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INTEGRATION AND ANALYSIS OF LEGACY BOULDER DATA, SURFICIAL GEOLOGY, AND RADIOMETRIC DATA OVER THE MCARTHUR RIVER URANIUM MINE AREA, SASKATCHEWAN, CANADA

BY

Yaozhu Li

A thesis

submitted to the University of Waterloo

in partial fulfillment of the requirements for the degree of

Bachelor of Science, Geology Specialization

Department of Earth and Environmental Sciences

University of Waterloo

Waterloo, Ontario, Canada

Declaration:

I hereby declare that this thesis, which I submit for the degree of Bachelor of Science, Geology Specialization, at the University of Waterloo, is my original work under supervision of Professor Martin Ross. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Yaozhu Li

University of Waterloo

March 2016

Abstract:

The McArthur River uranium deposit in northern Saskatchewan, Canada, is covered by a circa 500-meter-thick sandstone succession and by a variable-thickness cover of Quaternary sediments, locally in excess of 50 meters. A large database containing over 20,000 boulder descriptions and related geochemical data is available to support mineral exploration in the area. Airborne gamma-ray surveys provide data at a resolution of 100 m X 100 m for surficial radiometric eK (equiv-%), eTh (equiv-ppm), and eU (equiv-ppm) over the Athabasca Basin from which radiometric domains have been defined . The goal of this study is to analyze the boulder and the radiometric data, and assess the potential spatial relationships between the two types of data. Recent research has shown that contrasting tills, a distal till and a local end-member till, occur at the surface across the study area, which appears to match the radiometric domains. There is a clear cluster of anomalous normative illite values extending down-ice from McArthur River, which is within a radiometric domain (A4) characterized by a 'proximal' eTh:K signature. This spatial relationship suggests that the cluster is a true dispersal pattern from local subcropping alteration in the vicinity of the McArthur River uranium mine. Elsewhere in the study area, the patterns are more difficult to interpret. Dispersal patterns of altered sandstone boulders occur in all domains and could have multiple sources along the P2 structure, which hosts the uranium mineralization. More systematic recording of boulder lithologies (fresh and altered sandstones, basement) at each site will be useful in future boulder surveys to understand changing alteration mineral proportions across the different radiometric domains.

Acknowledgement:

I would like to thank my supervisor, Professor Martin Ross, for the opportunity to work on this project about the McArthur River uranium deposit and for his help throughout. Through countless discussions, Professor Martin Ross offered his guidance in this scientific research. I would also thank Shawn Scott, a Master's student with Professor Martin Ross, for the kindness and help he gave during the thesis project. This study was undertaken as part of the joint Natural Sciences and Engineering Research Council of Canada (NSERC) and Canadian Mining Innovation Council (CMIC) project "Integrated Multi-Parameter Footprints of Ore Systems". Fieldwork would not have been possible without the support of Cameco, as they funded the flights to McArthur River and accommodation as part of their in-kind contribution to the Footprints project. Additional support was provided by AREVA Resources Canada, and Denison Mines, especially David Quirt for the useful feedbacks and advice. Thanks also to Ken Wasyliuk who coordinated part of the review of this thesis and also provided several useful suggestions that helped improve the thesis. Funding through CMIC and the NSERC through the Collaborative Research and Development program is gratefully acknowledged. This is ***NSERC-CMIC-Footprints Contribution #102***.

Table of Contents

List of Figures

List of Tables

1. Introduction

The Athabasca Basin in northern Saskatchewan (Fig. 1) hosts numerous uranium deposits (McGill et al., 1993; Earle, 2001; Jefferson et al., 2007). High-grade uranium deposits, such as McArthur River (Fig. 1), are located at the unconformity between Paleoproterozoic sandstone successions and the underlying Aphebian and Archean gneisses and schists (Hoeve et al., 1980; Hoeve and Quirt, 1984; Jefferson et al., 2007). There is also an extensive cover of Quaternary sediments in this region resulting in few bedrock outcrops at surface. These uranium deposits may be deeply buried and may only leave subtle surface expressions of their presence at depth. This type of geological setting makes surface exploration, such as surficial sediment and soil geochemistry, particularly challenging. Exploration for these types of uranium deposits relies heavily on geophysics and drilling of geophysical targets, which is also affected by the thick cover, especially the low-density Quaternary sediment successions.

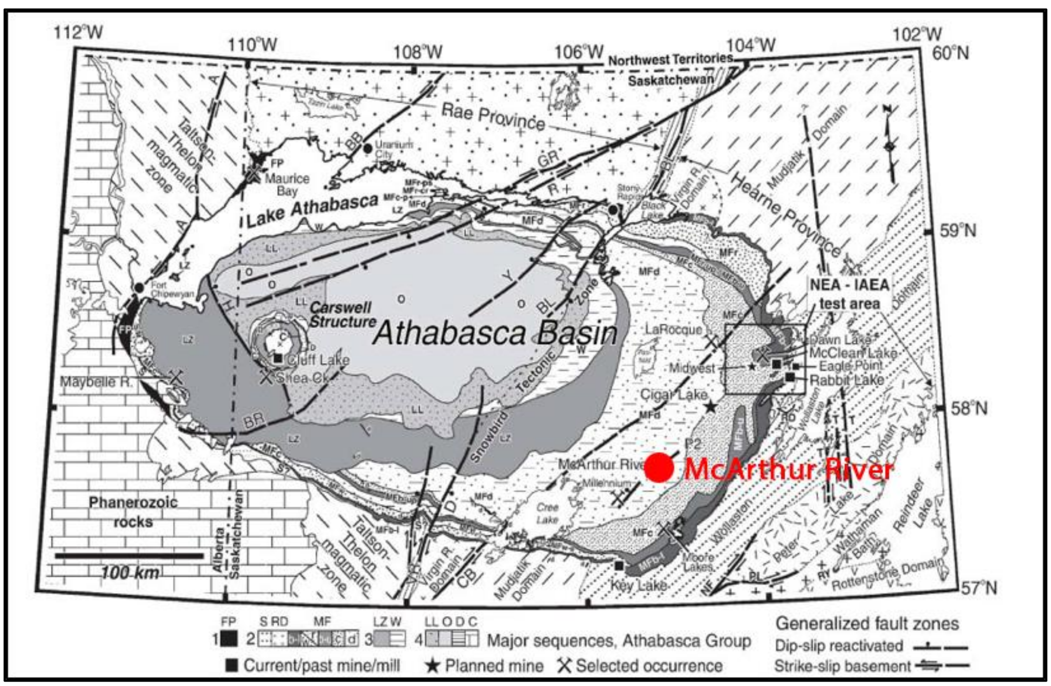


Figure 1. Generalized bedrock geology of the Athabasca Basin, location of mines, and McArthur River. (modified from Jefferson and Delaney, 2007; Campbell, 2009). McArthur River is the main area for this study.

Despite the challenges outlined above, surface exploration has been conducted over several years and interesting patterns were reported (e.g. Earle et al. 2001), which may indicate the presence of a surficial footprint in the vicinity of McArthur River possibly derived from subcropping alteration related to the uranium mineralization, located approximately 500 meters below the buried bedrock surface. The evidence at surface is found as alteration by-products (i.e. various clay mineral~~s~~ species) in glacially-transported sandstone boulders that are considered diagnostic of the alteration halos surrounding buried mineralization (Earle et al. 2001). However, several complications make it difficult to map boulder trains accurately and to relate the dispersal patterns at surface to specific buried sources such as the McArthur River deposit. One complication is that the contrast between alteration assemblages characteristic of the alteration halo and those related to sandstone diagenesis in the basin may be gradational rather than sharp and clear (eg. Hoeve and Quirt, 1984). Another complication is the fact that mineralization and alteration zones are structurally controlled and these structures, such as the P2 fault zone (Fig. 1), are oriented NE-SW approximately parallel to the net SW-trending glacial transport path. Sampling and analytical methodological issues also complicate the integrated use of the legacy boulder data produced over several years using different methods. Finally, the Quaternary sedimentary record of the region is complex (e.g. Campbell 2009), which would have implications for applying boulder tracing methods. This thesis provides an opportunity to: **1)** analyze these issues; **2)** revisit the legacy boulder data, and; **3)** compare with other datasets (radiometric and new glacial geological information) to gain new insights into the dispersal patterns and their significance in terms of glacial transport history and surficial footprint studies.

