Fractured continental crust: permeability, fluid-flow, and connectivity of fractures in the crystalline basement

Ingrid Stober

Karlsruhe Institute of Technology KIT, Institute of Applied Geosciences, Adenauerring 20b, Bld. 50.40, D-76131 Karlsruhe, Ingrid.stober@kit.edu

The permeability of fractured crystalline basement of the upper continental crust is an intrinsic property of a complex system of rocks and fractures that characterizes the flow properties of a representative volume of that system. Permeability decreases with depth. Permeability can be derived from hydraulic well test data in deep boreholes. Only a handful of such deep wells exist on a worldwide basis. Consequently, few data from hydraulically tested wells in crystalline basement are available to the depth of 4–5 km. The permeability of upper crust varies over a very large range depending on the predominant rock type at the studied site and the geological history of the drilled crystalline basement. Hydraulic tests in deep boreholes in the continental crystalline basement revealed permeability values ranging over nine log-units from 10^{-21} to 10^{-12} m². This large variance also decreases with depth, and at 4 km depth, a characteristic value for the permeability is 10^{-15} m².

At depths below the deepest wells down to the brittle ductile transition zone, evidence of permeability can be found in surface exposures of rocks originally from this depth. Exposed hydrothermal reaction veins are very common in continental crustal rocks and witness fossil permeability and its variation with time. The existence of deep circulating systems (e.g. thermal springs), huge water table fluctuations due to earth tides, or long-lasting hydraulic tests show that the fracture pore space is interconnected on a large scale and that the crust reacts hydraulically coherent.

INTRODUCTION

Features of brittle deformation, such as fractures, faults, joints and veins, are the principal water (fluid) conducting structures in crystalline basement rocks and provide the dominant conduits for fluid flow in the brittle upper continental crust. Fluid flow can be described by the flow law of Darcy. Flow is driven by a hydraulic head and controlled by the prime parameters of advective fluid, solute und heat transport in fractured crystalline rocks namely permeability and porosity. Depending on the scale of interest, different methods are used to determine the two parameters. These include laboratory measurements (e.g. Berckhemer et al. 1997), fracture analysis (Mazurek et al. 2003; Jakob et al. 2003; Caine et al. 1996), geophysical modeling of heat flow data (e.g. Hayba & Ingebritsen 1994) and in-situ testing of boreholes (e.g. Nielsen 2007; Peters 2012). Well tests provided permeability data from the crystalline basement to depths of 5 km and offered insights into the permeability structure of the crust and its variation with depth and lithology.

Darcy flow is limited to the brittle upper crust. Below the brittle-ductile transition zone (Duba et al. 1990; Wintsch et al. 1995), fluid cannot be transported by Darcy flow (Frost & Bucher 1994). The concept of hydraulic conductivity is not valid in the ductile lower crust (at ~ 15 km depth and 350 ˚C; Wintsch et al. 1995), because the fluid is an isolated batch and not part of a large interconnected porosity system like in the upper crust..

Fluid flow in fractured upper crustal aquifers is generally driven by hydraulic gradients, which may result from a number of different feasible causes and imbalances including topography, thermal and chemical disequilibrium. Pumping- or injection-tests carried out in boreholes are artificially induced hydraulic gradients as forcing for fluid flow. Hydraulic tests provide data on the hydraulic properties and the nature of aquifers, the permeability structure of the upper crust including the depths variation of permeability. An important and frequently overlooked driving force for fluid flow are tidal forces that prevent fluids in fractured systems from ever becoming truly stagnant and chemically completely inactive.

PERMEABILITY AND FLUID FLOW IN THE CRUST

The permeability κ [m²] of a volume of fractured crystalline rocks forming the upper continental crust relates to the structure and connectivity of the fluid-filled pore space. The permeability controls, together with the viscosity and density of the fluid, the ability of the volume of rock to conduct the fluid phase. Permeability is thus a decisive parameter controlling fluid flow. It can be retrieved from the measurement of the transmissivity T [m^2 s^{-1}] with hydraulic tests in boreholes. From the experimentally derived transmissivity T the hydraulic conductivity K [m s^{-1}] can be modeled using competent concepts and ideas about the structure of the underground, a hydraulic aquifer model. The model aspect of the parameter K needs to be kept in mind.

