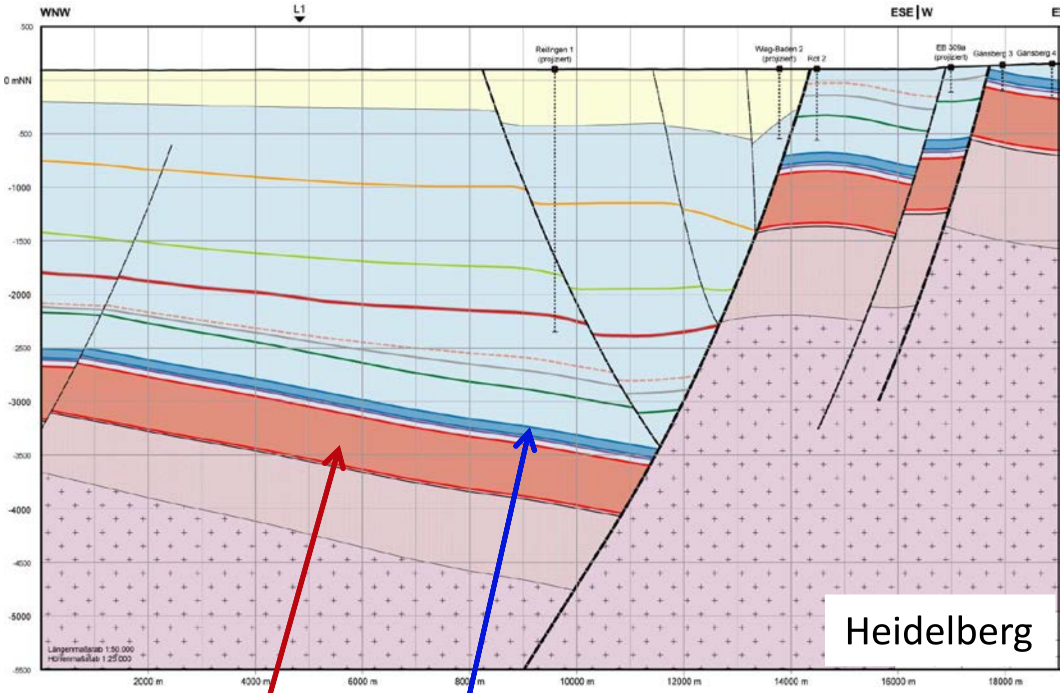
- Hauptrogenstein (Dogger) – limestone (S)
- Upper Muschelkalk (middle Triassic) - limestone
- Buntsandstein (lower Triassic) – sandstone
- Cenocoic sediments (Tertiary) – sandstone (N)



Examples

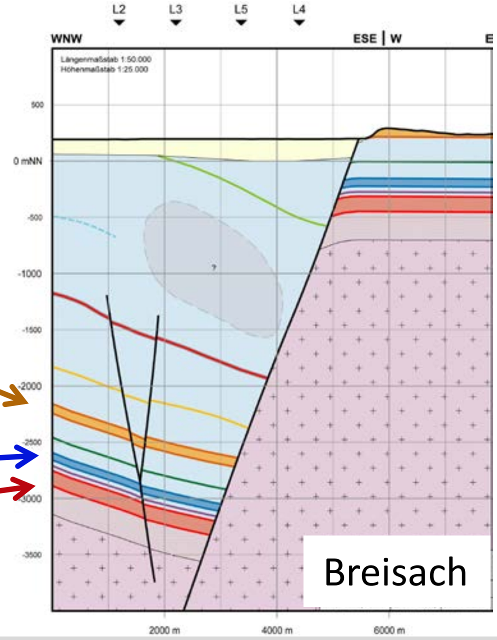
Cross sections through the eastern part of the Upper Rhine Graben, showing the 3 main thermal aquifers