1.1 Thesis objectives

The specific goals of this study are to: **1)** describe and analyze legacy boulder data; **2)** compare, contrast and interpret altered sandstone boulder dispersal patterns with surficial geology and airborne radiometric data, and, finally; **3)** develop recommendations to improve boulder tracing methods in areas of thick (multi-till) stratigraphy.

2. Background information

2.1 Glacial Geology

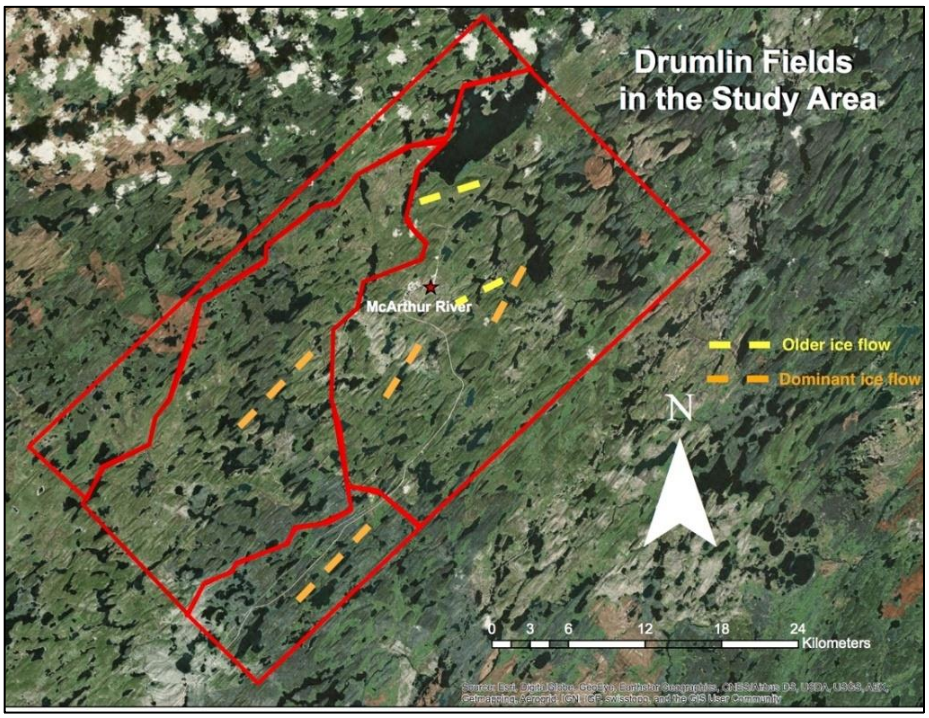


Figure 2. Drumlin fields in the study area. Rectangle box shows the study area. The landscape in the region is characterized by extensive drumlin fields. The yellow dash lines indicate large drumlins formed by an older ice flow; orange dash lines indicate the smaller drumlins formed by later ice flow.

The Athabasca basin region has been affected by multiple glacial flow phases which produced different glacial sediment layers including subglacial tills and other sediments laid down by the melting of the ice sheet. Glacial processes, particularly those of the last glacial episode (Late Wisconsinan), contributed to shaping the current topography and overall landscape of the area (Campbell, 2007, 2009).

The main ice flow direction in the study area, as recorded by outcrop-scale (e.g. striae) and landform-scale (e.g. drumlins) indicators, was to the southwest (Fig. 2; orange flow-set). Smaller drumlins oriented at a slightly oblique angle relative to the large drumlins have also been reported in the region and are interpreted to be the result of late-stage ice flow towards the south-southwest (Campbell, 2007; Fortin et al., 2015).

Tills of different compositions have been identified in the eastern Athabasca Basin (Campbell 2007). At McClean Lake and Rabbit Lake, near the edge of the basin (Fig. 1), at least two end-member tills are recognized at the surface (cf. Campbell 2007, 2009): a basement-rich till informally referred to as Till 2; and a sandstone-rich till (Till 3). In the vicinity of McArthur River, further down-ice into the basin, the till stratigraphy appears to be more complex with multiple stacked till sheets exhibiting hybrid compositions relative to the two end-member tills (Scott et al. 2015). The discontinuous distribution of these tills at the surface is captured by airborne radiometric patterns resulting from contrast in radiometric potassium content (Fortin et al. 2015).

2.2 Bedrock Geology

The Athabasca Basin is an unmetamorphosed Paleo- to Mesoproterozoic (~1.7 Ga) succession of siliciclastic sedimentary rocks, predominantly sandstone. More specific to the study area, the eastern portion of the basin consists of the lower part of the sedimentary succession, mainly the Manitou Falls Formation. It was demonstrated that the original detrital clay matrix of the sandstone was largely replaced during diagenesis by dickite, as well as illite and chlorite (Hoeve and Quirt, 1984; Quirt 2001, Wasyliuk 2002). Other details of the geology and diagenetic history of the basin are found in Hoeve and Quirt (1984), Jefferson et al (2007), and Rainbird et al. (2007), and references therein. A major unconformity separates the base of the basin from the underlying basement rocks. There is also extensive paleoweathering of the basement rocks along that surface. In the study area, basement rocks underlying the unconformity consist of pelitic gneiss and other gneisses of the Wollaston-Mudjatik domains that are folded and intruded by pegmatites (e.g. Jefferson et al. 2007). Details of the genetic models of uranium emplacement are found in Jefferson et al. (2007) and references therein.

Of importance to this study is the recognition of a corridor of anomalous clay mineral proportions relative to regional diagenetic levels, that extends approximately from Key Lake to Cigar Lake (Earle and Sopuck, 1989; Earle et al., 1990) (Fig. 1), and also vertically along fractures through the sandstone sequence. This corridor is thus spatially associated with the uranium deposits in the eastern part of the basin (Jefferson et al. 2007). The alteration that discontinuously subcrops along that corridor is characterized by anomalous relative proportions of illite with zones of anomalous chlorite and dravite (Earle and Sopuck, 1989). Dravite is enriched in boron, which makes it a useful pathfinder element in surficial sediments.

2.3 Boulder tracing

Glacial boulders are rock fragments >256 mm in diameter that have been transported over some distance by glacial processes (Bouchard and Salonen 1990). Boulders originate from the quarrying and plucking of fractured and jointed bedrock, a process which generally take place on the down-ice side of bedrock knobs (Benn and Evans 2010). Boulders at the surface may have been deposited by either downwasting of ice containing rock debris (meltout) or may be derived from the underlying subglacial till. Boulder mantles produced by meltout can have variable boulder frequencies over a certain area, but they tend to contain abundant perched boulders standing on smaller clasts. Dense boulder fields lacking perched boulders are generally considered as lag concentrates produced by various processes which lower the till surface (e.g. washing, deflation, or frost-heaving of till) (Bouchard and Salonen 1990). Boulder streams in drumlin swales, for example, generally occur along meltwater corridors. These characteristics and their interpreted origins are important considerations in boulder tracing studies as they can affect both the concentration of boulders, lithologies, and transport distances.

