Fluid saturation and Permeability of Crystalline Basement of the Continental Crust

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FORCE 2018 Stavanger, Norway

Former considerations: Upper Continental Crust

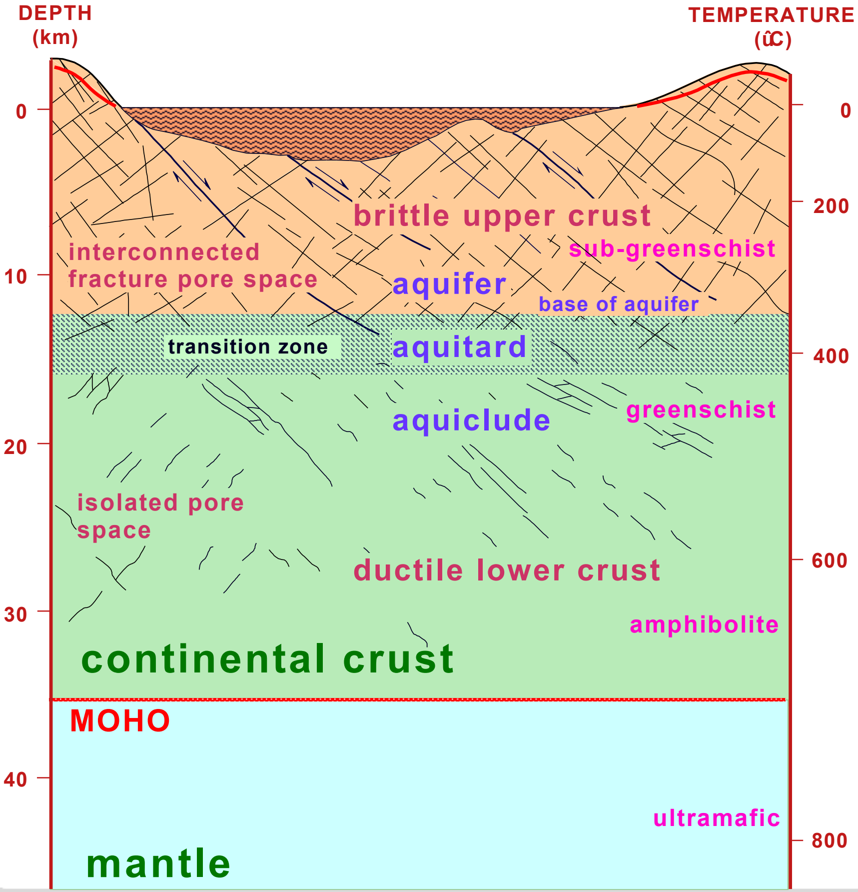
- Fluid absent, impermeable
- In numerical models of hydrogeologists: fluid tight basement
- Deep geothermal exploration: concept of Hot-Dry-Rock (HDR), thermal energy is stored exclusively in the rock. Thus, to harvest the energy, fractures had to be created artificially → fracturing:

  Los Alamos, Urach3, Cornwall etc.
- Nagra, CH: disposal of high-level radioactive waste: crystalline basement rocks as geological barrier

Outline

- Groundwater in the Upper Continental Crust - Observations
- Hydrogeologist‘s experience – wet continental crust
- Permeability of crystalline basement
- Example: KTB pumping test
- Flow – Thermal springs

“Groundwater” in the continental crust

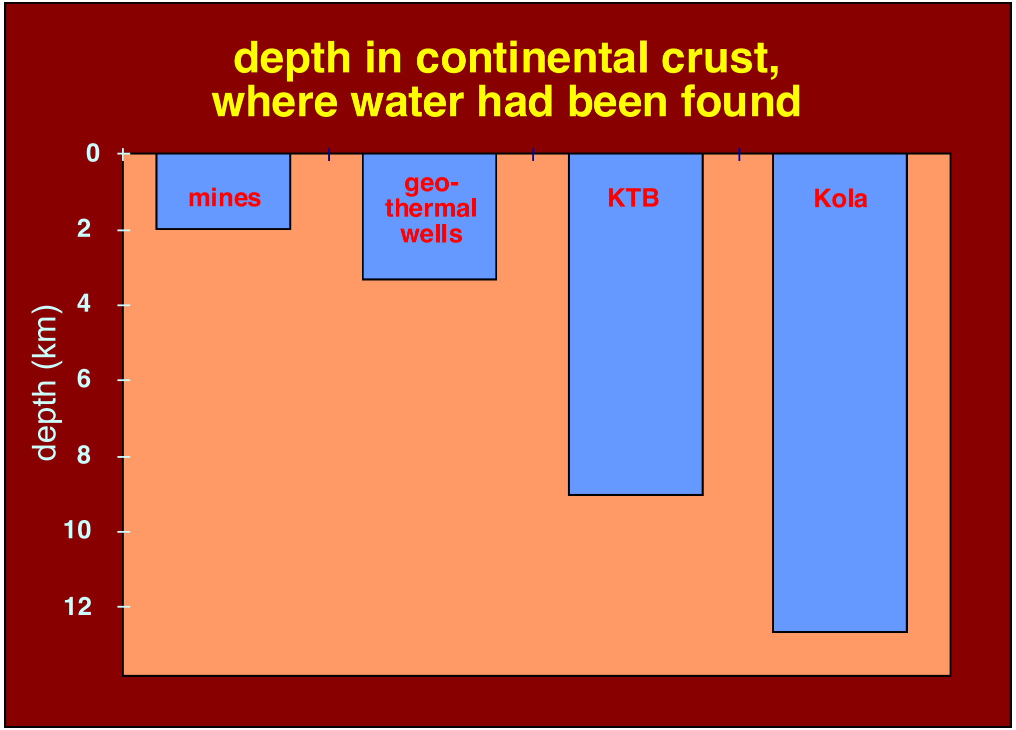


<u>Upper Continental Crust:</u>
Descriptions of drilling foremen, geophysical logs of boreholes together with geological profiles, and findings in mines show that water-bearing features are related to:

- **<u>Fault and fracture zones</u>, rock bodies extremely damaged by brittle deformation zones of sheared, broken, shattered, and crushed rock (breccia).**
- **<u>Contact zones</u> between granitic rocks (granites, granite dykes and granite porphyries) and paragneisses (also intensively fractured granite dykes within paragneisses).**
- **<u>Old circulation-path</u> like: hydrothermally altered or deformed zones, mineral veins or open fractures filled with minerals.**

The majority of the common biotite-rich gneisses on the other hand could be extremely low permeable.