Northern Graben



Vertical Displacement: 3,700 m

Southern Graben



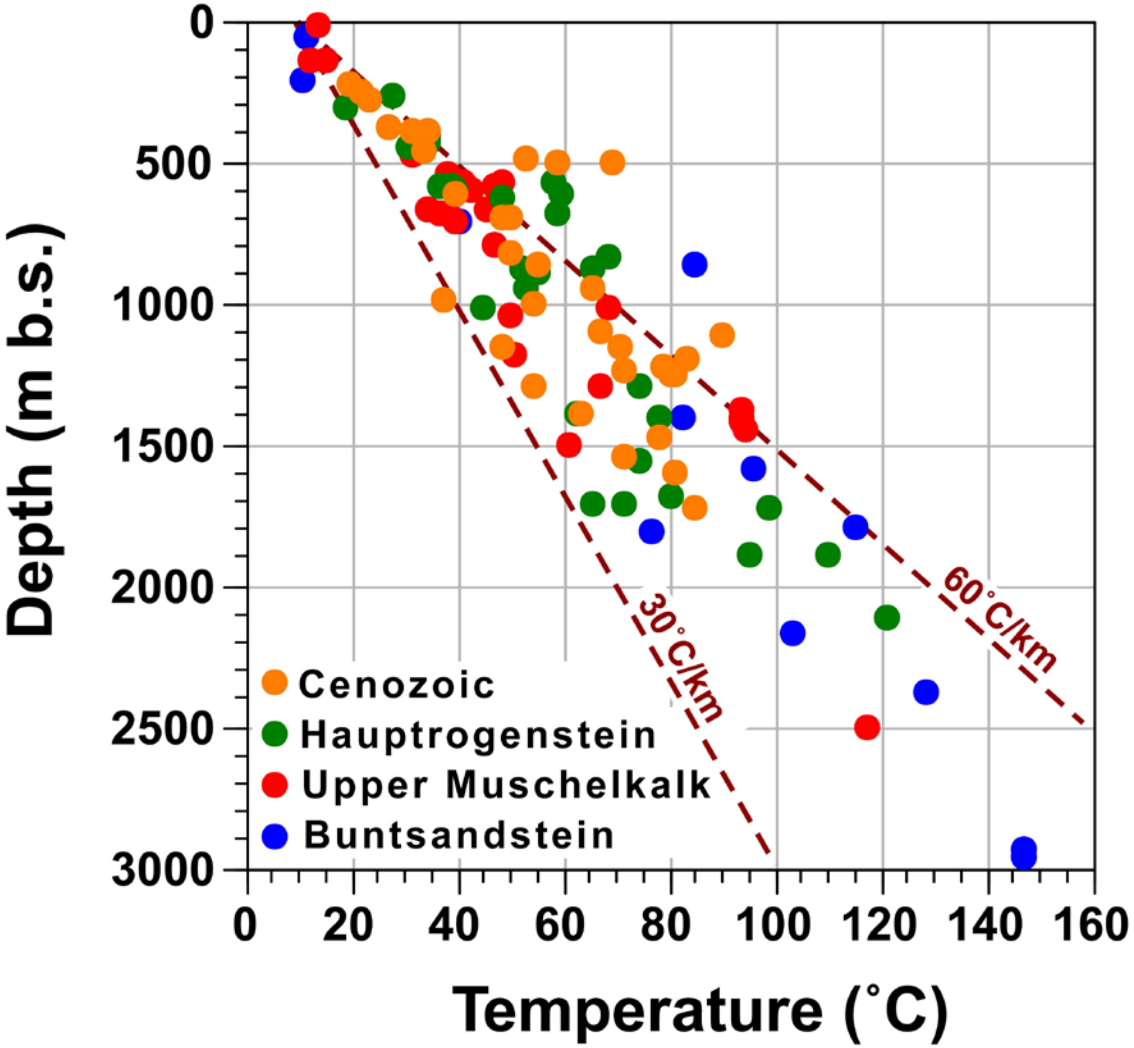
Vertical Displacement: 3,000 m

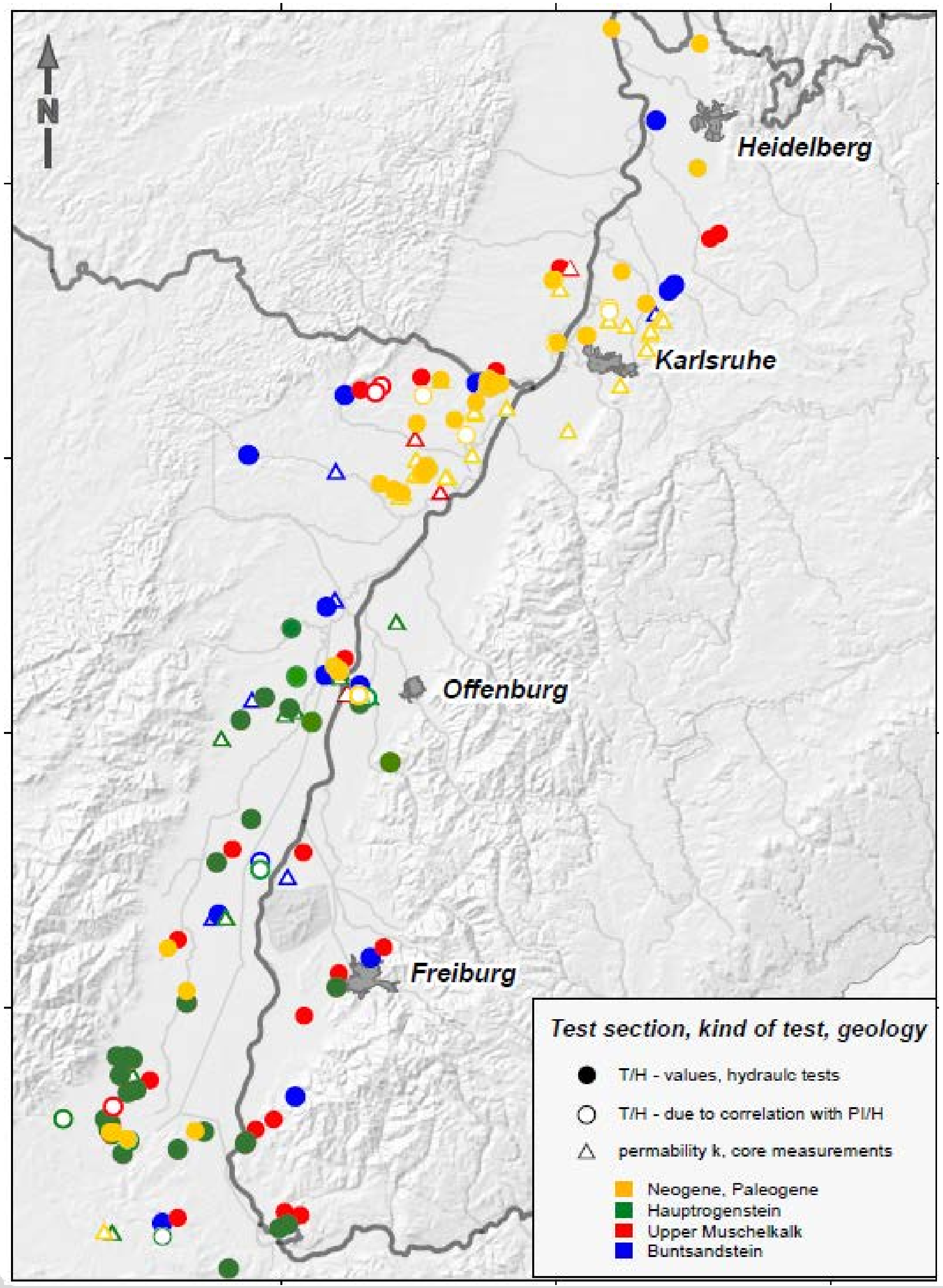
Hauptrogenstein (Dogger)

Upper Muschelkalk (middle Triassic)

Buntsandstein (lower Triassic)

