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The importance of geochemical processes for the sustainability of deep geothermal systems: insights from coupled thermal-hydraulic-chemical modeling of the geothermal system at Bad Blumau, Austria

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We use reactive-transport models patterned after the geothermal system at Bad Blumau, Austria, to track the fate of a fluid during its ascent from the geothermal reservoir to the surface, where it undergoes heat- and CO2-extraction, and during its subsequent reinjection into the deep aquifer. The fluid in the reservoir is in equilibrium with the carbonate-dominated mineralogy of the aquifer rock at local temperature and pressure conditions. Pressure and conductive temperature changes during ascent and descent of the fluid induce changes in mineral solubilities. Subsequent mineral precipitation within the borehole changes the fluid composition and gradually clogs the borehole, thereby obstructing fluid flow. Because different minerals exhibit different solubilities as a function of temperature, the mineral assemblages that precipitate in the production well are distinct from those in the injection well. For instance, if the fluid in the reservoir is saturated in quartz, then the prograde solubility behaviour of quartz favours its precipitation in the production well. Conversely, carbonate minerals tend to precipitate in the injection well owing to their retrograde solubility functions. However, calculating the distribution of mineral phases is complicated by the fact that the precipitation of some minerals is kinetically controlled, such that they may continue to precipitate far into the injection well (e.g. quartz).

The strongest modification of the fluid composition and the greatest potential for mineral precipitation occurs during heat extraction, and, in the particular case of Bad Blumau, during the extraction of CO2 at the surface. The extraction of CO2 entails a dramatic increase in the pH and leads to massive precipitation of carbonate minerals. Simulations suggest that, in the worst case, the extraction of CO2 can cause the borehole to be sealed by carbonate minerals within a few weeks. Thus, the use of chemical additives to inhibit carbonate precipitation is imperative in the Bad Blumau system.

Furthermore, any modification of the fluid composition caused by mineral precipitation along the fluid's pathway means that the reinjected fluid is no longer in equilibrium with the aquifer rock. Consequently, rock-water interaction and fluid mixing at the base of the injection well drive chemical reactions that cause changes in porosity and permeability of the aquifer, potentially compromising the efficiency of the geothermal system.

One concern during geothermal energy production is that of chemical corrosion of the borehole casing. For a range of "what-if" scenarios we explore the effect of corrosion on the fluid composition and on mineral precipitation to identify chemical fingerprints that could be used as corrosion indicators. Once suitable indicators are identified, incipient corrosion could be detected early on during regular chemical monitoring. Corrosion of the casing is typically associated with the release of Fe and H2 into the circulating fluid. However, the implications of this release depend on the local chemical conditions where corrosion occurs. For instance, elevated H2 in the fluid is a corrosion indicator only if it is not involved in subsequent redox reactions. Similarly, low H2 concentrations do not rule out possible corrosion. In general, the interpretation of a fluid or a mineral sample requires the understanding of chemical processes that occur along the flowpath throughout the geothermal system. If direct observations are not possible, then this understanding can only be achieved through numerical simulations that integrate and couple fluid flow, heat transport and chemical reactions within one theoretical framework. Our simulations demonstrate that these models are useful for quantifying the impact and

minimizing the risk that chemical reactions may have on the productivity and sustainability of a geothermal system.