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Lithogeochemical Facies of Athabasca Basin clastics, Saskatchewan - the use of PCA as a reconnaissance and mapping tool

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Abstract

This study illustrates how Principal Component Analysis (PCA) of lithogeochemical data may be used to identify and map lithogeochemical facies using a regional-scale database of ca. 40,000 samples. This database also includes ca. 11,000 samples with enough stratigraphic data to permit this to be done in three dimensions to a rudimentary degree. The facies distribution by stratigraphy and deposystems furthers the understanding of depositional, alteration history, and ore processes of the Athabasca Basin and its high-grade unconformity-related U deposits.

PCA permits distinction and mapping of detrital and alteration facies, separating uraniferous detrital facies from those related to mineralization processes. The analysis helps to form working hypotheses about the ore systems in the basin, identify areas of further interest, as well as areas whose high U values suggest that they might be important, but which, in fact, are not involved in the mineralization processes. Uranium bound in minerals released during partial dissolution techniques contributes less than a third of the U signal in the non-mineralized sandstone. Thus, immobile U not related to alteration can mask the signal of hydrothermal U that still may be recognized by PCA. PCA also highlights potential large, but complex metal depleted zones around some of the major orebodies. If true, then the interpretation of low raw data element values or low U component scores from PCA in a regional context is as important as the interpretation of high values. Samples from above or very near mafic intrusive suites in the basin show anomalously high and low values for some elements, as well as for a number of PCA components. This suggests that the mafic intrusions generated hydrothermal systems of only limited extent.

Consistent with recent fluid-flow modelling, differences in alteration facies above and below the Wolverine Point Formation show that the unit was an aquitard. Low levels of alteration facies in the basal unit in the Athabasca Basin imply that it was an aquifer in many areas. Both these observations reinforce long-standing field observations.

Introduction and Objectives

For exploration, one purpose of looking at ore deposits is to find out how to recognize the pathway of fluid on its way to and from orebodies. It is also useful to find indicators of mineralization at levels that are not obvious, or less than what might be expected in terms of the commodity of interest. Such areas form the outermost reaches of the ore system, the most widespread haloes of the deposits. To this end, this study concentrated on determining what background-level geochemical samples can contribute to exploration and hopefully go some way to remedying prospectors' complaints that geologists explain why mines are there, but do not help in finding them.

Large amounts of multi-element lithogeochemical data from the Athabasca Basin exist in the Saskatchewan Geological Survey assessment reports and have recently been compiled by Wright et al., (2015). This dataset was analyzed using Principal Component Analysis (PCA) to find to what extent it could be used to recognize and map sedimentary, diagenetic or hydrothermal facies. The purpose of this paper is to present some of the regional and stratigraphic results of that study to show the potential of the method.

At first, the Athabasca Basin was considered as a whole; then, recognized components were plotted by Athabasca Group stratigraphic units, using the much smaller subset of data with good stratigraphic control. Their distribution gives some insight into the development of the basin and of its alteration. Sedimentological facies, or alteration facies controlled by the sedimentology (e.g. by porosity), can form over large areas that are more likely to be sampled and, thus, are more likely to be recognized in studies with the sample densities present in Wright et al., (2015). In contrast, alteration facies dependent on post-lithification hydrothermal systems are restricted to relatively narrow fault zones. These zones include the systems that emplaced the unconformity-related U ore in the Athabasca Basin, and they are much less likely to be sampled during the early phases of exploration.

This study is regional in nature but the samples used here are largely from background drill holes, i.e., distal to known deposits. Thus, despite the large number of samples it is of a reconnaissance nature in its analysis of the mineralized fault zones. It is beyond the scope of this paper and the capability of the dataset to investigate particular mineral deposits or mineralized zones. The major ore zones in the basin that do not show up in this study are missing here solely because multi-element data was not available for them. Basement data was considered separately and produced similar results, but they are not further discussed here in the interest of brevity.

The Data and its limitations

Stratigraphic and sedimentologic data

The stratigraphic maps used here reflect work done since the EXTECH IV project (Ramaekers et al., 2007), and were

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previously presented in Ramaekers et al., (2010). Figure 1 is a map of the Athabasca Group that was deposited 1760–1500 Ma, showing the emendations to date in the nomenclature of the units and their mapped extent. On all maps the unconformity-related U deposits are indicated by plus signs, with reported resources indicated by the size of the symbol. Athabasca Basin mafic intrusive rocks mapped from outcrop and magnetic surveys (e.g. Buckle et al., 2011) are shown as generally northwest-trending lines. Blue lines are linear, northwest-trending mafic dykes with some outcrops known and are typical of 1267 Ma Mackenzie dykes (LeCheminant and Heaman, 1989). Green lines indicate a west-northwest trending dyke system also sampled in some outcrops. Dark red lines are less regular intrusive bodies, generally with an overall northwest trend that also have been sampled at outcrops. They may include Mackenzie dykes, but also lopolithic bodies similar to the ca. 1.11 Ga Moore Lakes complex (MacDougall and Heaman, 2002), and intrusions south of Cree Lake, shown as pale blue. In pale red are other possibly lopolithic bodies, perhaps including sills, which thus far have not been found in outcrop, and may be largely confined to deeper parts of the basin.

