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Identification of sandstones above deeply buried uranium deposits using multivariate statistical methods

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Abstract. The Athabasca Basin in northern Saskatchewan, Canada, hosts the world's largest high-grade U resources. Principal component analysis (PCA) of sandstone composition from the Denison Mines' Wheeler River property shows that U is positively associated with Y, Cu, Zn, Na, W, Co, Ni, B, Mg, HREEs, Cr, Sc, Mo, V and LREEs due to cryptic alteration associated with the uranium mineralization. In contrast, PCA of the regional sandstones shows that U is positively associated with Th, Ti, Zr and Hf, suggesting that U is hosted by detrital heavy minerals. Linear discriminant analysis (LDA) based on PCs of elements associated with U shows three groups of sandstones with high accuracy (95.5%) of discrimination; Group those above the Phoenix ore (Group PHX), in the Wheeler River property (Group WR) and regional sandstones (Group Regional). Several samples in the Group WR are classified into Group PHX by LDA, suggesting that these samples are considered possibly cryptically altered, even far (>200 m) from the ore. Therefore, there may be potential of U mineralization underlying these sandstones. This study shows that PCA and LDA are able to identify elemental assemblages associated with U and sandstones that are cryptically altered.
Keywords. lithogeochemical exploration, unconformity-type U deposits, linear discrimination analysis

1 Introduction

Many unconformity-type U deposits occur in the Athabasca Basin in northern Canada where they occur along the unconformity between sandstones and the crystalline basement. Major U deposits, including the world's largest McArthur River deposit, are located in the eastern margin of the Basin (Fig.1) where sandstones are relatively thin (less than 400 m) compared to those in the interior of the basin where they are up to 1400 m in thickness. The thick sandstones pose difficulty in exploration in the central area of the Basin. The recognition of the composition of the sandstones that have underwent uraniferous hydrothermal activity may help in exploration for deeply buried U deposits.

This study uses R - Q mode PCA to determine element assemblages associated with U in sandstones and linear discriminant analysis (LDA) to investigate whether sandstone compositions in the area underlain by U deposits are different from regional background sandstones in the Athabasca Basin. The Wheeler River property is ideally suited to examine the elemental assemblages of sandstones. The property hosts the Phoenix and Gryphon U deposits (Figs. 1 and 2). This property is not disturbed by mining activities. Furthermore, the high-quality geochemical data are available since the analysis was done at the Saskatchewan Research Council with the same analytical method since 2010.

2 Study area

Unconformity-related uranium deposits in the Basin are accompanied by extensive alteration halos extending over several hundred meters from deposits, which overprint diagenetic minerals of the sandstones and the metamorphic minerals of the basement rocks (e.g., Hoeve & Quirt, 1984). Common alteration minerals include kaolinite, illite, chlorite, and dravitic tourmaline, aluminum phosphate-sulphate (APS) minerals and chlorite (e.g., Hoeve & Quirt 1984; Jefferson et al., 2007; Adlakha and Hattori, 2015).

The Phoenix deposit is located along the unconformity, at a depth of approximately 400 m below the surface. The Gryphon deposit is a newly discovered U deposit which is approximately three kilometers northwest to the Phoenix deposit. The Phoenix deposit is estimated to contain indicated resources of 70.2M lbs U_3O_8 at a grade of 19.1% U_3O_8 (Roscoe, 2015). The Gryphon deposit is hosted in basement rock and currently estimated to contain inferred resources of 43M lbs U_3O_8 at a grade of 2.3% U_3O_8 (Denison Mines, 2016).

Alteration in the study area is typical unconformity-associated style. The Athabasca Group sandstones is mostly ~ 400 m in thickness in the research area and consists of the Read Formation (RD) and three members of the Manitou Falls Formation: the Bird (MFb), the Collins (MFc) and the Dunlop (MFd) members (Fig. 2).

