

Fluid History of the Athabasca Basin and Its Relation to Uranium Deposits¹

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Studies of clays and other minerals in and around unconformity-uranium deposits of the Athabasca Basin have resulted in genetic models that involve interaction between high-temperature basin and basement fluids at the unconformity between Archean metasedimentary and overlying Helikian sedimentary rocks (Hoeve and Sibbald, 1978; Hoeve and Quirt, 1984 and 1986). These models have been further refined by isotopic and fluid inclusion studies (Pagel *et al.*, 1980; Bray *et al.*, 1988; Wallis *et al.*, 1983; Wilson and Kyser, 1987; Kotzer and Kyser, 1990), which indicate that uranium mineralization has resulted from mixing of a high salinity, metal-bearing basinal brine with a reducing basement fluid at temperatures of 200°C along well-developed fault zones. Zones of fluid mixing are marked by well-developed geochemical haloes containing illite, tourmaline, Mg-chlorite, euhedral quartz and Ni-Co-As and Cu sulfides. A regional diagenetic assemblage of illite and kaolinite occurring within the Manitou Falls Formation throughout the basin attests to the high permeability of the sediments in the basinal aquifers that allowed large-scale fluid flow.

Late-stage incursion of low-temperature meteoric fluids into the basin along the fault zones which host the uranium deposits has altered the isotopic and chemical compositions of both the clay and uranium minerals. Relatively young K-Ar ages of illite and U-Pb ages of uranium minerals, formation of kaolinite in the fault zones, remobilization of uranium into fractures in the re-activated fault zones (Wilson and Kyser, 1987; Kotzer and Kyser, 1990) and formation of secondary sulphides with highly variable $\delta^{34}\text{S}$ and Pb isotopic compositions (Kyser *et al.*, this volume) are all indicative of these late-stage fluid events.

The various types of fluids and fluid-flow events have characteristic mineralogical and geochemical signatures, so that it is likely that the metallogenic and mineralogical evolution of the Athabasca Basin has been controlled by large scale fluid events associated with prograde and retrograde basin diagenesis. The association between fluid flow events, basin diagenesis, and uranium ore formation in the Athabasca Basin is similar to the mechanism of ore formation in other types of sediment-hosted

mineral deposits (Gustafson and Williams, 1981).

This report summarizes data from stable and radiogenic isotope and fluid inclusion analyses obtained mainly from uranium deposits in the southeastern portion of the Athabasca Basin (Figure 1) and places them within a fluid evolution framework.

1. Fluid Inclusion and Isotopic Evidence for Fluid Movements in the Athabasca Basin

The results of petrographic work carried out by CAMECO combined with stable and radiogenic isotopic compositions, fluid inclusion and scanning electron data allow formulation of a fluid-mineral-age paragenesis of the Athabasca Basin (Figure 2).

Correlations between the petrographic and geochemical data indicate that many of the basin-wide events which

