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Coupling structural evolution and fluid flow in metallogenic and geothermal systems

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Abstract. Understanding the structural framework of metallogenic provinces and identification of transient events during which fluid circulation and trapping of mineralization occur is a major challenge for exploration of mineral systems. Analogies between geothermal systems, orogenic gold and unconformity related deposits reveal the role of permeability enhancement during episodes marked by the coupling of tectonic activity and fluid flow. Thus, in the case of Unconformity-Related Uranium deposits of the Athabasca Basin (Saskatchewan, Canada), a new model can be proposed considering that the interplay between compressional fault reactivation and thermal convection is the main driver of this fluid flow system. Short-lived, deformation-driven fluid flow are recorded by the structural and mineralogical evolution of the reactivated basement-hosted fault system.

1. Introduction

The mineral system concept applied to Unconformity-Related Uranium (URU) deposits of the Athabasca Basin (Ledru 2019, Bruce et al. 2020, Ledru et al. 2023;) highlights the major role of crustal scale structures and of the geodynamic context in the onset and sustainability of the hydrothermal systems driving formation of the main orebodies. Within a structural framework defined by the geometry, kinematics and mechanical properties of the fault systems, the identification of transient pulses during which mineralizing fluids are circulating and trapped is critical for the reassessment and definition of exploration pathfinders and guides (McCuaig and Hronsky 2014).

Analogies between hydrothermal ore deposits formed at overpressured conditions during high fluid flux through fault zones and geothermal systems has been developed by Cox (2016). In the case of Enhanced Geothermal Systems, the overpressure induced by injection of fluids produces a stimulation of the permeability network of the drilled domain accompanied by seismic swarms that give a scanning of the fault system. Recent experiments in the Rhine graben have also demonstrated that following the early stages of stimulation, a geothermal reservoir hosted in the fault network has been revealed and can be considered as a self-organized hydrothermal system (Glass et al. 2021).

In the case of the Unconformity-Related Uranium deposits, recent studies have revealed common features with this configuration in which the coupling between structural evolution and fluid flow is critical to explain the formation of large deposits.

2. The architecture and the structural framework

The tectonic history of deeply rooted structures is critical to understand the natural processes at the origin of metallogenic provinces (McCuaig et al. 2010). These structures are responsible for crustal segmentation and are natural links between deep and shallow processes. They guided in many cases the intrusion of magma extracted from the mantle or generated during crustal melting and have recorded significant retrograde metamorphic evolution and hydrothermal alteration during the late orogenic evolution. By referring to geophysical imagery, Card (2020, Tschirhart et al. 2022) considers that protracted reactivation of deep-seated structures and their subsidiaries was a fundamental control on uranium mineralization in the southwestern Athabasca Basin. Based on the structural analysis and resulting cross sections (Ledru et al. 2023) and on numerical modelling (Poh et al. 2020), a similar interpretation is proposed for the Wollaston-Mudjatik transition zone that concentrates the main large to giant uranium deposits.

At the prospect and camp scale, the structural control for focusing mineralizing fluids and mineralization is well established as ore formation is spatially and temporally focused by the reactivation of the pre-Athabasca fault system (Jefferson et al. 2007). The general concept summarized in IAEA (2018) is that deposits were formed in fault zones and along the unconformity where reduced fluids from the basement and oxidized fluids from the basin were mixed. Structural traps opened during active faulting and were repeatedly brecciated (Hoeve and Quirt 1987; Kyser et al. 2000). In more detail, the alteration haloes considered to be related to the deposits are always developed in the vicinity of a fault system that crosscuts the unconformity. Most of these faults correspond to reactivated-inherited fault zones of the basement and have an associated reverse offset of the unconformity, up to several hundred meters along the Virgin River shear zone and below 100 m in the Wollaston-Mudjatik Transition Zone. These faults are often graphite-rich and cohesive to non-cohesive breccias are the most obvious expression of this reactivation.

