Structural controls on uranium mineralization at the Kiggavik Project (NE Thelon area, Canada)

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Abstract. This paper deciphers the complex multiphase fracture network associated with uranium mineralization of the unconformity-related uranium deposits in the Kiggavik area. It combines field work, drill-core logging and sampling, and macro- to micro- petro-structural analyses. Key results from this study show that uranium bearing ENE-WSW and NE-SW fracture systems formed early during the Thelon and Trans-Hudsonian orogenies and were mineralized in three stages with distinctive fracture patterns, alteration and mineralization types. The first stage mineralization, inferred from a magmatic source, is related to micro-brecciation and is crosscut by intense quartz brecciation and veining (silica breccia) that predates formation of the Thelon basin. The second stage of mineralization (fluids of unconstrained origin) is coeval with the formation and reactivation of the E-W trending faults in the area, locally reusing the previously formed quartz veins of the silica breccia event. The third stage of uranium enrichment and reconcentration occurred with post-Thelon NE-SW compression and reactivation of the NE-SW and E-W trending faults, and is inferred to form from oxidizing basinal brines circulating on trans-tensional fault zones. Later sinistral offset by NNW-SSE faults and uranium remobilization by meteoric fluids gave uranium ore bodies their final architecture.

1 Introduction and geologic framework

Uranium deposits in the Kiggavik area, located 80km west of Baker Lake in Nunavut Territories (Canada) (Fig. 1), are commonly described as unconformity-related (Friedrich et al. 1989). A noteworthy role of faults as fluid conduits through impermeable basement metamorphic rocks or as traps is observed in the formation and location of ore bodies that are otherwise hosted by a variety of lithologies (Fig. 1). However, the tectonic framework remains poorly understood due to the lack of outcrops, the complex fracture pattern that results from a long lasting polyphase tectonic history (~2.00-1.27 Ga), and strong fluid-related alteration that often obliterates fracture and fault attributes in exploration drill-hole cores.

This work establishes the structural controls of the uranium mineralization at Kiggavik, with focus on the recently discovered Contact and 85W prospects (Fig. 1).

Uranium deposits in Kiggavik are hosted in metamorphosed sedimentary, volcanic/plutonic rocks (ca. 2.7 to 2.5 Ga) of the Amer and Ketyet River groups and in granitic gneiss of Archean age (Fig. 1). These rocks are intruded by the Hudson (ca. 1.84 Ga) and Nueltin (ca. 1.72 Ga) intrusions, and the Mackenzie diabase dyke system considered to be the last tectonic event in the region (ca 1.27 Ga). In Kiggavik, dextral-oblique collisional tectonics occurred as the Slave foreland province was subducted beneath the Rae hinterland to the east (Thelon-Taltson orogeny, ca. 2.0-1.9 Ga; Hoffman, 1988). The Trans-Hudsonian orogeny (ca. 2.0-1.8 Ga) overprinted and reworked the inherited tectono-metamorphic signature. The region was then marked by extensional to transtensional tectonics leading to the development of the Baker Lake and Wharton basins (Baker Lake and Wharton groups at ca. 1.85-167 Ga). These tectonic events were followed by thermal relaxation and normal faulting that gave birth to the intracratonic Thelon basin (ca. 1.67-1.54 Ga) which detrital rocks that unconformably overlie the metamorphic basement.

The Thelon, Judge Sissons and Andrew Lake regional faults of the Kiggavik area (Fig. 1) are still poorly known. They are inferred to be formed through this complex tectonic history before the formation of the Thelon basin. These faults were likely active from ca. 1.80-1.27 Ga and later reactivated under successive far-field tectonic stresses (Hadlari and Rainbird 2011).