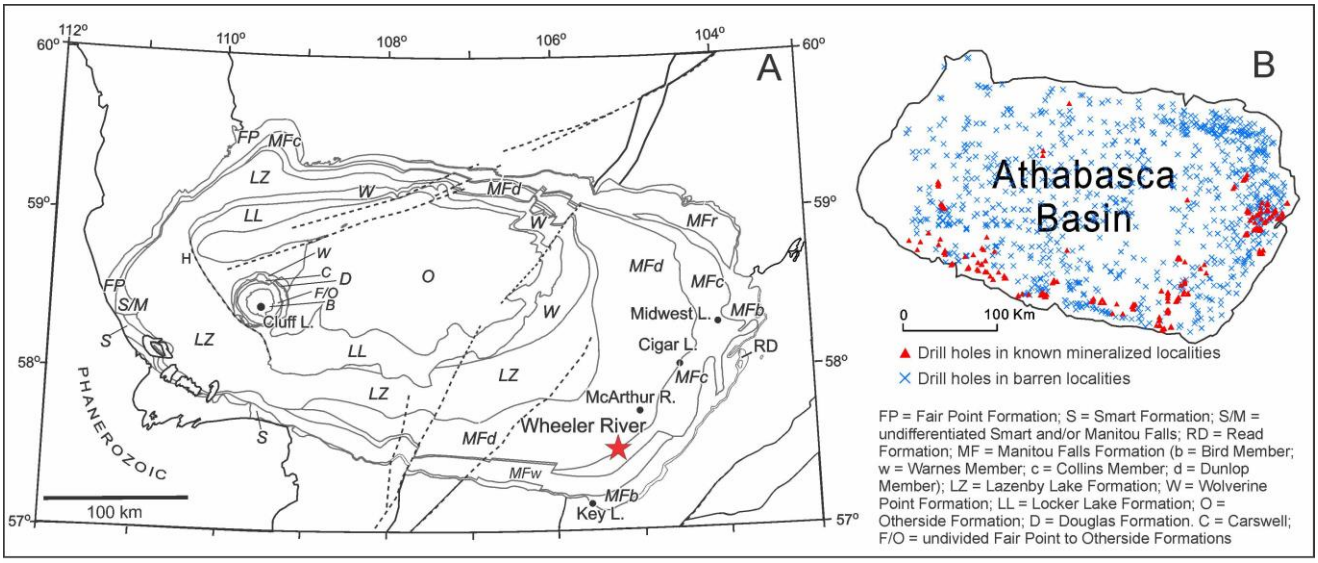

Figure 1. A. The general geological map of the Athabasca Basin, Saskatchewan, Canada (after Jefferson et al. 2007) and the locations of selected major U deposits (solid circle). Grey lines denote boundaries of stratigraphic units. Black lines denote boundaries of geological domains. Dashed lines denote major basement structures. The Wheeler River Property is shown by solid star. B. Drill core locations in Athabasca Basin.

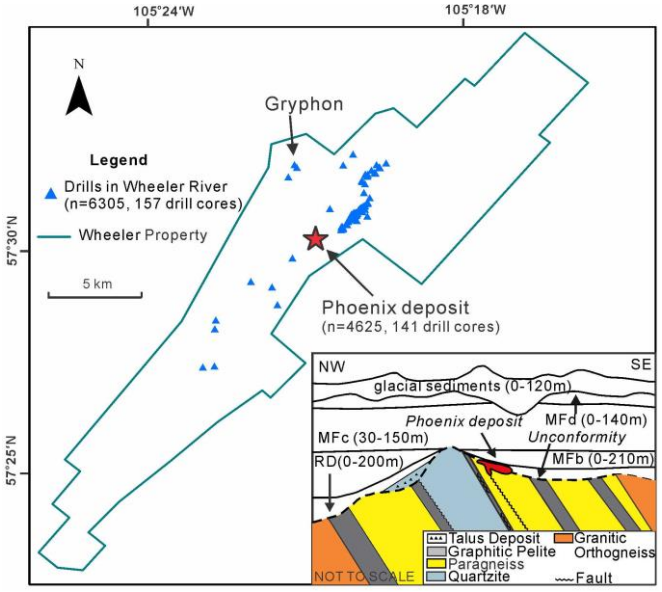

Figure 2. Locations of the drill holes in Wheeler River Property. Inset: NW-SE cross-section of the Phoenix deposit (modified after Gamelin et al. 2010).

