Geophysical Research Abstracts
Vol. 13, EGU2011-10790, 2011
EGU General Assembly 2011

Depth- and Pressure dependent Permeability in the Upper Continental Crust - Data from the Urach 3 Geothermal Well

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The 4500 m deep research borehole 3 at Urach (South Germany) has been extensively used for hydraulic testing of the crystalline basement since the late seventies The data permit a general interpretation of the hydraulic properties of the crystalline continental upper crust at different depth intervals. The typical gneissic basement contains an interconnected fluid-filled fracture system.

Low-pressure hydraulic tests show that the basement on a larger scale can be described as a homogeneous, isotropic aquifer and this characteristic hydraulic behavior persists at least several hundred meters away from the borehole. This demonstrated homogeneity of the aquifer (or fluid reservoir), together with the highly saline water in an interconnected system of copious fractures is characteristic of the continental upper crust in general. On a smaller scale, however, the fractures, crossing the uncased sections in the borehole, define the flow-behavior locally. So, at the beginning of a hydraulic test the pressure data show the influence of wellbore storage and skin, followed by a linear and a bilinear flow-period, and later on by a pseudo-radial flow-period. The transmissivity of the bulk rock can be derived from the data of the pseudo-radial flow-period.

We present a compilation of existing data and describe and interpret new hydraulic test data from the Urach 3 well. The complete data set shows that in the crystalline basement permeability decreases with depth. There is also evidence for pressure dependent hydraulic phenomena, in paricular permeability is found to vary with pressure.

Numerous high-pressure tests, some with well-head pressures of more than 600 bar, corresponding to overpressure of more than 700 bar, were carried in the Urach 3 borehole. The test data clearly show a pressure-dependence of permeability. During hydraulic tests with well-head pressures above 176 bar permeability of the crystalline basement increases dramatically, showing the elastic reaction of the rock due to pressure. At pressures below 176 bar the hydraulic data show no significant elastic reaction of the rock. A mathematical description of the pressure dependent increase of transmissivity has been derived from the data.
The elastic behavior of the crystalline basement can also be described in terms of transmissivity (T, m^2/s). Using the approximation T $\approx$ E-8 Q g/p (Q in l/s, p in bar) with = 985 kg/m3 the corresponding equations are:

Open-holes: T = 6.25 E-7 / Q Exp-0.7490
Perforation sections: T = 3.74 E-7 / Q Exp-0.7095

Thus an injection-rate of 60 l/s in the open-hole will lead to the transmissivity of about T = 1.34 10E-5 m^2/s, which corresponds to an increase of the natural transmissivity by a factor of about 30. The same injection-rate will rise the transmissivity of the perforation-sections by a slightly smaller factor.

The Navier Stoke equation

T = w Exp+3 g/(12μ)

describes the relationship between transmissivity and fracture width w (m). Using the Navier Stoke equation, the equations above can be rewritten to calculate the fracture width, whereas Q is in l/s and the dynamic viscosity μ = 7.0 E-10 1/Pa.

Open-holes: w = 8.16 E-7 / Q Exp-2.50
Perforation sections: w = 6.88 E-7 / Q Exp-2.37

These equations permit to estimate fracture widths in the open-holes and the perforation-sections respectively due to high injection-rates and accordingly high pressures, e.g. they enable the elastic reaction of the crystalline basement to be described. So, with an injection rate of Q = 30 l/s in the open-hole the width of the fracture is about w = 0.40 cm whereas rising the injection-rate to Q = 60 l/s the fracture-width will be on the order of w = 2.28 cm. Certainly, in reality the "fracture-width" is not the width of one single fracture, but it is the total width of several fractures.