At the camp scale, detailed structural and microstructural works reveal the polyphase history of these faults, rooted in the basement and propagating into the basin. Alteration paragenesis display a variety of association with microstructures that are often controlled by local faults and their

morphology (thickness and infilling of core and damage zones) and lithological contrast. The hydrothermal alteration within these deeply rooted faults, prior to the mineralization and presumably related to the pre-Athabasca exhumation, seems to have an efficient control on the further channeling of the mineralizing fluid, having deeply modified the original properties of the host rocks. Microbrecciation and brittle fracturing associated with the polyphase history show how the permeability of these zones has been enhanced (Benedicto et al. 2021).

3. The transient effect

Recent findings and the comparison with their modern counterpart exploited as geothermal reservoirs, suggest that the lifetime of such hydrothermal systems might be much shorter and more dynamic than previously assumed (McCuaig and Hronsky. 2014; Cox 2016). Such pulsations could correspond to modifications of the crustal stress regime marked by highly localized deformation and enhancement of the permeability of the geological systems (Manga et al. 2012). Although no geochronological constraints exist on the time required to form the Athabasca deposits, first-order approximation from Raffensperger and Garven (1995) and Dargent et al. (2015) suggest that 0.1–1Myr is a viable estimate for the duration of the mineralizing event that could then correspond to transient events limited in time and space.

Based on regional geochrono-stratigraphic data, it has been proposed that the deposits were formed at depths of < 3 km (Chi et al. 2018). This mineralization depth estimation has important implications for the hydrodynamic regime and the geothermal gradient, both affecting the potential mechanisms of fluid flow related to U mineralization. A shallow burial environment, together with the sandstone-dominated nature of the basin sediments, favors a hydrostatic regime in the basin (Chi et al. 2013), instead of a lithostatic regime as assumed in the conventional model that considers a paleodepth of 5km. A hydrostatic regime facilitates establishment of fluid convection in the basin, which is further enhanced by elevated geothermal gradients as implied by high temperatures at shallow depths (Wang et al., 2021). This regime at the base of the basin in a shallow burial environment suggests that the unconformity surface is unlikely a hydraulic interface between hydrostatic and lithostatic regime; such an interface is likely located at greater depths in the basement. This hypothesis is supported by the study of graphite in basement faults hosting URU deposits (Song et al. 2022), which suggests that the faults may be reactivated due to the fault-valve mechanism ~5 km below the unconformity surface, whereas the upper tip of the faults may attract fluids both from the basement and basin via the suction pump mechanism. Thus,

the formation of the URU deposits may be considered a result of coupled fault-valve and suction pump mechanism.

Dominantly C-O-H(-N) fluid inclusions trapped within ductile-brittle graphitic shear zones have been considered as associated to the retrograde metamorphism during the exhumation of the Trans-Hudson orogen (Martz et al. 2017). However, the temperature of the mineralizing fluids (150-250° C), suggested by the alteration mineral assemblages and fluid inclusion studies (Richard et al. 2016) and the revised paleodepth of the unconformity of <3km implies high geothermal gradient. The possible origin of such high geothermal gradient remains poorly constrained as no intrusion or volcanic activity has been so far identified within the basin. However, large wavelength anomalies related to mantle upwelling may have developed during the Nuna supercontinent breakup (Pehrsson et al. 2016). A bright band of reflectivity at about 8000m depth has been interpreted as a series of sub-horizontal sheet like diabase intrusions related to the Mackenzie igneous event at 1270 Ma (Jefferson et al. 2007) but nothing excludes that they could correspond to an earlier intrusion related to this Nuna breakup. Finally, modelling suggests that deeply rooted fault systems inherited from the pre-Athabasca orogens could operate as conduits to bring fluids and heat towards the upper parts of the crust, in particular during episodes of tectonic reactivation (Poh et al. 2022). In this case, the mineralized zones showing a high geothermal gradient could be “hot spots” situated at the intersection between this fault system and the unconformity. The discovery of carbonatite dykes within the fault system of the Patterson Lake corridor is another observation that supports such coupling between deep-seated and shallow processes (Johnstone et al. 2021).

