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Basin-scale thermal convection and associated brine-sandstone interaction as key factors for the generation of hyperacidic, exceptionally uranium-rich brines and high-grade uranium deposits in the Athabasca Basin (Canada)

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The Athabasca Basin hosts the world's largest and highest-grade uranium (U) deposits. Despite decades of studies dedicated to understanding the metallogenesis of these deposits, the fundamental reasons for its exceptional U endowment remain incompletely understood. The most widely accepted diagenetic-hydrothermal model proposes that U mineralization results from the interaction between oxidizing basinal brines carrying U and reducing basement-derived fluids or basement lithologies near the unconformity. The mineralizing fluids are believed to have originated from seawater evaporation beyond halite saturation up to epsomite saturation and are rich in potassium (K). Geochemical analyses of fluid inclusions from U deposits reveal extraordinarily high U concentrations (up to 3700 ppm) in the mineralizing fluids, indicating extreme leaching from source rocks and metal enrichment. However, the key geological and geochemical processes by which evaporated seawater evolved into metal-rich brines remain unclear. In particular, the mechanisms responsible for generating low pH brines capable of dissolving large amounts of U, and producing such fluids on a basin-wide scale remain unclear. We propose a unified fluid-flow and water-rock interaction model, in which K-rich evaporated seawater infiltrates the sedimentary basin and interacts with kaolinite-bearing quartzose sandstones. This process is particularly efficient under low water/rock ratios in a confined hydrostratigraphic setting, where basin-scale thermal convection (Wang et al., 2021) sustains the circulation of diagenetic fluids and promotes the widespread kaolinite illitization: 3kaolinite $[Al_2Si_2O_5(OH)_4]$ + $2K^+$ = 2illite $[KAl_3Si_3O_{10}(OH)_2]$ + $3H_2O$ + $2H^+$ (Wang et al., 2025). This reaction releases large amounts of free protons (H^+) into fluids, thereby significantly lowering fluid pH and enhancing U solubility. This model is supported by basin-wide petrographic observations and infrared hyperspectral logging data demonstrating the coexistence of kaolinite and illite in fluvial/alluvial sandstones. Furthermore, basin-scale thermal convection is supported by a coupled quartz cementation-dissolution pattern and reactive transport modeling of SiO_2. Recognition of these mechanisms provides a new perspective for understanding the mineralizing environments and ore-forming systems of the Athabasca Basin, as well as for evaluating U resource potential in this basin and other basins globally.

[1] Wang et al. (2021) EPSL 574, 117168. https://doi.org/10.1016/j.epsl.2021.117168
[2] Wang et al. (2025) GCA 397, 1–12. https://doi.org/10.1016/j.gca.2025.03.031