Groundwater in the Upper Continental Crust - Observations



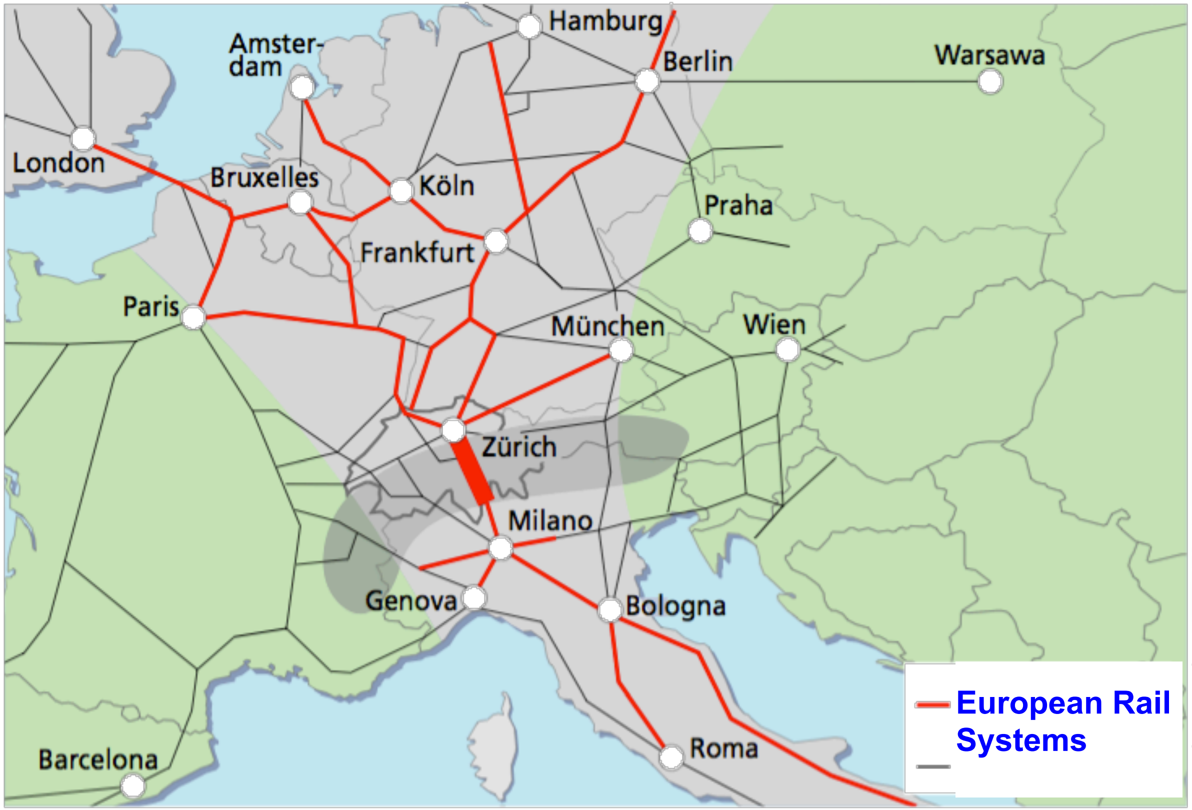
The Upper continental crust is not dry, it is water conducting!

Interconnected water-conducting pore-space (e.g. fractures, fault zones)

KTB - German continental deep drilling program, to 9.1 km

Kola - Russian super deep well on the Kola peninsula, to 12.5 km

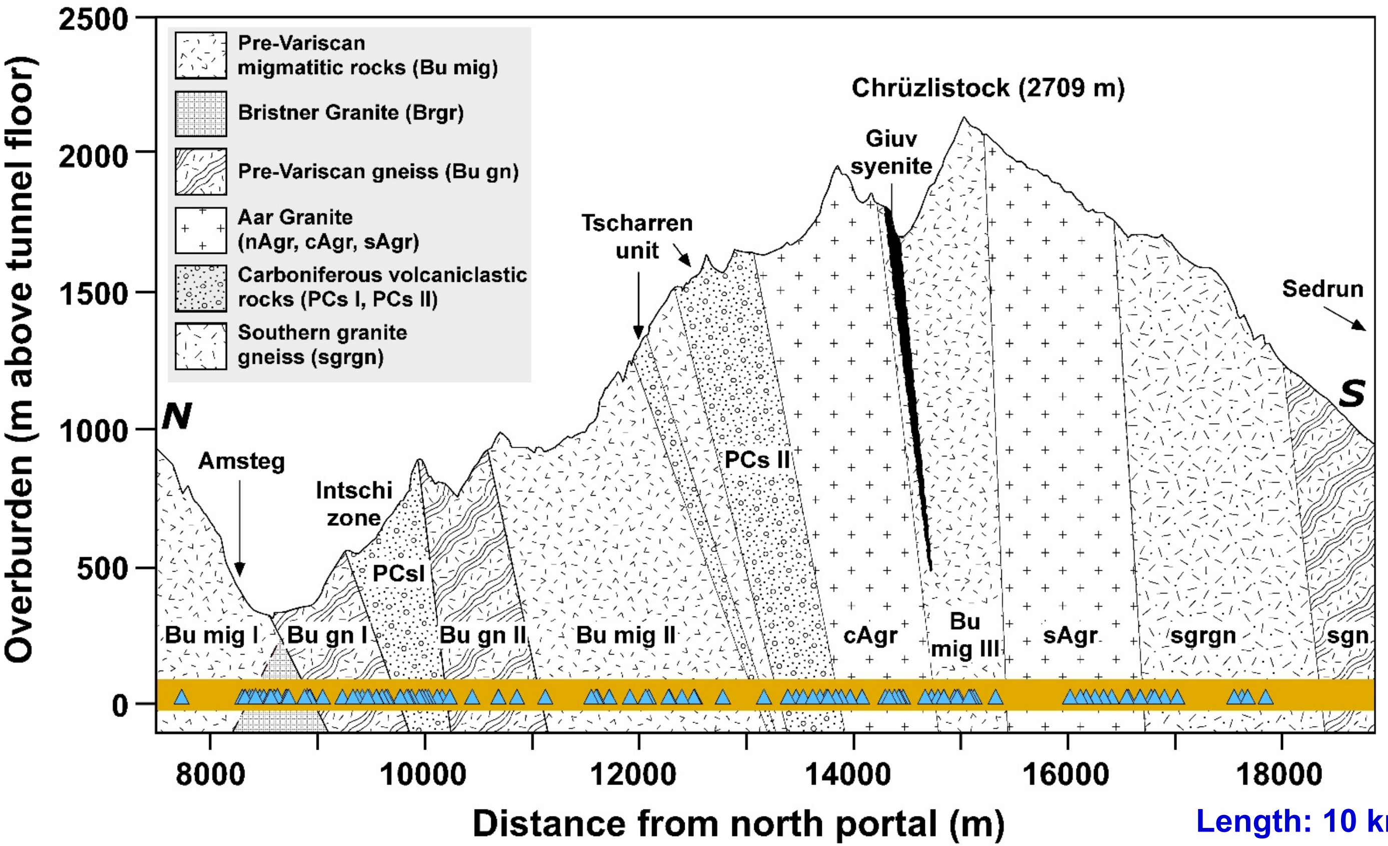
Observations: Gotthard Rail Base Tunnel



above the tunnel
up to 2700 m oberburden

In the Gotthard Rail Base Tunnel

Cross section and locations of water sampling in the GRBT



granites and gneisses

units are steeply dipping

meteoric water flows along fractures (parallel to gneissosity)

