Ground-truthing of the 'Eastern Athabasca Basin' Regional Airborne Gamma-ray Survey: Context for Exploration of Deeply Buried Unconformity-related Uranium Deposits in the Athabasca Basin of Northern Saskatchewan

Richard Fortin,[1] Janet E. Campbell[1], Brad J.A. Harvey[1], Martin W. McCurdy[1], Laurel E. Sinclair[1], Michelle, A. Hanson[2], Eric G. Potter[1] and Charles W. Jefferson[1]

1. *Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8*
2. *Saskatchewan Geological Survey, 2101 Scarth Street, Regina, Saskatchewan, S4P 2H9*

Abstract

With uranium exploration shifting to greater depths and more indirect targets, new tools and better use of existing data are needed to maximize exploration efficiency. Recent and historical research has demonstrated that although deeply-buried beneath Athabasca Group sandstones, unconformity-related uranium deposits still may be targeted by understanding subtle surficial geochemical anomalies.

Airborne gamma-ray spectrometric surveys can be used for effective surficial geochemical mapping of K, U and Th over large areas and have been conducted by the Geological Survey of Canada across much of the Canadian Shield over the past 50 years, notably in partnership with Saskatchewan over the Athabasca Basin. To apply the results of these surveys to uranium exploration, the effects of deposit-related geochemical anomalies on airborne gamma-ray measurements must be predicted. And, just as importantly, the background in terms of K, U and Th above which these anomalies have to be detected, has to be quantified and its genetic linkages understood.

The "Eastern Athabasca Basin" airborne gamma-ray survey was conducted in partnership with the Saskatchewan Geological Survey in 2009. This regional survey was ground-truthed along the corridor between Key Lake and the McArthur River mine site in 2013. High-resolution helicopter-borne gamma-ray acquisition, ground gamma-ray spectrometry, surficial material mapping, sampling and laboratory analyses were performed. Results indicate that the relationships between subsurface processes, glacial dispersal and airborne gamma-ray measurements are very intricate and responsive to detailed local surficial geological processes that have modified elemental dispersion from bedrock sources. In many cases, surficial sediments and landforms can be discriminated based on their K, U and Th geochemistry, relating in turn, to their provenance. Quantitative analysis of the airborne data, integrated with surficial geological knowledge, can differentiate between the complex patchwork of background domain levels and deposit-related surficial geochemical anomalies.

Introduction

From 2004 to 2010, through various provincial and federal programs, the Geological Survey of Canada (GSC), in partnership with the Saskatchewan Geological Survey (SGS), conducted airborne gamma-ray spectrometry and magnetic surveys in northern Saskatchewan and completed coverage of the entire Saskatchewan portion of the Athabasca Basin (Buckle et al., 2011). Gamma-ray spectrometry data acquisition followed up-to-date specifications as recommended by the International Atomic Energy Agency (IAEA, 1991, 2003). Usage of self-stabilizing digital spectrometers, state-of-the-art data processing, and continuous coverage with 125m survey altitude and 400m line-spacing contributed to the high quality of this unique data set.

Recent and historical research has demonstrated that although buried beneath Athabasca Group sandstones, unconformity-related uranium deposits may be targeted by understanding subtle surficial geochemical anomalies that reflect a variety of processes from regional diagenetic-mineralogical alteration patterns, through hydrothermal alteration halos more directly associated with deposits, to specific sites where mobile metals including decay products may be brought to the uppermost sandstones and surficial media along structural pathways (Sopuck et al., 1983, Clark, 1987, Earle and Sopuck, 1989, Thomas et al., 2000; Bonham-Carter and Hall, 2010, Power et al., 2012; Dann et al., 2014; Hattori et al., 2015). In regard to the interpretation of airborne gamma-ray spectrometry maps, expressions of these anomalies in surficial media have to be quantified in terms of K, U and Th concentrations. The background above which these anomalies have to be detected has also to be defined and quantified, and its genetic linkages to bedrock and Quaternary geology have to be understood.

The regional Eastern Athabasca Basin airborne magnetic and gamma-ray spectrometric survey was conducted in 2009 (Buckle et al, 2010), and includes coverage of the producing Key Lake - McArthur River corridor (Fig. 1). Distinct patterns in radioelement concentrations are recognized on the airborne maps, and to define the nature of this background, field validation activities were carried out in 2013. The relationships of these radiometric features to surficial geology are examined and the implication for targeting surface anomalies related to uranium deposit is discussed.