3 Data sources and methods

All data are obtained after near-total digestion (Analytical code 3AMS at Saskatchewan Research Council). This study uses three sets of data; sandstones above the Phoenix deposit, in the Wheeler River property, far (>200 m) from the deposit (Fig. 2), and regional data from unmineralized areas (> 5km from any known deposits,) in the Athabasca Basin sandstone data set (Wright et al. 2015) (Fig. 1). This study uses R-Q mode PCA with scripts developed by Grunsky (2001). When elements associated with U are identified, another PCA was conducted to the subset of the elements to produce linear combinations of these elements. Analysis of variance was applied to determine the 8 PCs with best discriminating ability. Linear discrimination analysis (LDA) based on the 8 PCs was conducted using "lda" procedure in R statistical software environment.

4 Results

4.1 Principal component analysis

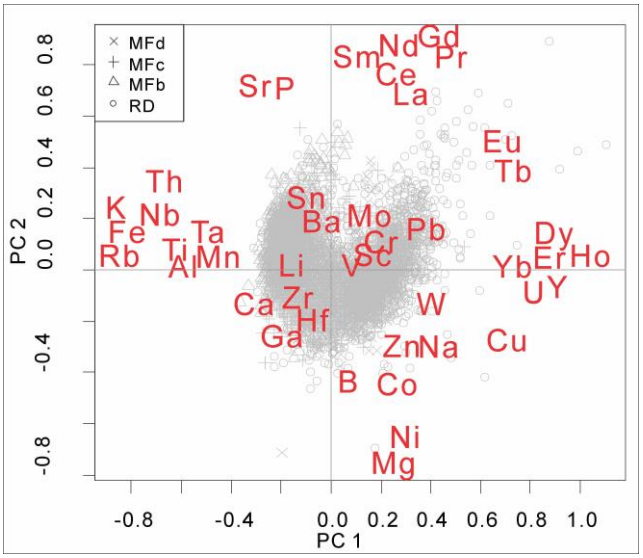

Figure 3. Biplot of PC1 vs.PC2 of Wheeler River data set, after log centred transformation of the composition data.

The PC1 and PC2 account for the large part of total variability (a total of 44.4%, 26.8% for PC1 and 17.6% for PC2) of the Wheeler River data set. Therefore, these PCs reflect the major geological process producing the elemental assemblages of the sandstones. PC1 also accounts for the majority of the U variability, 65.2%. The

U variability in other PCs is much smaller (<3.6%). Fig. 3 shows that U is positively associated with REEs+Y, Cu, Na, Zn, W, Co, Ni, B, Mg, Pb, Sc, Mo and inversely with Th, Zr, Hf, Fe, Ti etc in PC1. Positive, but veryweak association of U and Zr+Hf+Ca+Ga is observed in PC2.