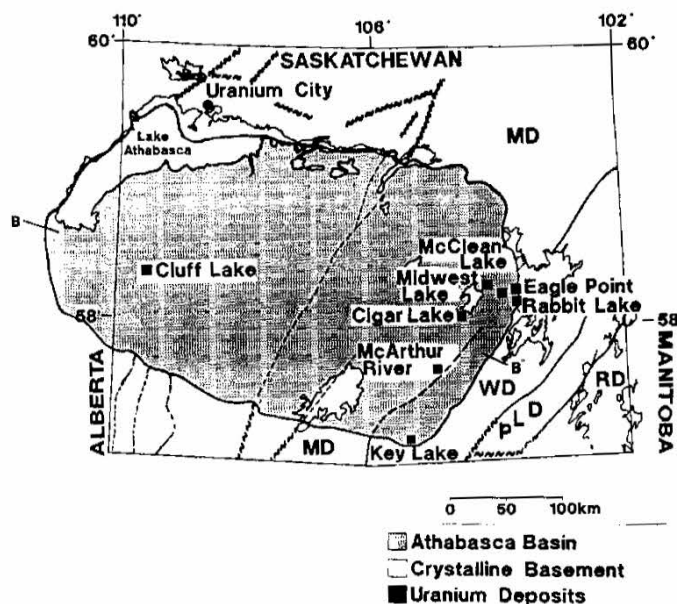


Figure 1 - Map indicating the present extent of the Athabasca Basin, locations of uranium deposits and major lithostructural domains in the crystalline basement of Saskatchewan (after Hoeve and Sibbald, 1978). MD = Mudjatik Domain, WD = Wollaston Domain, PLD = Peter Lake Domain, RD = Rottenstone Domain.

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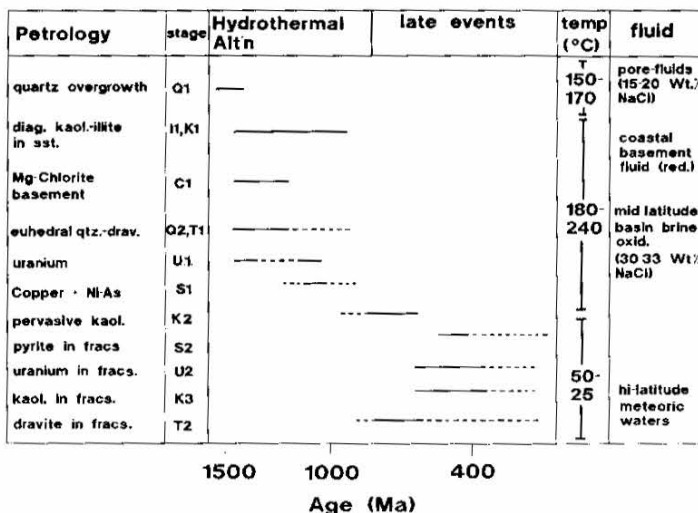


Figure 2 - Fluid-mineral-age relationships for various minerals within the Athabasca Basin developed from petrographic work, stable and radiogenic isotopes and fluid inclusion analyses. Data used for correlations are from drill core and hand specimens from Key Lake, McArthur River (Bermuda and Phoenix Lake), Eagle Point and Midwest Lake.

are seen petrographically have distinct temperatures and stable isotopic composition. Initial diagenesis (Q1), evolved to high-temperature basin diagenesis, basin-basement fluid mixing, and polymetallic uranium mineralization (I1-K1, C1, Q2-T1, U1, S1), followed eventually by uplift and fracturing of the basin resulting in incursion of oxidizing meteoric fluids producing retrograde mineral assemblages and destruction of the previously formed unconformity-type uranium deposits (K2, S2, U2, K3, T2). Some of the later events, such as late kaolinite formation and remobilization and destruction of uranium deposits, are a continuum of events which began around 800 Ma and have persisted periodically until the past few million years (Figure 2).

a) Fluid Inclusions

Microthermometric analysis of fluid inclusions in paragenetically distinct mineral phases from the McArthur River Area (Bermuda and Phoenix Lake) and Eagle Point North indicate that there was an increase in the salinity and temperature during early prograde diagenesis and a subsequent decrease in temperature and salinity of the fluids involved with late retrograde diagenesis. The temperatures and salinities of fluids determined in the fluid inclusions from the McArthur River Area and Eagle Point are similar to the fluids in inclusions measured in equivalent phases at Cluff Lake and Rabbit Lake (Pagel *et al.*, 1980) thereby indicating that these fluids were basinal in extent.

Primary, two-phase, H₂O fluid inclusions (representative of the earliest diagenetic fluid within the basin) occurring along the interface between the original detrital quartz grain and the quartz overgrowth (Q1), have homogenization temperatures of 80 to 180°C and salinities from 5 to 28 wt.% NaCl equivalents (Figure 3 a + b). The large range of homogenization temperatures and salinities of

the inclusions reflects heterogeneities in the composition of the fluids during the initial stages of basin diagenesis.