2 Methods

Re-filtering and re-interpretation of ground magnetic and VLF (Very-Low-Frequency) maps with field observations and structural analysis of oriented data from drill-cores allow for accurately depicting the fracture network. Acoustic televiewer probing provided better definition of selected fracture and fault zones. Macro- and micropetrostructural analyses using optical, Scanning

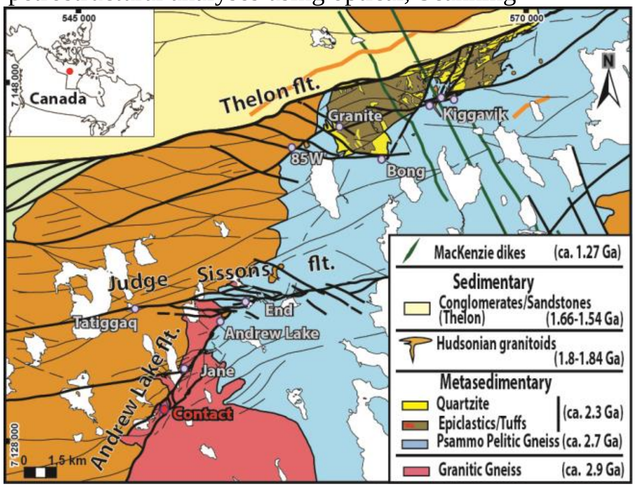

Figure 1. Simplified geological map of the Kiggavik Uranium Project showing the location of the uranium deposits.

Electron and cathodo-luminescence microscopy helped to define the textural, geometrical and chronological relationships between fluid-related alteration, mineralization and fractures. Oriented data were processed with Dips (Roc Science) software.

The most significant and key structural controls (I to V, Fig. 2) for all the fracture phases identified (12) are presented in the following sections from the oldest to the youngest events (Fig. 2).

3 Structural controls on U-bearing fluids

3.1 Pre-Thelon micro-fracturing and first stage of uranium mineralization (I)

A first stage of uranium mineralization is observed at Kiggavik Main, Bong, End and Andrew Lake deposits (Fig. 1). Mineralization is characterized by fine micro-fracturing to micro-brecciation of the host rock that can locally be foliation-parallel (Fig. 2). Monomictic mm to cm-scale clasts display dissolved boundaries. Alteration of the host rock is weak to non-observable and is characterized by bleaching (destabilization of iron oxydes) along with incipient illitization around fractures.

At the micro-scale, fractures display small steps and perpendicular micro-stylolites. Fractures are filled with Fe-rich chlorite, anatase, sulphurs, uraniferous-titanate and pitchblende. This micro-fracturing is usually observed in the vicinity of granitic intrusions at Kiggavik, and has been locally observed associated to granitic veins. This mineralization is cross-cut or overprinted by quartz-rich hydrothermal breccia (II) and so far is interpreted as being the oldest recognized mineralization stage predating the formation of the Thelon basin, inferred from a magmatic origin. This early brecciation and mineralization stage likely prepared the host-rock for later fluid circulation and new uranium mineralization.