Exploration Context

Airborne gamma-ray spectrometry (AGRS) surveys can be used for effective surficial geochemical mapping of potassium (K), uranium (U) and thorium (Th) over large areas, and have been conducted by the Geological Survey of Canada across much of the Canadian Shield over the past 50 years. Concentrations in uranium and thorium are usually reported as equivalent uranium (eU) and equivalent thorium (eTh) to emphasize that these measurements are based on the assumptions that these radioelements are in radioactive equi-

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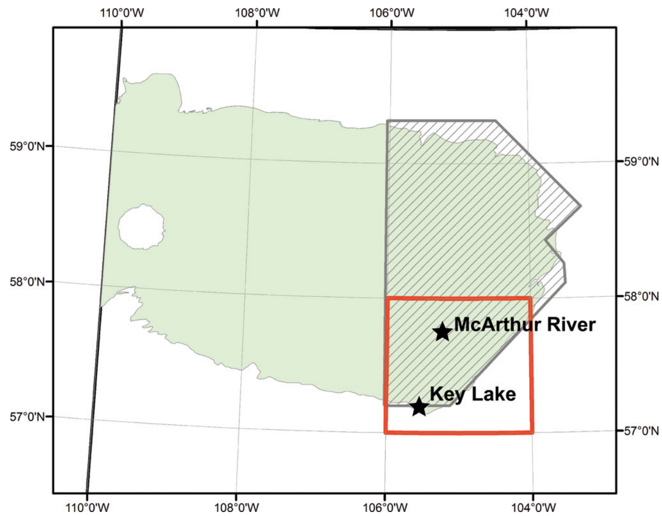

Figure 1. Location of the Athabasca Basin in Northern Saskatchewan (green), and of the Eastern Athabasca Basin airborne survey (hatched). Limits of NTS sheet 74H are outlined in red (see Fig. 3).

Table 1. Average radioelement concentrations in the Athabasca Basin in the area covered by NTS sheet 74H, calculated from the Eastern Athabasca airborne survey results.

	Potassium (%)	Equivalent Uranium (ppm)	Equivalent Thorium (ppm)
NTS sheet 74H – Basin limit	0.46	0.55	4.2
crustal averages	2.4	3	12
Sandstone	1.2	1.9	5.7

For comparison, average concentrations in the earth's crust (Dickson and Scott, 1997) and in sandstone (Galbraith and Saunders, 1983) are also presented. The very low radioactivity background observed in the surficial materials of the eastern Athabasca Basin appears favorable to the detection of weak anomalies.

librium (IAEA, 2003). In contrast to many of the other geophysical techniques that provide structural information about the subsurface, AGRS provides compositional information about surficial geological materials. As such, the interpretation approaches of exploration geochemistry are appropriate to AGRS data analysis. Applications of AGRS have been reviewed in various reports (e.g. Shives et al., 2000a; IAEA, 2003; Ford et al., 2007; Campbell et al., 2007).

Geophysical gamma-ray spectrometry is a surface technique; only about the first 30 cm of the surface is sampled by either airborne or ground-based measurements. It has however, a relatively large footprint, with a diameter of 2 to 3 m, for typical ground spectrometry instrument and about four times the flying height, for airborne spectrometry. The elements of the unconformity-related uranium deposit exploration model that are relevant to gamma-ray spectrometry surveying are therefore those which result in a surface expression.

An anomalous regional clay alteration pattern in the sandstone of the Athabasca Basin has been outlined by Earle and Sopuck (1989) and surrounds the Key Lake - Cigar Lake corridor where major deposits are located. Surface expressions of these alteration minerals have been observed in boulders (Earle et al., 1990, Shives et al., 2000b) and locally-derived till (Simpson and Sopuck, 1983). Illite anomalies, and resulting enrichment in potassium, could therefore provide a surface target for AGRS. Uranium anomalies in till and soils located above the alteration chimney of deposits have also been observed (Simpson and Sopuck, 1983; Matthews et al., 1997; Bonham-Carter and Hall, 2010; Power et al., 2012; Hattori et al., 2015) with concentration levels within the range of sensitivity of airborne and ground gamma-ray spectrometry. In many cases, these surficial anomalies have undergone secondary glacial dispersal and are displaced down-ice from their source, effectively enlarging the very subtle traces they are leaving at the surface.

Discriminating these weak potassium or uranium anomalies from the heterogeneous surficial background remains a challenge. For example, a 5 ppm uranium anomaly in the first 3 cm of soil, similar to results from Power et al. (2012), would appear diluted by a factor of 10 in the 30-cm deep sampling volume of a ground gamma-ray spectrometry measurement and would then result in values in the order of 0.5 ppm eU. This value is within the same range as the average background uranium concentrations measured in the surficial materials of the Athabasca Basin (Table 1), and exemplify that it is essential to characterize the radioelement background in terms of the Quaternary geological framework in order to discriminate anomalies of interest.