Primary, three-phase, H₂O fluid inclusions, containing halite, hematite and phyllosilicate daughter minerals, are found along well-developed growth planes in euhedral quartz (Q2) associated with the fluid producing the uranium deposits. Primary fluid inclusions in the euhedral quartz yield homogenization temperatures of 120 to 340°C and salinities of 29 to 36 wt.% NaCl equivalent (Figure 3 a + b). In addition, the fluids within the inclusions have a δD value of -53 per mil. This value is similar to the δD value of the basinal fluid calculated to be in equilibrium with early diagenetic illite (I1) which is found pervasively throughout the sandstones in the Athabasca Basin (Wilson and Kyser, 1987; Kotzer and Kyser, 1990).

Two-phase, H₂O fluid inclusions having homogenization temperatures of 40 to 60°C and salinities of 2 to 5 wt.% NaCl equivalent are found in siderite having a similar paragenesis to the late kaolinite (K3)

in fractures in the McArthur River Area (Figure 3a). These low temperatures and salinities represent late-stage meteoric waters which infiltrated the basin and destroyed some of the uranium deposits.

b) Stable Isotopes

Stable isotopic compositions (O and H) of clay minerals and silicates at Key Lake, Midwest Lake, Eagle Point and McArthur River (Wilson *et al.*, 1987; Kotzer and Kyser, 1990) indicate uranium and other metals were deposited by mixing of high salinity basinal brines, represented by the three-phase fluid inclusions in euhedral quartz (Q2) and diagenetic illite and kaolinite (I1, K1), with reducing basement fluids which produced Mg-chlorite (C1) (Figure 4). The occurrence of an illite alteration halo in the sandstones, a Mg-chlorite halo in the basement pelites and gneisses, and uranium which is concentrated in fault zones at the unconformity where fluids can be channelled suggest fluid interaction of these two fluids are a necessary pre-requisite for sufficient quantities of uranium to form. Although differences exist between the Athabasca Basin deposits, such as the amount and types of metals in the arsenides and sulfides with uranium ore and the degree of clay formation and silicification around the ore, the occurrence of two fluids mixing in structurally controlled areas appears to be the dominant control on uranium mineralization.

Late-stage kaolinite, having δD and $\delta^{18}O$ values similar to modern meteoric waters in the Athabasca Basin, occurs in reactivated fault zones hosting the uranium deposits (Figure 4). The amount of kaolinite formation depends upon the integrated water/rock ratio of the late meteoric fluids in the re-activated fault zones, and ranges from extreme in highly permeable, fractured areas to negligible in areas where early silicification, clay

