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A review of the geochronology of the Precambrian of Saskatchewan—some clues to uranium mineralization

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ABSTRACT. Assessment of available geochronological information, as well as new whole-rock Rb-Sr data from several granitoid rocks of Saskatchewan, shows a close relationship between magmatic-metamorphic events in the Hudsonian orogen and uranium mineralization. Most uranium deposits lie to the west of the Needle Falls Shear Zone and occur as either: (i) vein-type deposits or (ii) unconformity-type deposits close to the contact between the Athabasca sediments and their basement. At least two metamorphisms have affected the pre-Athabasca rocks: the Kenoran at about 2500 Ma ago, and the more pervasive 'main' Hudsonian event at 1740 Ma. A much younger thermal event (perhaps associated with uplift and cooling) at 1540 Ma is also indicated. The post-Kenoran K-Ar dates suggest prolonged thermal activity from about 1900 Ma through to about 1500 Ma ago. Granitoid events at 1870 Ma and 1740 Ma ago are outlined by both U-Pb zircon and Rb-Sr whole-rock isochron data. Whole-rock Rb-Sr data from the unmetamorphosed Athabasca sediments suggest an approximate depositional age of 1450 ± 50 Ma, a figure that is consistent with the age of the underlying Hudsonian basement and the truncation of the sediments by the Cree Lake diabase dyke swarm at about 1200-1300 Ma ago. Although several episodes of uranium deposition have been documented, the main ones seem to have occurred at 1860 Ma (syngenetic uraninite in pegmatites), 1740 Ma (the Beaverlodge vein-type deposits) and between 1300 and 800 Ma (the epigenetic uranium of the unconformity-type deposits). Whereas the two earlier episodes can be correlated with periods of either magmatic or metamorphic activity, the late Proterozoic episodes cannot. The close agreement between the age of the Cree Lake dyke swarm and the late Proterozoic mineralization suggests that at about 1300 Ma ago possible hydrothermal activity from relatively deep-seated fractures may have been responsible for the solution and transportation of the uranium of the unconformity-type deposits. The period 1300 Ma to about 900 Ma, in other parts of the Canadian Shield, was a time of crustal rifting, basic magmatism, carbonatite activity, and intense deformation. Prior to the deposition of the Athabasca sediments uranium was concentrated by Hudsonian magmatic and metamorphic processes whereas subsequently, transportation and intermittent deposition of the unconformity-type deposits were related to fairly long-lived, low-temperature hydrothermal activity.

WITHIN the last decade the discovery of several uranium deposits of major importance within the Churchill Province of the Canadian Shield has made Saskatchewan one of the key areas for studying uranium mineralization. In addition, detailed field mapping in several critical areas has shown that the Saskatchewan section of the Hudsonian orogen is extremely useful for evaluating the wide variety of geological processes that take place during the evolution of a mobile fold belt and the formation of basement-cover relationships.

The main subdivisions of the Saskatchewan Shield, termed lithostructural domains by Lewry and Sibbald (1977), divide the Hudsonian orogen and adjacent areas into a series of roughly parallel, northeast-trending, often fault-bounded belts, some of which have repeatedly suffered tectonothermal events from about 2000 Ma through to about 1540 Ma ago. This activity culminated in the 'main' Hudsonian event some 1740 Ma ago.

The sub-Athabasca crystalline basement in Saskatchewan (consisting of Aphebian supracrustal remnants and older rocks) is overlain unconformably by the flat-lying, unmetamorphosed Athabasca sediments that now cover about 100 000 km^2, almost a third of the northern part of the province. Uranium occurrences are found in Archaean granitoid rocks, in Aphebian supracrustal remnants and at or close to the Athabasca Group-crystalline basement contact. Almost all of the known uranium deposits of Saskatchewan lie to the west of the Needle Falls Shear Zone (Lewry and Sibbald, 1979), a major lineament that has been tentatively correlated with the North American Central Plains conductivity anomaly (Camfield and Gough, 1977). These geological relationships, as well as the main lithostructural domains, are shown in fig. 1.