Geological and Quaternary Setting

The conglomeratic sandstone bodies that constitute the Athabasca Basin are thoroughly oxidized terrestrial redbed sequences with a complex alteration history (Ramaekers et al., 2007; Jefferson et al., 2007). In the area of interest, the underlying basement rocks are the supracrustal metasediments of the Wollaston Group that rest on Archean granitic gneiss domes (Card et al., 2007). Variations in surface concentrations of the natural radio-elements result from this geological context but also from the physical processes shaping the surface environment.

The present day landscape of the eastern Athabasca Basin area is primarily a product of the advance and retreat of the ice sheet during the Late Wisconsinan. The main ice flow direction during the deglaciation was to the south-west and produced the large drumlins seen in the eastern part of the basin. A more localised late stage re-advance or margin re-adjustment shifted the ice flow towards the south. This late flow is recorded primarily by flutings, small scale drumlinoids and minor east-trending moraine ridges which discontinuously overprint the large-scale drumlins (Campbell, 2007). The tills related to these two ice flows differ in composition and provenance. In this region, the material which comprises the regional large-scale landforms is generally a silty sandy basement-rich till while the overlying deposits

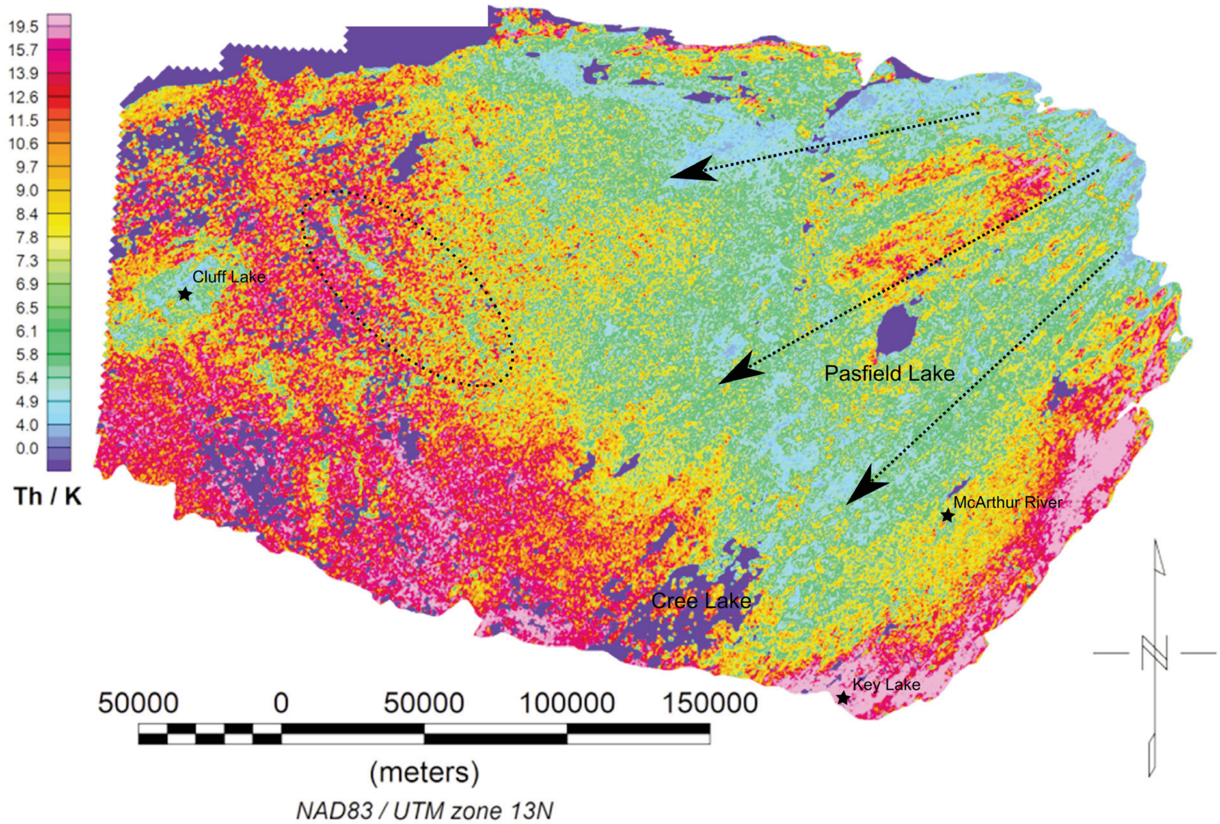

Figure 2. Compilation of thorium concentration over potassium concentration (RTK) obtained from airborne gamma-ray surveys conducted by the Geological Survey of Canada and Saskatchewan Geological Survey over the entire Saskatchewan portion of the Athabasca Basin. Southwest- to west-trending features (arrows), reflect regional ice flow during the Late Wisconsinan early deglaciation. An east-west transition from low RTK to high RTK values may represent the extent of the regional glacial dispersal of basement-derived material over the basin. Low RTK values with north-westerly trends, (dashed circles), are suggestive of end moraines of the retreating ice margin. Deep-blue color represents nulled values, due to waterbodies.

are a sandier, predominantly sandstone derived till.

