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Fluid sinks within the Earth's crust

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The Urach 3 research borehole in SW Germany was drilled through sedimentary cover and reached gneisses of the Variscian crystalline basement at 1600 m (Black Forest basement). An additional 2800 m was drilled through fractured crystalline rocks and the borehole has been used for hydraulic testing in the context of a "hot-dry-rock" (HDR) project exploring for geothermal energy. The crystalline rocks include banded biotite-amphibole gneiss, migmatitic gneiss, quartz-diorite, cordierite gneiss and similar rocks. The basement fracture system is fluid saturated. At 4.4 km depth the fluid contains ~70 g/l dissolved solids and has a temperature of 175˚C. The water is a relatively pure NaCl brine; the total components other than NaCl < 10 mole%. Cl/Br ratio of ~90 (wt. basis) is characteristic of crystalline basement water. The mole fraction Na/(Na+Ca) is ~97.

Water table observations in the borehole cover a period of 13 years, during which the water table continuously dropped with an increasing rate with depth and did not reach steady state. This unique set of data shows that hydraulic potential decreases with depth causing a continuous flow of fluid to the deeper parts of the upper continental crust. The potential decrease and associated downward migration of fluid is evidence for the progress of water consuming-reactions in the crystalline rocks. Fixing H_2O by chemical reactions at depth is a sink for H_2O that acts like suction pump. The overall use of H_2O is larger than the migration of H_2O to the reaction sites, limited by the small permeability of the gneiss.

Computed stability relations among relevant phases at the PT conditions in the fracture system and documented fossil fracture coatings in granites and gneisses suggest that the prime candidate for the H_2O-consuming reaction is the zeolitization of feldspar. The two generic reactions:

anorthite + 5 quartz + 7 H_2O = stilbite ($CaAl_2Si_7O_{18}$•7 H_2O)
2 albite + 2 H_2O = natrolite ($Na_2Al_2Si_3O_{10}$•2 H_2O) + 3 quartz

show that zeolitization does not affect pH and chemically binds free H_2O into the structure of a framework silicate. The mechanism passively increases the TDS of the water without changing the cation proportions in the solution. Thus a dilute Na-Ca-Cl water will, after reaction with fresh unstable plagioclase, evolve to a saline brine.

The consumption of H_2O by chemical alteration of basement rocks may be an important and significant process that could be responsible for a pervasive loss of free water in fracture porosity at depth, a process that lasts over long periods of time and resulting in widespread "reduced hydraulic pressure" and high-TDS brines at depth.

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What can oxygen isotope "sides" say about fluid flow in heterogenous metamorphic aquifers: Insights from the Alta Stock aureole, Utah, USA

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Within 350-400 m of the contact with the Alta Stock, dolomitic marbles ($\delta^{18}O_i$ = +25 to 27 permil) are extensively depleted in $^{18}O/^{16}O$ owing to fluid infiltration during contact metamorphism. In detail, there are significant bed-to-bed variations in the extent of this $^{18}O/^{16}O$ depletion, indicating significant bed-to-bed variations in the time-integrated fluid flux (q_T) and permeability of these individual beds. Differences in $\delta^{18}O$ values of as much as 8 permil exist between adjacent beds; periclase (Per)-bearing beds are the most depleted ($\delta^{18}O$ =10.5 to 12 permil), and hence were the highest permeability beds. Detailed (mm scale) sampling traverses across boundaries between isotopically distinct beds record steep $\delta^{18}O$ gradients—isotopic "sides"—that are displaced small distances (<1 to 8 cm) into the higher $\delta^{18}O$ layers. Because the flux ($q_T = 3000 m^3/m^2$), timescale (~5000 yrs), and principal direction of fluid flow (sub-horizontal, down-T) are known for the inner Alta aureole, it is an excellent natural system in which to evaluate what insights isotopic sides provide for the dynamics and aquifer properties of metamorphic flow systems.

Advective-diffusive transport modeling of these isotopic sides, assuming simultaneous flow in adjacent beds, requires either very low porosity in the higher $\delta^{18}O$ beds (< 10^{-4}) or very short timescale of flow (< 0.1 to 1.5 yrs). Because these higher $\delta^{18}O$ beds are themselves significantly depleted ($\delta^{18}O$ = +14 to +17 permil), it is difficult to produce their observed depletions at either these low porosities or short timescales. A better interpretation is that the higher $\delta^{18}O$ layers were depleted in $^{18}O/^{16}O$ during the initial stages of fluid infiltration. The steep isotopic "sides" were then imposed on these higher $\delta^{18}O$ beds <u>after</u> their porosity and permeability were reduced dramatically as rock reaction and fluid flow ceased within these beds, while fluid flow, periclase production, and further $^{18}O/^{16}O$ depletion continued in the adjacent, higher permeability beds. Hence the geometry and displacement of these isotopic "sides" provide little information on the fluid flux, timescale of flow, or aquifer properties (porosity, permeability) for these individual marble beds during active fluid flow in the Alta system. These detailed isotopic studies emphasize that individual beds in the Alta flow system have experienced different <u>fluxes</u>, <u>timing</u> and <u>duration</u> of fluid flow.