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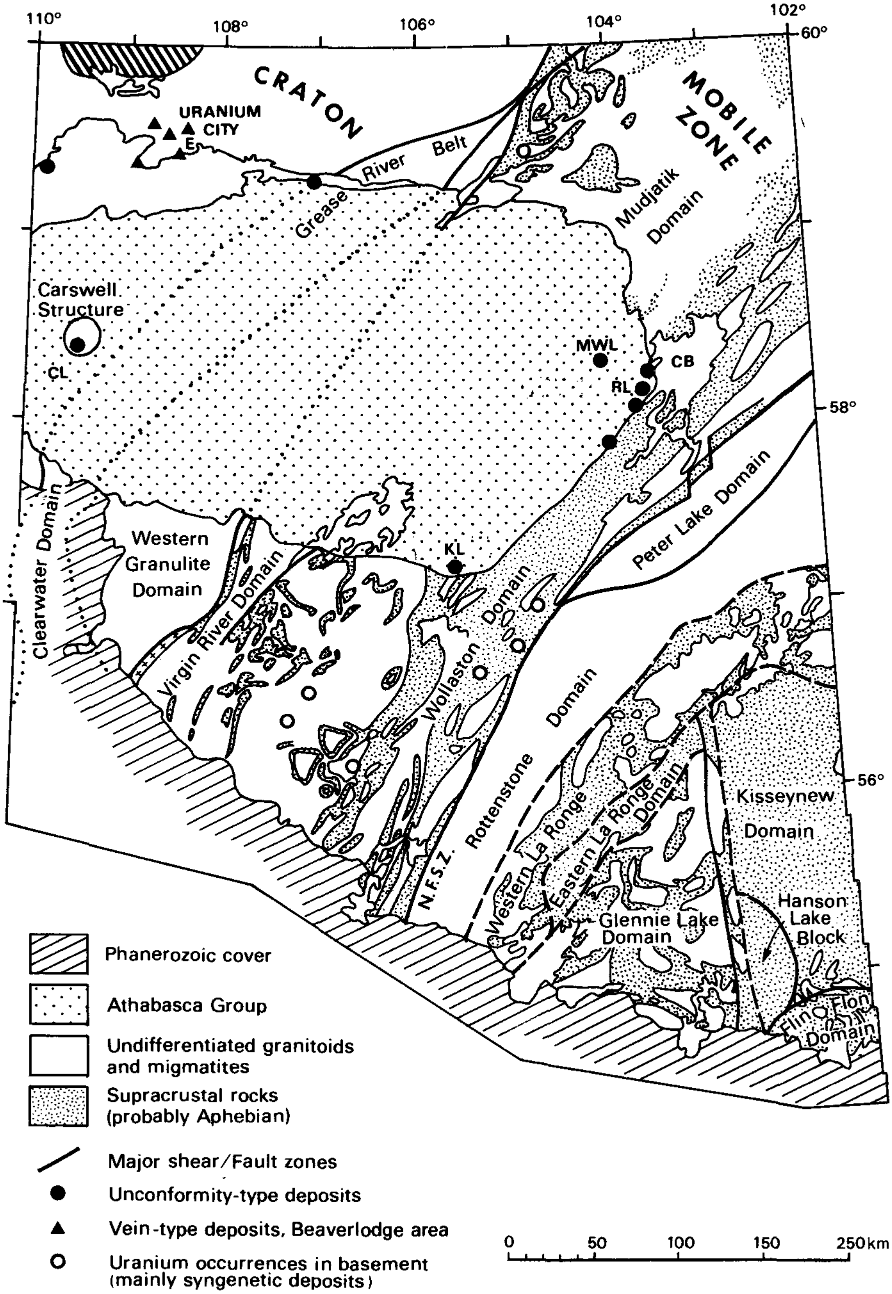

FIG. 1. Geological map of N. Saskatchewan (after Lewry *et al.*, 1978; Macdonald and Broughton, 1980) showing the distribution of the main uranium occurrences. Labelled deposits are as follows: C.B. = Collins Bay, C.L. = Cluff Lake, E. = Eldorado, K.L. = Key Lake, M.W.L. = Midwest Lake, and R.L. = Rabbit Lake. Diagonal hatching in upper left hand corner of diagram shows the Nolan Block, an area apparently unaffected by the Hudsonian Orogeny. N.F.S.Z. = Needle Falls Shear Zone.