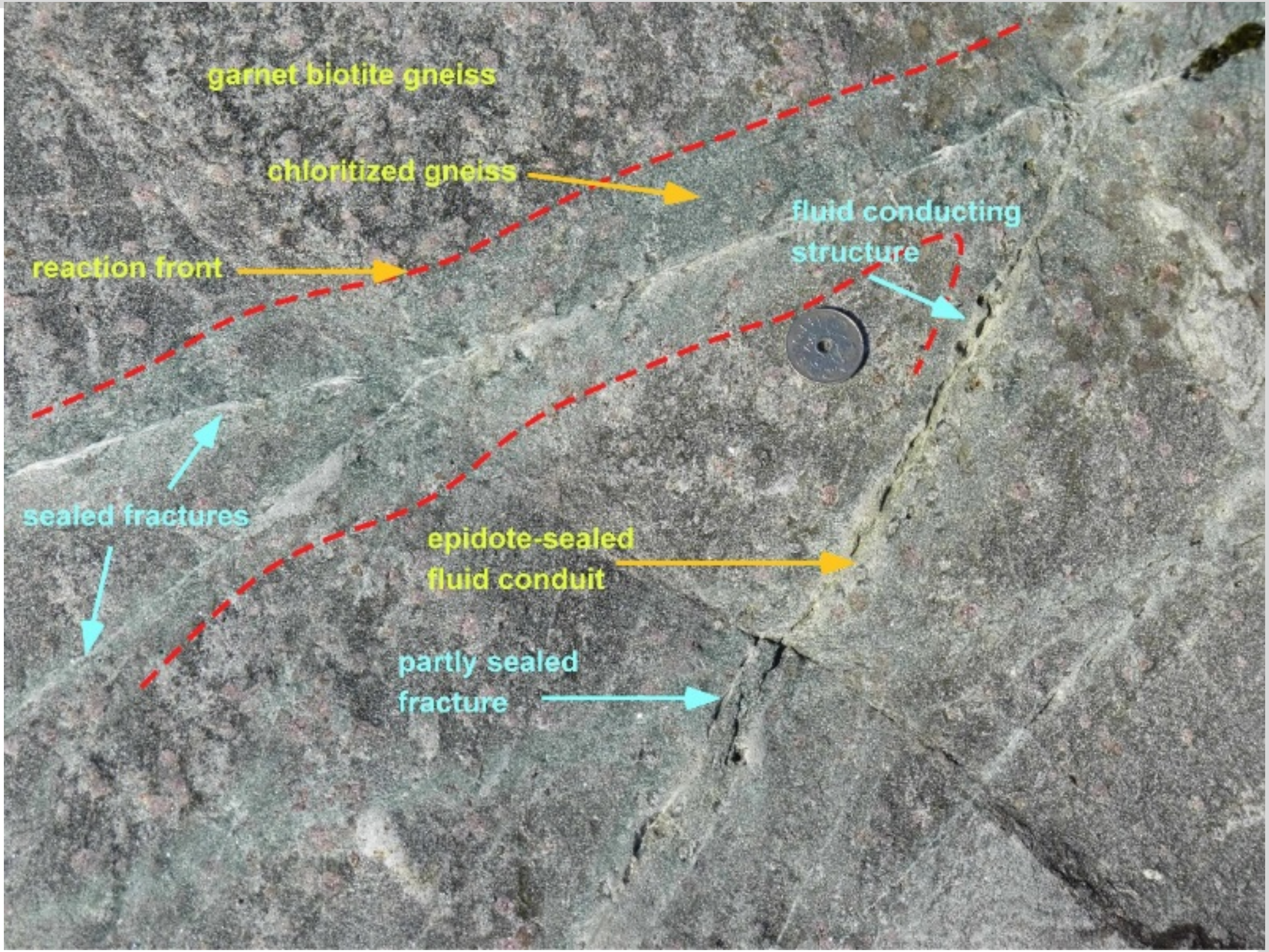
150 water samples along Amsteg section

along flow path: reaction of the fluid with the rock matrix

Length: 10 km

Observations in rocks:

Geochemical indications of young and older (former) water conducting features



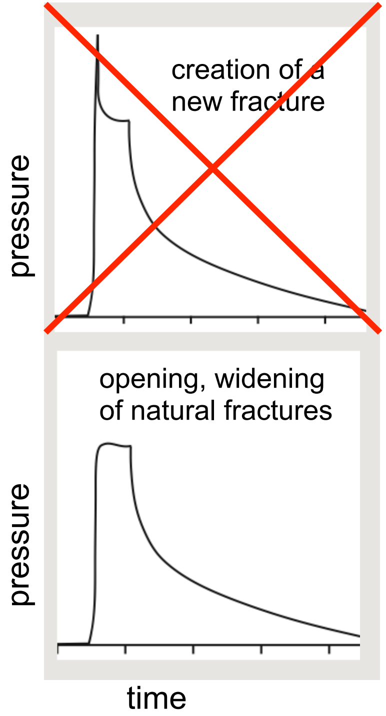
Hydrogeologist‘s experience: Wet continental crust

In 1970s the deep crystalline basement was thought to be dry and without open fractures (Hot-Dry-Rock).

Therefore distinct hydraulic stimulation techniques from the oil industry were used with the intention to create artificial open fractures to extract the Earth‘s heat from the rocks. Investigated depth: 2-5 km.

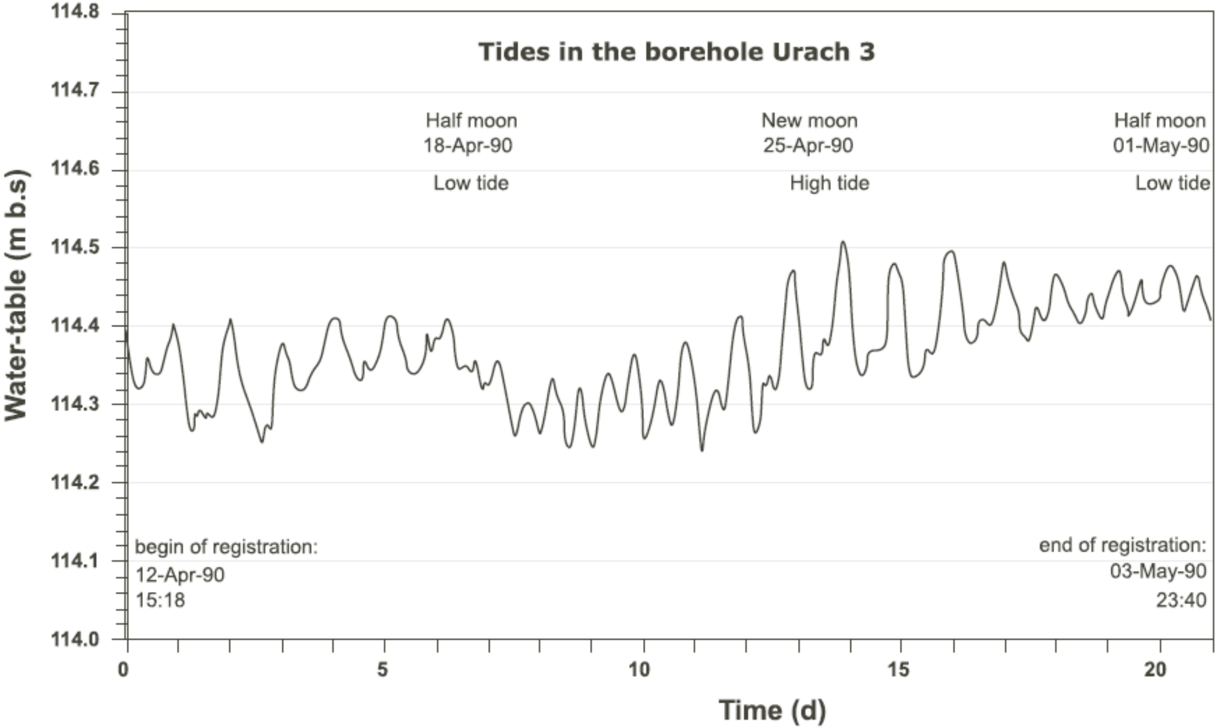
These tests showed that the creation of new hydraulic fractures was not the dominant process. It was the opening, widening and sometimes the shearing of natural joints, depending on the induced pressure.