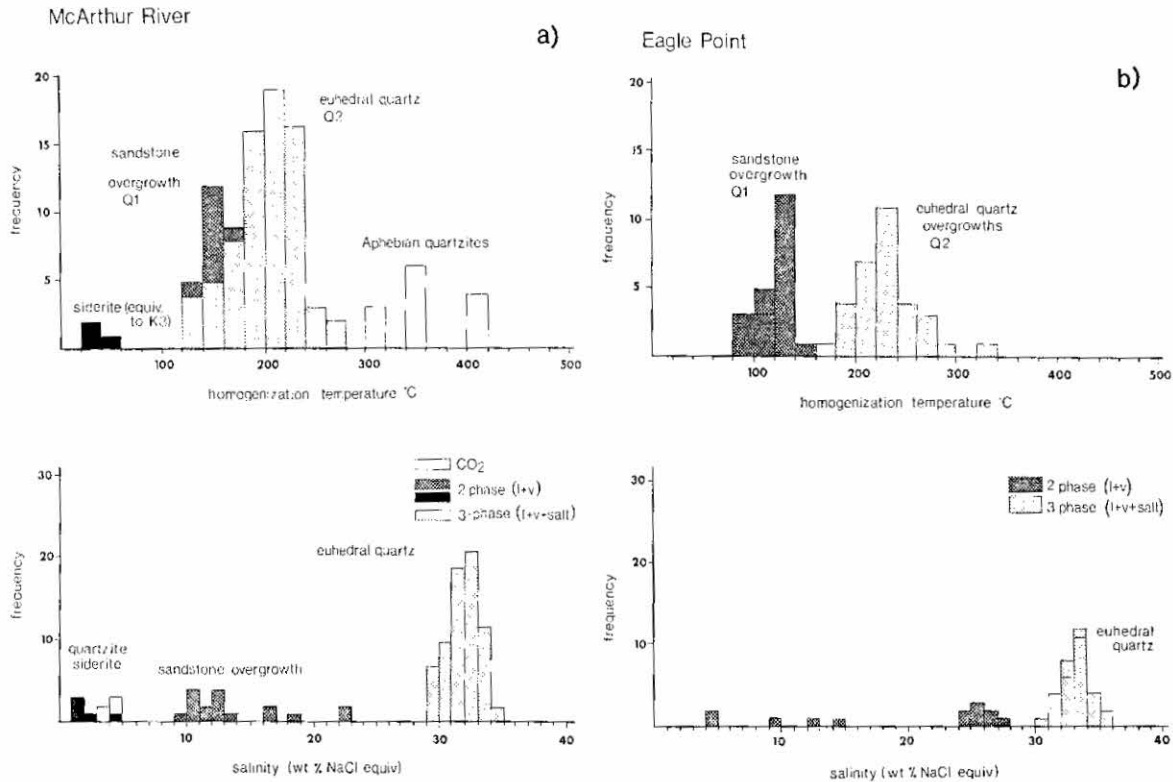


Figure 3 - Fluid inclusion histograms indicating the homogenization temperatures and salinities of fluid inclusions occurring in paragenetically distinct minerals at a) McArthur River (Bermuda and Phoenix Lake) and b) Eagle Point North. Similar fluid inclusion temperatures and salinities in euhedral quartz at both McArthur River and Eagle Point North suggest the basinal fluid was quite pervasive.

development or restricted fault movements have impeded permeability. As most of the uranium deposits examined so far in the Athabasca Basin show some evidence of retrograde alteration, it can be concluded that the later, low-temperature fluid event was widespread. Therefore, the condition of the uranium ore deposits today is dependant upon the amount of permeability existing around the uranium deposits at the time of incursion of the later, oxidizing fluids.

Sulphur isotopes from sulphides occurring with uranium ore lend further support to the model involving mixing of reducing basinal fluids and oxidizing basinal fluids in fault structures that have focussed fluid flow. Nickel arsenide and sulphide at Key Lake and copper sulphide minerals at Bermuda Lake, directly associated with uranium minerals, and considered to be paragenetically equivalent (S1), have $\delta^{34}\text{S}$ values indicative of mixing between two isotopically distinct sources and sulphide formation during relatively closed-system, reducing conditions (Kotzer *et al.*, in prep.). Later formed iron sulphides peripheral to the uranium have a large range of $\delta^{34}\text{S}$ values which indicate sulphide formation during highly variable $f\text{O}_2$ conditions resulting from incursion of

meteoric waters along re-activated fault structures hosting the uranium deposits.

The occurrence of highly variable, anomalously high $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios in most of the sulphide minerals analyzed in the Athabasca Basin suggests high lead mobility due to alteration of uranium mineralization by the numerous fluid events which have affected the Athabasca Basin (Kotzer *et al.*, in prep).

c) Radiometric Age Determinations

The wide range of ages from the uranium mineralization and sediments (Tremblay, 1982) reflects the complex fluid history of the Athabasca Basin. However, the general overlap of U-Pb ages from uranium mineralization and Rb-Sr ages of diagenetic clay minerals in the Athabasca sediments suggests that uranium mineralization and high temperature basin diagenesis are closely linked (Kotzer and Kyser, 1990).