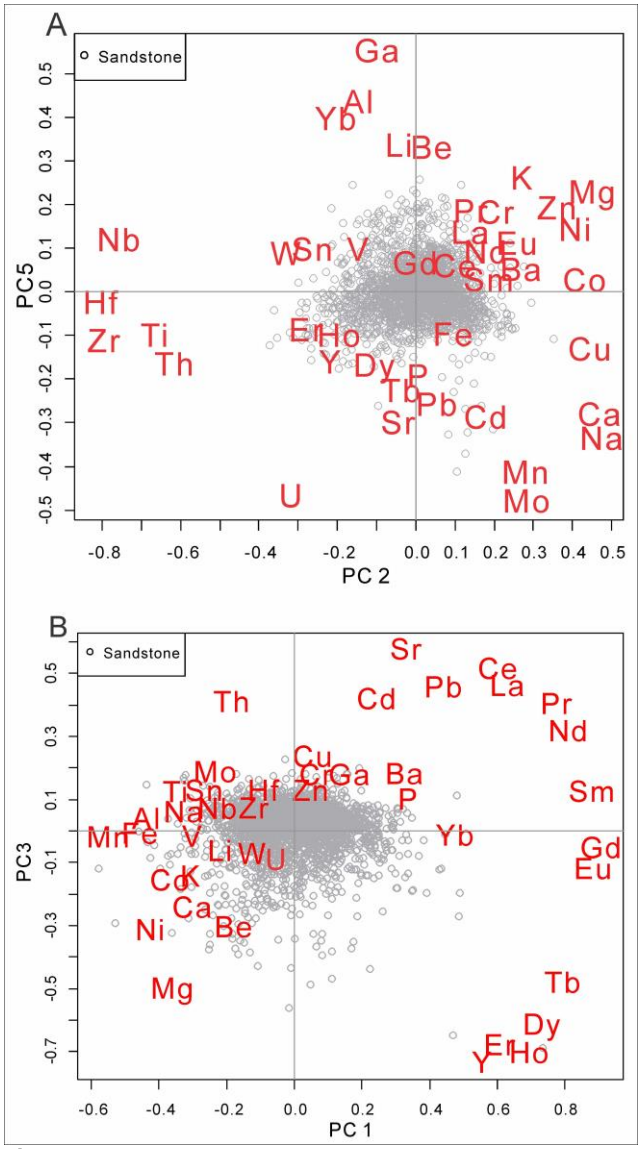

Figure 4. A. Biplot of PC2 vs.PC5 of regional data set, after log centred transformation. B. Biplot of PC1 vs.PC3 of regional data set.

The regional sandstone data shows that PC2 and PC5 account for the majority of U variability, 32.8%. The biplot shows that U is strongly associated with HREEs, Y, Th, Ti, Zr and Hf (Fig. 4A). PC1 and PC3 account for the majority of variability of REEs+Y (62.7%~84.6%) and they are not associated with U (Fig. 4B). The elemental assemblages suggest that U are not in REE-hosting minerals but mainly in heavy minerals.

4.2 Linear discriminant analysis

The LDA based on the elements positively and inversely associated with U yields three groups; PHX, WR and Regional groups. They represent the sandstones above the Phoenix ore (PHX), sandstones far from the ore but within the Wheeler River (WR) and regional background sandstones of the Athabasca Basin (Regional) (Fig. 5) These three groups have very minor overlaps with total accuracy rate of 95.5%.

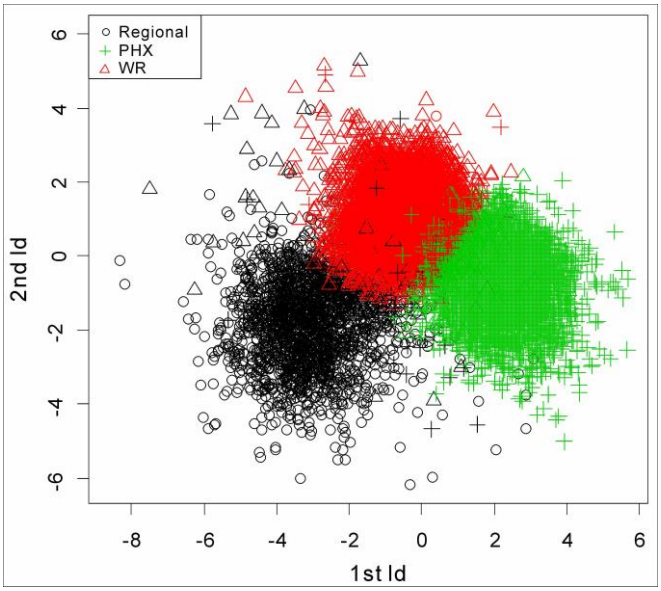

Figure 5. Linear discriminant plot of the first two discriminant functions, ld = linear discriminant. For each sample, the color represents the predicted classification and the symbol represents the observed classification.