In the eastern Athabasca Basin, this landform-sediment relationship and resulting compositional differences in surface tills are reflected in the map of the ratio of thorium to potassium concentrations (RTK), which exhibit numerous south to southwest trending features (Fig. 2) and comparatively elevated concentrations of potassium. These features are overprinted by distinctive areas of elevated concentration of thorium, especially on the south-eastern margin of the Basin and in southwest trending features, to the north. These features appear to be part of a regional scale pattern that fans out over the Athabasca Basin from the north-east in direction of the ice flow (Fig. 2). The potassium dominated and low RTK signature reaching past the middle of the basin toward the west may represent the extent of the regional glacial dispersal of basement-derived material over the basin. North-westerly linear features just to the east of the Carswell structure and Cluff Lake are moreover suggestive of end-moraines that may relate to this dispersal. In contrast, the thorium-dominated and high RTK areas, bordering the south-eastern margin of the Basin and also observed locally in the northern-eastern part, appear as a surface trace of the thorium-rich Manitou Falls Formation Bird and Collins Members (Mwenifumbo and Bernius, 2007) and are therefore indicative of more locally derived material in the surface till.

The potassium dominated signature is indicative of a higher proportion of extra-basinal igneous or metamorphic materials in the surface media, while the thorium dominated signature relates to the potassium-poor and thorium-rich sandstones of the Athabasca group, with RTK values quantitatively discriminating between these basement-derived and sandstone-rich surface materials. As till is the most common glacial deposit in the eastern Athabasca Basin region, this first-level heuristic classification of surface materials based on RTK contrast appears to correlate with the Till 2 and Till 3 Quaternary stratigraphic units defined by Campbell (2007). Till 2 contains a significant component of more distally derived, crystalline shield detritus, and is the most extensive till deposit in the region. Till 3 has a higher component of locally derived sandstone material and discontinuously overlies till 2. Till 3 is associated with the late stage re-advance of the ice sheet during the late Wisconsinan deglaciation.

Field Validation

Field validation activities were conducted in July and October 2013 in the region covered by NTS sheet 74H within seven areas located in the corridor between Key Lake and McArthur River (Fig. 3). These locations were selected to cover the radiometric domains identified in a preliminary data parsing exercise (Fortin et al., 2014). Each area also intersected either a known geological element potentially capable of producing a contrasting gamma-ray output, or a distinctive feature in term of its radioelement concentrations, as recognized from the regional Eastern Athabasca airborne survey.

High-resolution airborne gamma-ray spectrometry surveys were conducted over all seven areas with a Bell 206B helicopter. The survey system consisted of two 40 cm by 10 cm by 10 cm thallium-doped sodium iodide gamma-ray detectors, a geodetic GPS receiver, an inertial measurements unit and a laser altimeter, and was carried in an externally skid-mounted cargo expansion. The survey parameters for the two areas selected for discussion below are presented in Table 2. Maps of radioelements (K, eU and eTh) concentrations were produced.

Ground gamma-ray spectrometry measurements were collected at targeted stations in each of the seven areas. Typically, a series of 120-seconds measurements were taken using a hand held spectrometers equipped with either a 103 cm^3 bismuth germanate detector or a 347 cm^3 thallium-doped sodium iodide detector. The measurements were collected within 2 meters of the station's location and averaged. Sediments within the first 30 to 50 cm from the surface were documented and samples were collected from primarily the Ae or B soil horizon. The samples were prepared as bulk and less than 2mm size fraction subsamples for measurement of K, eU and eTh concentrations in the GSC gamma-ray spectrometry laboratory in Ottawa. Geochemistry of the less than 2 mm size fraction, matrix texture and pebble lithology were also determined for further composition characterisation of the sediments, although these results will not be discussed here.

Results

A preliminary analysis and interpretation of the high resolution airborne gamma-ray spectrometry surveys is presented below for field study areas A5 and A4 (Fig. 3).

A5 Area

This area was selected for ground validation activities because it contains a variety of glacial landforms ranging from large drumlins typical of this region, to streamlined, smaller drumlinoid ridges, smaller-scale flutings and flat plains, all within the 5 km^2 area covered. Potassium concentrations show southwestward trends (Fig. 4a), with ridges of elevated concentrations (0.5–0.8 % K) intercalated between "valleys" exhibiting comparatively lower concentrations (0.2–0.4 % K).