3.2 Hydrothermal quartz breccia (II)

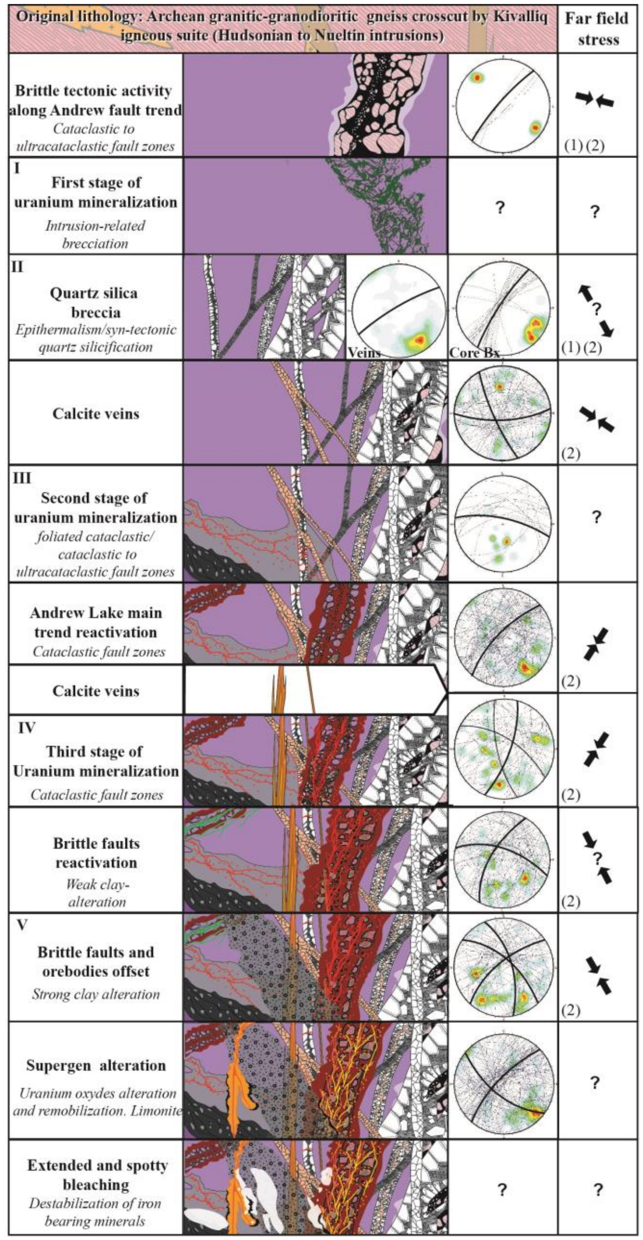

Figure 2. Fracture phases and mineralization events in the Kiggavik area. Far field stress inferred from bibliography (1), field data (2)

A major hydrothermal quartz-rich brecciation and veining event is recognized at Kiggavik along the Judge Sissons and Andrew Lake faults (Figs. 2 and 3). A pervasive deep red hematization is linked to this fracturing event. The breccia displays abundant pervasively hematized heterolithic clasts from various hosting rocks, sealed by massive quartz. Breccia and veins crosscut and/or silicify previous features. At the Contact prospect, the main m-thick breccia core trends NE consistent with the main strike of the Andrew Lake fault (Fig. 3).

The so-called quartz or silica breccia played a major role in the Contact prospect in terms of fracture accommodation and fluid compartmentalization, since most fractures, alteration and mineralization occurred within its hanging wall. Accordingly, at Andrew Lake, End, Bong and Kiggavik deposits where silica brecciation is less intense, ore bodies are found both above and below the silica breccia fault zone.

The silica breccia formation has been correlated with the deposition of the Baker and Pre-Thelon Wharton groups (Hadlari and Rainbird 2011). The related dextral movement along the Judge Sissons and Andrew Lake faults, deduced from the offset of the Hudsonian intrusions (Fig.1), therefore predates the hydrothermal silica event. It is inferred that the quartz-rich breccia formed synchronously with the emplacement of rhyolitic flows of the Pitz formation and the associated Nueltin granite intrusions of the Wharton group, in response to a likely NNW extensional stress. The silica breccia is capped by the Thelon formation, hence predates its deposition.

