

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 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.

The complete set of test data shows that in the crystalline basement permeability decreases with depth. There is also evidence for pressure dependent hydraulic phenomena, in particular permeability is found to vary with pressure.

Numerous high-pressure tests, some with well-head pressures of > 600 bar were carried in the Urach 3 borehole. The test data clearly show a P-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.

How do mineral substrates affect calcite nucleation and growth?

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Calcite was precipitated in flow-through experiments at 25 °C from supersaturated aqueous solutions in the presence of seeds of calcite and six different silicates: augite, basaltic glass, enstatite, labradorite, olivine, and peridotite. The aim of the experiments was to determine how calcite nucleation and growth depends on the identity and structure of the growth substrate. Calcite saturation was achieved mixing a CaCl₂-rich solution with a NaHCO₃-Na₂CO₃ buffer in a mixed-flow reactor containing 0.5-2 grams of mineral grains. This led to a calcite saturation index of 0.6 and pH 9.1 for the reactive solution inside the reactor.

Although chemical conditions, flow rate and temperature were identical for all experiments, the onset of calcite nucleation and the amount of calcite being precipitated depended on the identity of the substrate. With calcite as the growth substrate, new calcite crystals formed instantaneously. Calcite nucleated relatively rapidly on olivine, enstatite, and peridotite (mainly composed of Mg-olivine). Scanning Electron Microscope images showed silicate crystals to be almost completely covered with calcite coatings at the end of the experiments. Less calcite growth was found on labradorite and augite, and least on basaltic glass. In all cases, calcite precipitation occurs on the mineral substrate and not adjacent to them.

These findings indicate that calcite nucleation and its subsequent growth depends on the crystal structure of the silicate substrate. Orthorhombic silicate minerals (olivine and enstatite) are the easiest for trigonal calcite to nucleate on. Monoclinic augite and triclinic labradorite show intermediate behavior, whereas basaltic glass with its non-ordered crystal structure is the least favorable platform for calcite growth. The results have implications for CO₂ mineralization in ultramafic and basaltic rocks [1] indicating that trigonal carbonates easier precipitate on crystalline rather than glassy rocks, but even glass surfaces can serve as a substrate for calcite nucleation.

[1] Oelkers *et al.* (2008) *Elements* 4, 333–337.