The main sedimentological basis for the Athabasca Group stratigraphic subdivisions that affect the bulk chemistry of the sandstones are shown in Figure 2. These are: 1) conglomerates, pebbly sandstones and associated heavy mineral beds; and 2) siltstone and clay distribution, largely in the form of clay intraclasts in the fluviatile units, and in bedded clays in the Wolverine Point and Douglas formations. The latter features are largely contained in the northwest-trending central trough that forms the depositional basin axis. Outcrop paleocurrent data allow the subdivision of

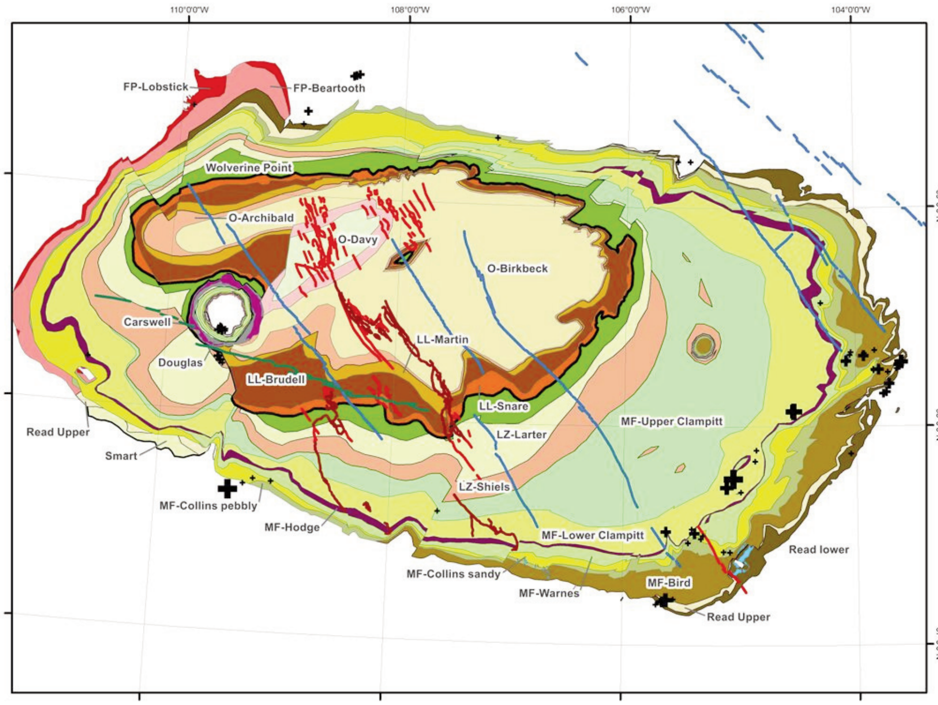

Figure 1: Athabasca Basin stratigraphy and U deposits, modified from Ramaekers et al., (2007). Deposits indicated by '+' sign, scaled to reported resources. Formation abbreviations: FP=Fair Point, MF=Manitou Falls, LZ=Lazenby Lake, LL=Locker Lake, O=Otherside, Member names indicated following the formation abbreviations. Linear lines represent northwest trending dykes and lopoliths determined from exposure and geophysical survey data (e.g. Buckle et al., 2011).

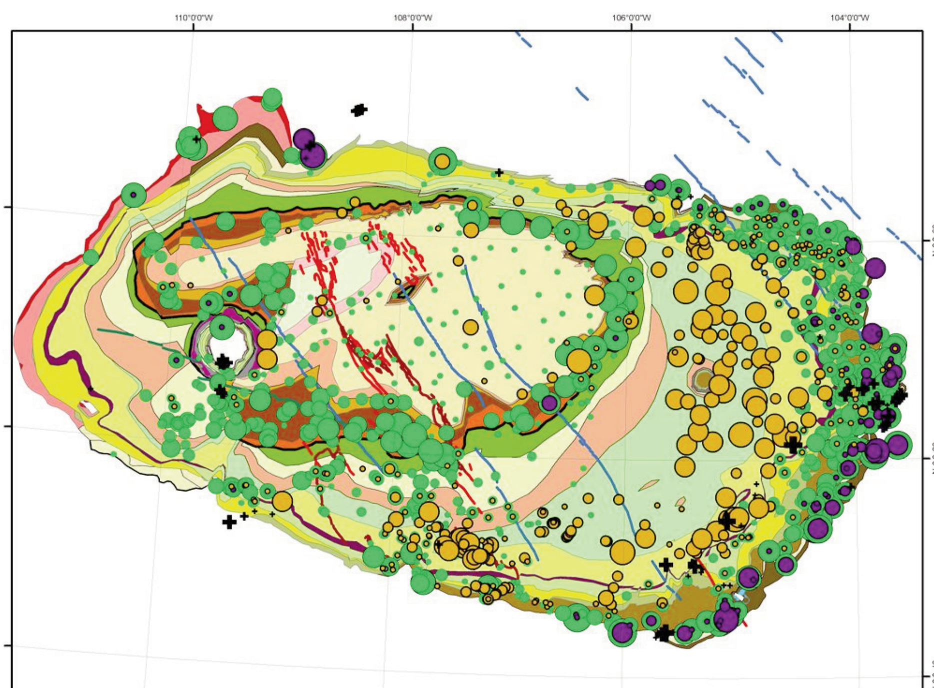

Figure 2: Main sedimentological basis for the Athabasca Group stratigraphic subdivisions that affect the bulk chemistry of the sandstones. Conglomerates shown by blue circles (size scaled by percentage), maximum grain size in green (size scaled to reflect grain size) and clay pebble content in brown (size scaled by percentage).

the Athabasca Group into deposystems. These are packages of strata united and defined by a common river drainage system in the case of fluviatile units, or longshore flow in the coastal areas in lagoons or nearshore areas in the case of the paralic and lacustrine units (Larter Member and Wolverine Point Formation). Deposystems may include many formations (they persist through time longer than most formations), and several may be found within a single formation. Figure 3 shows the named units, and Figure 4 the same map with the paleocurrent data on which the subdivisions were made.