The permeability κ [m^2] can then be derived from the modeled hydraulic conductivity using the fluid property data viscosity μ [kg m^{-1} s^{-1} or Pa s] and density ρ [kg m^{-3}]: $\kappa = K\,\mu/g\rho$. Both fluid parameters depend on the temperature, the pressure, the mineralization and the gas content of the fluid. This means that hydrochemical analyses must be available from sampling points at depth in addition to depth and temperature data (Stober 1995).

The hydraulic test produces information on the hydraulic properties of the ground to a certain distance from the wellbore. This distance depends strongly on the test duration. The hydraulic properties of the rocks in the vicinity of the wellbore are commonly altered by the drilling process itself or by drilling mud and added chemicals. Thus, short-term hydraulic tests will not be able to “see” beyond this alteration zone near the wellbore.

The permeability of rocks can also be measured on drill cores in the laboratory. It is difficult or impossible to correctly represent fractures, faults and larger cavities in core samples. The lab-measured permeability typically characterizes a property of the unfractured rock matrix. In general it is significantly lower than the permeability of large volumes of fractured basement derived from well tests (Stober & Bucher 2007).

Hydraulic tests in wellbores to 5000 m depth worldwide revealed a remarkable variation of permeability κ of the crystalline basement from 10^{-21} to 10^{-12} m^2. The upper 1000 m are generally characterized by the higher values but also by a greater variance (Stober 1996; Stober & Bucher 2007). The mean variation of the hydraulic conductivity decreases rapidly with increasing depth. The decrease of the permeability κ with depth has been derived from well tests in the basement of SW Germany, NE France and N Switzerland (Stober & Bucher 2007) and can be described by

$$\log \kappa = -1.38 \log z - 15.4 \quad (1)$$

with z the depth in km and κ in m^2. Ingebritsen and Manning (1999) in their geophysical study of terrestrial heat flow derived a surprisingly similar power-law function for the permeability decrease with depth. The described decrease of the hydraulic conductivity with depth (eq. 1) is mainly controlled by the properties of biotite gneiss and other metamorphic rocks. We suspect that the decrease of the hydraulic conductivity in granitic basement would be slower with depth, because of contrasting mechanical properties of mica and feldspar. Granitic basement has a higher expected permeability at a given depth and tectonic environment than gneissic basement, given that granite is dominated by feldspar and quartz and gneiss typically contains significantly more mica than granite (Stober 1995). In tectonically inactive areas, the hydraulic conductivity of large volumes of granite can be very low (Stober & Bucher 2007).

With increasing depth the vertical pressure component exceeds the horizontal pressure components (Brown & Hoek 1978) with the result that the open water conducting fracture system changes from predominantly horizontal to mostly vertical orientation. Vertical fluid flow and fluid exchange becomes dominant at depth, particularly in areas with significant topography. The steep fluid conducting fractures support deep fluid circulation systems (Bucher et al. 2009). Thermal springs and hydrothermal alteration zones along vertical fractures document the existence of significant vertical permeability (Lee et al. 2011).

Hydrochemical and isotope data suggest that thermal spring waters represent upwelling deep waters. The conclusions from chemical data are supported by the evidence from numerical modeling (e.g. Kukkonen 1995). Topography driven hot water flow from several thousand meter deep sources have been reported (Tóth 1978; Bucher et al. 2009). Topography driven deep water circulation in the Black Forest region (Germany) resulted in the outflow of warm saline deep water (Stober et al. 1999, Rolker et al. 2015). Hydrothermal circulation systems, ascent and descent channels alike, use open highly permeable steep fracture systems. Ascent channels must be extremely conducting structures permitting high flow rates if hot water reaches near the surface environment at high temperature and finally appears as hot spring. The ascent flow may follow zones of strongly fractured granite or highly permeable fault zone. In areas lacking topography or in the absence of suitable steep high permeability structures, deep-reaching vertical circulation systems may not develop and natural hot springs will not be present.

STAGNANT FLUIDS, AN UNREALISTIC CONCEPT

The Darcy flow law implies that fluid flow ceases if the pressure gradient disappears. The major forces driving fluid flow in the crust are thermal disequilibrium and topographic relief. If the driving force approaches zero, fluid flow stops. The fluid becomes stagnant. The concept of stagnant fluid thinks of a fluid residing in the fracture pore space at no-flow and chemically interacting with the rock matrix at a very slow rate. The fluid interacts with solids and pores by diffusion.