Although the Saskatchewan uranium deposits are, in detail, complex they can be broadly divided into two groups (Hoeve, 1978): (i) syngenetic deposits including uranium in pegmatites, calc-silicates and other supracrustals involved in the Hudsonian Orogeny, and (ii) epigenetic deposits including the well-known vein-type deposits of the Beaverlodge area and the unconformity deposits associated with the basement-Athabasca contact. Although the syngenetic deposits are not, at present, economically important, some epigenetic deposits are of considerable grade and may average several percent of U_3O_8. The variation, both in type and tonnage, of these deposits has produced a great deal of speculation about their origin including a variety of mechanisms that range from hydrothermal deposition through to supergene enrichment. An excellent summary of prevailing ideas can be found in the volume of collected papers called 'Uranium in Saskatchewan' published by the Saskatchewan Geological Society and edited by C. E. Dunn (1977).

Many of the current arguments related to the origin of the Saskatchewan deposits have been summarized by Beck (1977) and Hoeve *et al.* (1980). In an interesting historical overview Beck (1977) points out that many of the arguments involve interpretation of age and temperatures of formation. Because the epigenetic deposits are economically the most significant they have attracted a great deal of attention. Among the proposed mechanisms of origin are: (i) deposition from either magmatic or metamorphic solutions of relatively deep-seated origin (Beck, 1969, 1970; Tremblay, 1970, 1972; Little, 1974; Munday, 1978), (ii) supergene enrichment by migrating groundwaters (Knipping, 1971, 1974; Langford, 1974), and (iii) deposition from diagenetic solutions (Hoeve and Sibbald, 1978).

The present paper attempts to relate Saskatchewan uranium mineralization to geochronological work carried out in the province. A recent programme of whole-rock Rb-Sr determinations and a review of other determinations in the province, summarized by Bell and Macdonald (in prep.), are largely drawn on in this presentation. Wherever possible all dates quoted in this paper are based on the internationally agreed-upon decay constants that are summarized by Steiger and Jäger (1977). All dates are rounded off to the nearest 5 Ma. An attempt is also made to summarize and integrate some of the geochronological data with the available geochemical and field information. A number of important questions relating age and uranium mineralization are dealt with. At what time was the uranium concentrated? Was the uranium re-worked and if so when? How old are the Athabasca sediments?

Dating of the uranium deposits. During the fifties, when attention became focused on the Beaverlodge deposits, some attempts were made to define the age of uranium-rich minerals by the U-Pb method (Robinson, 1955). In any well-behaved uranium-bearing mineral the two independent $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ dates should yield identical results, which in turn should agree with a third, but not independent, $^{207}Pb/^{206}Pb$ date. Most U-Pb dates from uranium-bearing minerals are however, discordant and this is partly due to the ease with which radiogenic Pb migrates out of the system, particularly if the minerals have been affected by regional metamorphic activity. Most of the dates in the Beaverlodge area are known to be discordant. Other factors that have supposedly contributed to the discordancies in the Beaverlodge area are the presence of various generations of pitchblende, in other words uranium mobilization (Koeppel, 1968), and disequilibrium in the uranium series by the gaseous diffusion of radon (Robinson, 1955).