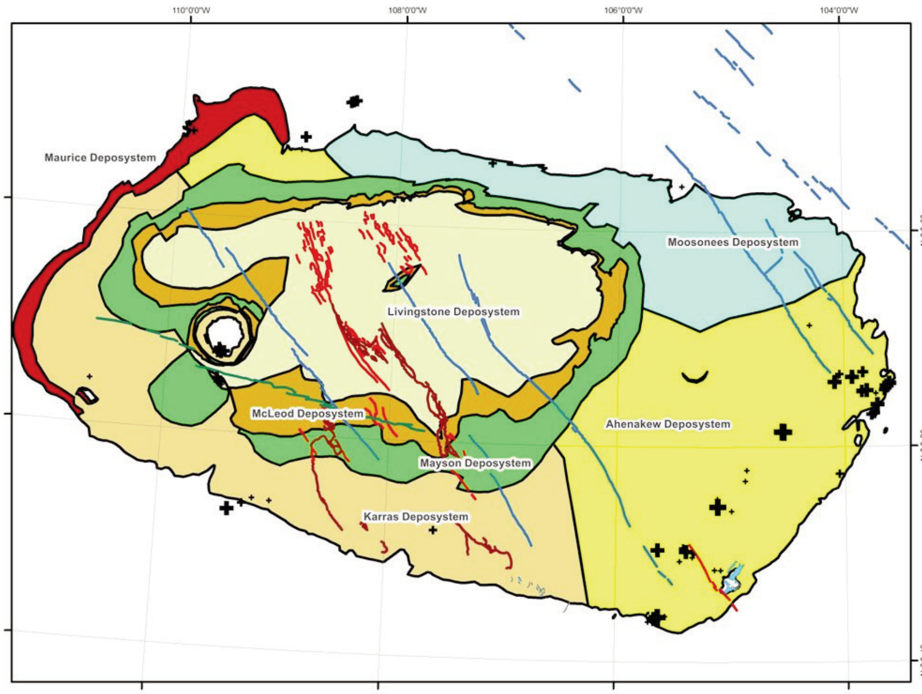

Figure 3: Athabasca basin deposystems, modified from Ramaekers et al., (2007).

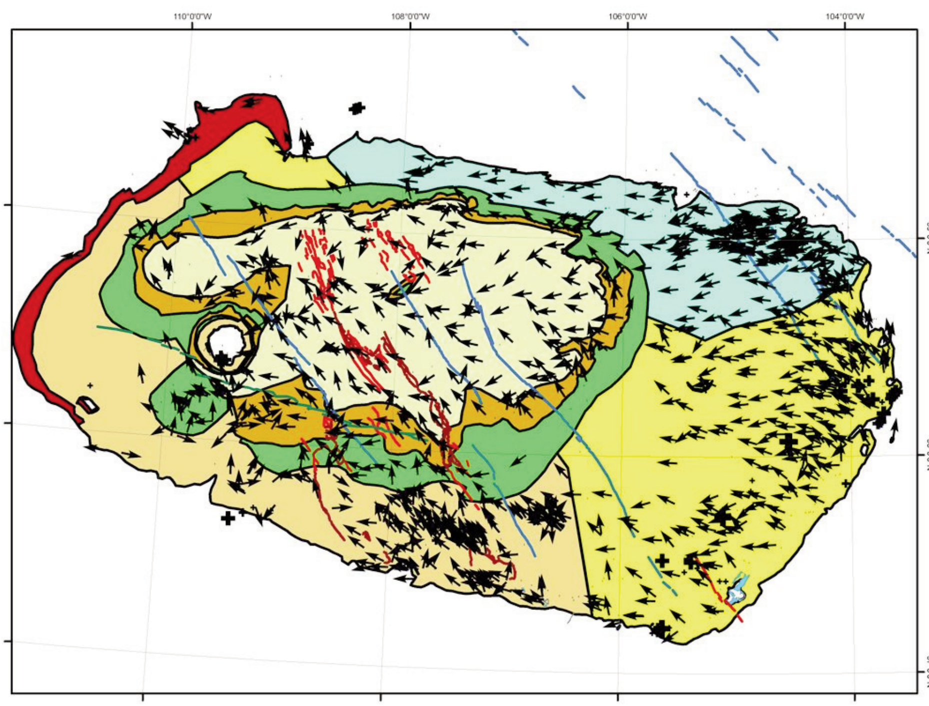

Figure 4: Paleocurrent data on which the deposystem subdivisions were based (Ramaekers et al., (2007). Outcrops are located at the base of the arrows.

Lithogeochemical data

The data used in this study is derived from the Athabasca Basin U geochemistry database (Wright et al., 2015). The database contains 40,378 sample analyses from 1261 drill holes and 837 outcrop samples. These include basement, Athabasca sandstone, and samples from mafic dykes intruded into the sandstone. Only the clastic data (sandstone, clay pebbles, mudstones) are considered in this study. The objectives of the study require the analyses of the major elements and enough others to permit interpretation of the alteration processes. That includes the metals of interest, using both partial and total digestion techniques, and the rare earth elements (REE), both light (LREE), and heavy (HREE). As outlined in Wright et al., (2015), the samples were analyzed by several labs, not all using comparable procedures (especially in their partial digestion method), and for most samples only a limited set of elements was analyzed. The result was that only a fraction of the samples could be used. Nearly all samples were collected by the mining industry for U exploration and grade control. Many are chip samples collected over 10 m of core. The best are half-metre samples from the high-grade zones. The U orebodies formed in fault zones, and many of the alteration processes left their record over much smaller intervals, often minute veins, especially away from the ore zones. The results of subsequent studies could be improved significantly by using small samples specifically collected to document a particular alteration or sedimentary facies.

