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Significance of Hydraulic Conductivity as Precondition to Fluid Flow in Fractured and Faulted Crystalline Basement and its Impact on Fluid-Rock Interaction Processes

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ABSTRACT

The permeability of the fractured upper continental crust is an inherent property of a complex system of rocks, fractures and fault-systems that characterizes the flow properties of that system. The permeability of the crystalline basement rocks decreases with depth. Permeability can be derived from hydraulic well test data in deep boreholes. Only a handful of such deep wells exist even on a worldwide basis. Consequently, very few data exist to the depth of 4 – 5 km, which is most interesting for geothermal energy use. Generally, distance and permeability of faults could be derived from long lasting pumping-tests. Derived permeabilities of the upper crust vary over a very large range depending on the predominant rock type in the bore and the occurrence of fracture and fault systems in crystalline basement.

The permeability of the crystalline basement varies with time due to deformation related changes of aperture and fracture or fault geometry and as a result of chemical reaction of flowing fluids with the solids exposed along the fractures. Particularly dissolution and precipitation of minerals contribute to the variation of the permeability with time. The time dependence of κ is difficult to measure directly. At depths below the deepest wells to the brittle ductile transition zone evidence of permeability variation with time 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. A quantitative description of permeability variation with time in the deeper parts of the brittle part of the continental crust is not possible at present.

1. 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, fracture analysis, geophysical modeling of heat flow data and in-situ testing of boreholes measurements (e.g. Berckhemer et al. 1997, CFCFF 1996, Caine et al. 1996; Konzuk & Kueper 2004, Hayba & Ingebritsen 1994, Stober 1996, 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. However, our investigations are concentrated on the fluid behavior within the brittle upper crust.

Within geological time scale, porosity and permeability are continuously changing in the brittle upper continental crust. Reactive fluid flow along fractures consistently modifies the aperture and surface structure of the fractures mostly by chemical dissolution and precipitation reactions due to p- / T-changes, changes in fluid flow direction and thus fluid composition (e.g. Alt-Epping et al. 2013).

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.

Permeability of the crystalline basement rocks is one of the key parameters for geothermal energy use, since it is directly related to the discharge rate of an EGS (Enhanced Geothermal System). It is possible to increase the natural permeability by carrying out stimulation tests, but only to a certain degree depending as well on the local stress field and other parameters (Genter et al. 2010). Hydraulic tests will as well give information on the extension of the geothermal reservoir (Stober 1986, Stober & Bucher 2005). Barrier and infiltrating boundaries could be identified via hydraulic tests, thus making fault zones visible. They show as well if the boreholes are hydraulically connected with each other. Pumping test give as well information on the fluid chemistry, an additional parameter to calculate thermal productivity of an EGS and to treat the fluid once pumped to the surface to minimize mineral scales and material corrosion.

2. HYDRAULIC TESTS, BOUNDARIES AND FAULTS

Principally, during a pumping test water, or in the case of deep wells a saline brine (fluid), is pumped from a well, ideally at a constant rate. Hydraulic model concepts for the aquifer and hydraulic parameters can best be derived from constant rate tests (e.g. Theis 1935; Stober 1986; Boonstra 1989; Krusemann & de Ridder 1991). For the duration of pumping, the drawdown of the watertable in the pumped and in observation wells is measured regularly. After stopping the pump the recovery of the watertable is

also measured continuously. The response to pumping in wells may also be monitored by pressure measurements instead of observing the watertable. The measurement of analogous pressure drawdown and pressure buildup data is preferred in testing thermal and saline aquifers and has been the method of choice for the KTB (continental deep borehole) test. We present here the hydraulic results from a pumping test carried out in the 4 km deep KTB-VB well.

Detailed information on the hydrogeologic and hydraulic properties of the deeper parts of the upper continental crust is scarce. The pilot hole of the deep research drillhole (KTB) in crystalline basement of central Germany provided access to the crust for an exceptional pumping experiment of 1-year duration. The hydraulic properties of fractured crystalline rocks at 4 km depth are derived from the well test and a total of 23100 m^3 of saline fluid was pumped from the crustal reservoir. The experiment shows that the water-saturated fracture pore space of the brittle upper crust is highly connected, hence, the continental upper crust is an aquifer. The pressure–time data from the well tests showed three distinct flow periods (Fig. 1): the first period relates to wellbore storage and skin effects, the second flow period shows the typical characteristics of the homogeneous isotropic basement rock aquifer and the third flow period relates to the influence of a distant hydraulic border, probably an effect of the Franconian lineament, a steep dipping major thrust fault known from surface geology. The distance of the hydraulic barrier border from the pumped well, calculated by using drawdown data, was on the order of 1.6 – 1.7 km. This calculated distance matches the distance from the KTB-VB hole (depth of open-hole: 3750 – 4000 m b.s.) to the projected position of the steeply dipping Frankonian Lineament remarkable well (Stober and Bucher 2005).