The vein-type deposits in the Beaverlodge area fall into two groups. The most important group is characterized by a simple mineral assemblage (pitchblende, hematite, and pyrite) while the other has a complex mineralogy that includes not only these minerals but also substantial amounts of sulphides and arsenides of Ni, Co, and Bi as well as gold and silver (Tremblay, 1958, 1978). Koeppel's (1968) detailed work on samples from the Beaverlodge area showed that the syngenetic occurrences, mainly uraninite in pegmatites, were considerably older than the vein-type deposits and that the vein-deposits had been re-worked throughout their history. Re-calculation of Koeppel's data using more recent decay constants for U and using the same episodic Pb-loss model for the data from the epigenetic pitchblendes of simple mineralogy yielded an age of 1750 ± 25 Ma and a lower intercept of about 85 Ma (see line 'a', fig. 2; Koeppel, 1968). Although it is difficult to interpret the lower intercept, the upper one is thought to indicate the age of the uranium mineralization. Almost concordant U-Pb dates from four euhedral pitchblendes also cluster around 1740 Ma. The concordancy between the pitchblende dates and those of the main Hudsonian thermal event at 1740 Ma (see fig. 2) suggests that the uranium mineralization occurred during a major phase of the Hudsonian Orogeny.

The uraninite-bearing pegmatites of the Beaverlodge area are considerably older than the pitchblende veins and although the U-Pb dates are discordant, a continuous diffusion trajectory through the data points indicates a date for the uranium that is almost 100 Ma older than that concentrated in the pitchblende veins (Koeppel, 1968). Whichever model is used (i.e. an episodic Pb-loss or continuous diffusion model), the dates are still older than those from the vein-type deposits and range from 1875 to 1855 Ma with an uncertainty of about 20 Ma.

Much younger ages have been obtained from the unconformity deposits than either of the two uranium occurrences just mentioned. Pitchblendes from the Key Lake uranium deposit (Wendt *et al.*, 1978) define intersection dates of about 1200, 920, and 270 Ma, while Dahlkamp (1977) reports an age of about 1100 Ma from the same deposit. Data from Cluff Lake, located at the southern end of the Carswell Structure, indicate uranium mineralization at 1050 ± 50 Ma, with a second mineralizing event at about 800 Ma (Gancarz, 1979). An age of 1280 Ma (Cumming and Rimsaite, 1979) was indicated from Pb-depleted, U-bearing pitchblendes from the Rabbit Lake deposit, while a second discordia indicated a significantly younger mineralizing event at about 1085 Ma. The latter agrees with a previously published figure of 1075 Ma (Little, 1974).

In summary, the isotopic data from the uranium occurrences indicate syngenetic uranium mineralization at about 1860 Ma, the formation of vein-type deposits in the Beaverlodge area at about 1750 Ma, and possible deposition of the unconformity-type deposits at irregular intervals between 1300 and 800 Ma ago.

Regional geochronology. One of the key questions involves the possible role of Hudsonian magmatism and metamorphism in concentrating and transporting uranium prior to its deposition. Recent whole-rock Rb-Sr work (Bell and Blenkinsop, 1980; Bell and Macdonald, in prep.) has started to reveal the complexity of the Hudsonian Orogeny in Saskatchewan.

Single mineral K-Ar dates obtained mostly from micas during the early reconnaissance studies of the Geological Survey of Canada, when plotted on a conventional histogram (fig. 2), show a bimodal distribution with peaks at about 2350 and 1740 Ma. The oldest dates are preserved in granitoid gneisses almost entirely restricted to the Nolan Block, north of Uranium City (fig. 1). This at present seems to be the only part of the province where the K-Ar system still retains Kenoran dates. The remaining 99% of the crystalline rocks of Saskatchewan has been pervasively affected by the Hudsonian Orogeny.