These low-potassium valleys are observed to be coincident with topographic highs that are expressed by small streamlined drumlinoid ridges, whereas in the southern corner of the survey area more prominent potassium features are observed in relation to larger scale landforms. This is confirmed by ground spectrometry measurements and laboratory analysis of the samples obtained from the 6 targeted ground-truthing stations, where RTK values offer a better contrast between the measurement stations (Fig. 4d).

Basement-derived Till 2 was observed on the large drumlin in the south corner of the survey area, where higher potassium content, and lower RTK values, is measured by both airborne and ground-based spectrometry. This is representative of the main ice-flow of the late stages of the late Wisconsinan glaciation. In contrast, sandstone-rich Till 3 was identified in the three smaller drumlinoid ridges to the north, where lower potassium concentrations, and higher RTK values, are obtained. The axis of the drumlinoid ridges have a slightly more southward orientation in comparison to the larger drumlin, suggestive of a remoulding of theses landforms, consequent from the re-advance and shift in flow direction of the ice margin towards the south. Finally, glaciofluvial deposits observed between the smaller drumlinoid ridges yield higher potassium content measurements, indicative of their more diverse provenance.

A4 area

This area, located along the P2 fault was selected to compare measurements with the study of Shives et al. (2000b) in which sandstone boulders were surveyed to identify potassium enrichment due to illite-rich clay alteration.

For the series of northeast-southwest trending drumlins sampled by stations 1 to 4 and extending from the south corner to the north border of the survey area, the low potassium concentrations obtained from the airborne measurements (0.15–0.30 % K) and comparatively higher RTK values obtained from ground spectrometry agrees with the observations of sandstone-rich till at the measurement stations (Fig. 5). However, the results from the gamma-ray spectrometry laboratory analysis don't agree as well with the airborne measurements and the till observations. It is suggested that the location of the targeted measurement stations, at the margins of the landforms, were not optimal. The samples collection was conducted in location of discontinuous Till 3 coverage and the larger footprint of the gamma-ray spectrometry measurements may have provided more representative measurements than the laboratory analysis, on much smaller samples, by effectively averaging local heterogeneity in till coverage.

Sandstone-rich till coverage would also be expected on the series of drumlins toward the southwest corner of the survey block, but airborne measurements shows a large region of higher concentrations in potassium, reaching values in the range of 0.50 % K, covering all these narrow landforms. By highlighting troughs between the drumlins, it can be seen, however that this seemingly uniform area in potassium concentration present in fact a series of southwest trending