The fracture pore space of the upper part of the continental basement rocks is filled with an aqueous fluid. The crustal basement is a confined, fractured hard-rock aquifer of low permeability with water present in an interconnected fracture system.



Hydrogeologist‘s experience: Wet continental crust

Water conducting <u>fractures</u> are <u>interconnected</u> over large volumes

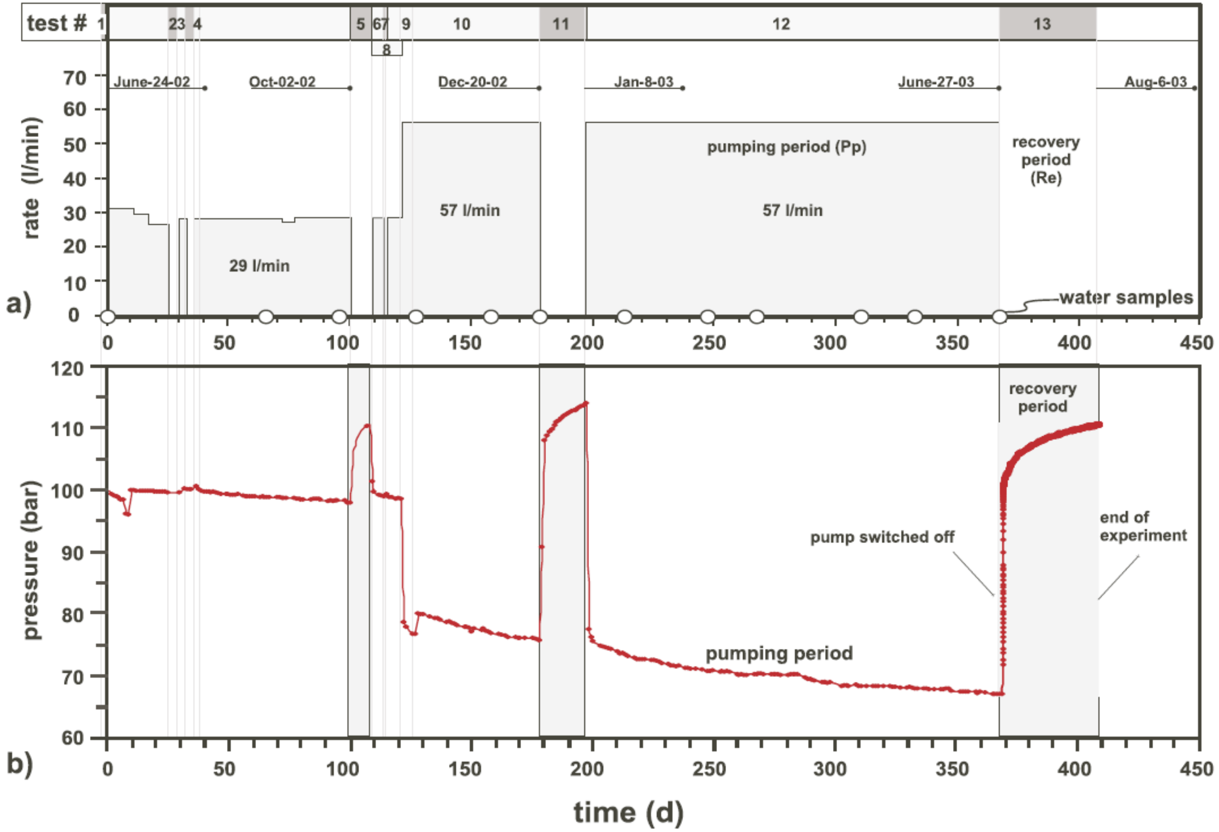


Rise and fall of the Earth surface 2 times per day (<u>earth-tides</u>), causes fluctuations of water table in deep boreholes due to compressibility of up to 18 cm.

Porosity of crystalline basement is very low (~ 0.5%). Thus, a huge volume of <u>interconnected pore space in fractures</u> reacts.

Depth of Urach3 borehole: 4444m

Hydrogeologist‘s experience: Wet continental crust



Water conducting fractures are interconnected over large volumes

Long-lasting pumping-tests, KTB-site, 4 km depth:

- **rate ± 86 m³/d (1 l/s)**
- **1 year**

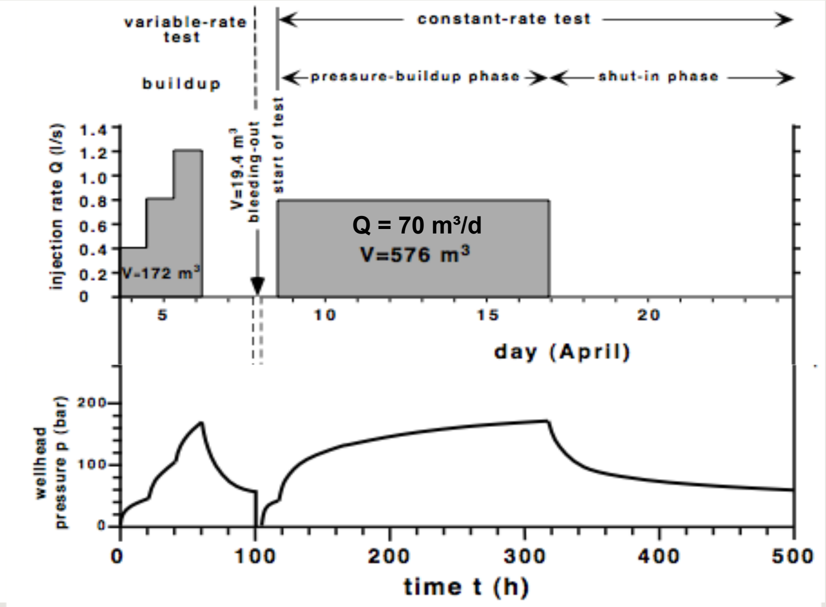
Hydrogeologist‘s experience: Wet continental crust

Pressure-dependence of hydraulic conductivity

In the Urach borehole (depth: 4444 m) many low- and high-pressure injection-tests of up to 660 bar well-head pressure were carried out.

During hydraulic injection-tests with well-head pressures below 176 bar, the natural capacity of the rock to absorb water is tested, resulting in the magnitude of the rock’s natural permeability.

→ standard hydraulic test, no elastic reaction, no widening of fractures, no creation of new fractures.



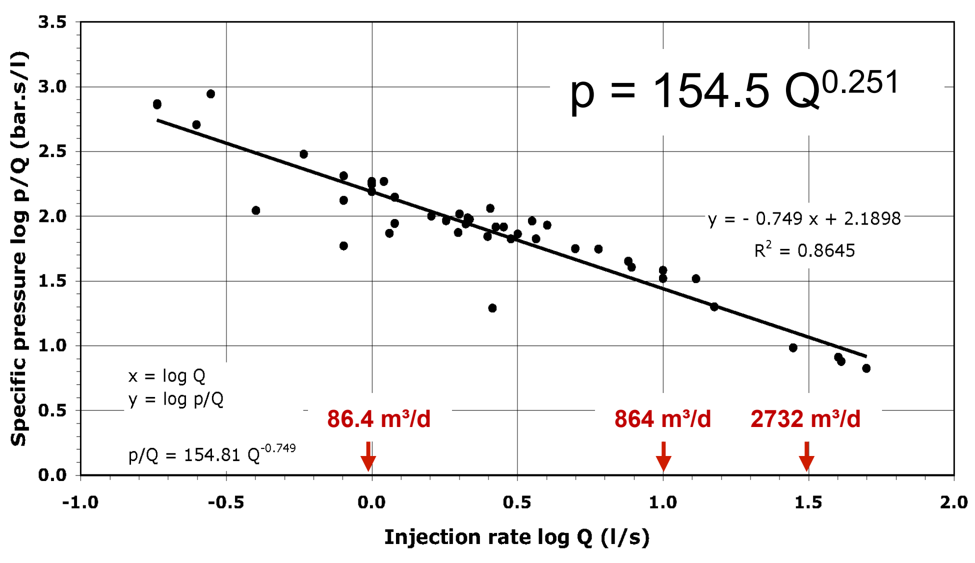
Hydrogeologist‘s experience: Wet continental crust

High pressure-tests in the open-hole (and perforated sections), Urach borehole

During hydraulic tests with well-head pressures above 176 bar, permeability of the crystalline basement rocks increases dramatically, due to the elastic reaction of the rock: open fractures were widened. (negative slope).