Temperature in the Upper Rhine Graben





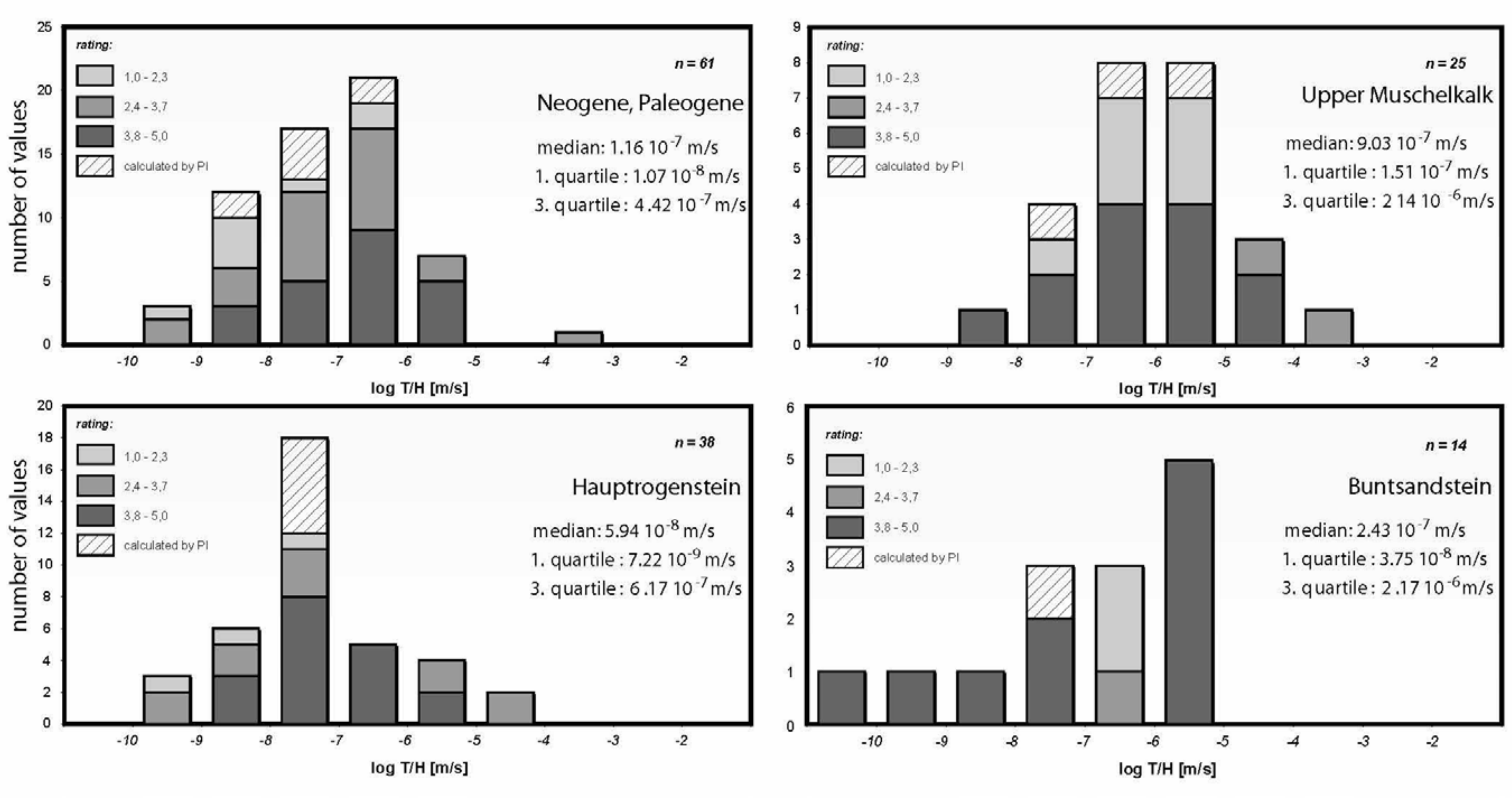
Karlsruher Institut für Technologie

Location of hydraulic test data from deep wells

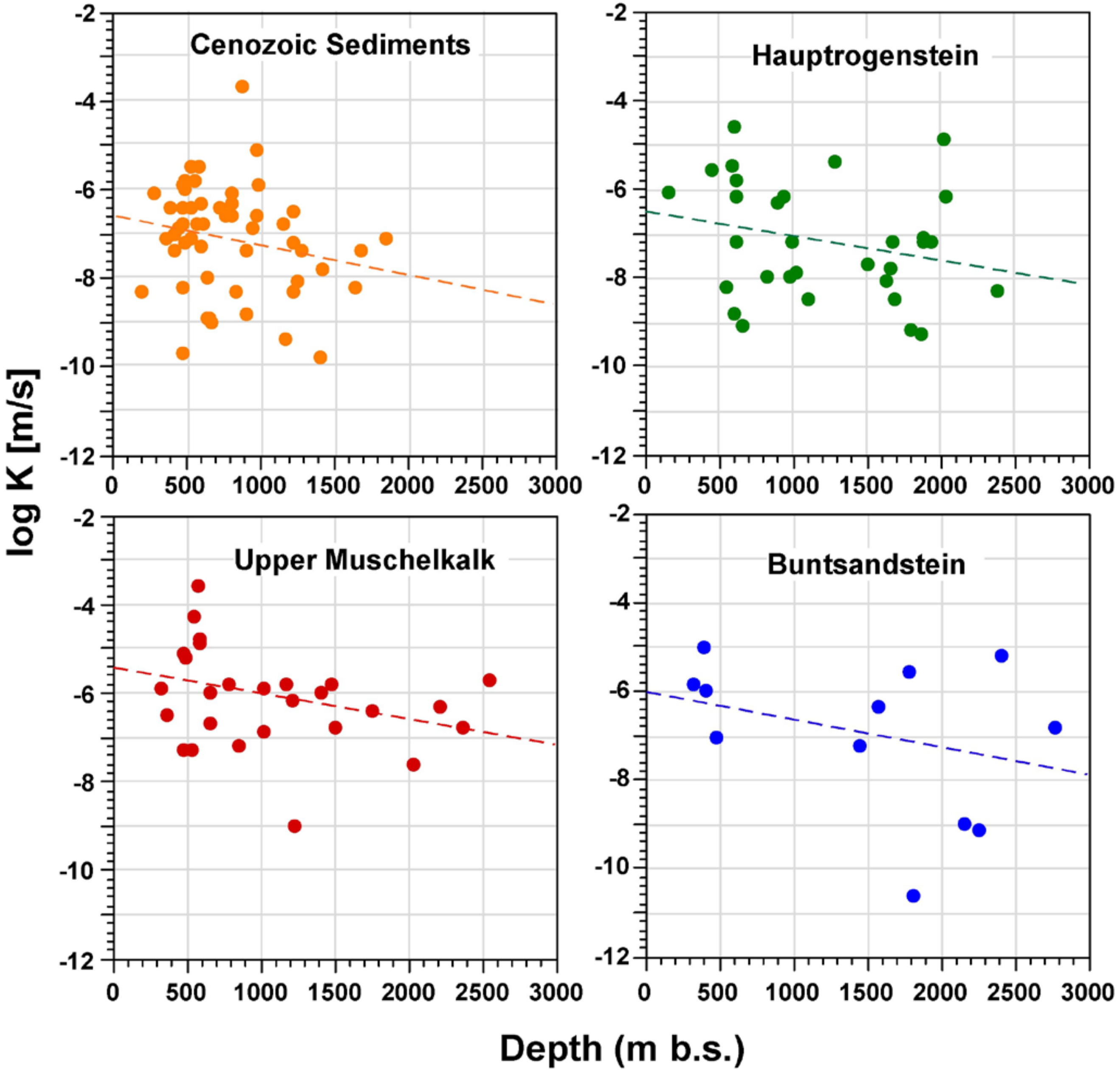
- deep wells of the oil- / gas-industry
- wells of spas
- geothermal wells