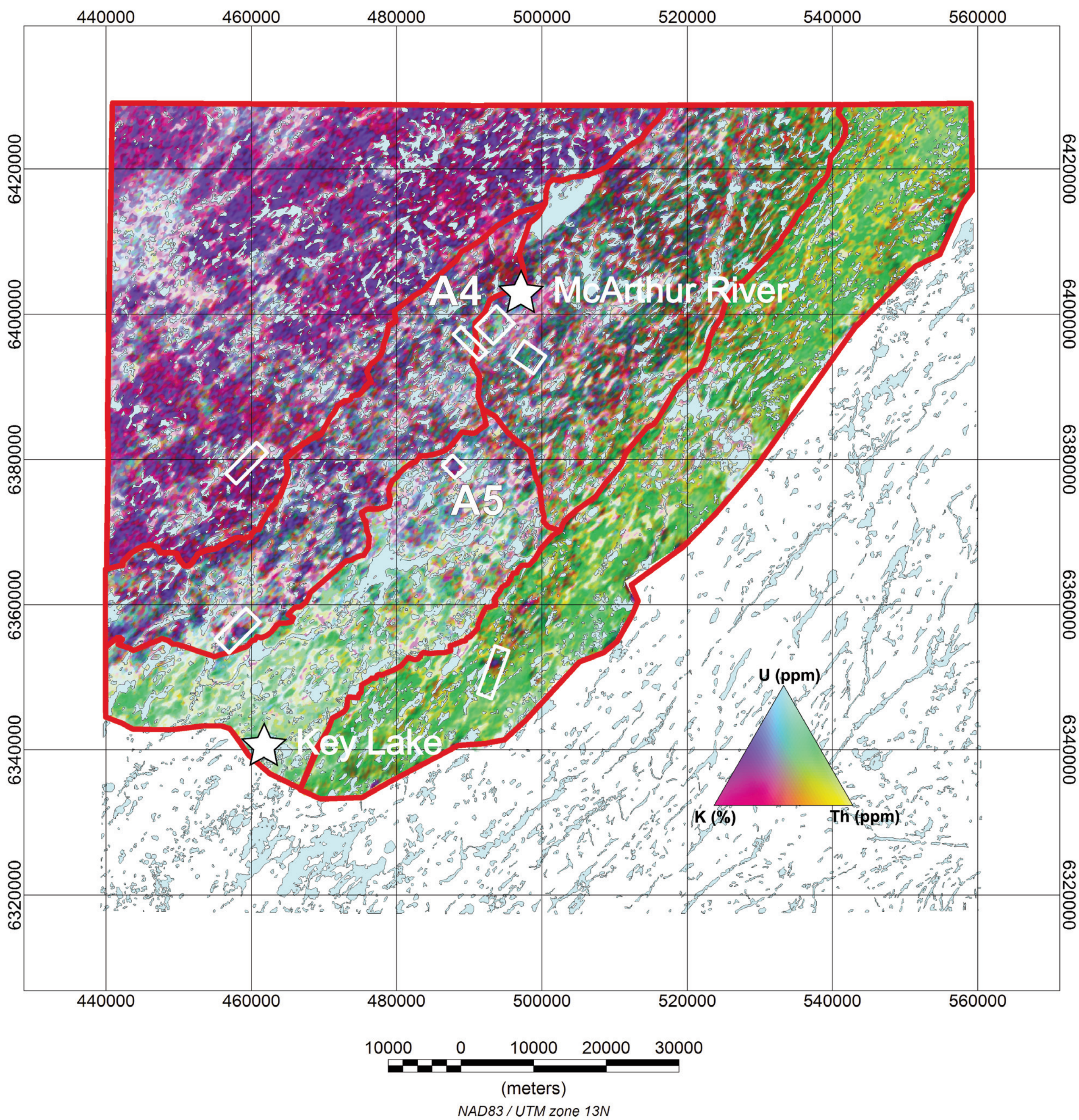

Figure 3. NTS 74H area map presenting the location of the field validation areas (white outline). Areas A4 and A5 that are discussed in the text are highlighted. Background map is the composite ternary image of natural radioelements computed from the Eastern Athabasca Basin airborne Survey data. Red outlines correspond to radiometric domains defined and reported by Fortin et al. (2013).

Table 2. Flight parameters of the airborne survey areas A4 and A5.

Survey Area	*line length (m)*	*line azimuth (deg)*	*line spacing (m)*	*lateral extent (m)*	*flight lines*	*total line-km (km)*	*nominal survey speed (m/s)*	*flight altitude (m)*
A4	3500	135	100	4000	41	143.5	30	40
A5	2400	135	25	2000	81	194.4	25	25