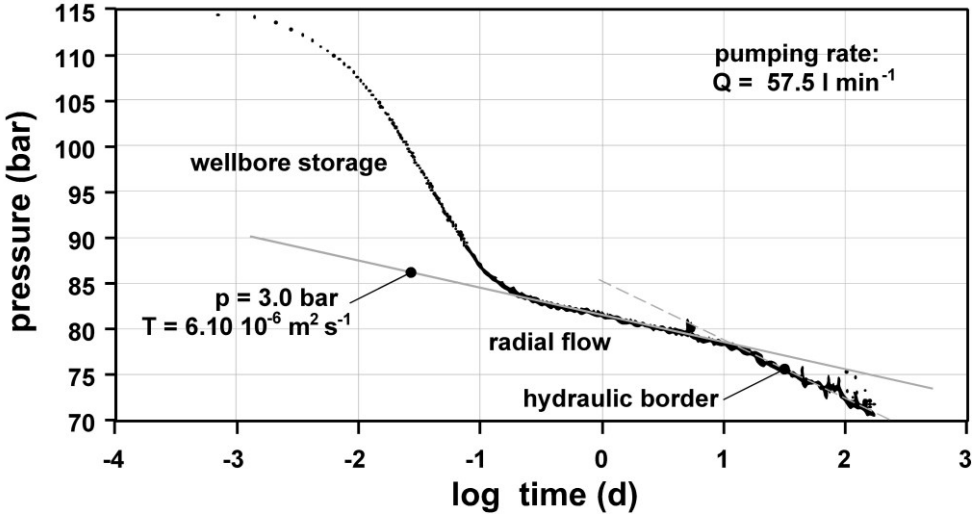

Figure 1: Pressure versus log time data of the pumping test in the KTB-VB borehole showing the indicated three flow periods (Stober and Bucher 2005).

The derived permeability (κ = 1.18 x 10^{-15} m^2) can be taken as a representative and characteristic value of the upper continental crust and is well within the conditions of possible advective flow. The total of dissolved solids of the pumped water amounts to 62 g l^{-1} and comprise mainly a mixture of $CaCl_2$ and NaCl; all other dissolved components amount to about 2 g l^{-1}. The cation proportions of the fluid (XCa approximately 0.6) reflects the mineralogical composition of the reservoir rock and the high salinity results from desiccation (H_2O-loss) due to the formation of abundant hydrate minerals during water-rock interaction. The constant fluid composition and temperature of 120°C suggests that the fluid has been pumped from a rather homogeneous reservoir lithology containing abundant Ca-rich plagioclase (Stober & Bucher 2005).

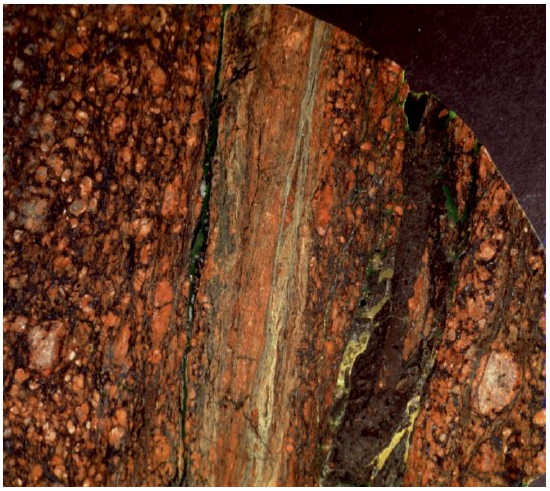

Figure 2: Fault in granite, components from left to right: fractured granite, mylonite, reactivated cataclasite, fractured granite (Mazurek et al. 2003).

By evaluating hydraulic tests in crystalline basement rocks, we often detected barrier boundaries like at the KTB-site, but never infiltrating boundaries. These examples show that prominent fault systems in the basement may not necessarily be characterized by a higher conductivity than the surrounding fractured basement, in contrary. The hydraulic observations give us hints of the internal structure and composition of major faults. So, hydraulically the core of the fault must be built up with tight material of very low permeability to act as a barrier boundary. Geological findings suit to the hydraulic observations showing that the central part of a fault usually consists of low permeable mylonites within a cataclastic and high fractured granitic surrounding of high permeability (Fig. 2). Thus, the conceptual model of the fault geometry and of rock properties adjacent to a fault match and we will use it later as input for further geomechanical modelling of deep geothermal energy use (Seithel et al. 2014).

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.