Methods

Raw Data

Simple plots of raw data from the outcrop suite show obvious correlations between high or low element values and deposystems, formations, and mafic intrusive rocks. This knowledge is helpful in identifying PCA components as depositional or hydrothermal. As an example, the distribution of Ti (as TiO_2), an oxide common in heavy minerals separate, is shown in Figure 5. It is less susceptible to remobilization than most elements, and shows that the heavy minerals were deposited with the pebbly units, and, possibly as beach placers, or introduced with volcanic glass in the Wolverine Point Formation. Note that in the south-eastern Athabasca Basin outcrops of the basal units, TiO_2 shows similar or perhaps larger values than in the north-western margin of the basin (although there are fewer outcrops sampled in the south-east), indicating that the heavy mineral input was similar in both areas.

For purposes of discussion, the metal values produced by partial dissolution are referred to as ‘mobile’ metals (e.g. Pb_p), and the values released only by total dissolution as ‘resistate’ metal (e.g. Pb_d). The resistate values are the difference (hence ‘d’) between the total dissolution values and the partial dissolution values. They were treated as separate variables because they represent the metal held in different minerals of less solubility, or encapsulated in another, e.g. in detrital quartz as inclusions, trapped by diagenetic grain overgrowths, or in hydrothermal quartz. Figure 6 gives the distribution of U_p, the U extractable by partial dissolution, and shows that anomalously high contents of mobile U is found mainly in the Wolverine Point and Locker Lake formations and in the Read Formation in the Moosonees Deposystem (the northeastern basin corner). Despite the abun-

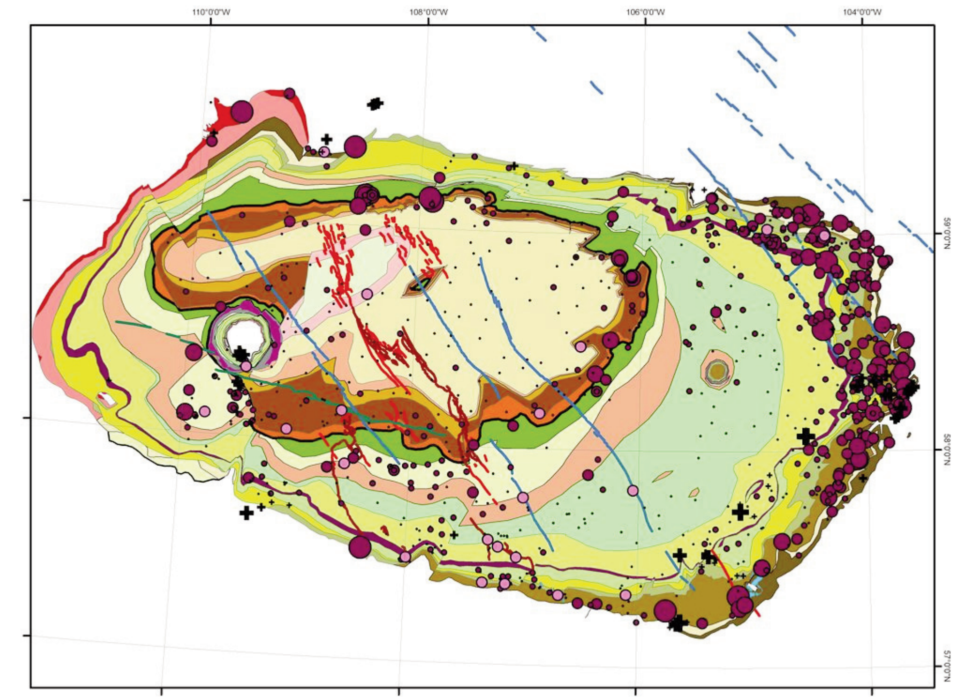

Figure 5: Raw TiO_2 values from outcrop samples in the basin (DF2930 database). Pink circles denote samples with TiO_2 values <half of median, dots denote samples with TiO_2 values from >half of median to the median value, dark red circles denote values >median value, with anomalous values denoted by progressively larger circles