The timing of the high temperature diagenesis event in the sediments of the Manitou Falls Formation has been determined using Rb-Sr systematics on interstitial illites having similar $\delta^{18}\text{O}$ and δD values. A Rb-Sr isochron

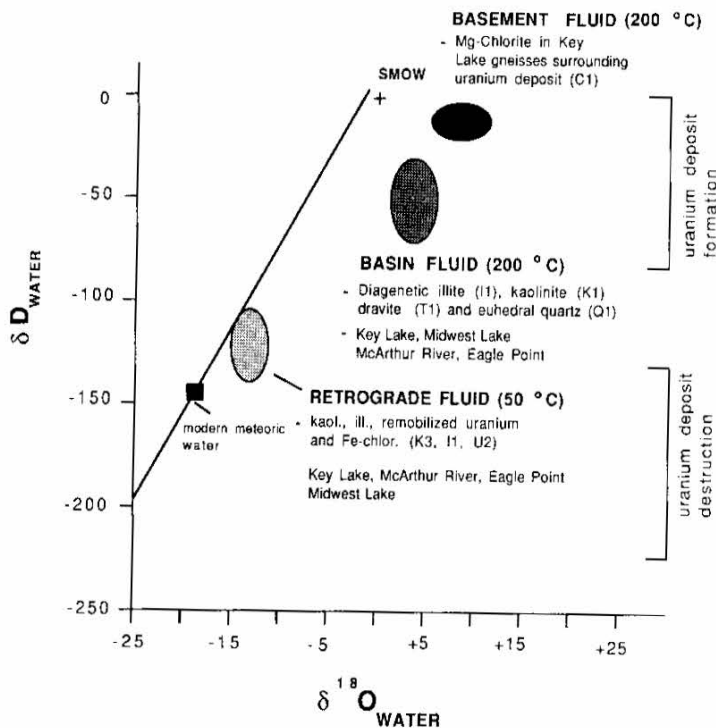


Figure 4 - Calculated $\delta^{18}\text{O}$ and δD values for various fluids associated with unconformity-type uranium deposits in the Athabasca Basin. Shaded areas represent fluids in equilibrium with: 1) Mg-chlorite formed at approximately 200°C in basement rocks at Key Lake (Wilson and Kyser, 1987) and Bermuda Lake in the McArthur River area (Basement Fluid), 2) diagenetic illite at 200°C from Key Lake, Midwest Lake (Wilson and Kyser, 1987), McArthur River and Eagle Point (Kotzer and Kyser, 1990) (Basin Fluid) and, 3) kaolinite associated with remobilized uranium in fractures which is similar to the fluids measured in fluid inclusions in siderite. Also shown are the values for modern meteoric waters in the Athabasca Basin, the meteoric water line (MWL) and ocean water (SMOW).

age of 1477 ± 57 Ma (Figure 5a) for diagenetic illite formation in the Athabasca sediments pre-dates the earliest age for uranium emplacement at 1406 Ma (Carl *et al.*, 1988) in the basin and suggests that large-scale fluid flow occurred before uranium mineralization. The time difference of approximately 50 Ma between high temperature diagenesis and uranium emplacement would allow the fluids to leach sufficient quantities of uranium from heavy minerals in the Athabasca sediments.

Euhedral quartz-dravite (Q2-T1) assemblages occur in the hydrothermally altered sediments associated with the uranium deposits in the Manitou Falls Formation. In some areas of the Athabasca Basin, strongly developed zones of euhedral quartz-dravite breccias are evident and appear to be the result of early dissolution of Athabasca sandstones. An Rb-Sr age of approximately 1270 Ma (Figure 5b) has been determined for this event using the Rb-Sr and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from both the tourmaline and fluids extracted from the fluid inclusions in coexisting euhedral quartz. The age determined from this event is similar to the ages of much of the uraninite at Key Lake (Ruhmann, 1987) and some of the diabase dikes (Armstrong and Ramaekers, 1985) in the Athabasca

Basin and possibly represents a major pulse of basement fluids out of the fault zones to mix with basal fluids and further the production of high-grade uranium ore.