The pressure-dependence is described in terms of power laws relating injection rate (Q) to fracture width (w)

$$w = 8.14\ 10^{-7} / Q^{-2.50}$$

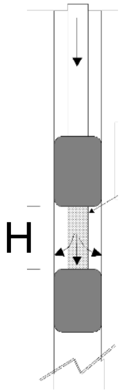


Due to the lack of shear stress, rock reacted elastic; therefore no significant remaining increase in hydraulic conductivity after any high-pressure test.

Permeability of crystalline basement

Permeability data are based on hydraulic tests (pumping tests)

- in a test section H [m]
- transmissivity T [m^2/s] of the tested rock
- convert T into hydraulic conductivity K [m/s]
- convert K into permeability κ [m^2] or [D], fluid parameters (ρ, μ) are needed.

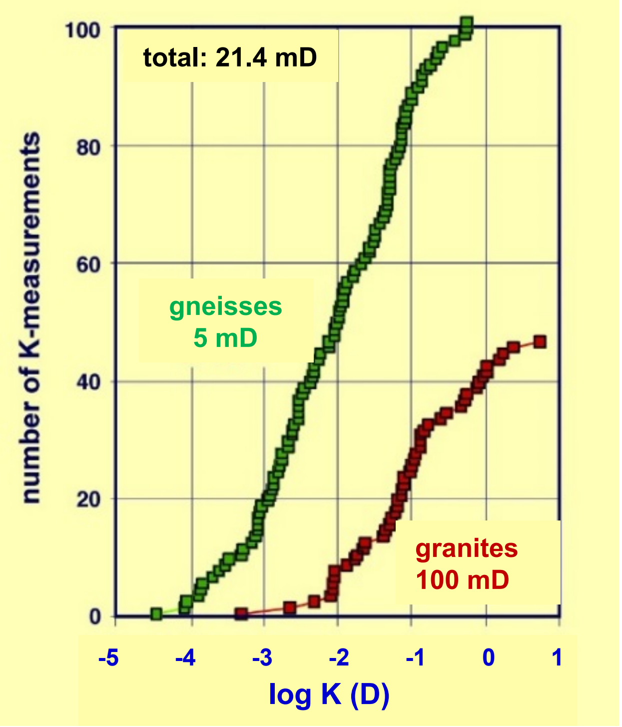


Investigation areas: Central Europe

In the upper part large variability of permeability (several log-units), with highest values similar to those of gravel-aquifers.

In highly deformed areas granite seems to be more permeable than gneiss.

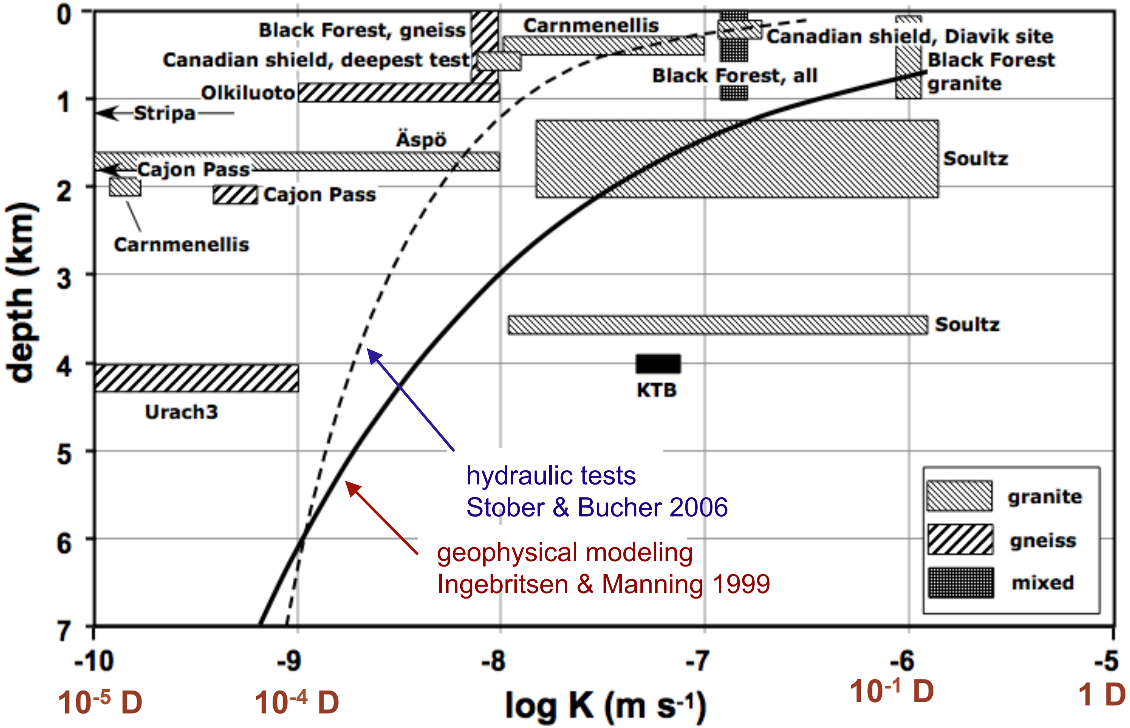
In weakly deformed areas the conductivity of granite can be very low.

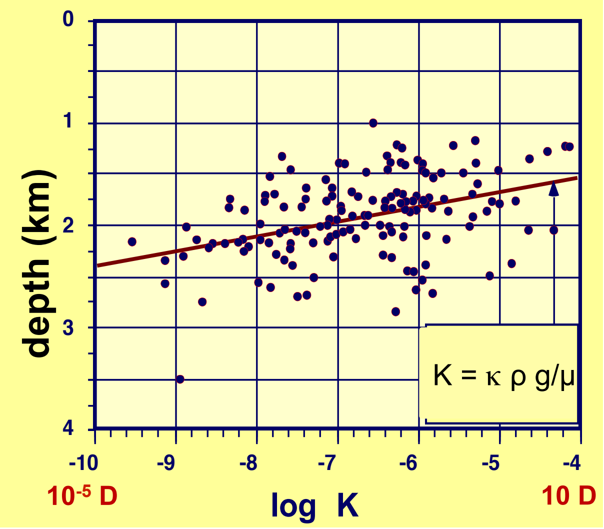


Permeability decreases with depth:

