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H_2 and sulfate production via radiolysis in tight crystalline rocks: implications for habitability, resource potential, and DGRs

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Natural hydrogen (H_2) is a candidate low-carbon energy source for society and, when paired with oxidants such as sulfate, can sustain microbial life over geologic timescales. Understanding how H_2 forms, accumulates, and is consumed in the deep subsurface is therefore critical for energy exploration, biogeochemistry, astrobiology, and the assessment of candidate deep geologic repositories (DGRs) for spent nuclear fuel. In crystalline settings, water radiolysis induced by U, Th and K decay can produce H_2 – and, via indirect oxidation of sulfide minerals, sulfate – but quantifying these production rates is challenging where porosity, permeability, and fluid accessibility are extremely low (such as in DGR host rocks).

This work presents a Monte Carlo approach to translate process-based understanding from fluid-rich, fracture-dominated sites to hydrogeologically tight systems using only bulk rock properties (i.e., without relying on direct fluid or gas samples). The model is applied to estimate H_2 and sulfate production rates via radiolysis in the Revell batholith (Ontario, Canada), a well-characterized site representative of hydrogeologically tight conditions. Results from Revell were then compared to Kidd Creek (Ontario, Canada) – a similarly isolated but more fractured site where direct sampling has previously taken place – to examine the spectrum of elemental cycling and habitability that may exist across these globally widespread settings. At Revell, production rates for both H_2 and sulfate are substantially lower than at Kidd Creek, driven primarily by Revell's lower porosity and sulfide concentrations. Although statistical analyses suggest a small theoretical probability of low levels of biological activity, Revell's potential for sulfate-supported habitability is likely among the lowest investigated to date in subsurface settings globally, and any potential biosphere is additionally limited by poor pore connectivity and small pore throats.

This work establishes a transferable, statistically robust approach to estimate H_2 and sulfate production rates via radiolysis in low-porosity crystalline rocks where fluids, gases, and biomass cannot be directly sampled[1]. The approach can be applied to safety assessments of potential DGR host sites, screening subsurface settings for natural H_2 resource potential, and evaluating rock-hosted habitability on other planetary bodies.

Reference:

[1] Higgins, Song et al. (2025), *JGR:Biogeosciences* **130** (6)