Tracing mineralized boulders back to their source was the first technique to use glacial sediments for the purpose of mineral exploration. Numerous examples of boulder tracing studies exist in the literature showing the success of the approach in mineral exploration across different glaciated terrains (Bouchard and Salonen 1990; and references. therein). The main advantage of using boulders over till geochemistry is they represent a sample of the source lithology, even after long transport, rather than a mixture of various minerals from multiple sources (Puranen 1990). Mineralized boulders can thus provide important insights into the nature of a buried mineralized zone prior to drilling, and can also help interpret geophysical data. Boulder tracing can be relatively straightforward, especially where a single or dominant ice flow is responsible for the boulder dispersion. However, the erosion, transport, and deposition history is often more complex, making it difficult to relate the head of a dispersal pattern to a precise subcropping location (Bouchard and Salonen 1990). In addition, the capacity of plucked boulders to survive glacial transport, even over short distances, largely depends on the resistance of different lithologies to abrasion and crushing (Bouchard and Salonen 1990). Certain alteration and mineralization styles may be underrepresented due to their soft properties. Kimberlite boulders are an example where their soft and easily eroded nature makes them survive only proximal to their source, and therefore being of only limited use in grass root diamond exploration.

Different techniques have been developed and applied to reconstruct and map a boulder train, which generally involve some measure of frequency of indicator lithologies in a boulder field and abundance/frequency plots. This is based on the common observation that boulders of a specific lithology will reach a maximum frequency close to its source (Bouchard and Salonen 1990), which will decrease down-ice (e.g. exponential decay) (e.g. Klassen 1997), However, several glacial dynamics complications can result in more complex dispersal patterns (e.g. Parent et al. 1996).

2.3.1 Boulder tracing in eastern Athabasca Basin

Large surficial boulder surveys have been conducted over the eastern portion of the Athabasca Basin by exploration companies to map the occurrence of altered sandstone boulders in the area. More than 20,000 sites were sampled (boulder chips) over a decade of exploration and samples analyzed for their geochemical composition. The preferred sampling location was undulated ground moraine or, more specifically, drumlin terrains (Earle et al., 1990). Large angular sandstone boulders with lithogeological properties similar to local outcrop exposures across drumlin fields were preferentially sampled (Earle et al., 1990). The assumption was that these large angular sandstone boulders were mainly transported over short distances. The rationale was to minimize the complications related to overlapping dispersal patterns of different sources. A notable difference with the approach used in the eastern Athabasca Basin and most other boulder tracing studies is that the focus was on obtaining the geochemistry of selected sandstone boulder chips rather than on recording the frequency of specific boulder lithologies on the ground.

Survey line direction was perpendicular to the dominant SW-trending ice flow direction, with a total line length from 800 to 2000 m-used for the reconnaissance survey with sample intervals of approximately 100 m. Ten boulder chip samples (about 2 cm^3 in size) were collected at each survey point within a 10 m radius (Fig. 3). Survey lines with spacing 300 – 500 m and interval 50 m were also set up for high density investigation (Earle et al., 1990).

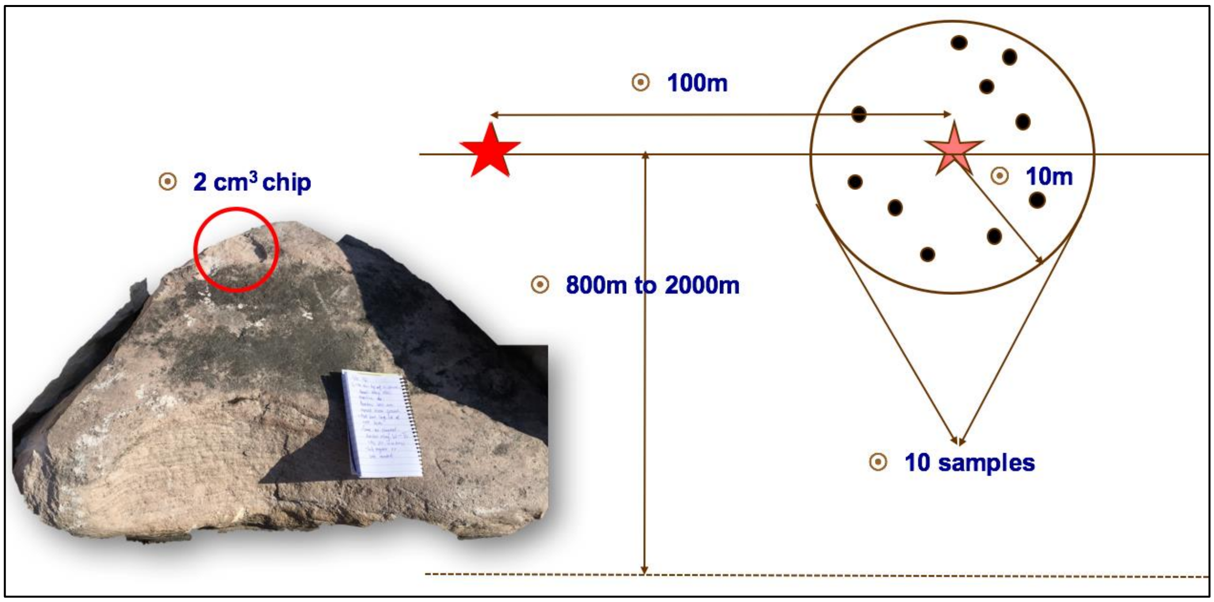


Figure 3. Sampling procedure. The image on the left illustrates the sampling procedure on a sandstone boulder, and the diagram on the right shows the general survey design.

Different analytical methods were applied on the boulder samples to digest uranium and other metals (Table 1). Method 1 applied total digestion for uranium and analysis by fluorimetry, with partial digestion for lead and other metals and analysis by atomic adsorption spectroscopy (AAS). Method 2 also used total digestion for uranium and delayed neutron counting analysis, but used partial digestion with analysis by AAS for the other metals. Method 3 and Method 4 used partial digestion for uranium which was analyzed by fluorimetry. The latter two methods also used partial digestion for other metals; Method 3 analyzed the samples using inductively-coupled plasma atomic emission spectroscopy (ICP-AES) and Method 4 used AAS.

Major element oxides were analyzed and a normative clay mineral algorithm, based on the concentration of Al_2O_3, K_2O, MgO and boron, were used to estimate the relative proportions of kaolinite, illite, chlorite, and dravite (eg. Quirt, 1995).

By applying the geochemical analysis methods to the sandstone boulder samples, identification of altered boulders and associated relative proportion anomalies of illite and chlorite down-ice of McArthur River was successful (Earle, 2001). Illite anomalies were determined by a normative mineral content ratio: illite / (illite + kaolinite), and chlorite anomalies were determined by using the MgO/Al_2O_3 ratio as a chlorite proxy (Earle 2001). Silicification is another type of alteration in the area. Silicified boulders would resist glacial transport, but have not been used as much as the other types of alteration in boulder studies.

Table 1. Summary of Geochemical Analysis Methods. AAS is atomic absorption spectroscopy; ICP-AES is inductively-coupled plasma atomic emission spectrometry.

Method	**U**	**Pb and Other Metals**
Method 1	Total digestion and fluorimetry	Partial digestion and AAS
Method 2	Total digestion and delayed neutron counting	Partial digestion and AAS
Method 3	Partial digestion and fluorimetry	Partial digestion and ICP-AES
Method 4	Partial digestion and fluorimetry	Total digestion and AAS

2.4 Previous work; radiometric surveys

Airborne gamma-ray spectrometry and magnetic surveys were conducted by the Geological Survey of Canada in partnership with the Saskatchewan Geological Survey from 2004 to 2010 (Fortin et al., 2015). The survey covered the Athabasca Basin at a resolution of 100m (GSC, 2009; Buckle et al., 2011; Fortin et al., 2015).