In this context, possible deeply rooted basement fluids mixed with fluids originated from the basin lead to a major revision of the current model (Rabiei et al. 2021). Investigating gradients downdip in the main reactivated shear zones recorded by mineralogy and fluid inclusions could be one way to test the hypothesis that brittle faults marking a significant offset of the unconformity could be rooted at depth and have a ductile equivalent enabling metamorphic fluids to be generated. Thus, the role of active faulting and shearing processes would be a trigger of the initiation of a self-organized hydrothermal system (Micklethwaite et al. 2010, Hronsky 2011) and the brittle-ductile transition could be considered as a threshold barrier.

Thermo-Hydraulic and Mechanic (THM) modelling evaluates different scenarios under which the fluid flow was controlled by faulting-related deformation and permeability enhancement. Modelling of simplified geometries of several deposits (Li et al. 2018, 2020; Eldursi et al. 2020), shows that basement faults generally promote fluid flow, fluids circulating downwards

from the basin within the basement (ingress flow) or upwards from basement reservoirs towards the basin (egress flow) both generated by either compressional deformation or fluid convection. The actual flow direction for a given basement fault is influenced by a combination of many factors, especially the dip angle and dip direction as well as spacing of neighbouring basement faults (Chi et al. 2013).

Understanding the geodynamic trigger of this reactivation is a major stake. Based on the dispersion of the U/Pb ages of the mineralization, many attempts of correlation with compressional far-field tectonic events have been done (Kyser and Cuney 2015). These correlations are based on geochronological data which are too much spread to be conclusive (Chi et al. 2018). Several structural observations can be advanced to constrain this trigger. Because of the unfavourable dip of these faults in the compressive stress field, their reactivation could only occur when fluid pressure exceeded the lithostatic load (Sibson et al. 1988; Sibson 2020). The presence of significant amount of graphite must also be underlined as a lubricant facilitating faulting and fluid flow that led to uranium mineralization (Song et al. 2022).

4. Discussion

The review of these different parameters highlights several critical elements that are compatible with other mineral systems (McCuaig and Hronsky 2014). A new model can be proposed considering that the interplay between compressional fault reactivation and thermal convection is the main driver of this fluid flow system (Li et al. 2020, Song et al. 2022). Short-lived, deformation-driven fluid flow are recorded by the structural and mineralogical evolution of the reactivated basement-hosted fault system. This tectonically active period may be associated with a far-field tectonic event and separated by long periods of quiescence. However, by analogy with enhanced or natural geothermal systems (Cox 2016), the possibility that these episodes are related to transient tectonic activity caused by fluid over-pressure should be also considered, interplay between compressional fault reactivation and thermal convection being still applicable. Thus, the formation of the giant deposits could happen during times when the prevailing geodynamic conditions impose strong threshold barriers to fluid flow, causing fluid-flux systems to become self-organized (Hronsky 2011). In this scenario, the presence of a basement hosted reservoir is suggested and the fluid expulsion occurred through transient exit pathways, faults acting like valve system (Sibson et al. 1988, Sibson 2020). In this framework, uranium may precipitate in structural traps as jogs and veins within the core and damage zones of the faults during inter seismic periods, graphite and sulphide being potential reducing agents facilitating the precipitation or reach the

unconformity and be trapped in the permeable sediments at the base of the basin if a clay or silicified cap is present.

5. Conclusion

Analogies between geothermal and mineral systems are applied to evaluate the processes at the origin of unconformity-related uranium deposits as known in the Athabasca Basin. Thus, the stimulation of inherited permeability networks and the role of structures in a given tectonic context appear as essential conditions in both systems to initiate, develop and sustainably operate high fluid fluxes within heat exchangers and chemicals that will lead to the formation of geothermal deposits or reservoirs. The recently conceptualized analogies between the induced seismicity of experiments in the development of improved geothermal reservoirs and the polyphase injection of hydrothermal fluids in the shear zones (Cox 2016) open new perspectives for the predictive targeting of reactivated and mineralized fossil zones in the deposits by comparison of the coupling between the deformation regimes and the circulation of fluids in the systems stimulated in a natural (deposits) and anthropogenic (improved geothermal) way.

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