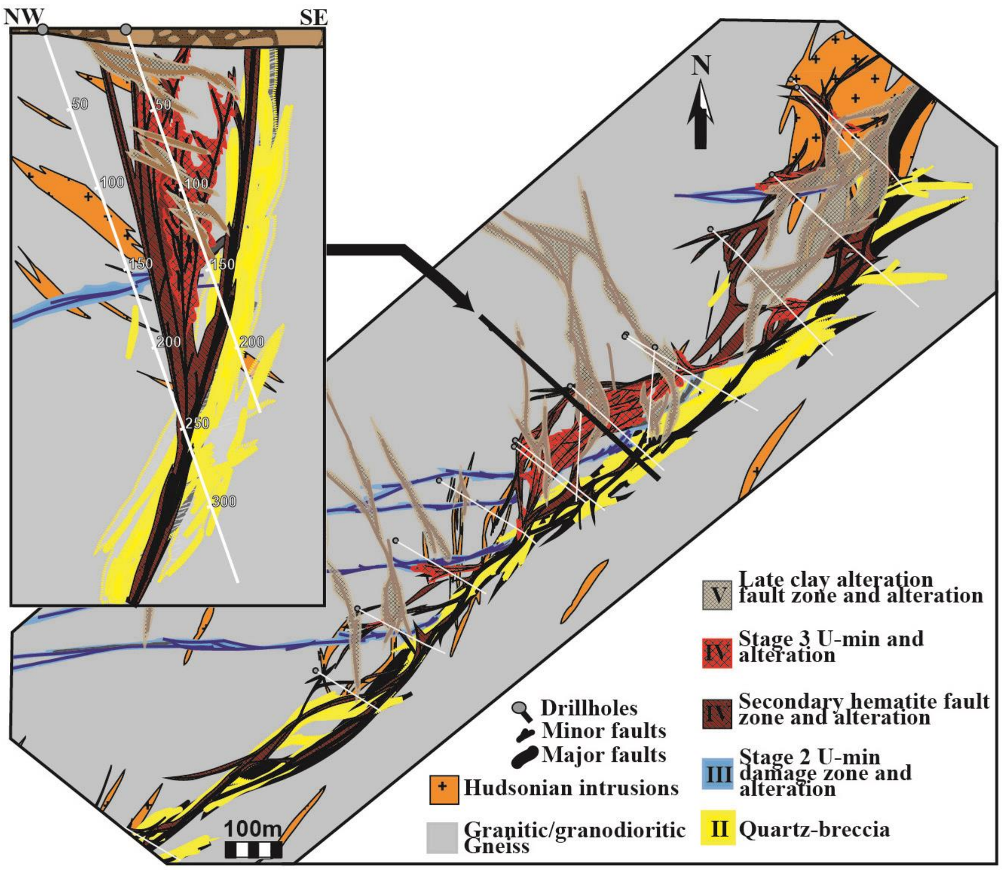

Figure 3. Simplified cross-section (top left) and map view of the Contact prospect showing main fracture and mineralized systems. Stage 1 U-min related fracture was not observed at Contact.

3.3 Formation and reactivation of E-W fractures/faults and second stage of uranium mineralization (III)

The second stage of mineralization occurred in cataclastic faults and in associated fractures coated with uranium and sulphurs, and locally in re-utilized quartz veins inherited from the quartz-rich brecciation event (Figs. 2 and 3). Mineralized micro-fractures cut orthogonally across former quartz veins and are usually restricted to the quartz veins with rare propagation into the host rock. Macro- and micro-structural cross-cutting relationships support that this fracturing event postdates the hydrothermal quartz breccia event.

Ore minerals related to this second mineralization stage are mostly represented by colloform and xenomorph pitchblende and coffinite, uraniferous titanate, titanium-oxides with pitchblende micro-inclusions and iron sulphide, mainly pyrite but also chalcopyrite, bravoite and illite. Mineralization is observed along the boundaries of the quartz veins, associated with quartz dissolution. Rare occurrences of native bismuth and unidentified Ni-As xenomorph minerals have been also observed.

Oriented data indicate that the second stage of uranium mineralization occurred along east-west oriented faults and along re-opened quartz veins from the previous hydrothermal stage (Fig. 3).

3.4 Oxidizing fracturing event and third stage of uranium mineralization (IV)

The third stage of uranium mineralization is associated with brown to brick red oxidation and clay alteration of the host rock (Figs. 2 and 3). It often appears as pervasive and involving greater volumes of rocks compared to the second mineralization stage. Nevertheless, in some holes and samples, it appears clearly driven by faults and fractures, and often re-uses previous quartz vein generations. Remnant minerals like iron sulphide, micrograins of pitchblende of primary mineralization are common, together with spherulitic pitchblende with iron-removal halos, and disseminated pitchblende grains. Pitchblende is observed associated with/or in impregnation of clay minerals such as illite and sudoite. Sudoite especially fingerprints the circulation of Mg-rich brines in the Athabasca Basin uranium deposits (Renac et al. 2002). This supports downward flow of oxidizing basinal diagenetic-hydrothermal fluids at this stage, leading to new uranium mineralization and reconcentration (Figs. 2 and 3).