Airborne gamma-ray spectrometry is efficient in investigating large surficial areas by detecting the radiation from the decay of uranium (U), thorium (Th), and potassium (K). The concentrations of these elements are commonly reported as eU, eTh, and eK based on the assumption that these radioactive elements have reached their equilibrium state (radioactive equilibrium) (IAEA, 2003; Fortin, 2015). The signal from airborne gamma-ray spectrometry can penetrate 30 cm to 50 cm from the surface. Therefore, results from the method are representative of surficial materials only (Fortin et al., 2015). Table 2 provides average radiometric concentrations in the Eastern Athabasca Basin, calculated from the airborne gamma ray survey, as well as global averages for granite and sandstone for comparison.

Table 2. Average Radiometric Concentration of Eastern Athabasca Basin. (Fortin et al., 2015). Granite and sandstone global average values are from Rose et al.(1979)

	Equivalent Potassium K (%)	Equivalent Thorium (ppm)
NTS sheet 74H Basin limit	0.46	4.2
Granite global average	4.2	20
Sandstone global average	1.07	5.5

2.4.1 Radiometric Proxy

According to Rose et al. (1979), the global average values of Th for sandstone and granite are 5.5 ppm and 20 ppm, respectively, and the global average values of K (%) for sandstone and granite are 10,700 ppm (1.07%) and 42,000 ppm (4.2%) (Table 1), respectively. Since Fortin et al. (2015) used eTh (ppm) divided by eK (%), we can look at the global average ratio of Th (ppm) and K (%) (RTK) for sandstone and granite, which are 5.14 and 4.76, respectively.

This type of data is particularly useful for discriminating surficial sediments derived from sandstone bedrock from those that contain a higher proportion of mineral and lithic particles derived from the basement domains up-ice of the basin.

Sandstone rocks in the basin have much lower K content than most basement rocks, such as granite and gneiss, but it may have comparable Th content (Table 2). In the study area, glacial sediments all have a high proportion of sandstone clasts; however some have a higher proportion of granite and other basement lithologies and will thus have a lower Th:K ratio than glacial sediments with lower proportion of basement lithologies (and thus higher sandstone content).

Figure 4 shows a plot of the eTh and eK ratios (RTK) over the Eastern Athabasca Basin. The data is directly from Natural Resource Canada, and the waterbodies have been removed on this map by using the mask provided by Natural Resource Canada. The blue color represents low RTK values (basement signature) and red to pinkish color represent high RTK values (sandstone signature). The ice flow direction on the map is to the southwest.

Based on this, and comparing with Fig. 4, it appears that the sandstone within certain parts of the basin has a higher Th:K ratio (RTK) than the global average. The lower ratios are interpreted to be mainly the result of basement debris transported over the basin by southwestward ice flow and mixed with local rocks (Campbell 2007, Ross et al. 2009, Fortin et al. 2015).

The RTK data can be used as a proxy for relative glacial transport distance to identify the surficial tills with different composition and provenance The higher potassium content in the basement rocks, however, makes it challenging to use this data to identify potassium anomalies related to sandstone alteration. Areas that are relatively high in both Th and K may indicate the presence of altered sandstone debris at surface and be related to the surficial mineralization footprint.

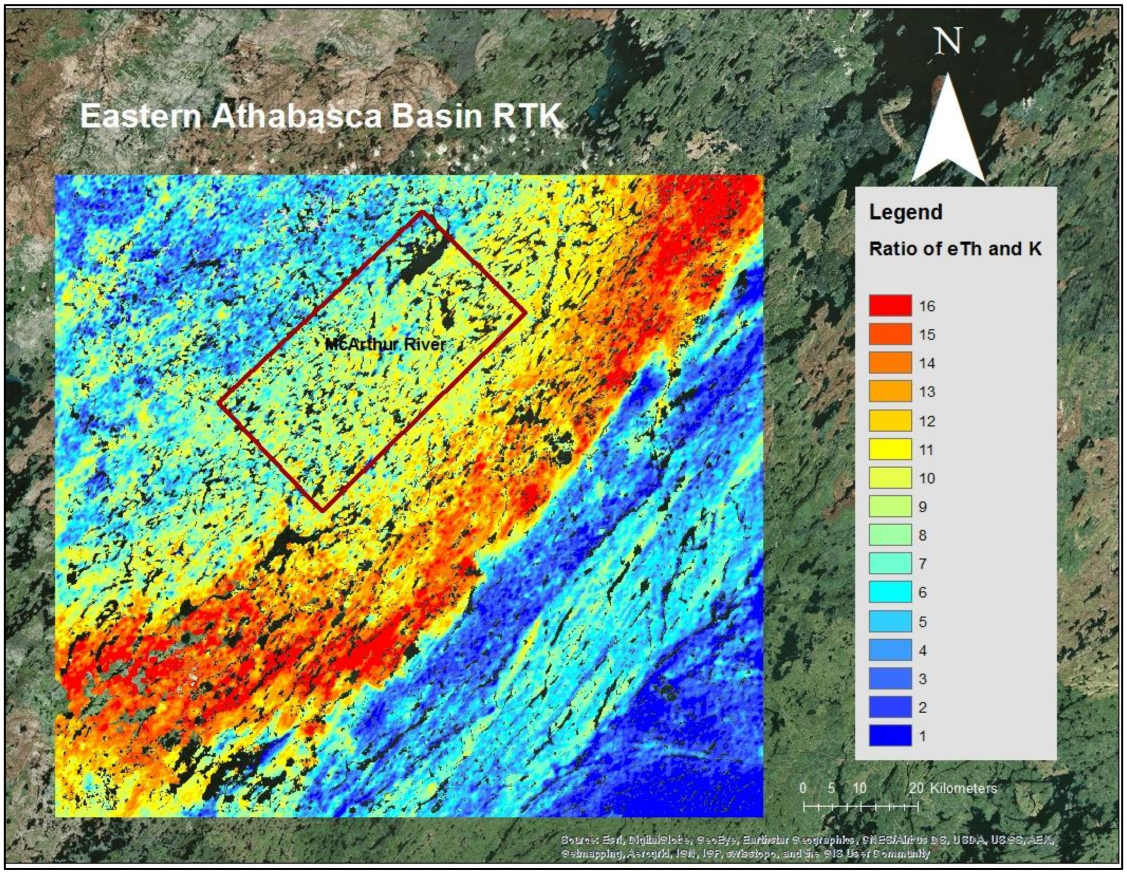


Figure 4. Radiometric eTh/K ratio plot. The RTK data is from Natural Resources Canada. The basemap is from ArcGIS World Imagery. The rectangular box shows the location of the study area. The raster data of RTK Map is from Natural Resource Canada.

2.4.2 Radiometric Domains

Fortin et al. (2015) defined radiometric domains over the Athabasca Basin, which outlines areas within which radiometric values do not vary as much as across the domain boundaries (Fig. 5).

Each domain was determined by its distinctive radiometric signature. In the study area, four sub-domains of domain A, namely A2, A3, A4 and A5, are identified (Fig.5). A2 has higher

K(%) content and lower RTK values; A3 is a transition zone from lower RTK value to higher RTK values; A4 apparently was selected as a potential area of K alteration footprint based on boulder data; A5 encompasses some of the highest RTK values (Fig.4) (Fortin et al., 2015).