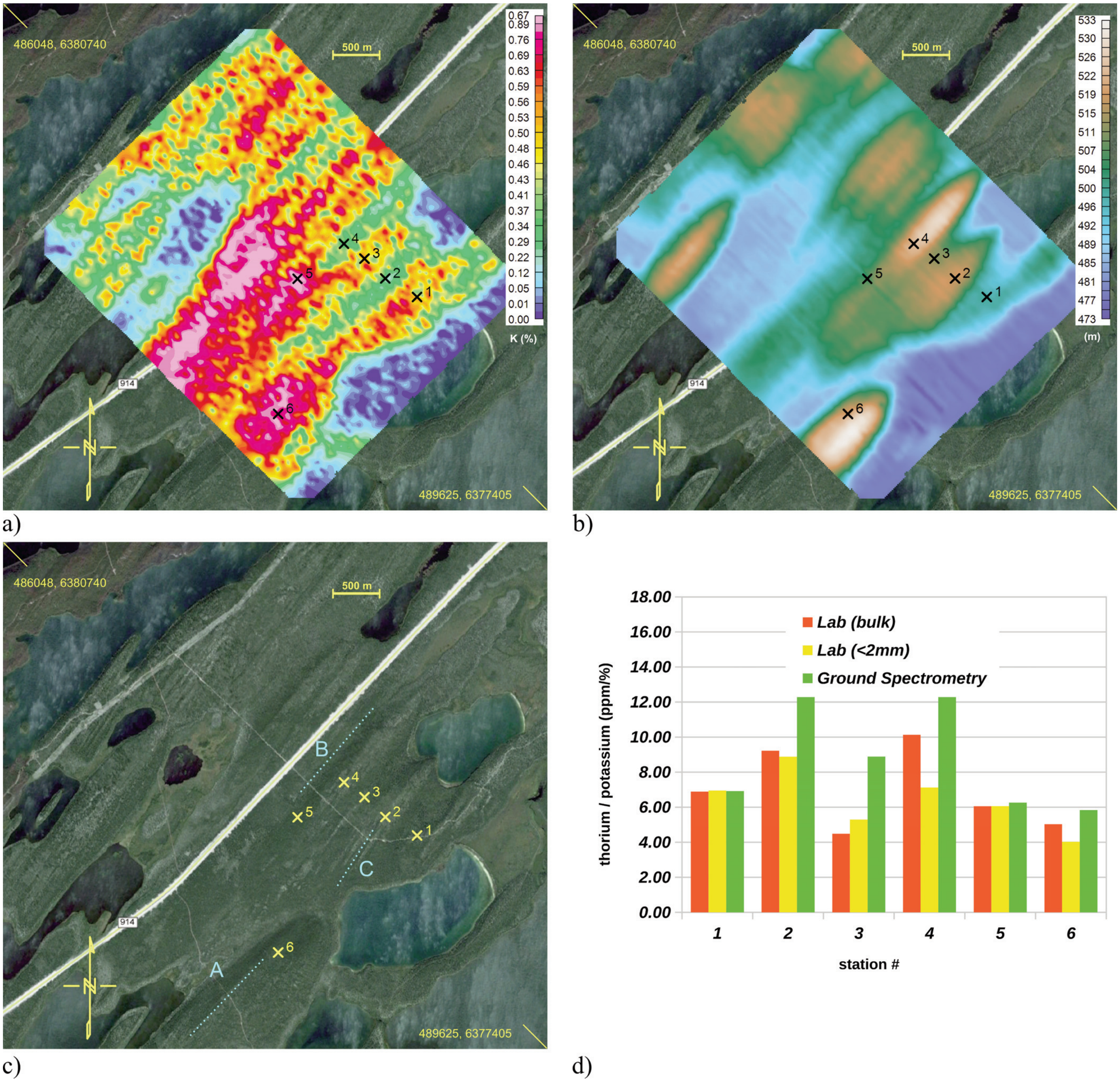

Figure 4. Field validation results from the A5 area. Crosses labelled 1 to 6 indicates locations of ground truthing measurement stations. Coordinates are in the UTM 13N, NAD 83 system. A) Map of K concentrations (%) obtained from the 2013 high resolution airborne survey. B) Digital terrain model (height above the GRS80 Ellipsoid) created with the laser altimetry data obtained from the 2013 high resolution survey. C) Interpreted satellite imagery (Google Earth) of Area A5. 'A' line indicates trend of large drumlin from main ice flow. Lines 'B' and 'C' indicate trends of remoulded drumlinoids and flutings, respectively, resulting from the ice readvance during the late stages of the Late Wisconsinan. D) Results of field measurements of K and Th concentrations (as RTK ratios) by ground and laboratory gamma-ray spectrometry for each of the ground stations.

ridges in potassium concentration (Fig. 5). A sandy diamicton with an elevated basement component, identified at station 6, as well as glaciofluvial sands filling the topographically low areas exhibit locally high signal in potassium concentrations that nearly mask the comparatively lower signature of the sandstone-rich till on top of the drumlins in the footprint of the airborne gamma-ray detector. A discontinuous low potassium signal can be observed along these topographical ridges on the airborne measurement map (Fig. 5a).

Conclusion and Implications for Exploration

Airborne gamma-ray spectrometry data is available for the entire Saskatchewan portion of the Athabasca Basin and its analysis should be part of exploration programs in this region. AGRS maps can be segmented into radiometric domains (Campbell et al., 2007; Fortin et al., 2014) to enhance their readability and to provide local baselines against which gamma-ray spectrometry measurements can be identified as anomalous. A further approach consists in