Frequency distribution of hydraulic conductivity (T/H) in the thermal aquifers

T – transmissivity (m^2/s)
H – test length (m)



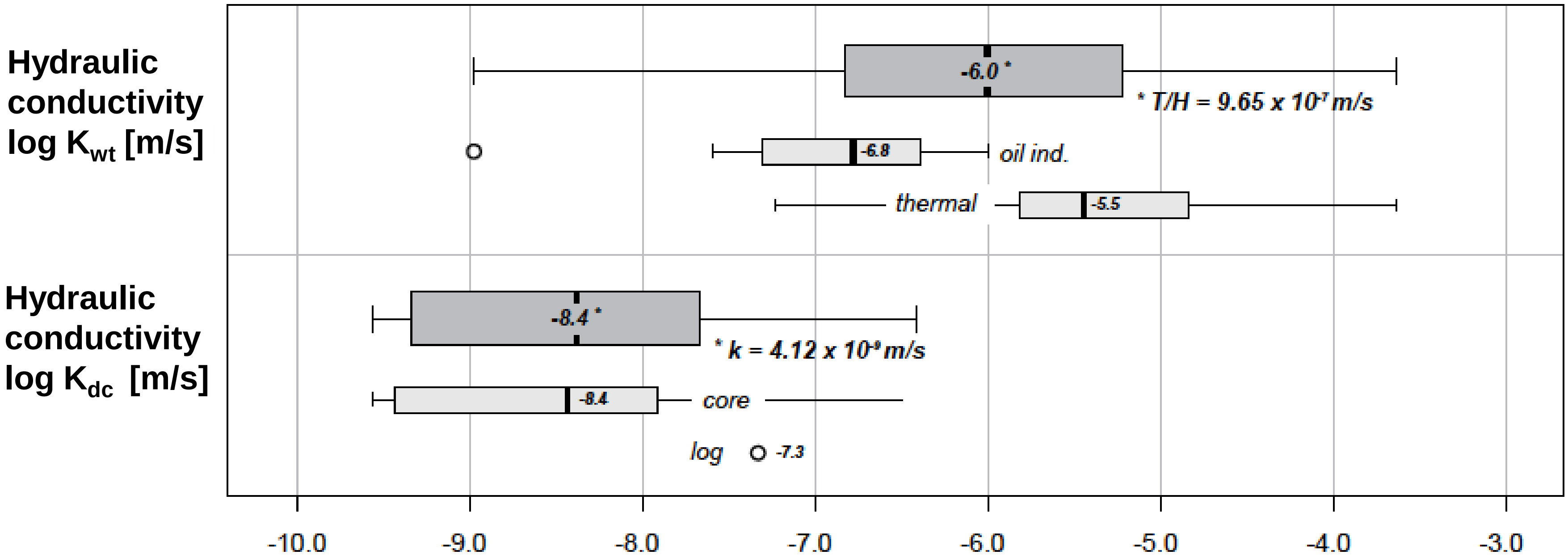
fractured sandstone, karstified limestone aquifers



Hydraulic conductivity: dependence of depth (?)

Box-Whisker-Plot:
Comparison of drill core and well test derived data
example: Upper Muschelkalk-aquifer

K_{wt} = Hydraulic conductivity (T/H) [m/s] derived from well tests
K_{dc} = Hydraulic conductivity [m/s] derived from permeability (κ) [m^2] measurements on drill cores



Hydraulic conductivity K_{dc} [m/s] in fractured or karstified aquifers derived from **permeability κ** measurements on drill cores, is always orders of magnitude lower than **hydraulic conductivity K_{wt}** (T/H) [m/s] derived from of hydraulic tests.

Thus **T/H data** should be used for characterization of fluid flow in these aquifers.

Table 1: Median and 1. & 3. quartiles of hydraulic conductivity and permeability of thermal aquifers in the Upper Rhine Graben. Number in bracket (n) indicates total number of values from different boreholes.

Aquifer	**Hydraulic conductivity (T/H, m/s)** **Hydraulic well test** [1. / 3. quartile]	**Permeability (κ, m/s)** **Core test** [1./ 3. quartile]
Paleogene-Neogene	$1.16\ 10^{-7}$ (n = 53) [$1.07\ 10^{-8}$ / $4.42\ 10^{-7}$]	$2.82\ 10^{-8}$ (n = 98) [$4.27\ 10^{-9}$ / $2.11\ 10^{-6}$]
Hauptrogenstein (middle Jurassic)	$5.94\ 10^{-8}$ (n = 32) [$7.22\ 10^{-9}$ / $6.17\ 10^{-7}$]	$2.38\ 10^{-9}$ (n = 42) [$8.50\ 10^{-10}$ / $8.14\ 10^{-9}$]
Upper Muschelkalk (middle Triassic)	$9.03\ 10^{-7}$ (n = 22) [$1.51\ 10^{-7}$ / $2.14\ 10^{-6}$]	$3.69\ 10^{-9}$ (n = 8) [$4.15\ 10^{-10}$ / $9.24\ 10^{-9}$]
Buntsandstein (lower Triassic)	$2.43\ 10^{-7}$ (n = 14) [$3.75\ 10^{-8}$ / $2.17\ 10^{-6}$]	$7.65\ 10^{-8}$ (n = 7) [$2.04\ 10^{-9}$ / $1.33\ 10^{-8}$]

Quality of the hydrochemical samples from deep wells

- Most water-samples are old (from archives). A lot of the samples originate from production tests of the oil-industry in the 1970th to 1990th; these boreholes are closed now.