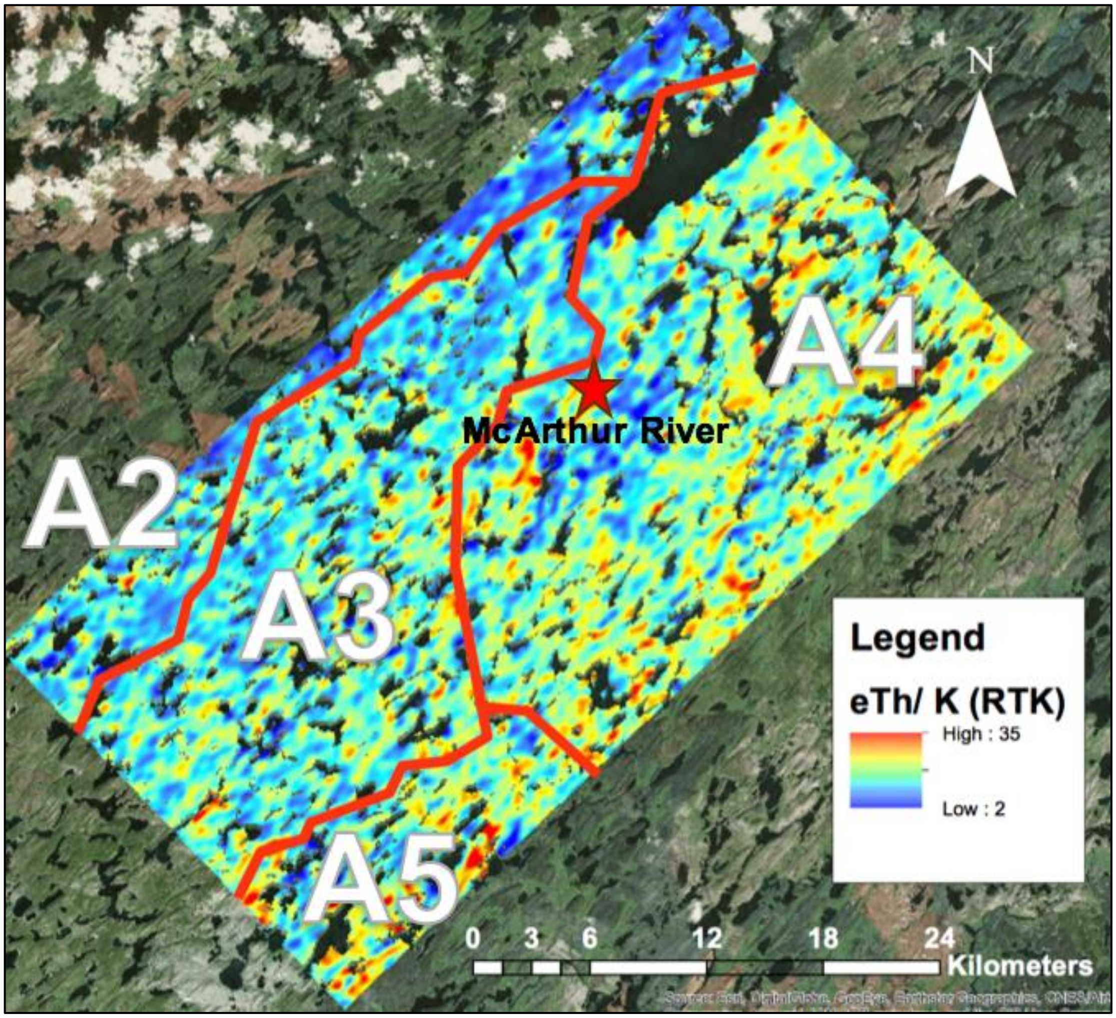


Figure 5. Radiometric domains within the study area.

3. Methodology

3.1 Analysis of the Legacy Boulder Data

The Cameco legacy boulder database was revisited using ArcGIS shapefiles (.shp) which allows one to open, edit and project the data points. The UTM zone 13N projection was used to import the boulder data.

A total of 4469 sandstone boulder sample stations had been collected in the study area and data provided in database format with the analytical results and methodologies. The concentration of uranium, lead, and other metal elements, with the major oxides (Al_2O_3, MgO, K_2O) and B contents were provided in the boulder sample database. The relative normative proportions of the dominant clay mineral species (illite, kaolinite, chlorite and dravite) in the region were also provided in the dataset. The normative proportions of clay minerals had been calculated and determined based on the Al_2O_3, MgO, K_2O, B content. The geochemical data could then be used to regenerate patterns of alteration mineral anomalies over McArthur River.

As explained above (Section 2.3.1), boulder sampling surveys were conducted over several years and boulder (chip) samples analyzed for U and other metals using different digestion and analytical methods. Method 1 and Method 3 (Table 1) were the dominant methods used in the study area, followed by Method 2 and Method 4, which have fewer samples. In order to examine the need for data levelling resulting from the different methods used in geochemical analysis, points from different methods that were adjacent to each other were extracted from the database and analyzed in R, a statistical software, to generate quartile-quartile plots (q-q plots). Quartile-quartile plots (q-q plots) are useful data exploratory tools to examine whether samples within a relatively local area, but analyzed differently and/or over different years by different laboratories, have similar result structure or major differences that would require the application of levelling techniques before the data can be integrated and compared. The relative proportions of illite was chosen as it was found to-have a better distribution when generating q-q plots.

Points were carefully selected from Method 1, Method 2 Method 3, and Method 4. In order to avoid selecting too many small values when generating q-q plot, the points were selected within the illite anomaly area. In addition, all points were selected so as to have not crossed radiometric domains. For example, to compare Method 1 and Method 3, points were selected within the same radiometric domain. Method 1 is the dominant method of the study area, and it has better distribution that connects every other method, hence the points from this method were used to compare with points from other methods. Further discussion on the need for levelling and the q-q plot analysis can be found in section 4.1.1, below.

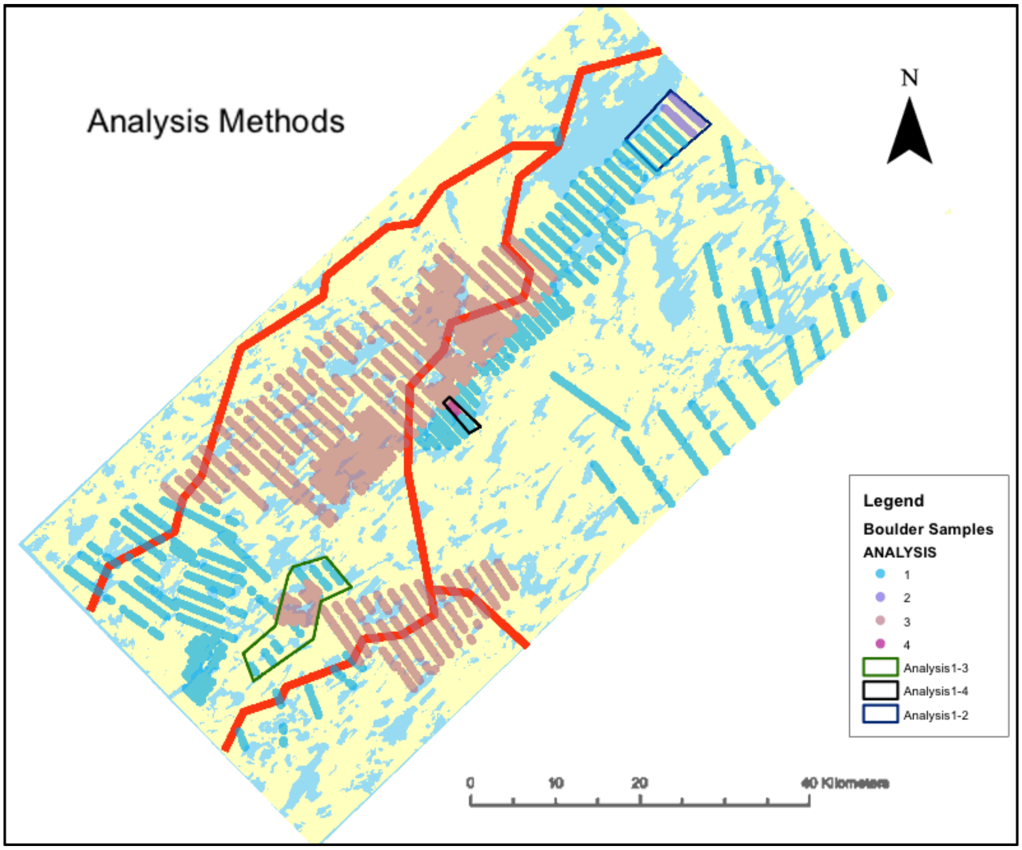


Figure 6. Analysis methods and points selection. Red lines illustrate the radiometric domains; points selections are made without crossing domains. Points were all within the regional illite anomaly area.