This stage is linked to the post-Thelon reactivation of the pre-existing fracture networks along the Andrew Lake and Judge Sissons faults (Fig. 3). Regional kinematic data indicate sinistral-reverse reactivation of the Judge Sissons fault under a roughly NE-SW compression, and dextral strike-slip reactivation of the Andrew Lake fault. The Contact, Andrew, End, and Kiggavik deposits appear to be located in transtensional jogs along the reactivated pre-existing faults.

3.5 Post mineralization faulting stages (V)

At Contact or 85W, several distinctive structures are observed in barren zones or cutting across the uranium mineralization stage 3. These faults are characterized by strong to complete clay alteration (illitization) of the host rock. Clasts of pitchblende with various clay generations (illite and sudoite) are observed within fault zones, and are interpreted to be relicts from the third mineralization stage.

Oriented data indicate that this stage is linked to a NNW-SSE compression reactivating NNW-SSE and NW-SE faults as sinistral and dextral strike-slip faults, with extensional fault jogs providing favourable conditions for fluid circulation and alteration. The sinistral offset of the ore bodies observed in various deposits (i.e. End or Main Zone) by NNW faults can be linked to this tectonic stage, along with strong clay alteration of the host rock.

NNW-trending faults and ore deposits were ultimately cut by the Mackenzie dykes (1.27Ga). After 1.27 Ga, the fracture/fault network was only weakly reactivated under changing far-field stress. Meteoric water circulated through the fracture system and led to local remobilization and reconcentration of uranium oxides along redox fronts (Fig. 2). Still later, spotty to widespread bleaching of the host rock destabilized and removed iron bearing oxides.

4 Discussion and conclusions

Petrological, textural and structural studies allowed for the characterization of the nature and sequence of the successive tectonic, alteration and mineralizing episodes that occurred and controlled the mineralization in the Kiggavik Uranium Project. This work shows that in the Kiggavik area the uranium mineralization deposition was controlled by faults and related fractures that formed and were reactivated several times in the brittle tectonic domain, but also with different types of fluids and P-T conditions.

The first stage of uranium mineralization predates the development of the Thelon basin, and appears to be the oldest uranium enrichment of the host rock, probably intrusion-related by analogy to the Nueltin intrusions timing. Oxygen isotopes studies on illite synchronous to pitchblende at Main Zone and Bong deposits indicate that fluids were of meteoric-hydrothermal (Sharpe et al. 2015) to magmatic hydrothermal (Friedrich et al. 1989) origin. The Nueltin granite (observed at Kiggavik) which is associated with a more fractionated melt and which displays enrichment in U, Th and REE compared to the Hudson intrusions (Scott et al. 2015) is inferred to be the source of the first mineralization at Kiggavik. Complementary geochemical studies are in progress. Later, syn-to post Thelon reactivation of fault zones generated further uranium enrichment and re-concentration (mineralization stages 2 and 3). Finally, lately reactivated NW and NNW faults offset orebodies and drove fluids that strongly altered the host-rock. Late meteoric water circulation locally remobilized and re-concentrated uranium oxides along redox fronts.

This study emphasizes (1) the key role played by fractures and faults on fluid circulation within the basement at various times, (2) how macro- to micro-structural studies are essential to precisely decipher the fracture pattern, its relative chronology and its relationships with alteration and mineralization. (3) It also demonstrates that uranium deposits are more complicated that initially proposed as unconformity –related, the similarities with Athabasca uranium deposits are not as numerous as supposed.

Acknowledgements

The authors thank D. Quirt, K. Martin, R. Zerff, D. Hrabok and R. Hutchinson from Areva Resources Canada for their help and enriching discussions during field work and data interpretation.

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