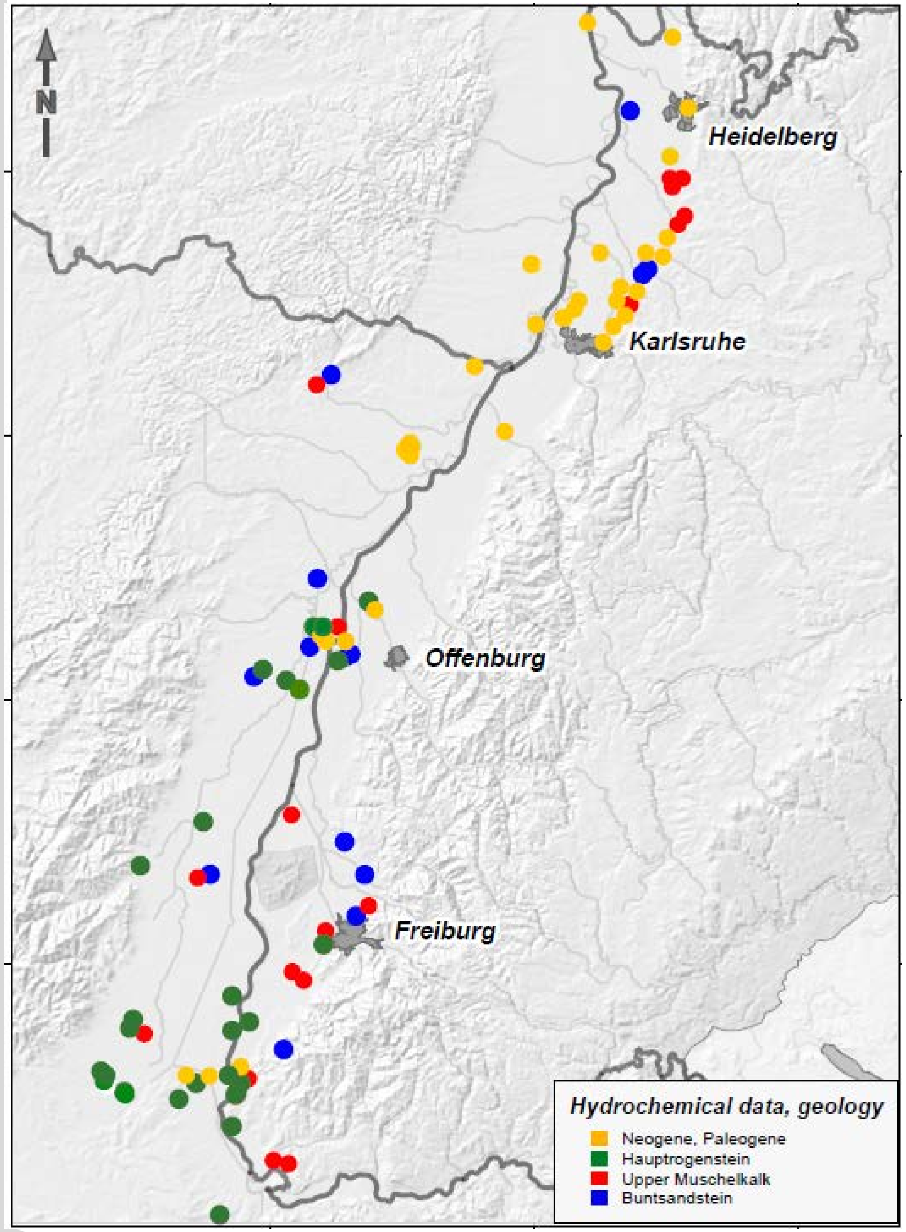
- The few new collected samples are from thermal spas and geothermal wells.
- Different laboratories analyzed the water-samples. So, first of all the analyses had to be controlled and checked on plausibility.

On a total, the quality of the samples should not be overestimated.

Nevertheless the data seem to be very valuable, if scheduling a geothermal project or planning deep wells for other purposes like CO_2-sequestration, thermal spas,….

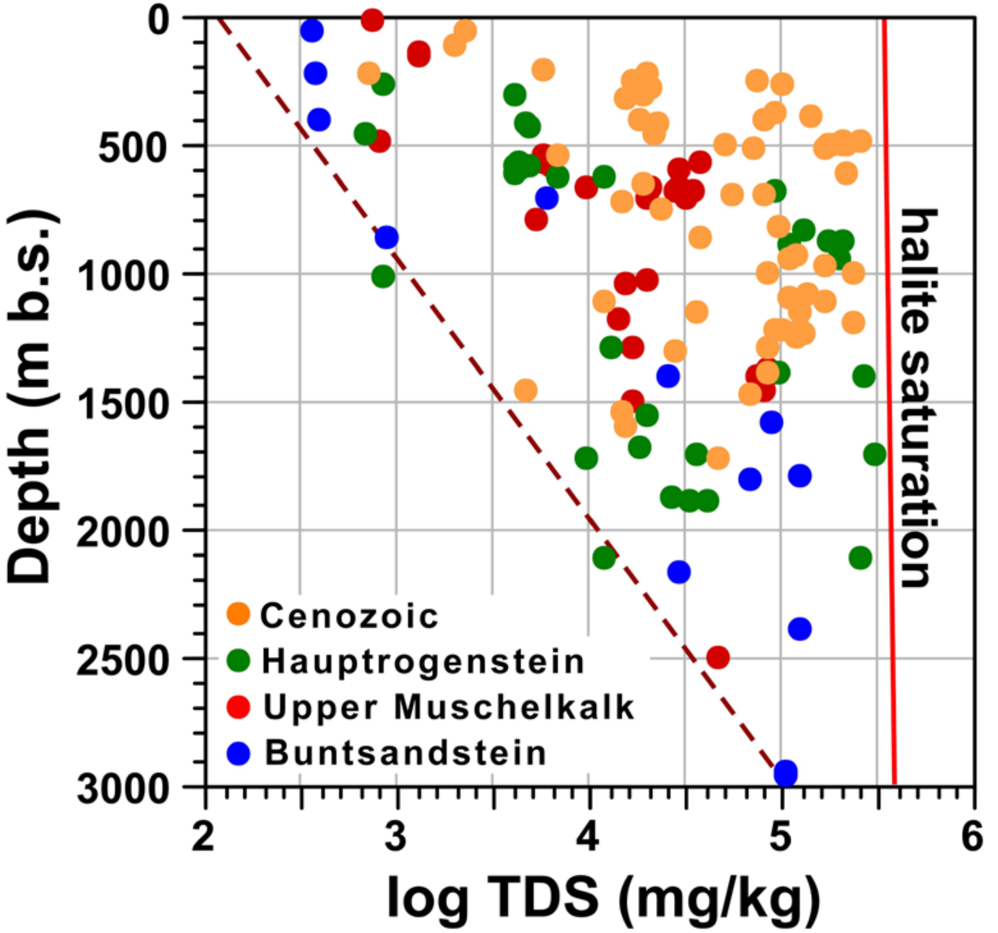
Collection of hot, gas-rich, strongly mineralized waters