3.2 Radiometric Maps and Radiometric Domains

Radiometric data for the entire eastern Athabasca Basin are available from the Natural Resources Canada website (http://gdr.agg.nrcan.gc.ca). Extraction of the radiometric data for the study area (NTS/SNRC 74H) was achieved using the extraction tools available through ArcGIS.

The website provided various formats of raster data, and Arcview/Binary Raster was selected for this study. This format allowed ArcGIS to open and edit raster data without installing additional plug-ins. UTM zone 13N was used to project the radiometric maps.

Waterbodies can absorb radiometric signals and result in low values on the maps. Therefore, it was necessary to remove waterbodies from the maps completely. Natural Resource Canada website also provided an accurate waterbody mask that allowed ArcGIS to remove most of waterbodies in the study area.

Radiometric domains developed by Fortin et al. (2015) were overlain on the RTK plot of the study area. Four sub-domains of domain A were in the study area (Fig.5). In order to analyze the radiometric values in each domain, 3,000 random points were generated in ArcGIS over the study area, and RTK values were extracted into points and organized in an Excel table. 2,746 points had valid values. By using Inter Quartile Range (IQR) method, outliers were removed from the table to analyze the data and compare the different domains using box plots.

The use of ArcGIS allows one to overly the radiometric maps with the geochemical boulder data. In this study, radiometric domains were overlain with illite / (illite + kaolinite) ratio from the database examine possible dispersal patterns and overall relationships.

4. Results

4.1 Boulder Data Analysis

4.1.1 Relative Proportion of Sandstones and Basement Rocks

In a classical boulder tracing study, the proportion of fresh and altered sandstone boulders relative to basement derived boulders would have been measured on the ground at each station. In the study area, 1,454 stations of the 4,496 stations or 32%, have some kind of record of lithologic proportions (either the sandstone or basement proportion ~~is~~ are provided in the database). Most stations have greater than 90% sandstone (Fig. 7 A), which is possible; however, no methodology details are provided as to how these values were recorded and whether the method was applied rigorously and systematically across the study area. Nonetheless, it does show that the proportion of basement-derived boulders is higher in the northeastern part of the study area which is closest to the up-ice contact with basement rocks.

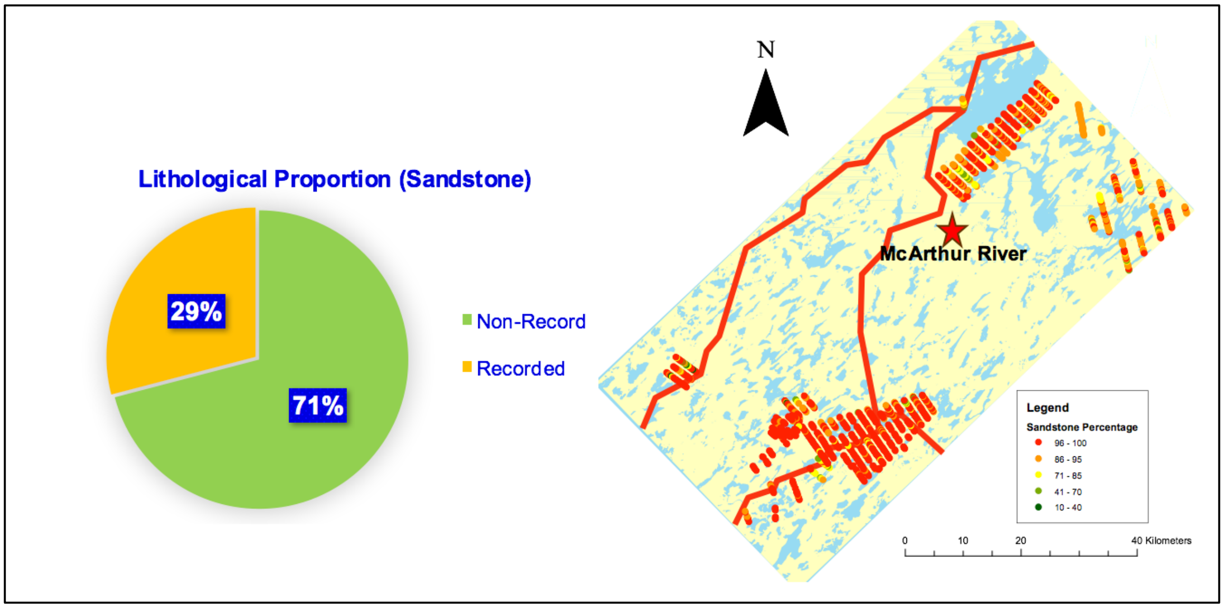
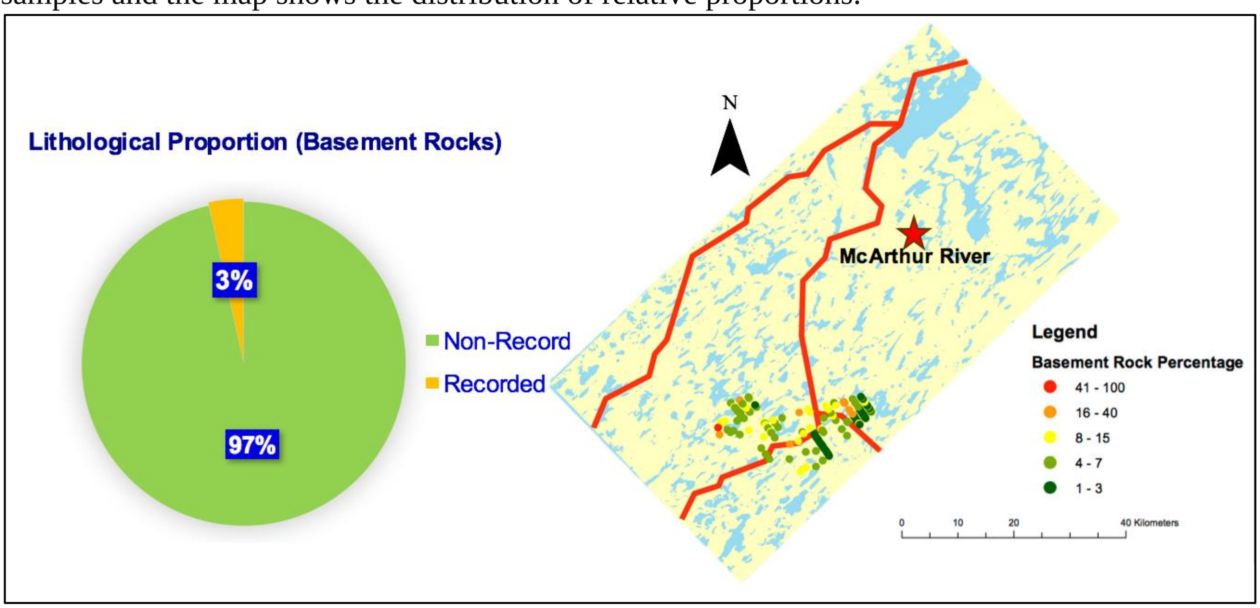


Figure 7. A) Lithological proportion of sandstone. Pie chart shows the percent of recorded samples and the map shows the distribution of relative proportions.