This view ignores a very efficient driving force for fluid flow, the Earth tides. Two times every day a tidal wave moves through the Earth crust. The rise and fall of the Earth surface amounts to some tens of cm (Emter et al. 1999). The Earth is not a rigid body; it reacts elastically to the gravitational forces of moon and sun. The moving layers of rocks exert compressional and extensional forces on each other. The pore space of the rocks also deforms elastically as a reaction on tidal forces with the result that the fluid residing in the pore space suffers an everlasting alternation of compression and extension. The consequence of the ever-changing tidal forces can be observed as water table fluctuations in boreholes. The magnitude of the fluctuations depends on the position of the sun and the moon (e.g. Bredehoeft 1967). Therefore, the highest amplitudes occur at full moon and new moon. In the fractured crystalline basement at the deep drilling site Urach 3, water table fluctuations related to tidal forces of up to 20 cm per day have been measured (Stober 2011).

It can be concluded from the observed alternations of the water table in the wellbore that they indicate the reaction of a very large volume of deep water. The conclusion is in accord with the very low fracture porosity of about 0.002 and the very low compressibility of deep fluid $c_w = 5.3\ 10^{-10}\ Pa^{-1}$. A pressure change of $\Delta p = 1$ bar results in a relative change of the volume of water of $\Delta V_w/V_w = 5.3\ 10^{-10}$ and relative to the crust of $\Delta V_w/V_{rock} = 1.1\ 10^{-12}$. This implies that the fracture pore space is interconnected on a large scale and the crust reacts hydraulically coherent.

Hydraulic long-term tests in deep boreholes confirm that a large volume of fluid hydraulically react on the test signal and prove that the fracture porosity of the basement is an interconnected network of water conducting structures. The one year long pumping test at the 4000 m deep research drillhole (KTB-VB) in SW Germany extracted a total of 22,300 m^3 saline thermal fluid from the open hole at 3850 – 4000 m at a rate of 0.5 L s^{-1} and later 1.0 L s^{-1}. The composition of the thermal fluid remained constant during this time (Stober & Bucher 2005).

In regions with high topographic relief deep flow systems develop in the crystalline basement. Temperature profiles in very deep boreholes can be used for estimating the water circulation depths. For instance, in the 5000 m deep geothermal well GPK-2 in Soultz-sous-Fôrets near Strasbourg, France (Genter et al. 2010) efficient water circulation reaches to 3700 m depth, which is 2300 m into the crystalline basement. Below 3700 m the geothermal gradient is identical to the regional average (~ 27 K km^{-1}). Above this depth water temperature decreases only a little indicating advective heat transfer by upwelling hot deep water. Finally, in the near surface area fluid temperature decreases very rapidly resulting in a very high geothermal gradient (> 100 K km^{-1}). Thermal signatures of advective fluid flow may be absent in some areas because permeability of the basement is low or because pressure gradients as a required driving force gradually disappear.

Temperature profiles of km-deep boreholes, data and observations from hydraulic tests and tidal water level fluctuations all consistently show that fluids in the continental crust occupy an interconnected communicating pore space that permits fluid flow on a large scale, provided that an appropriate driving force exists in addition to the tides. In the examples above, topography drives the fluid flow at Soultz-sous-Fôrets and pumping, an anthropogenic force, at KTB. Hot springs discharging highly mineralized waters from crystalline basement for 2000 and more years are clear evidence for deep fluid circulation and an interconnected fracture network providing sufficient permeability for fluid flow in the brittle crust.

Deep waters in the brittle upper crust are never truly stagnant because tides keep them permanently in movement.

ACKNOWLEDGEMENTS

The project is supported by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMU, no: 0325623C).

REFERENCES

Berckhemer H, Rauen A, Winter H, Kern H (1997) Petrophysical properties of the 9-km-dep crustal section at KTB. *Journal of Geophysical Research*, **102**,18337‑18361.

Bredehoeft JD (1967) Response of well-aquifer systems to Earth tides. *Journal of Geophysical Research*, **72**,3075-3087.

Brown ET & Hoek E (1978) Trends in relationships between measured in-situ stresses and depth. *International journal of rock mechanics and mining sciences & geomechanics abstracts*, **15**,211-215.

