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From Dissolution to Detection: Krypton as a Tracer in Hydraulic Injection Experiments

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Noble gas tracers are a powerful tool for investigating subsurface fluid transport, yet their deliberate use in high-energy hydraulic injection experiments remains underexplored. This study investigates the use of krypton (Kr) as a dissolved conservative tracer during hydraulic stimulations conducted at the Bedretto Underground Laboratory (Switzerland) within two research projects. The first experiment formed part of the FEAR (Fault Activation and Earthquake Rupture) project, which aimed to hydraulically induce and monitor a controlled magnitude-zero seismic event. The second was conducted within the BEACH (Bedretto Energy Storage and Circulation of Geothermal Energy) project, investigating geothermal energy storage and circulation in fractured crystalline rock. In both cases, assessing hydraulic connectivity between injection and monitoring boreholes was key for improved understanding of fluid behaviour.

We present methodological developments covering tracer dissolution, injection strategies, and high-resolution monitoring. Two methods for dissolving Kr into injection water—direct bubbling and diffusion across a silicone membrane [1]—were compared in terms of efficiency, preparation time, and gas consumption. Kr-saturated water was injected into the same isolated borehole interval during both projects. Tracer transport was monitored at one borehole during FEAR and at two boreholes during BEACH, characterised by different discharge regimes. Dissolved Kr concentrations were measured continuously using gas equilibrium membrane inlet mass spectrometry (GE-MIMS) which included a portable miniRUEDI mass spectrometer [2] equipped with an adapted membrane contactor [3], enabling high-temporal-resolution breakthrough detection.

Distinct breakthrough curves were observed, with arrival times ranging from one to several days after injection. The borehole closest to the injection interval showed a rapid and steep breakthrough, whereas the more distal borehole exhibited a broader and more gradual response, reflecting differences in fracture connectivity and transport pathways. Since the BEACH experiment followed the magnitude-zero stimulation, the results allow comparison of hydraulic connectivity before and after induced seismic slip. This sequential design provides rare insight into how fracture activation modifies flow pathways and permeability evolution in fractured crystalline rock, with implications for geothermal reservoir performance and heat storage efficiency.

[1] Blanc et al., 2024 https://doi.org/10.1016/j.watres.2024.121375
[2] Brennwald et al., 2016 https://doi.org/10.1021/acs.est.6b03669
[3] Brennwald & Kipfer, 2022 (EP4109092A1)