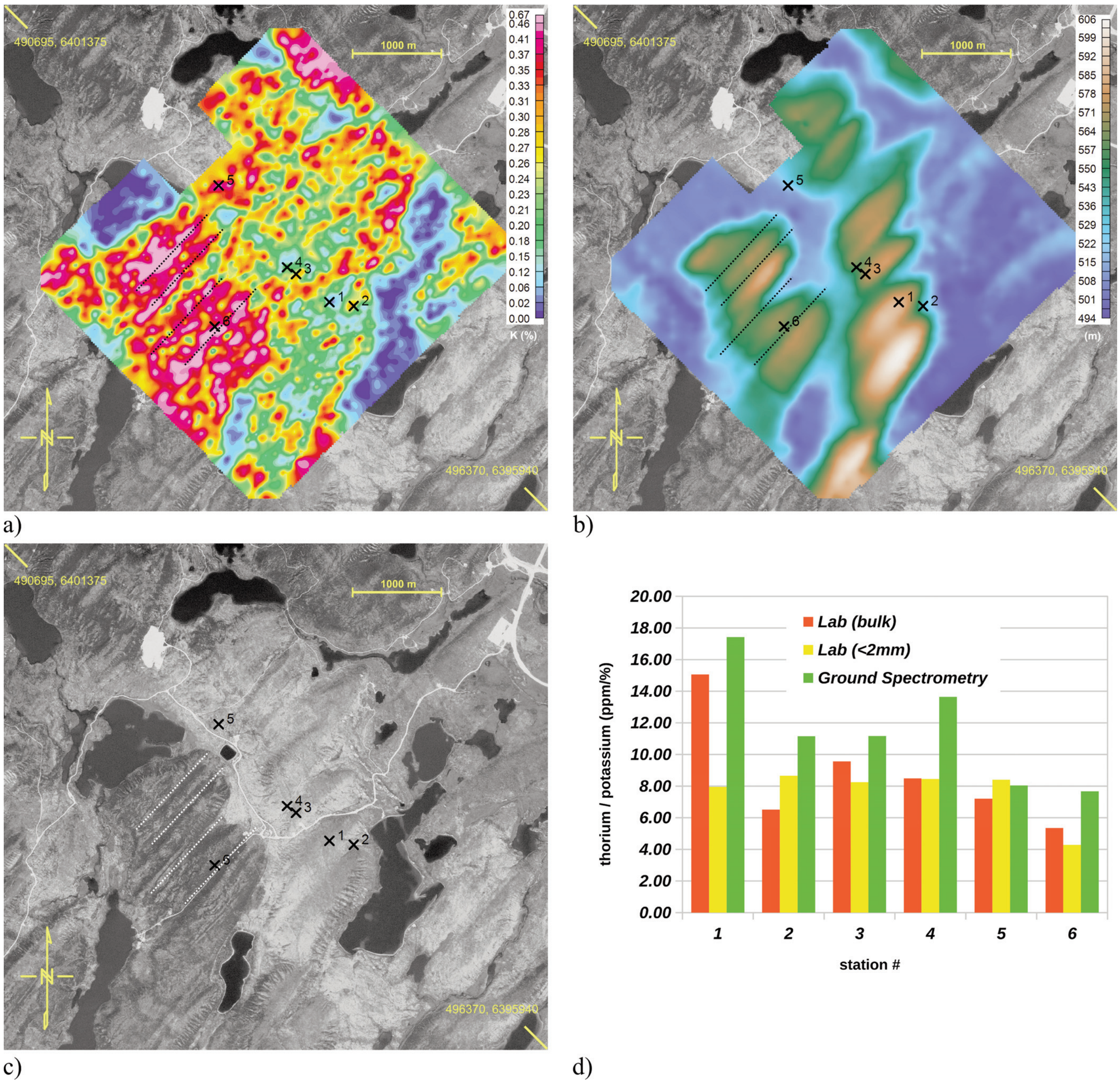

FIGURE 5. Field validation results from the A4 area. Crosses labelled 1 to 6 indicates locations of ground truthing measurement stations. Coordinates are in the UTM 13N, NAD 83 system. A) Map of the potassium concentration (in percent) obtained from the 2013 high resolution airborne survey. B) Digital terrain model (height above WGS84 Ellipsoid) created with the laser altimetry data obtained from the 2013 high resolution survey. Troughs between streamlined landforms in the western portion of the survey area have been highlighted and are reproduced on the other maps. C) Satellite imagery (SPOT) of area A4. D) Results of field measurements of K and Th concentrations (as RTK ratios) by ground and laboratory gamma-ray spectrometry for each of the ground stations.

integrating gamma-ray data with lineament analysis from aeromagnetic surveys and regional geochemical data to highlight hydrothermally altered structural features (Wright, 2014).

In this regard, characterizing the radioelement background to deposit-related surficial radiometric anomalies is an essential step and requires an understanding of the regional Quaternary geology. In the eastern Athabasca Basin, surficial sediments and landforms can be discriminated based on their K, U and Th geochemistry, linking to their provenance, but glaciofluvial sediments are pervasive in the areas studied and often mask signal of interests. Due to their higher concentrations in radioelements, the gamma-ray response of these sediments could cover anomalous signal from targets of exploration interest. From an exploration perspective, areas of sandstone-rich till, which exhibit a weak gamma-ray background signature in K and eU, appear much more favorable to the detection of weak anomalies from deposits alteration halos. When combined with surficial geology, sandstone and surficial geochemistry, and bedrock structural framework, airborne gamma-ray spectrometry surveys can help delineate and prioritize areas of interest thus resulting in more successful and cost effective uranium exploration programs in the Athabasca Basin.

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