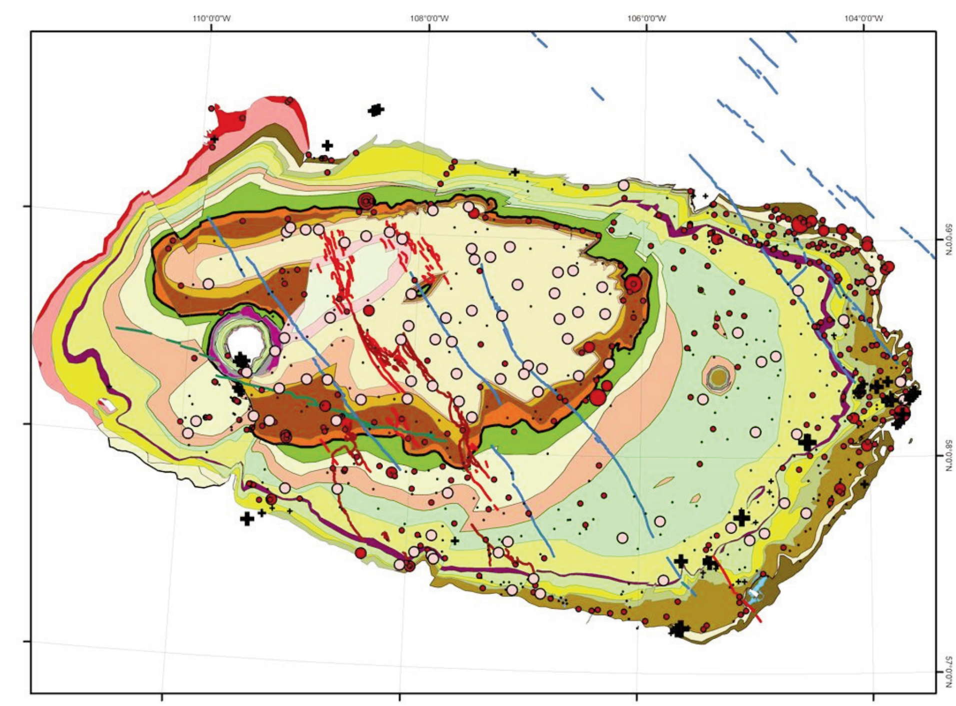

Figure 6: Raw U_p (partial digestion) values from outcrop samples in the basin (DF2930 database). Pink circles denote samples with U_p values <half of median, dots denote samples with U_p values from >half of median to the median value, dark red circles denote values >median value, with anomalous values denoted by progressively larger circles.

dant presence, or past presence of heavy minerals in the Ahenakew Deposystem, as shown by the TiO_2 distribution, U values there are much lower, particularly in the area of the large orebodies, suggesting U depletion of the sandstones in the area. Note that in the unmineralized samples (U < 2 ppm), the average U_d is 3.2 times greater than their U_p values.

Principal Component Analysis (PCA)

First introduced by Pearson (1901), PCA uses the matrix of correlations between variables, in this case ppm of elements or percent of the major element oxide, to replace the original variables by components that preserve the original variance, but rearrange it so that many fewer components account for the bulk of the variance in the data. Geoscientific applications of PCA include many different types of data: digitized shape differences in morphometric studies (Ramaekers, 1975), determining elemental assemblages associated with geochemical processes, hydrothermal alteration and mineralization (Grunsky, 1986; Chen et al., 2015), evaluation of mineral assemblages in regional stream sediment geochemical data and styles of mineralization (Ramaekers, 1986; Grunsky et al., 2009; Grunsky, 2010), and in identifying exploration targets from them (Ramaekers, 1986). In a sedimentary basin, elements are grouped depending on the distribution of detrital minerals (i.e. groups of elements) by sedimentary processes (resulting in grouping by minerals), and their reworking by diagenetic/hydrothermal/metallogenetic processes. Thus, with lithogeochemical data, the PCA components represent sedimentary and alteration facies, either singly, or in various combinations. As a result, a geochemical facies may show up in more than one component, or several facies may be placed on the same component in a particular study. The interpretation of the components may be made from the component loadings, which give the correlation between the component and the elements. The importance of each component in a particular sample is shown by the component scores for that sample. Excel tables for the data, component loadings, and component scores for each database outlined below are found in Appendix 1.

Four main runs of useable samples were made. The first (MAXVAR, for maximum number of variables) used all samples with all the major elements, all the REE, the metals of interest for which many exploration firms obtain both partial and total digestion data (Co, Cu, Mo, Ni, Pb, U, V, Zn) in both partial and total digestion, and others, including As and B that are not available for many samples, so that only about 6,000 samples were available. The MAXVAR analysis was done to provide the best chance at interpreting the components for STRATDEPO. For the STRATDEPO database and PCA other samples were added to the dataset that did not include TiO_2, B, or As. The results of MAXVAR helped to recognize the STRATDEPO components without these elements. This permitted the use of about 11,000 samples in the STRATDEPO database, making it the main study of the four. For all of the STRATDEPO samples, deposystem data are available, and for about 3,400 of them, the stratigraphic unit is known, permitting a degree of 3-D mapping of the STRATDEPO components.

STRATDEPO included enough mineralized samples to characterize ore emplacing facies, but as PCA is sensitive to outlying high values, it does so at the cost of obscuring the small changes in background level samples that provide pointers to ore. For this reason, the outcrop samples from Card et al., (2011) and Card and Bosman (2012) were analyzed separately in the DF2930 database. The outcrop samples are the only dataset of Athabasca sandstones that were sampled more or less randomly (there is a bias in favour of hard sandstone), as in almost all cases drill holes are located, in theory, only on ground favourable for mineralization characterized by faulting and the presence of favourable chemical environments (e.g. basement conductors). The DF2930 dataset and a further analysis of samples with < 2 ppm U_p (ULT2PPM) explore how to use the results of MAXVAR and STRATDEPO PCA in the usual exploration situation: finding information from seemingly unmineralized background samples.

Results

The Athabasca Group sandstones are virtually all quartz arenite in composition, comprised of more than 95 per cent quartz. This makes it relatively easy to interpret the components. PCA of the Athabasca sandstones generally resulted in 7 to 9 interpretable components. With a dataset this large, one might expect to find more interpretable components; the large size of the samples, usually incorporating material from more than one geochemical facies is probably the main reason for this. The PCA of the sandstones in these studies generally produced a similar set of components, and as there are more than 9 sedimentary and alteration facies present in the basin, few, if any of them are represented as single components among the ones extracted in this reconnaissance study. Their presence may be evaluated by analyzing the variation in the components between the four studies reported here, and in other studies that can be made by using carefully chosen subsets of the data.