At the Eagle Point North uranium deposit, an Rb-Sr model age of 957 Ma has been calculated from illite in altered pegmatite (Figure 5c). The younger age for the illite at Eagle Point may indicate that the high temperature diagenetic fluids in the Athabasca Basin persisted for some time or that the nature of the hydrothermal system was episodic because the illite at Eagle Point has similar δD and $\delta^{18}\text{O}$ values to the illites having an age of 1477 Ma.

2. Conclusions

Stable isotopic, fluid inclusion, and radiometric age determinations on mineral phases having an identifiable paragenesis in the Athabasca Basin suggest a long and protracted fluid history. Fluid inclusion and stable isotopic compositions indicate that the Athabasca Basin was affected by early, high salinity diagenetic fluids having temperatures near 200°C and by later, meteoric fluids having temperatures less than 100°C. Coincident with the high and low-temperature fluid events are periods of uranium deposit formation and destruction, respectively, with the magnitude of uranium formation and destruction directly dependant on the quantities of reactive fluids involved. The late, meteoric fluid event

has remobilized much of the uranium and has had the most pronounced effect on the current state of some of the uranium deposits in the Athabasca Basin. The magnitude of uranium deposit destruction is directly related to the permeability developed within the sediments and fault structures hosting the uranium deposits.

3. References

- Armstrong, R.L. and Ramaekers, P. (1985): Sr isotopic study of Helikian sediment and diabase dikes in the Athabasca Basin, northern, Saskatchewan; *Can. J. Earth Sci.*, v22, p399-407.
- Bray, C., Spooner, E.T.C. and Longstaffe, F.J. (1988): Unconformity-related uranium mineralization, McClean deposits, northern Saskatchewan, Canada: Hydrogen and oxygen isotope geochemistry; *Can. Mineral.*, v26, p249-268.
- Carl, C., Hoehndorf, F., Pechmann, E.V., Strnad, J.G., and Ruhmann, G. (1988): Geochronology of the Key Lake uranium deposit, Saskatchewan, Canada (abstract); *J. Chem. Geol.*, v70, p133.

