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Why Is the Proterozoic Athabasca Basin Endowed with Rich and Large Unconformity-Related Uranium Deposits?

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The Proterozoic Athabasca Basin in northern Canada hosts a number of high-grade (mostly >1%, some >10% U) and large-tonnage uranium deposits, making Canada the second largest producer of uranium in the world. These deposits are mostly located near the basal unconformity between the basin and crystalline basement and are termed unconformity-related uranium (URU) deposits. The deposits are spatially associated with reactivated basement faults and hydrothermal alteration halos characterized by chlorite, tourmaline, kaolinite, and illite. They are generally interpreted to have resulted from reaction between oxidizing, uranium-bearing, basin-derived brines and reducing lithologies in, or reducing fluids derived from, the basement. Although this "diagenetic-hydrothermal" model adequately describes formation processes and conditions of the URU deposits, it does not explain why the Athabasca Basin is exceptionally endowed in uranium mineralization; indeed, although URU deposits occur elsewhere in the world, few of them (e.g. Kombolgie Basin in Australia) are comparable to those in the Athabasca Basin.

Chemical analyses of fluid inclusions in quartz overgrowths in sandstones of the Athabasca Basin, and drusy quartz in both mineralized and barren areas along structures hosting URU deposits, suggest basin-wide development of uranium-rich brines. Such unusual, large-scale formation of uranium-rich brines, which is possibly the critical reason for the rich endowment of uranium deposits in this basin, may be attributed to several geological factors. First, the basin is flanked by two orogens, the Taltson Magmatic Zone-Thelon Orogen to the west and the Trans-Hudson Orogen to the east, both of which contain large amounts of granitic rocks that may have provided abundant uranium-rich detritus to the basin. Second, the low mud content of the sandstones, related in part to the lack of land vegetation in the Proterozoic, enhanced fluid circulation. Third, increased atmospheric oxygen levels in the late Paleoproterozoic, as recorded by the red beds in the basin, enhanced extraction of uranium from the sediments. Fourth, basinal brines derived from seawater evaporation, as indicated by evaporitic carbonate rocks above the sandstones and high-salinity fluid inclusions in quartz overgrowths, increased uranium extraction. Finally, elevated temperatures, as recorded by fluid inclusions, clay geothermometry, and zircon thermochronology, facilitated fluid convection and uranium extraction. Fluid convection is reflected by basin-scale quartz precipitation-dissolution patterns and demonstrated by reactive mass transport modeling. The elevated temperatures may be related to high-radiogenic heat-producing felsic intrusions at depth or upwelling of the asthenosphere in relation to the breakup of the Nuna supercontinent. Based on regional geological and geochronological data, we propose that that these conditions came together in the Athabasca Basin at ca. 1550 Ma, which, together with reactivation of basement-rooted structural zones channelling deep-sourced reducing fluids toward the unconformity, resulted in large-scale URU mineralization. Although individual factors may be satisfied in many other basins, the combination of them all is rare. Therefore, the unusually rich uranium deposits in the Athabasca Basin are the result of coupling of multiple favorable geological factors, including both shallow (basinal) and deep (thermo-tectonic) processes, at a specific time and location in the Earth's crust.