The recurring components for purposes of discussion are here called the LREE, the HREE, the HV (detrital heavy minerals), the barren clay, the MgB (chlorite, borates, Ni_d), several mobile metal components, including one that is associated with much of the mobile U, and a FeMn component (hematite, limonite, Mn-rich). Generally, there are also one or more resistate mineral components. These represent metals found in hard to dissolve minerals, or phases trapped within such minerals. Examples include metals trapped in detrital quartz, trapped by quartz overgrowths during early diagenesis, or in hydrothermal vein quartz emplaced with the ore. As nearly all samples are quartz arenites, with high and nearly invariant SiO_2, silica is nearly invisible in these studies. It only shows up as an antipathetic element in the clay components, or any other component that has less silica than the average sandstone. All the component scores are presented in the appendices. Over 100 maps showing the distribution of component scores in the various studies have been made but only a few are presented and discussed below to illustrate the main component scores in relation to lithological units (Figs. 7-14).

The results are attached in the appendices as Microsoft Excel® files, with include individual files for: a) raw data, (b) PCA loadings, and (c) PCA scores, for each database (i.e. STRATDEPO, DF2930 and ULT2PPM).

Discussion

Lithological and alteration facies in PCA components

The degree to which PCA components represent lithogeochemical facies depends on how the element suites involved in each facies are distributed over the samples in the study. The samples reflect the sum total of the entire history of that sample. This represents the total of all sedimentary influence, diagenetic changes as burial increased, hydrothermal changes at any depth, and further alteration during the unroofing history of the sample. For a single PCA component to represent a single lithogeochemical facies, the samples under study must not overlap completely with another facies. Such overlaps do occur, for example, if more than one alteration process is controlled by the same condition, e.g. porosity that did not change between the two alteration events. Facies may be recognized by their element suite, and how that suite stays together between various studies of the data set. Usually PCA only partially unravels the diagenetic/hydrothermal history, especially when the dataset has been subjected to just a few runs of subsets, the sample size is small, or samples are large and incorporate multiple facies within most samples.

Field mapping, core logging and petrographic work have demonstrated the presence of a variety of sedimentological and alteration facies within the Athabasca Group clastic strata. A cursory discussion of the facies and their expression in the PCA components is given here. In interpreting the PCA components, a basic subdivsion was made into those that represent suites stable in an oxidizing environment (i.e., not ore in this case), and those stable in a reducing environment (the mobile metals components), which include all ore zones. Given the long burial and unroofing history of the basin, it is a reasonable working hypothesis that reducing facies were once more extensive than at present; therefore, the examination of components should be attentive to remobilization of the mobile metals from reduced zones into associations that are stable in oxidizing environments such as adsorption to clays and limonites, and incorporation into arsenates, vanadates, and phosphates among others.

In the MAXVAR and STRATDEPO databases, the distinction between oxidized and reduced facies is fairly clear because high-grade samples from the reduced ore zones were included. The distinction is more difficult in the studies of purely non-mineralized samples. When the mobile metals are not associated with hematite, vanadates, arsenates, phosphates or clays they are likely to represent a reduced environment. Thus, in the DF2930 and ULT2PPM databases, remobilized mineralization (the mobile metals) may be found with a FeMn component, a clay component or associated with P or V (Figs. 16, 17, 18). These represent the passage of metal-rich fluids, and it is up to the interpreter to deduce what parts of the ore system were sampled: the record of metals on their way to mineralized reducing zones; or the record of remobilized mineralized zones. Both are likely to be present.

The HV component is often mainly a detrital facies, as are any components representing kaolinitic clays (high Al_2O_3, low K_2O). The illitic barren clay components may represent a variety of detrital, diagenetic and late alteration facies. The LREE and HREE components are often largely alteration components with varying amounts of detrital influence indicated by their TiO_2 or Zr contents. The MgB component is probably an early alteration component recording the movement of brines. The mobile metal components always represent alteration. This might represent the initial stages of metal mobilization, with little actual movement of the metals from their source in the nearby host rock, or it might represent substantial migration of metals from its previous source. Note that this previous source may not have been the ultimate source, which is the basement to the basin, either directly below, or in the sediment source areas. What is of interest is not the ultimate source, but those stages of the U migration that are of exploration interest, i.e., that may be of help in finding the location of the ore zones.

Comparison of the component scores with the raw data U_p values shows that the HREE component always is most strongly expressed in the core of the high-grade mineralization in the orebodies (e.g. Shea Creek, Centennial, Millennium, West Bear in this study; Fig. 15; Phoenix and other deposits in Wright and Potter, 2015; Potter and Wright, 2015). As an initial working hypothesis, it is here regarded as the trace of the primary mineralization event, or a U-concentrating reworking of this event. High HREE component scores lacking U may represent the trace of this event in areas lacking a reducing environment, or the core zones of re-oxidized mineralization, now stripped of metals stable only in reducing zones. Thus, with or without U, this facies has important exploration significance, but not necessarily always with the same exploration implication.

The mobile metal component with U is strongly expressed in the samples around the core zone of the orebodies, generally with U values much lower than in the core zones. It may represent mineralization in a less favourable area (less reducing?) or a reworking of the primary mineralization.