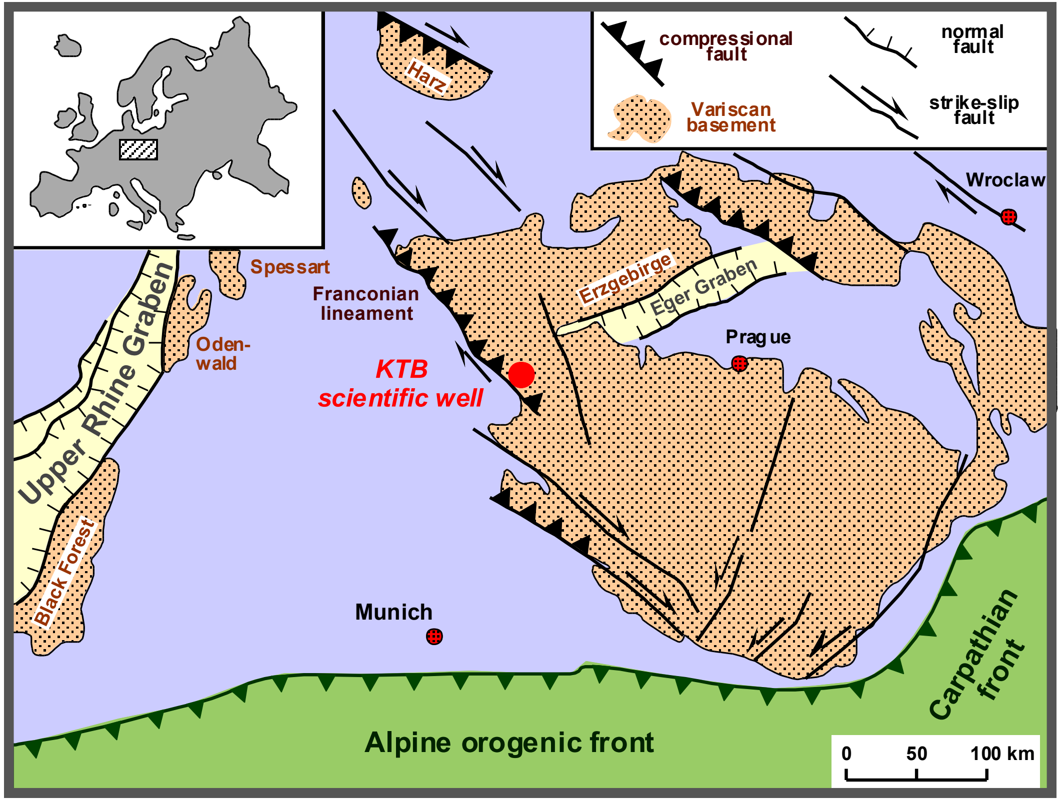
$$\log \kappa = -1.38 \log z - 15.4$$

with: κ (m^2) – permeability; z (km) – depth

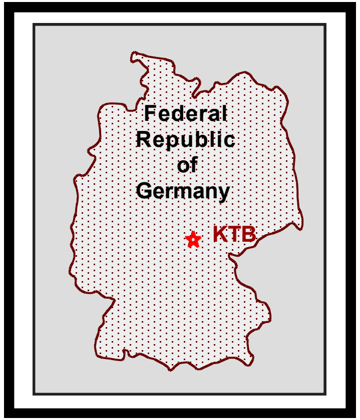




Location of KTB test site

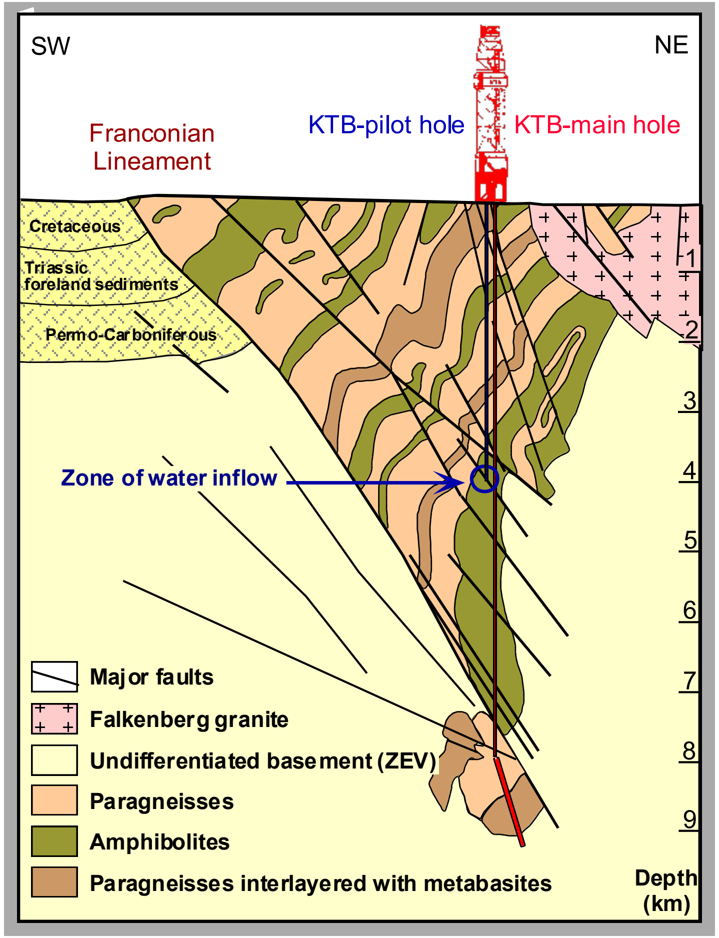


modified from Zulu & Duyster, 1997



KTB site:

Central Germany
two boreholes:
4000 m, 9100 m
crystalline basement



modified from Harms et al., 1997

KTB-boreholes

main hole (HB): depth 9100 m
pilot hole (VB): depth 4000 m

Lithological units

- paragneisses
- amphibolites
- paragneisses interlayered with metabasites

KTB-pilot hole

casing and cementation: to 3850 m depth
open hole: 3850 - 4000 m, 6"
bottom hole temperature: 120˚C

During the one year pumpingtest an amount of 23,100 m^3 water was removed from the crystalline basement rocks at 4000 m depth.

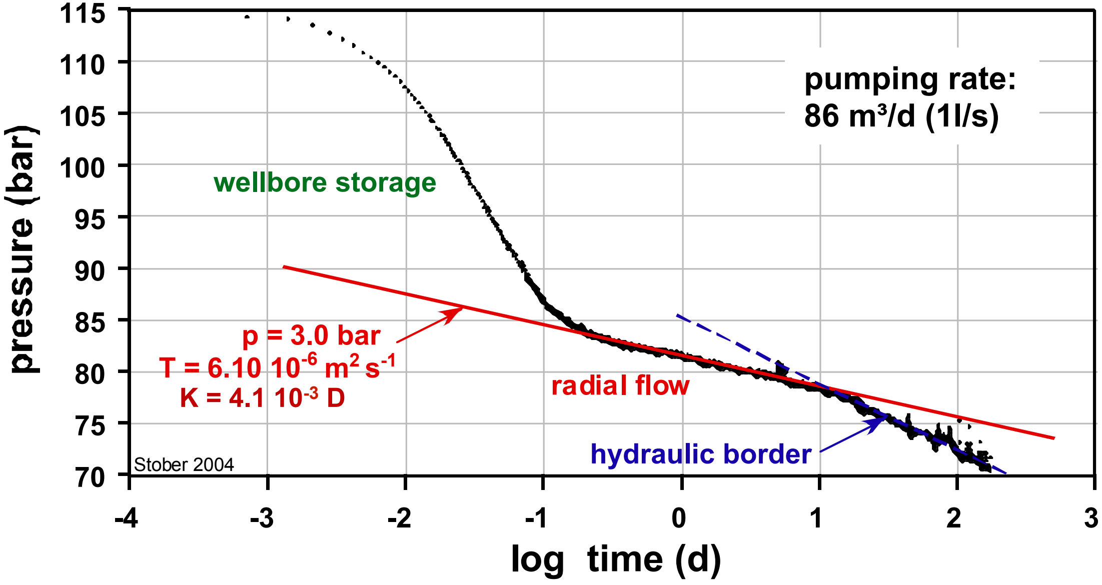
This water derived from a rock-volume of about 4,620,000 m^3 (n = 0.5%) or from a radial distance of up to 310 m around the 150 m long open-hole.