Location of chemical water analyses from deep wells



Hydraulic testing with water sampling

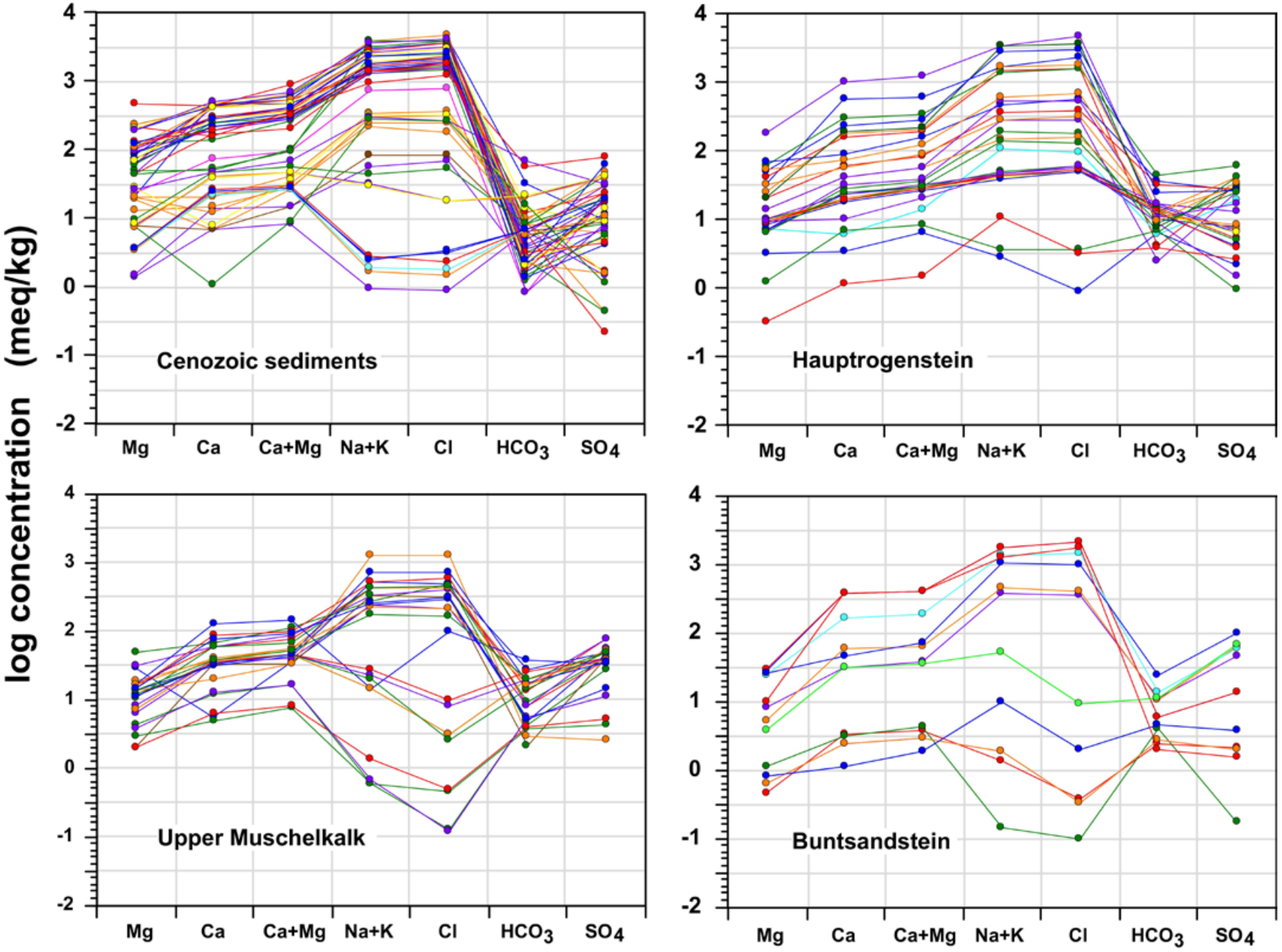
Hydrochemical properties of deep seated hot waters



- Deep thermal waters are always strongly mineralized.
- No weakly mineralized deep waters.
- Highest TDS in Hauptrogenstein (Dogger) aquifer with several 100 g/kg.
- All waters below halite saturation. KCl and $CaCl_2$ saturation is about 0.5 log units higher than halite saturation.