Although there are difficulties in trying to estimate the onset of the Hudsonian Orogeny, the range of post-Kenoran K-Ar dates implies a fairly

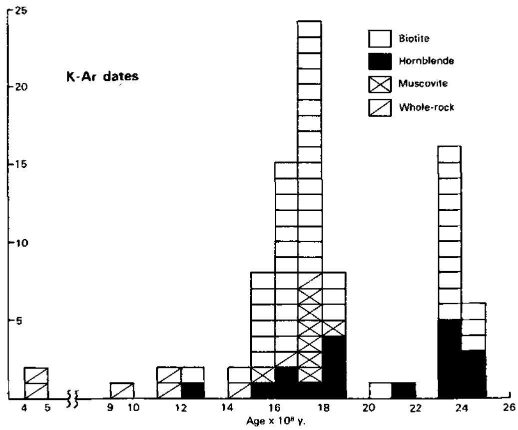

FIG. 2. Histogram of K-Ar dates from Saskatchewan (after Bell and Macdonald, in prep.). Included are dates from both metamorphosed and unmetamorphosed rocks. The younger dates between 400 and 500 Ma are from the Carswell Structure.

complicated thermal history for the region, involving either prolonged cooling or a series of superimposed metamorphic events that ended about 1550 Ma ago. To generalize about the spatial distribution of the K-Ar dates is difficult but there does seem to be a tendency for dates less than 1700 Ma to be restricted more towards the south-eastern corner of the province.

The relationships of some of the deposits to major faults and fractures together with extensive alteration led early workers to believe that the uranium was transported from depths by hydrothermal solutions associated with igneous activity. Several new whole-rock Rb-Sr (many unpublished) and U-Pb mineral dates from Saskatchewan have outlined a metamorphic and magmatic history for the areas adjacent to and within the Hudsonian orogen that is much more complicated than the one indicated by the K-Ar data. Some of the new dates are referred to in Bell and Blenkinsop (1980) and summarized in Bell and Macdonald (in prep.). The oldest event so far recognized at 2500 Ma (U-Pb, zircon) includes the intrusion of the Johnson River granite, a basement inlier in the Wollaston Domain, and the Peter Lake Complex (U-Pb, zircon), a dioritic-tonalitic body that forms part of the Peter Lake Domain (Ray and Wanless, 1980). Subsequent magmatic events at about 1870 Ma (Ray and Wanless, 1980; Carleton University, unpublished data) that include the Wathaman batholith (Rottenstone Domain) and at 1740 Ma are now documented; the latter includes granitoid bodies intruded into the Virgin River, Wollaston, and La Ronge Domains (Carleton University, unpublished data). Because the 1740 Ma figure is based on whole-rock Rb–Sr isochron data it is thought to represent the average age of a distinct magmatic event and not just a figure that reflects an updating of older granites by the Hudsonian Orogeny. Whole-rock Rb–Sr isochron dates from lamprophyre dykes of 1740 ± 70 Ma in the north-western part of the province have been documented by Sassano *et al.* (1974).

There is some indication from both radiometric studies and petrofabric work that each of the 2500, 1870, and 1740 Ma magmatic events was accompanied by metamorphic activity. The whole-rock Rb–Sr method has revealed a significant metamorphic event at about 1670 ± 70 Ma in the Liz and Planinshek Lakes area, Glennie Lake Domain. This event may be younger than the 'main' 1740 Ma peak but with the available information no significance, as yet, is attached to this interpretation. A significantly younger event at 1540 Ma, based on a whole-rock Rb–Sr isochron, from a charnockitic enderbite in the Kisseynew Domain in the south-eastern part of the province is tentatively interpreted as an uplift age primarily because similar rocks along strike in Manitoba give ages that are significantly older at about 1740 Ma (McRitchie, pers. comm., 1979).