Water composition was constant during the pumping test:
TDS = 62.4 g/kg; pH = 7.8 (at 25°C);
Cl = 38.7 g/kg; Ca = 15.8 g/kg; Na = 6.4 g/kg;
Gases: N_2 = 68% vol.%; CH_4 = 31 vol.%

Thus the fracture-system in the crystalline basement is interconnected.

The fractured Upper Continental Crust is water saturated and behaves like any other near surface aquifer.

1 year pumping test KTB site



Hydraulic border = Franconian lineament

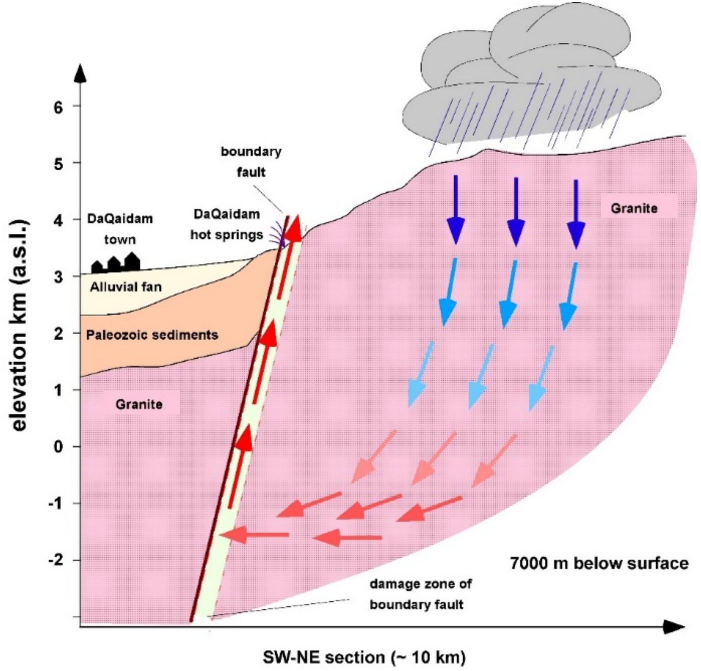
Flow of water in crystalline basement
Deep circulation-systems (thermal springs)

Water flow needs a driving force:
Topographic gradient induces a hydraulic gradient

Deep circulation systems (some 1000 m depth):
- **thermal springs**
- **upwelling of saline water (± constant TDS)**

Downstream of cold low mineralized water due to the hydraulic gradient occurs in open water conducting fractures being interconnected with each other over large volumes.

Faults (damage zone) drain the fracture water and lead it to the surface due to the overall gradient.



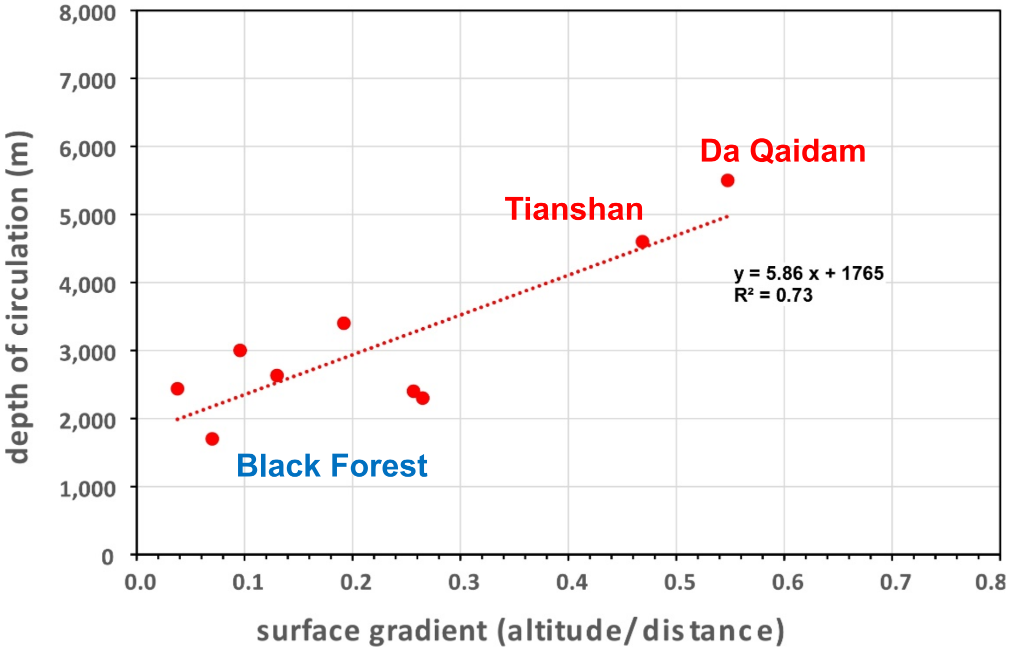
Flow:

Mechanisms of water flowing

Water-conducting features, e.g. permeability
+
Some kind of a motor, a driving force

As driving force can act:

- **Hydraulic gradient due to topography**
- **Earth tides**
- **Thermal or hydrochemical gradients**



The higher the surface gradient, the deeper the circulation!

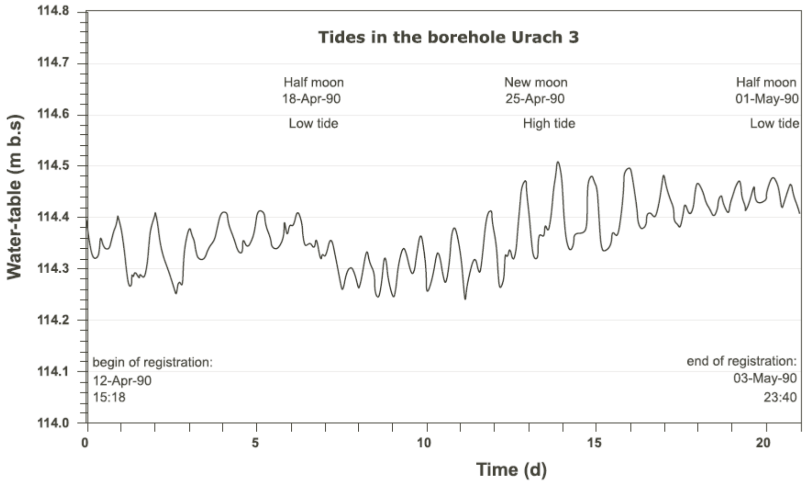
Stagnant fluids, an unrealistic concept

Fluids in the Upper Continental crust are generally not stagnant:

<u>Earth-tides</u> keep fluids in motion and are kept chemically active

As a result, overall equilibrium is not achieved and the fluids unceasingly react with the rock matrix

In areas with topography we observe <u>deep circulation systems</u>, origin of thermal springs.



talc veins in peridotite (olivine)

Summery / Conclusions

- large variability in permeability in the upper part of the brittle crust
- granite seems to be more permeable than gneiss (in highly deformed areas)
- decrease of permeability with increasing depth
- interconnected open fracture-system over large volumes
- topographic gradient: deep circulation, thermal springs
- fluids in the Upper Continental Crust are generally not stagnant (earth-tides, deep circulating systems, thermal or hydrochemical gradients,….)