TDS = Total Dissolved Solids

Hydrochemical properties of deep seated hot waters (> 500 m)



t: TDS: < 240 g/kg
depth: ≤ 1,700 m
Water-type at shallow depth:
Ca-HCO$_3$
Water-type at great depth:
Na-Cl

bjHR: TDS: < 300 g/kg
depth: ≤ 2,100 m
Water-type at shallow depth:
Ca-HCO$_3$
Water-type at great depth:
Na-Cl

mo: TDS: ≤ 79 g/kg
depth: ≤ 2,500 m
Water-type at shallow depth:
Ca-SO$_4$-HCO$_3$
Water-type at great depth:
Na-Cl

s: TDS: ≤ 127 g/kg
depth: ≤ 3,200 m
Water-type at shallow depth:
Ca-HCO$_3$
Water-type at great depth:
Na-Cl

Waters at shallow depth (500 – 800 m):

- **Middle & Lower Cenocoic:** Ca-HCO_3 waters, in sediments with carbonate components, SO4 locally enriched due to occurrence of gypsum/anhydrite.
- **Hauptrogenstein**: Ca-HCO_3 waters, in fractured and karstified limestone
- **Upper Muschelkalk**: Ca-SO_4-HCO_3 waters, in fractured and karstified limestone, containing gypsum/anhydrite-rich layers.
- **Buntsandstein**: Ca-HCO_3 waters with elevated SO_4-concentration, in fractured sandstone. The fracture surfaces are usually covered with calcite. The sandstone contains relics of gypsum lenses.

Waters at greater depth (> 800 m):

- **Middle & Lower Cenocoic:** Na-Cl waters. Gradually changing water type with TDS and depth.
- **Hauptrogenstein**: Na-Cl waters. Ca continuously increases with TDS. Gradually changing water type with TDS and depth.
- **Upper Muschelkalk**: Na-Cl waters. Abrupt change of water type from lower to higher concentrations.
- **Buntsandstein**: Na-Cl waters. ± Continuous transition from lower to higher concentrations.

Deep waters are Na-Cl-rich, independent of nature of aquifer-rock.

Origin of deep Na-Cl-rich thermal waters

Latest **seawater** transgression in the Upper Rhine Graben during Eocene-Oligocene. Evaporite deposits with **halite** and **sylvite** formed from Upper Eocene to the Lower Oligocene. Halite-rich strata also locally within Middle Muschelkalk.

Quartz saturation temperatures from SiO_2- geothermometers are typically higher than measured aquifer-temperatures, indicating upwelling thermal waters.

Cl/Br- and (Na+K)/Cl-ratios show:

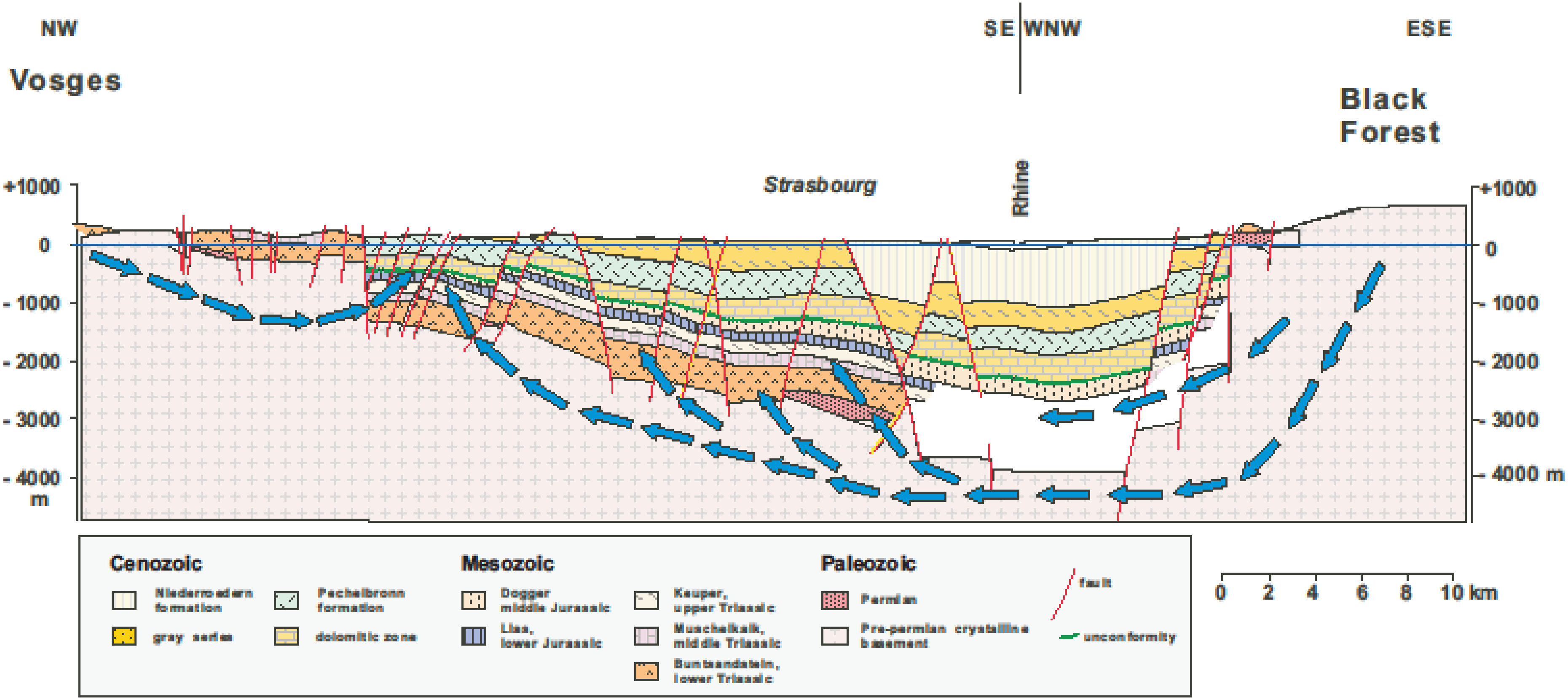
The high salinity in the Buntsandstein aquifer originates from upwelling saline waters from the crystalline basement,

The salinity in the Upper Muschelkalk derives from halite in the underlying Middle Muschelkalk,

The salinity in the Hauptrogenstein aquifer originates from halite in Tertiary strata.

To some extend there exists additionally a NaCl component from fossil sea water.