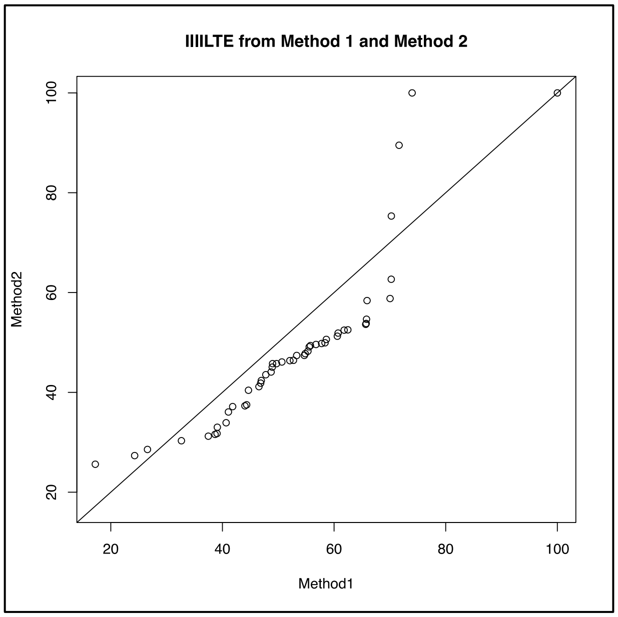


B) Lithological proportion of basement rocks. Pie chart shows the percent of recorded samples and the map shows the proportion of recorded samples.

4.1.2 Assessing the Need for Data Levelling

Figure 8 shows the q-q plots comparing Methods 1, 2, 3 and 4. If points are distributed along the diagonal, it means the data is consistent and comparable between methods; i.e. values from the two datasets vary similarly from low to high values. A systematic offset or an oblique line indicates a need for levelling and complex patterns may indicate it is not possible to level the data.

Fig.8 A) compares Method 1 and Method 2, and it shows a small shift towards Method 1. Method 1 thus produced larger values compared to Method 2; Fig.8 B) shows Method 1 against Method 3; the points follow closely the diagonal with the exception of the three lowest values. The two types of methods thus appear to be consistent enough and levelling is probably not required for these two datasets to be integrated and used together. Fig.8 C) shows the q-q plot of Method 1 and Method 4. Fewer sites are associated to Method 4 and they are surrounded by the points associated to Method 1. Therefore, all of the points from Method 4 were selected and the adjacent points using Method 1 were selected as well to generate the q-q plot. The plot shows large differences as the points do not lie on the diagonal and they do not exhibit a straight line. The highest values are comparable, but the lower values are much higher for Method 1. The trend is non-linear and thus more advanced levelling techniques are required to level these datasets for comparison.



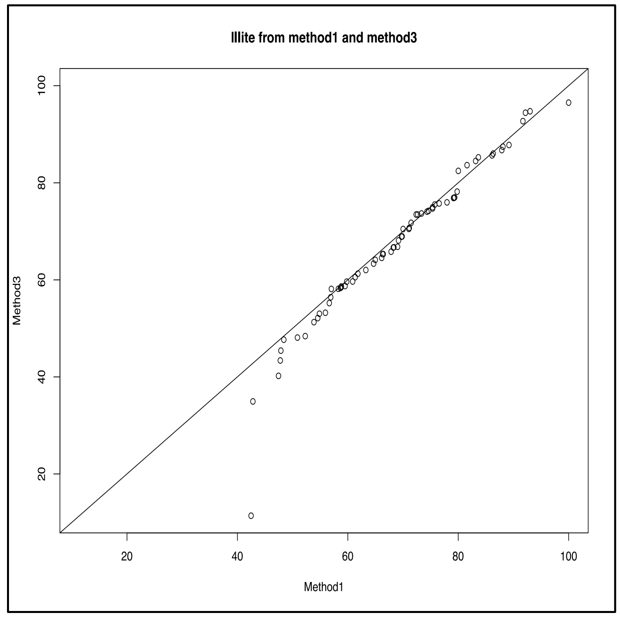
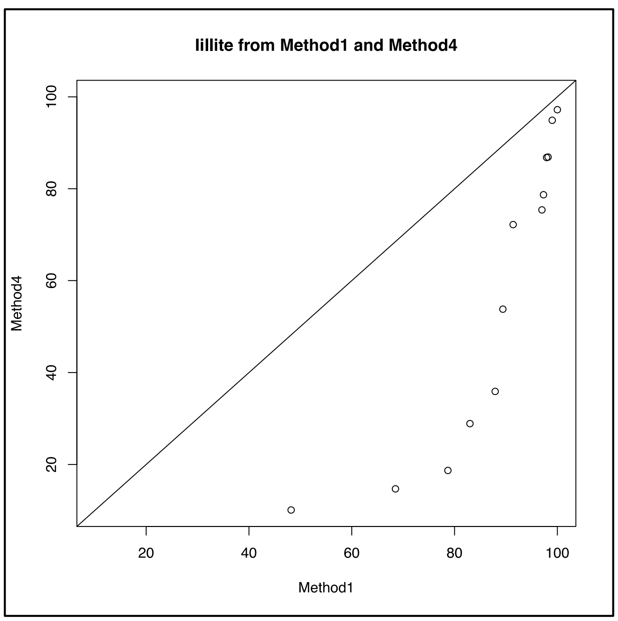


Figure 8. A) Method 1 and Method 2. B) Method 1 and Method 3.



C) Method 1 and Method 4.

4.2 Radiometric Data Analysis

4.2.1 Box-Whisker Diagram of Radiometric Domains

Fig. 9 shows the box-whisker diagram generated for different radiometric domains in the study area.

On the box-whisker diagram (Fig. 9), it is clear that A2 has smallest RTK values and A5 has largest RTK values compared with other radiometric domains. The difference between domains is not large and there is clear overlap, but this could be due to using ratios of ppm and percentage values.

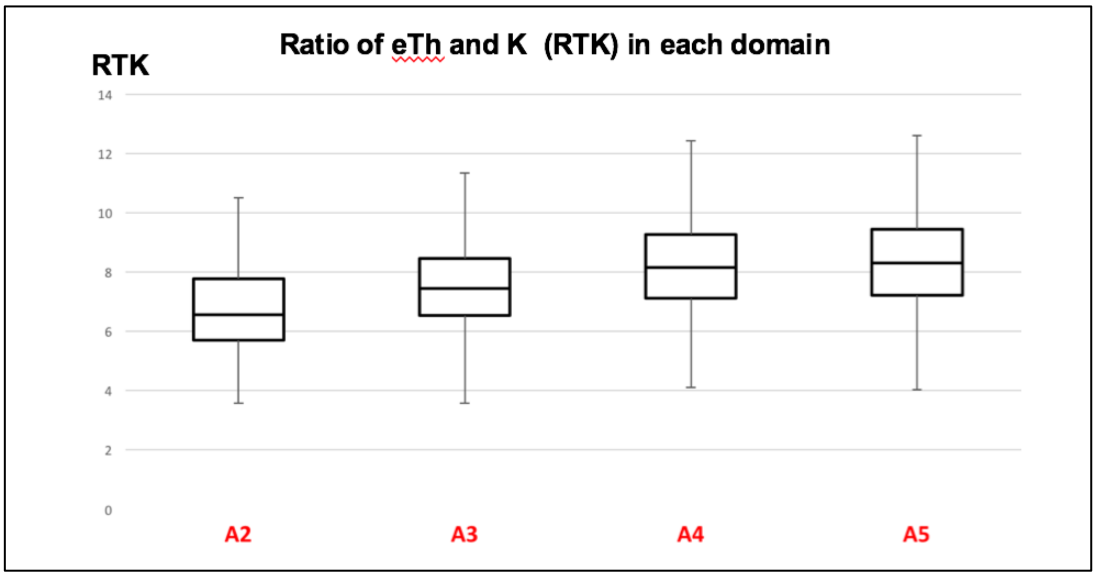


Figure 9. Box-whisker diagram of RTK values in radiometric domains.
Boxes represent different quartiles of the dataset. The first quartile was chosen as the median of the lower half of the data; second quartile as the median of the whole dataset; the third quartile as the median of the upper half of the data. The whiskers represent the maximum and minimum values of the dataset. 2746 out of 3000 valid points in study area were used to generate the box-whisker plot: 347 random points were in A2 domain; 943 random points were in A3 domain; 1207 random points were in A4 domain; 249 were in the smaller A5 domain.