Examples of component score distribution maps

Figures 7-10 show the distribution of component scores as extracted from the STRATDEPO dataset, which considers samples from the entire Athabasca Group, including a number of high-grade, ore-zone samples. Because of the sensitivity of PCA to outlying high values, this solution tends to divide the samples' U components results into highly anomalous and non-anomalous, while obscuring subtle distinctions among background and near background samples. Figures 7 and 8 show the distribution of U components in the Read and Smart formations. These units are the basal units in the bulk of the Athabasca Basin and host many of the sandstone-hosted egress or polymetallic deposits (deposit subdivision as per Everhart and Wright, 1953; Beck, 1969; Ruzicka, 1989, 1996; and others). Away from the ore zones the distribution of the U component scores are more or less like that of the other sand-rich formations in the basin, except that the basal strata are more likely to contain anomalous scores. Figure 7 shows the results of drill holes superimposed, while figure 8 shows such samples unobstructed, displayed concentrically around the drill hole location, with loss of data along the eastern margin of the plot due to limitations of the plotting program. Note that the heavy mineral (HV) component F5, has the second highest residual U loading, after the HREE component. Factor F5 is important in the northeast of the basin, less so in the southwest, and least of all in the central northwest trending trough of the basin, and suggests that U dissolution from detrital minerals was less complete to minimal in the northeast of the basin. The plots suggest that the mineralizing solutions, as evidenced by HREE component anomalies, moved widely in the basal Athabasca units, especially in the central trough, and that the limiting factor in the formation of orebodies may have been the presence of reducing traps, and their preservation potential.

Figure 9 shows the distribution of the significant U components in the Wolverine Point Formation, which like the other silt- and mudstone-rich unit, the Douglas Formation, shows many high component scores for the two main U components: the HREE component; and the U-rich mobile metal component. The latter is expressed relatively weakly, as it is rated in comparison with the ore-zone material of some drill holes in this study. The heavy mineral component is not significant in the Wolverine Point Formation.

The distribution throughout the basin of component scores for the STRATDEPO component 2, the mobile metal and U component, is shown in Figure 10. It shows a close association to known ore zones, and to fault structures in the vicinity of known ore zones.

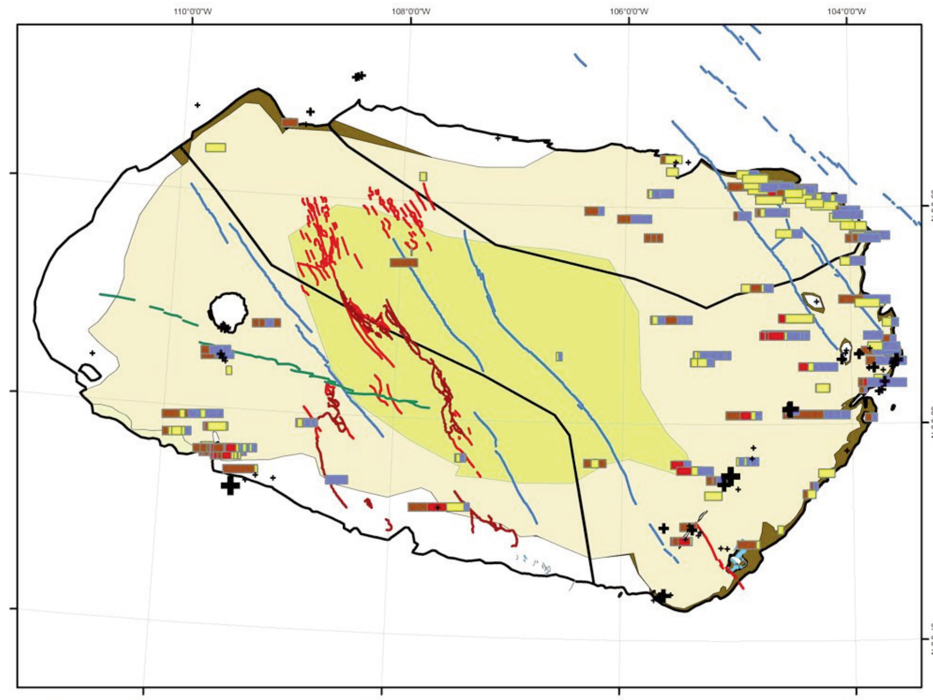

Figure 7: STRATDEPO values in drill holes and outcrop samples of the **Read and Smart** formations for Mobile metal (F2; red), U-HREE (F3; brown), resistate metals (F6; yellow) and HV minerals (F5; blue) factors. Significance of each factor indicated by length of bar and deposystem boundaries defined by black lines. Factors shown only if scores are above average values. Eastern basin margin values not plotted due to plot program limitations.