The Hudsonian Orogeny closed with uplift and the deposition of the Athabasca Group sediments, a series of supracratonic terrestrial and marine sandstones, conglomerates and siltstone-pelites, that unconformably overlie a well-developed, hematized regolith up to 50 m thick. The age of the Athabasca is bracketed by the 1740 Ma main Hudsonian event and by the emplacement of the Cree Lake dyke swarm, some 1300 Ma ago (Burwash *et al.*, 1962; Wanless *et al.*, 1974). Whole-rock Rb–Sr dating of the sediments themselves indicate an age of 1340 ± 50 Ma (Ramaekers and Dunn, 1977) although an assessment of recent whole-rock Rb–Sr data from the Wolverine Point Formation, an interbedded sand, silt, and mudstone succession within the Athabasca Group (Ramaekers, 1979), suggests a somewhat older age estimate of about 1450 ± 50 Ma (Carleton University, unpublished data; Ramaekers, pers. comm. 1980). No matter which of the currently available dates is accepted there seems to be little doubt that some, if not all, of the unconformity-type deposits are significantly younger than the Athabasca Group sediments and that the uranium mineralization post-dates the deposition of the sediments. Geological evidence also favours this conclusion.

Reworking of deposits. Many of the uranium deposits are known to have been reworked at various stages throughout their history, but to what extent this is due to circulating groundwater or metamorphic or magmatic fluids depends on temperatures of deposition and the time of re-working. Temperature estimates for the vein-type deposits are in excess of 400 °C (Robinson, 1955; Sassano *et al.*, 1972) while significantly lower values have been suggested for the unconformity-type deposits.

The mineralogical evidence and the U–Pb isotopic data suggest that the re-working was extensive. At least six stages in the paragenesis of the Beaverlodge deposits were demonstrated by Robinson (1955), while Rimsaite (1978) recognized five types or generations of pitchblendes from deposits south of Lake Athabasca. Re-working is also supported by some isotopic data. A discordia from Beaverlodge pitchblende samples intergrown with both specular or colloform hematite (Koeppel, 1968) gave an upper intercept date of 1100 ± 50 Ma and this was interpreted in terms of expulsion of radiogenic Pb from pitchblende at the time the hematite was deposited. Enriched radiogenic Pb from co-existing galena and clausthalite was also considered to have been derived from much older (*c.*1740 Ma) pitchblende. Other re-working events were indicated at about 300 Ma, and between 0 and 100 Ma. In passing it is interesting to note that the hematite in the Beaverlodge pitchblendes is associated with copper selenides. In the Rabbit Lake area the formation of uraniferous phyllosilicates and coffinite occurred about 440 Ma and *c.*200 Ma ago (Cumming and Rimsaite, 1979), while the replacement of pitchblende by sulphides, selenides and arsenides, along with migration of radiogenic Pb and mobilization of uranium from pitchblende, took place sometime after 800 to 900 Ma ago. Both Wendt *et al.* (1978) and Gancarz (1979) show a second episode of uranium mineralization at about 850 Ma with later disturbances at about 250 Ma.

From available data it is difficult to relate either the primary age of the unconformity-type deposits or any of the later re-working events to any well-defined tectonothermal events within the Hudsonian orogen. Alternative correlations must be sought.

Regional synthesis. A summary is given in fig. 3 of the geochronological information currently available from Saskatchewan. Several important features emerge from it:

(i) Granitoid activity at 1870 Ma and both granitoid and metamorphic activity at about 1740 Ma can be correlated with uranium mineralization of the same age.

(ii) The Cluff Lake, Key Lake, Rabbit Lake, and probably by analogy, other major deposits are certainly younger than the age of the Athabasca sediments and younger than any of the metamorphic and granitoid events that have so far been

AGE	GRANITOID ACTIVITY	METAMORPHIC ACTIVITY	DYKES	URANIUM MINERALIZATION
800–1300 m.y.			Diabase dykes	Cluff Lake Key Lake Rabbit Lake
1400–1500 m.y.	Deposition of the Athabasca sediments			
~1540 m.y.		Uplift and cooling		
~1740 m.y.	Hickson Lake pluton Junction pluton Macoun Lake pluton Middle Lake pluton	Main Hudsonian Event	Lamprophyre dykes	Beaverlodge (vein type)
~1870 m.y.	Wathaman batholith	? ? ?		Beaverlodge (pegmatites)
~2500 m.y.	Johnson River 'granite' Peter Lake complex			

FIG. 3. Summary of the geochronological information.

documented from this part of the Churchill Province.