2. DEPTH AND PRESSURE DEPENDENCE OF PERMEABILITY

Permeability of the crystalline basement characterizes the geometry and connectivity of water conducting structures such as fractures, voids and cavities in rocks. It is evident that permeability within this context cannot characterize the properties of a discrete flow channel but is meant to describe the hydraulic properties of a rock volume of sufficient size with conductive systems that have certain dimensions, connectivity and homogeneity.

Hydraulic tests in wellbores to 5000 m depth worldwide revealed a remarkable variation of hydraulic conductivity of the crystalline basement from 10^{-14} to 10^{-4} m s^{-1}. The upper 1000 m are generally characterized by the higher values but also by a greater variance (Stober 1996, Stober and Bucher 2007a). 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 and Bucher 2007a, 2007b) and can be described by equation 1.

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

with z the depth in km and κ the permeability 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. In general, the hydraulic conductivity of granite is higher than that of gneissic ground in areas of strong and young deformation (e.g. the three-country corner of Germany-Switzerland-France, including the Black Forest area). In tectonically inactive areas, the hydraulic conductivity of large volumes of granite can be very low (Stober and Bucher 2007a).

In the 4.5-km-deep Urach 3 borehole (southwest Germany) within the crystalline basement many high-pressure tests with well-head pressures of more than 600 bar were carried out. During hydraulic tests with well-head pressures above 176 bar, permeability of the crystalline basement increased dramatically, showing the elastic reaction of the fracture rock as a result of increasing pressure; during tests with well-head pressures below 176 bar, there was no significant elastic reaction of the rock.

The effect of the massive hydraulic stimulation in the Urach case seems to be comparable to inflating the fractures with highly pressurized water, leading to a widening of the fractures' apertures and thereby increasing the permeability. There is a confident correlation between specific pressure buildup and injection rate (Fig. 3). After the each hydraulic stimulation, the injected water was partially released out of the borehole (bleeding-out), whereas the other part dispersed in the crystalline basement. After bleeding-out, the fracture plane adopted its original "spacing", meaning the crystalline basement returned to its former transmissivity (Fig. 3). Therefore, massive hydraulic stimulation does not seem to cause a permanent increase of the basement's permeability. The initial rise in permeability was only of short duration. The response of the basement to the massive hydraulic stimulation was just an elastic reaction and, hence, reversible.

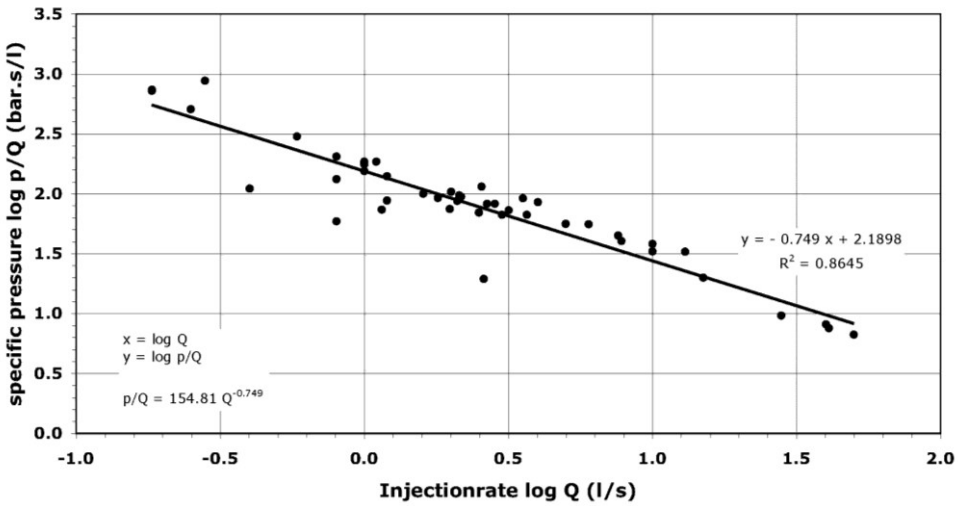

Figure 3: Correlation between injection rate (in log Q) and specific pressure buildup during tests carried out in the open holes of the borehole Urach 3 (Stober 2011)

Using the correlation equation in figure 3 an injection rate of Q = 60 l/s will result in a well-head pressure of about p = 432 bar or in terms of transmissivity: it increased from T = 2.28 • 10^{-7} m^2/s to T = 1.34 • 10^{-5} m^2/s (Stober 2011). With increasing pressure and widening fractures, pore space and transmissivity increase and then decrease again as pressure drops, i.e. the process is reversible. The pressure-dependent change of transmissivity was described in terms of a set of power laws relating injection rate to transmissivity and fracture width (Stober 2011).