Modelling Crystalline Basement Rocks: gigantic, interconnected, open fracture-systeme (i.e. permeability), fluid flow, deep circulation systems

Thank you very much for your interest!

Selected literature

If you are interested in some information please send me an e-mail: ingrid.stober@kit.edu

Stober, I., Zhong, J., Zhang, L., Bucher, K. (2016): Deep hydrothermal fluid–rock interaction: the thermal springs of Da Qaidam, China.- Geofluids, 16, 711-728, doi: 10.1111/gfl.12190.

Stober, I. & Bucher, K. (2014): Hydraulic conductivity of fractured upper crust: Insights from hydraulic tests in boreholes and fluid-rock interaction in crystalline basement rocks.- Geofluids, 16, 161-178 (doi: 10.1111/gfl.12104).

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Bucher, K., Zhu, Y. & Stober, I. (2009): Groundwater in fractured crystalline rocks, the Clara mine, Black Forest (Germany).- Int. J. Earth Sci (Geol. Rundschau), 98, p. 1727-1739 (DOI 10.1007/s00531-008-0328-x).

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Erzinger, J. & Stober, I. (2005): Introduction to Special Issue: long-term fluid production in the KTB pilot hole, Germany: Geofluids, **5**, 1-7.

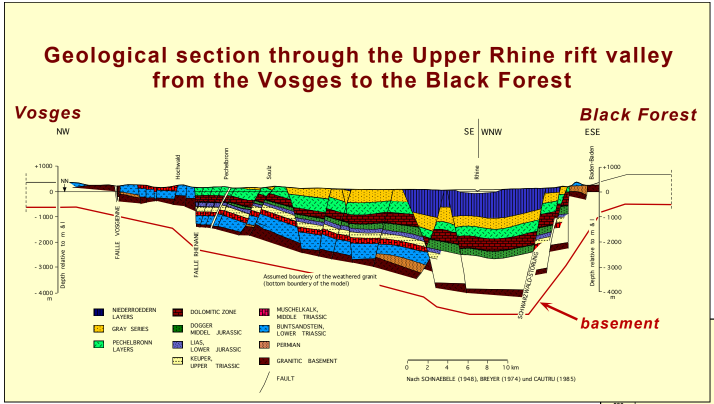
Stober, I., Bucher, K. (2005): The upper continental crust, an aquifer and its fluid: hydraulic and chemical data from 4 km depth in fractured crystalline basement rocks at the KTB test site.- Geofluids, **5**, 8-19.

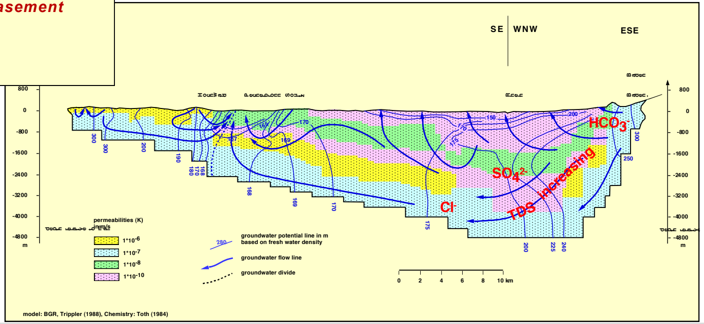
Stober, I. (1997): Permeabilities and Chemical Properties of water in Crystalline Rocks of the Black Forest, Germany.- Aquatic Geochemistry, 3: 43-60, Kluwer Academic Publishers, Dordrecht/Netherlands Boston London

Examples of hydraulic gradients as driving forces

Topographic differences often induce hydraulic gradients

→ Deep cross-formation-flow including flow through high permeable granite + gneiss In the Upper Rhine Graben

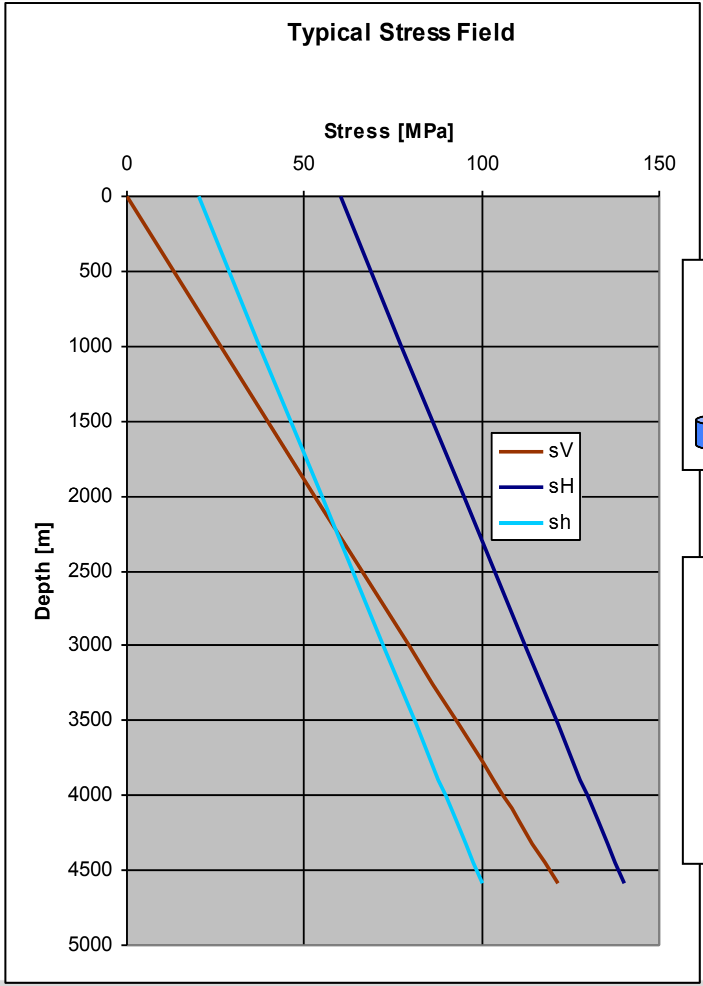


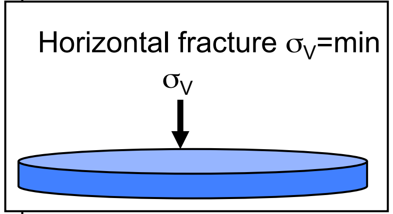


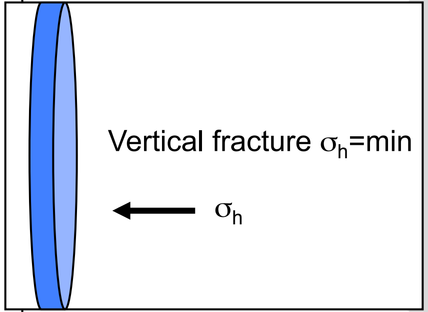
Change of fracture-orientation with depth

Deep circulation-systems

With increasing depth, open fractures tend to be <u>vertically orientated</u>, because vertical pressure increases stronger than horizontal pressure.







after: Brown & Hoek 1978, Valley & Evens 2003