(iii) The youngest known Proterozoic igneous event in northern Saskatchewan involved the emplacement of the northwest-trending diabase dyke swarm at about 1300 Ma.

This information as well as the known field relationships of the Beaverlodge vein-type deposits add support to the metamorphic hydrothermal and magmatic hydrothermal models (e.g. Beck, 1969, 1970; Tremblay, 1978) that attribute much of the concentration and transportation of uranium to events of Hudsonian age. The variable initial $^{87}Sr/^{86}Sr$ ratios of the 1740 Ma granites from 0.7020 to 0.7120 implies, in the simplest interpretation, that these bodies were derived from a variety of sources and that some crustal components were involved in their formation. It is interesting to note that some of the 1740 Ma granites show an enrichment in uranium (Sibbald, pers. comm., 1981).

The source of uranium for the younger unconformity-type deposits does not present a problem since concentrations of uranium were available from a variety of sources, including syngenetic uranium in pegmatites, epigenetic vein-type deposits, uranium-rich arkosic, pelitic and calc-silicate horizons in Aphebian supracrustals, and uranium associated with the Athabasca sediments. The real problem involves the way in which the uranium was taken into solution, transported and subsequently deposited at or near the Athabasca-basement unconformity. Four features of the unconformity-type deposits require explanation: (i) their deposition and reworking between 1300 and 800 Ma ago, (ii) their formation temperatures of about 200 °C (Little, 1974; Pagel, 1975), (iii) their post-Athabasca age, and (iv) their concentration at or near the unconformity.

The dates between 1300 and 800 Ma are difficult to correlate with any known metamorphic or granitic event in the immediate region, but in other parts of the Canadian Shield this period was one of large-scale faulting and rifting (sometimes associated with the emplacement of deep-seated rocks such as carbonatites and syenites), extensive basic magmatism in the Lake Superior region, and intense deformation in the Grenville Province. The only event that both temporally and spatially overlaps with the deposition of the unconformity-type deposits is the emplacement of the Cree Lake dyke swarm known to be, on both isotopic and geological grounds, younger than the Athabasca sediments.

Conclusions. The isotopic data suggest that the uranium in the Archaean rocks and in the Aphebian supracrustal succession underwent repeated re-working, concentration, and enrichment during a series of metamorphic and magmatic processes during a period of about 250 Ma that started some

1900 Ma ago. Sometime after 1500 Ma, uranium, both in the basement and in the Athabasca basin sediments, was then taken into solution, transported and under the right conditions deposited at the Athabasca-basement contact. The repeated metamorphism of a basement, already partly enriched in uranium, coupled with the additional concentration of uranium by both magmatic and sedimentary processes led to favourable abundance levels, perhaps on a local scale, in the continental crust. This uranium then became available for transportation by fluids. The geochronological information at present indicates: (i) granitoid magmatism at about 2500 Ma, (ii) granitoid magmatism and uranium mineralization at about 1870 Ma, (iii) the main Hudsonian metamorphism at about 1740 Ma with associated magmatism and uranium mineralization, (iv) uplift of crustal segments, perhaps accompanied by partial melting, between 1540 and 1500 Ma ago, (v) deposition of the Athabasca succession shortly thereafter, and (vi) intrusion of the Cree Lake dyke swarm with synchronous and/or subsequent low-temperature hydrothermal activity and the formation of the late Proterozoic unconformity-deposits.

The conclusions of Beck (1977), Hoeve and Sibbald (1978), Tremblay (1978), and Lewry and Sibbald (1979) that the Beaverlodge ores originated by metamorphic-magmatic hydrothermal processes and the unconformity-type deposits by a deep-groundwater or low-temperature hydrothermal system are consistent with the isotopic data presented here.

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