Since permeability is low, pressure will increase during injection with high injection-rates and widen the existing fractures at the same time. During pressure buildup, existing fractures expand and they shrink upon pressure decrease. Probably due to the lack of shear stress, no significant increase in permeability remained after any high-pressure tests. Therefore, in this kind of stress-environment artificially increased permeability of EGS can only be maintained by appropriate treatment with artificial materials, e.g. by acidizing fracture plains before inserting propping-material into the opened fractures, e.g. during the stimulation.

Nevertheless parts of the injected water will disperse and infiltrate into parts of the crystalline basement at increasing distance from the borehole. Water is not “lost”; it infiltrates due to the natural fracture-permeability of the basement. This means that the crystalline basement takes up ever increasing amounts of water as pressure is gradually raised.

3. TIME DEPENDENCE OF PERMEABILITY

Fluid flow along fractures is generally accompanied by chemical reactions between the aqueous fluid and the rock exposed along the fracture. The obvious effects of the reactions can be easily recognized in so-called reaction veins (Fig. 4). The reactions may dissolve components from the solid rock into the aqueous fluid and precipitate solid reaction products along the fractures. The dissolution and precipitation processes may proceed at different rates, which may in addition also vary with time. Fractures with associated reactive fluid flow are very common in crustal rocks. The final products of reactive flow along fractures can be studied as reaction veins in rocks exposed at the surface. Reaction veins have a structural component caused by rock deformation and a chemical reaction component that follows from irreversible reaction of the advective fluid with the exposed rock. Both components have consequences for the permeability of the fractured system and its variation with time. Reactive flow may dissolve components from the exposed rocks, import dissolved components from external sources and precipitate new minerals in the fractures that have not initially been present. These veins result from a fracture-reaction-seal mechanism (Bucher-Nurminen 1989). The structures contain a wealth of qualitative information on the development and time dependence of permeability in the brittle crust.

Figure 4: Vein system in mafic rocks (dolerite on Vannøya, Norway). The structures suggest that first a fracture system opened, then advecting fluid reacted with the mafic igneous rock (green) producing an albite-calcite rock (lightbrown) before the fluid conduit was finally sealed by brown (and white) carbonate in the central part of the veins.

The structures suggest that vein growth starts with an initial brittle fracture, and then a reaction period follows during which permeability increases and closes with a period of decreasing permeability until the vein becomes impervious and fluid flow stops. Thus, permeability follows a time evolution. The lifetime of high permeability conditions permitting fluid flow is difficult to quantify. However, the permeability of sealed veins may not be higher than that of the rock matrix.

The effects cannot normally be detected in well tests (not taking into account rapid changes due to earthquakes). Even if well tests could be repeatedly performed in e.g. 5 km deep boreholes over periods of 20 – 30 years, well-ageing and other technical effects would probably obliterate the signals from the undisturbed ground. There are, however, historical reports on the behavior of temperature and discharge of thermal waters in historical spas that indicate variations of permeability of the reservoir area in the basement with time. One example is the spa Badenweiler in SW Germany. The large and luxurious spa has been built and used by the Romans about 1800 years ago. The buildings have been heated by hot water in sophisticated thermal house heating systems. Today, discharge and temperature of the original hot springs are insufficiently low for spa operation. This indicates that the permeability structure of the ground and particularly the thermal water reservoir has changed on the time scale of hundreds of years (Filgris 2001).

4. SUMMARY

Worldwide exist only few deep boreholes in the crystalline basement rocks having carried out hydraulic tests and produced permeability data to depths of about 4 – 5 km below surface. It appears that permeability gradually decreases with depth. Brittle water-conducting structures become fewer and fracture width smaller towards depth. Prominent fault systems in the basement can be detected in hydraulic tests as so called boundaries. The hydraulic observations give hints on the internal structure and composition of major faults suiting to our geological findings. Hydraulic tests in the crystalline basement rocks showed exclusively just barrier boundaries, no infiltrating boundaries.

Variations of the permeability structure of the upper continental crust are related to tectonic processes and the chemical interaction of fluid with the rocks it comes in contact to along the flow path. Flow at a given instant in time can be approximated by the cubic law for fluid flow, where the flow rate per hydraulic head difference is proportional to the cube of fracture aperture. The fracture aperture is a function of time due to mechanical aperture variations such as extension, compression, shearing and other deformational effects in addition to the progressing chemical reactions. Thus, permeability alters with time.

It is possible to increase the natural permeability of crystalline basement rocks, to improve the circulation rate of EGS, by carrying out different kinds of stimulation tests, but only to a certain degree depending as well on the local stress field. In areas with a lack of shear stress, no significant increase in permeability remains after high-pressure tests. Therefore, in this kind of stress-environment artificially increased permeability can only be maintained by appropriate treatment with artificial materials, e.g. by acidizing fracture plains before inserting propping-material into the opened fractures, e.g. during the stimulation.

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