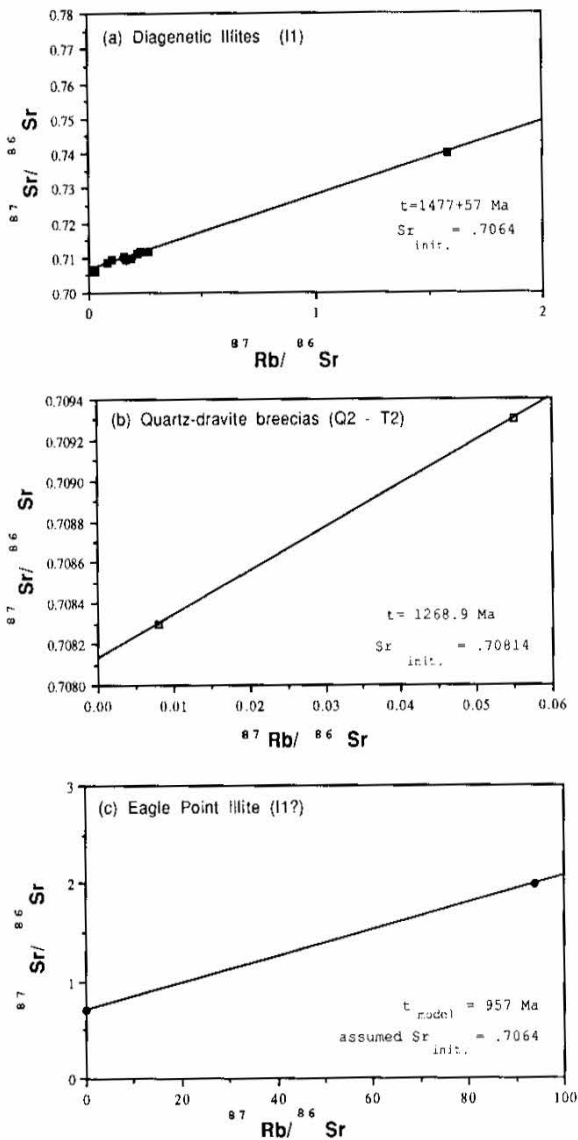


Figure 5 - Rb-Sr isochrons of: a) interstitial, diagenetic illite in the Athabasca sandstones give an age of $1477 \pm 57 \text{ Ma}$, b) the euhedral quartz-dravite event gives an age of approximately 1270 Ma and, c) diagenetic illite at Eagle Point gives an Rb-Sr model age of 957 Ma assuming an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7064 . Varying the assumed initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio would have little affect on the model age.

Gustafson, L.B. and Williams, N. (1981): Sediment-hosted stratiform deposits of copper, lead and zinc; in Skinner, B.J. (ed), Econ. Geol. (Seventy-fifth Anniversary Volume), p139-179.

Hoeve, J. and Sibbald, T.I.I. (1978): On the genesis of Rabbit Lake and other unconformity-type uranium deposits in northern Saskatchewan, Canada; Econ. Geol., v73, p1450-1473.

Hoeve, J. and Quirt, D. (1984): Mineralization and host-rock alteration in relation to clay mineral diagenesis and evolution of the middle-Proterozoic Athabasca Basin, northern Saskatchewan, Canada; Sask. Res. Council., Tech. Rep. #187, 187p.

(1986): A common diagenetic-hydrothermal origin for unconformity-type uranium and stratiform copper deposits; Sask. Res. Council., Publ. R-8555-5-A-81.

Kotzer, T.G. and Kyser, T.K., (1990): The use of stable and radiogenic isotopes in the identification of fluids and processes associated with unconformity-type uranium deposits; in Beck, L.S. and Harper, C.T. (eds.), Modern Exploration Techniques, Sask. Geol. Soc., Spec. Publ. 10, p115-131.

Kotzer, T.G., Kyser, T.K. and Ruhrmann, G., (in prep.): Sulphur and lead isotopic constraints on the sources and ages of the fluids involved with unconformity-type uranium deposits; Can. J. Earth Sci.

Pagel, M., Poty, B. and Sheppard, S.M.F. (1980): Contributions to some Saskatchewan uranium deposits mainly from fluid inclusion and isotopic data; in Ferguson, S. and Goleby, A.B. (eds.), Uranium in the Pine Creek Geosyncline; IAEA, Vienna, p639-654.

Ruhrmann, G. (1986): The Gaertner uranium orebody at Key Lake (northern Saskatchewan, Canada) - After three years of mining: An update of the geology; in Gilboy, C.F. and Vigrass, L.W. (eds.), Economic Minerals of Saskatchewan, Sask. Geol. Soc., Spec. Publ. 8, p120-137.

Tremblay, L.P. (1982): Geology of the uranium deposits related to the sub-Athabasca unconformity, Saskatchewan, Canada; Geol. Surv. Can., Pap. 81-20, 56p.

Wallis, R.H., Saracoglu, N., Brummer, J.J. and Golightly, J.R. (1983): Geology of the McClean uranium deposits; Geol. Surv. Can., Pap. 82-11, p71-110.

Wilson, M.R. and Kyser, T.K. (1987): Stable isotope geochemistry of alteration associated with the Key Lake uranium deposit, Canada; Econ. Geol., v82, p1540-1557.

Wilson, M.R., Kyser, T.K., Mehnert, H. and Hoeve, J. (1987): Changes in the H-O-Ar isotopic composition of clays during retrograde alteration; Geochim. Cosmochim. Acta, v51, p869-878.