Bucher K, Zhang L, Stober I (2009) A Hot Spring in Granite of the Western Tianshan, China. *Applied Geochemistry*, **24**,402-410.

Caine JS, Evans JP, Forster CB (1996) Fault zone architecture and permeability structure. *Geology*, **24**,1025-1028.

Duba AG, Durham WB, Handin JW, Wang HF & editors (1990) The Brittle-Ductile Transition in Rocks, The Heard Volume. *Geophysical Monograph 56*,243 pp.

Emter D, Wenzel HG, Zürn W (1999) Das Observatorium Schiltach. *DGG Mitteilungen*, **3**,1-15.

Frost BR & Bucher K (1994) Is water responsible for geophysical anomalies in the deep continental crust? A petrological perspective. *Tectonophysics*, **231**,293-309.

Genter A, Evans K, Cuenot N, Fritsch D (2010) Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of enhanced geothermal systems (EGS). *Comptes Rendus Geoscience*, **342**,502-516.

Hayba DO & Ingebritsen SE (1994) The computer model hydrotherm, A three-dimensional finite-difference model to simulate ground-water flow and heat transport in the temperature range of 0 to 1,200˚C, U.S. Geological Survey. *Water Resour. Invest. Rep. 94-4045*,234.

Ingebritsen SE & Manning CE (1999) Geological implications of a permeability-depth curve for the continental crust. *Geology*, **27**,1107-1110.

Jakob A, Mazurek M, Heer W (2003) Solute transport in crystalline rocks at Äspö--II: Blind predictions, inverse modelling and lessons learnt from test STT1. *Journal of Contaminant Hydrology*, **6**,175-190.

Kukkonen IK (1995) Thermal aspects of groundwater circulation in bedrock and its effect on crustal geothermal modelling in Finland, the central Fennoscandian Shield. *Tectonophysics*, **244**,119-136.

Lee S-G, Kim T-K, Lee TJ (2011) Strontium isotope geochemistry and its geochemical implication from hot spring waters in South Korea. *Journal of Volcanology and Geothermal Research*, **208**,12-22.

Mazurek M, Jakob A, Bossart P (2003) Solute transport in crystalline rocks at Aspo — I: Geological basis and model calibration. *Journal of Contaminant Hydrology*, **61**,157-174.

Nielsen KA (2007) Fractured Aquifers: Formation Evaluation by Well Testing. *Trafford Publishing, Victoria, BC, Canada*,229 pp.

Peters EJ (2012) Advanced Petrophysics: Volume 1: Geology, Porosity, Absolute Permeability, Heterogeneity, and Geostatistics. *Live Oak Book Company*,238 pp.

Rolker J, Schill E, Stober I, Schneider J, Neumann T, Kohl T (2015): Hydrochemical characterization of a major central European heat flux anomaly: the Bürchau geothermal spring system, southern Black Forest, Germany.- Geothermal Energy, 3-5 (DOI 10.1186/s40517-014-0021-1).

Stober I (1995) Die Wasserführung des kristallinen Grundgebirges. *Ferdinand Enke Verlag, Stuttgart*, 191 pp.

Stober I (1996) Researchers Study Conductivity of Crystalline Rock in Proposed Radioactive Waste Site. *EOS, Transactions of the American Geophysical Union*, **77**,93-94.

Stober I (2011) Depth- and pressure-dependent permeability in the upper continental crust: data from the Urach 3 geothermal borehole, southwest Germany. *Hydrogeology Journal*, **19**,685-699.

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 & Bucher K (2007) Hydraulic properties of the crystalline basement. *Hydrogeology Journal*, **15**, 213-224.

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

Stober I, Richter A, Brost E, Bucher K (1999) The Ohlsbach Plume: Natural release of Deep Saline Water from the Crystalline Basement of the Black Forest. *Hydrogeology Journal*, **7**,273-283.

Tóth J (1978) Gravity-induced cross-formational flow of formation fluids, red earth region, Alberta, Canada: Analysis, patterns, and evolution. *Water Resources Research*, **14**,805-843.

Wintsch RP, Christoffersen R, Kronenberg AK (1995) Fluid-rock reaction weakening of fault zones. *Journal of Geophysical Research*, **100**,13021-13032.