4.2.2 Overlay Radiometric Domains with Legacy Boulder Data

In order to interpret dispersal patterns, RTK domains for the study area and regional illite anomalies from the legacy boulder data were overlain (Fig. 10). The ratio of illite/ (illite +

kaolinite) or IIK was used as a proxy to present the illite anomalies. Boulder patterns extended across radiometric domains boundaries. High illite content boulders appear in all four sub-domains. However, in A4, boulders on the southwest of McArthur River have illite/ (illite + kaolinite) values consistently greater than 50% and ~~it~~ also has relative high RTK values (A4 domain). This may indicate that these boulders are more locally derived, and extend across a zone of relatively higher eTh, compared to A2 and A3.

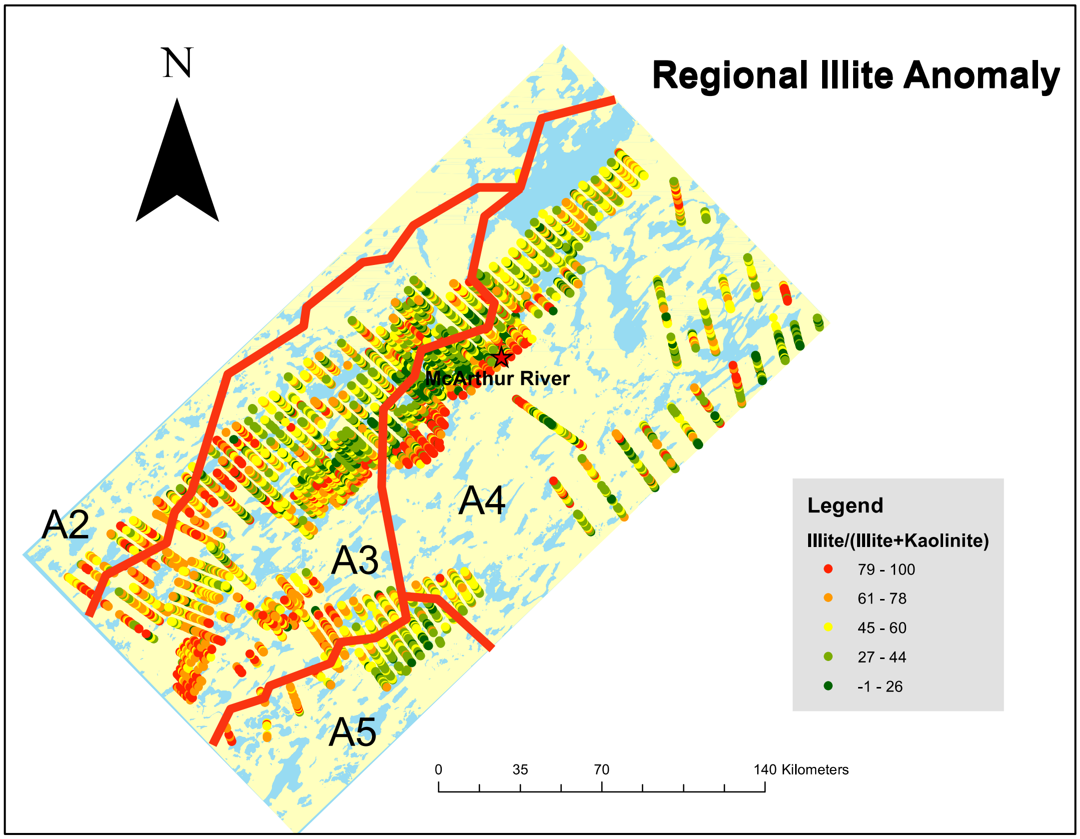


Figure 10. Radiometric domains overlay with illite/ (illite + kaolinite). The ratio is used as a proxy to indicate the regional illite anomalies (Earle, 2001). Based on the results from q-q plot in section 4.2.1, this map only shows the points from Method 1 and 3. The boulders in A4 with constantly higher IIK values correspond with high eTh and high RTK values on radiometric maps.

Despite the fact that the illite anomaly appears to be widespread along the P2 structure, which runs subparallel to the dominant ice flow direction, there is a clear cluster of anomalous values extending down-ice from McArthur River (Fig. 10) which is within the A4 radiometric domain characterized by a ‘proximal’ RTK signature. These spatial relationships suggest that the cluster is a true dispersal pattern from subcropping alteration in the vicinity of McArthur River. The anomaly is approximately 6 km to 17 km wide and extends down-ice for about 78.5 km before it crosses the A3 domain, after which it becomes less distinctive. The anomalous boulders in the western part of the map (Fig. 10) are within A3 and A2 domains, and are thus probably mixed within a higher proportion of basement derived boulders. The sandstone boulders that produced these anomalous values could also be locally derived, but they are more likely to represent a mix of sources along P2 (a longer and wider source zone or catchment), possibly from more than one ice flow direction. The source of these boulders is thus more uncertain.

5. Conclusion

This study analyzed available surficial geology datasets (legacy boulder samples and radiometrics) in the vicinity of the McArthur River uranium mine in the eastern Athabasca Basin. The main goals of the study were to analyze legacy boulder data and compare against radiometric data and other surficial geology observations, and to identify potential spatial relationships which could provide insights into their significance. The motivation is to determine whether using these datasets together can help better understand patterns and contribute to the definition or mapping of a surficial footprint derived from subcropping clay alteration surrounding the McArthur River deposit.

A number of issues were identified, which make the exercise of identifying a surficial footprint difficult. First, the legacy boulder data is heterogeneous as it was developed over several years using different analytical methods. Nonetheless, it was found through basic q-q plot visualization, that most data in the study area was derived from two methods (Methods 1 and 3) which appear to have consistent structures and distributions suggesting they can be compared and used together. As the host structure (P2 fault) of the uranium mineralization is developed subparallel to the dominant ice flow direction(s), it is challenging to identify a point source up ice of an anomaly in the glacial overburden. Finally, the till at surface contains various amounts of basement-derived debris rich in both Th and K, which complicates the use of these two elements as pathfinders for subcropping alteration. Nonetheless, airborne radiometric data can be used as a proxy for the relative abundance of local versus distal debris , which can then be used to determine whether anomalous sandstone boulders (i.e. boulders anomalous in illite) are more likely to be locally-derived or whether they are more likely the result of complex (more uncertain) provenance.

Results from this study suggest that a cluster of anomalous boulders extending down-ice of McArthur River is also spatially associated with a radiometric domain with a ‘local’ sandstone signature suggesting relatively short transport distance in that area. These boulders thus appear to form a glacial dispersal pattern likely emanating from subcropping altered bedrock in the vicinity of McArthur River. In contrast, anomalous boulders found in the western part of the study area (in A2-A3 domain) likely have a more complex provenance history because these domains have a higher proportion of distal debris. Robust and detailed boulder lithological counts in the different domains will be useful in future boulder train studies to determine the exact proportions of basement versus basin lithologies and how they compare spatially to the radiometric domains. This information will lead to a more comprehensive spatial analysis. Local (short-transport) patterns could be more readily identified and distinguished from composite patterns which may be derived from more distal sources.

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