5 Discussion

Uranium is positively associated with REEs+Y, Cu, Na, Zn, W, Co, Ni, B, Mg, Pb, Sc, Mo. The abundances of Cu, Pb, Mo, Co, Zn and Na are usually low in sandstones because they are not present in detrital minerals. The data suggest that these elements were likely introduced to sandstones through hydrothermal activity. Sudoite is Mg-rich chlorite and common as an alteration mineral associated with in unconformity-type U deposits (Hoeve and Quirt 1984). Magnesiofoitite, alkali-deficient Mg tourmaline, is the only mineral containing a significant amount of B in the study area and also a common alteration mineral (Rosenberg and Foit, 2006; Adlakha and Hattori, 2016). Close association of LREEs, P and Sr with U in PC2 suggests these elements are also associated with the alteration minerals, such as such as monazite and aluminum phosphate sulfate (APS) minerals. Xenotime is the major host of HREEs in the hydrothermal REE deposit, the Maw Zone (Chen et al. 2016), in the south part of the Wheeler River property.

The high discrimination of LDA indicates that the elemental assemblages can characterize the lithogeochemistry of sandstones of three groups. The composition of sandstones in the Wheeler River Property are similar to those directly above the Phoenix deposit reported earlier by Chen et al., (2015), suggesting that

these sandstones were likely affected by uraniferous hydrothermal activities. There are 156 samples of Wheeler River sandstones classified into the Group PHX, indicating that these samples are cryptically altered as samples overlying Phoenix ore. Fig 6 shows that these sandstones mostly located close to the Phoenix deposit. The drill holes above the Gryphon deposit also show the similar lithogeochemistry as those above the Phoenix ore. The sandstones with similar geochemical features also occur in the northeast part of the area where weak mineralization has been identified at the unconformity.

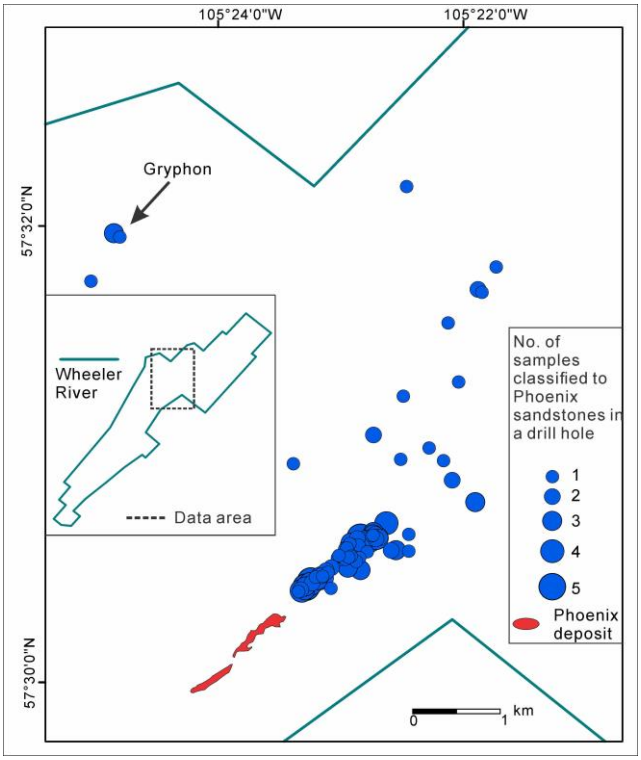

Figure 6. Locations of the WR drill holes containing cryptically altered sandstones. The size of symbol reflects the number of cryptically altered sandstones in a WR drill hole

6 Summary

Elements associated with U in sandstones in the Wheeler River Property are different from those in the regional sandstones in the Athabasca Basin. The difference reflects cryptic alteration in the sandstones of the Wheeler River Property. LDA based on the elements positively and inversely with U identifies sandstones associated with U mineralization. The use of PCA and LDA of shallow sandstone compositions is useful in exploration for buried U deposits.

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