Flow Model in the Upper Rhine Graben



Technical consequences

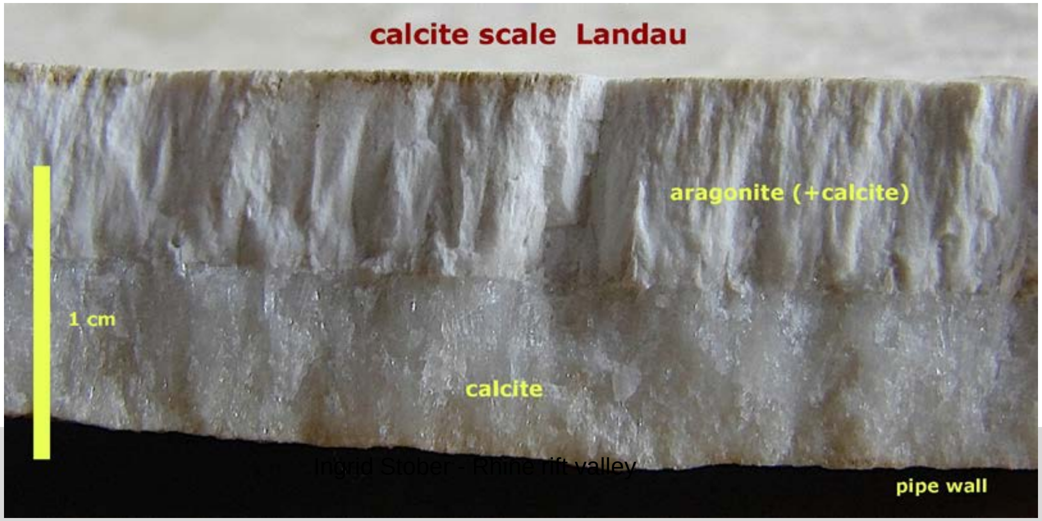
Deep thermal waters in the Upper Rhine Graben are highly mineralized (Na-(Ca)-Cl) and rich in dissolved gasses (CO_2,…)

- During production of hot water (reduction of pressure) calcite is precipitating
- during degassing of CO_2 precipitation of calcite, very rapidly
- During contact with atmospheric oxygen (O_2) precipitation of iron and/or manganese oxide scales.

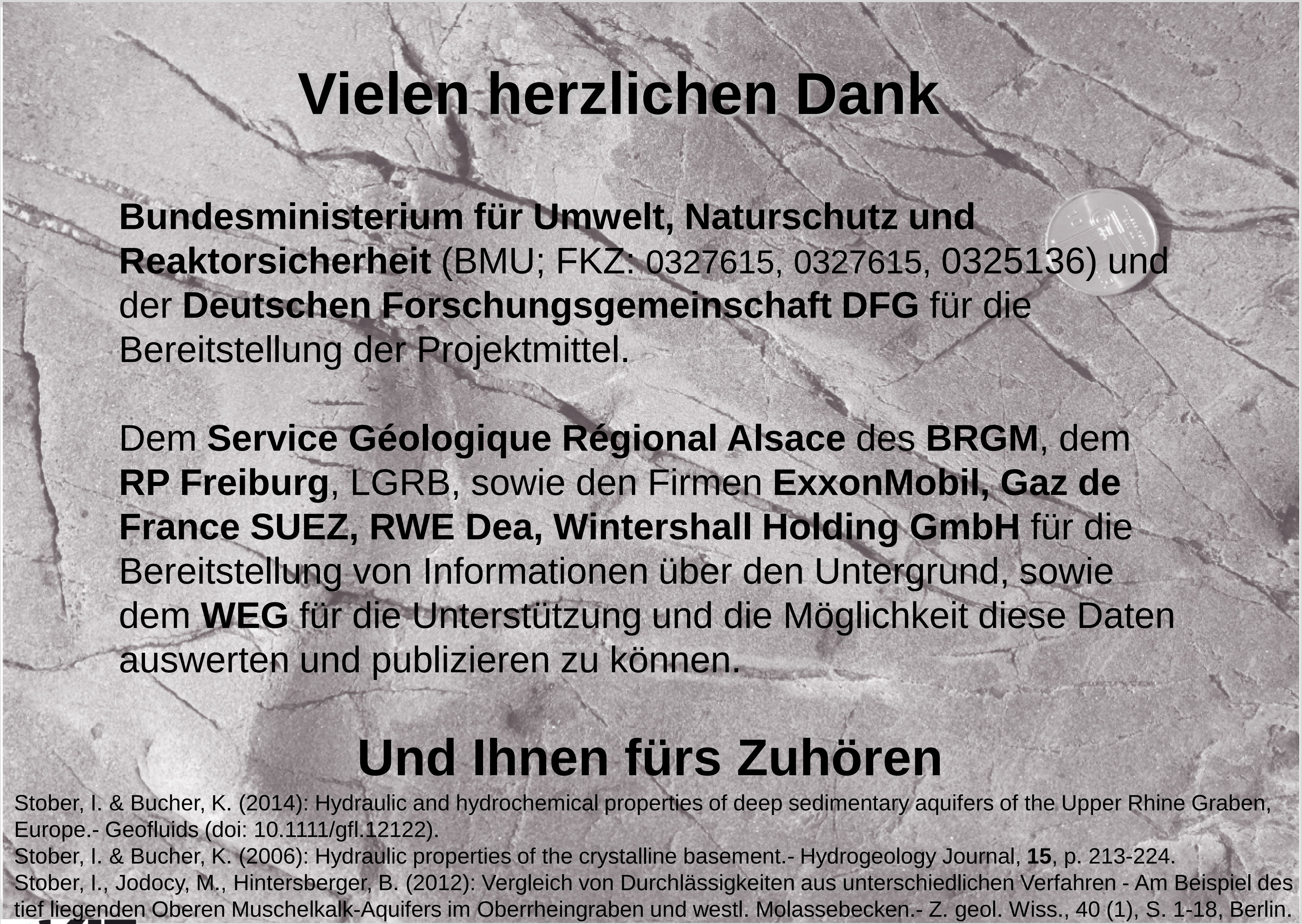
Therefore the produced waters must be circulated in a closed system under pressure (10-25 bar) to prevent degassing and contact with surface conditions.


Bruchsal: pipe for degassing with scale


Baden-Baden: Aragonite in tubing


calcite scale Landau


Bruchsal: coating in pipe



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Und Ihnen fürs Zuhören

Stober, I. & Bucher, K. (2014): Hydraulic and hydrochemical properties of deep sedimentary aquifers of the Upper Rhine Graben, Europe.- Geofluids (doi: 10.1111/gfl.12122).
Stober, I. & Bucher, K. (2006): Hydraulic properties of the crystalline basement.- Hydrogeology Journal, **15**, p. 213-224.
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