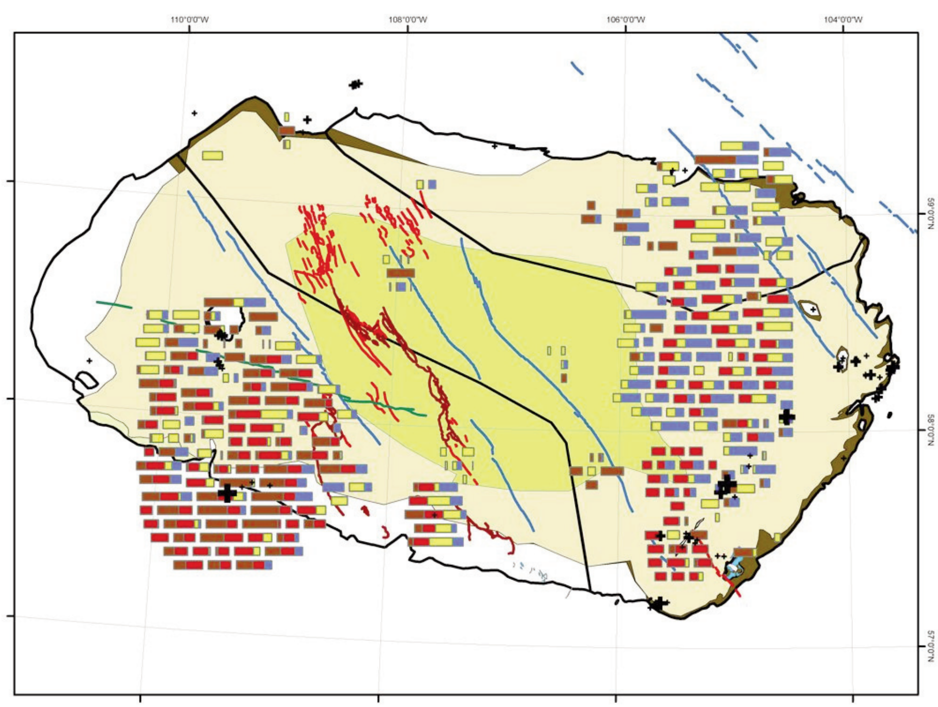

Figure 8: STRATDEPO values for drill hole and outcrop samples of the **Read and Smart** formations, with drill hole values shown as clusters around the drill colar: Mobile metal (F2; red), U-HREE (F3; brown), resistate metals (F6; yellow) and HV minerals (F5; blue) factors. Significance of each factor indicated by length of bar and only shown if scores are above average.

Figures 11 to 14 show selected component score distributions from the DF2930 dataset, the outcrop samples. The outcrop samples have been exposed to prolonged weathering, and although bedrock, they are similar to the soil A-horizon in this respect. For this reason this group was kept separate from the drill hole samples. The highest sample in drill holes might have served as a proxy for outcrop in areas with thick cover (which generally includes the mineralized zones), but it is likely to have gained some mineral content from fluid flow in the more reducing environment below the soils rather than lost them like the outcrop samples.

The component score distribution of components related to heavy minerals from the DF2930 (outcrop) dataset is shown in Figure 11. Note that the bulk of the U in the unmineralized samples is accounted for by component F3, the HV component, with high values in pebbly units of the Read to Hodge formations. This U is still in disseminated state, and its relative paucity around the large deposits (Figs. 7, 8) suggests the presence of a depletion zone. This diagram also clearly shows differences between sandstones above and below the Wolverine Point Formation.

Figure 12 shows the distribution of the DF2930 main mobile U component F4. It has high loadings for As, Sb, U_p, Ca phosphate and mobile metals, especially Pb in addition to lower amounts of Ni and Zn. This element association is recognized only by the PCA on unmineralized samples. The highest component scores are all from the Wolverine Point Formation apatite-rich layers. Apatite ages in the Athabasca Basin between 1640–1620 Ma (Rainbird et al., 2003; Davis et al., 2008), record a regional low temperature alteration event at about the same time as localized pre-ore alter-

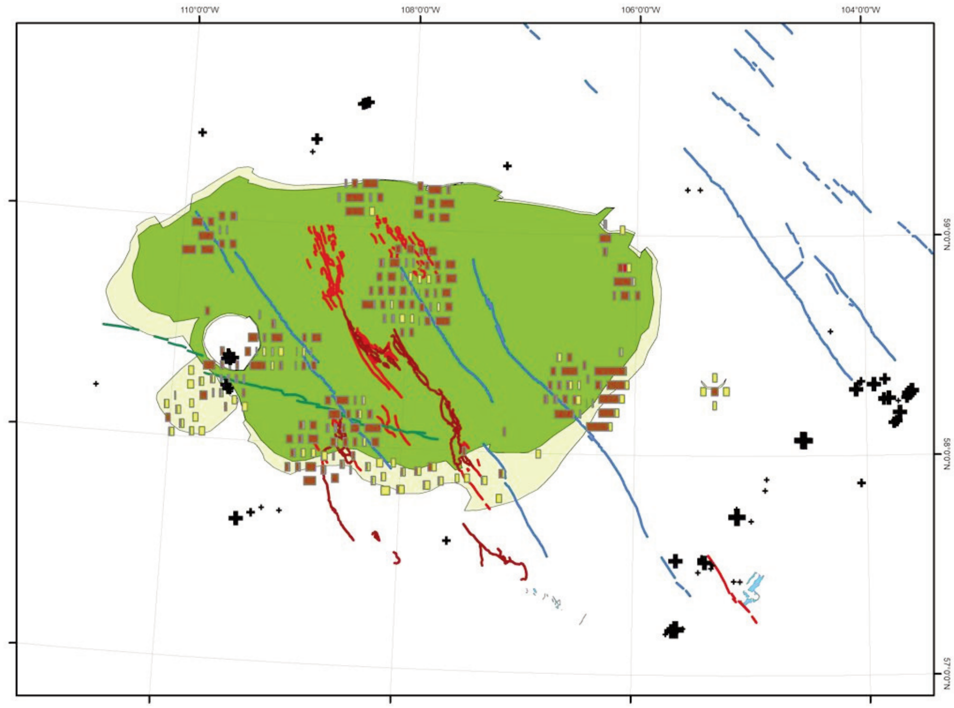

Figure 9: STRATDEPO Main U factors: Mobile metal (F2; red), U-HREE (F3; brown), resistate metals (F6; yellow) and HV minerals (F5;' blue) for drill hole and outcrop samples of the **Larter Member and Wolverine Point** Formation. Significance of each factor indicated by length of bar and only shown if scores are above average.

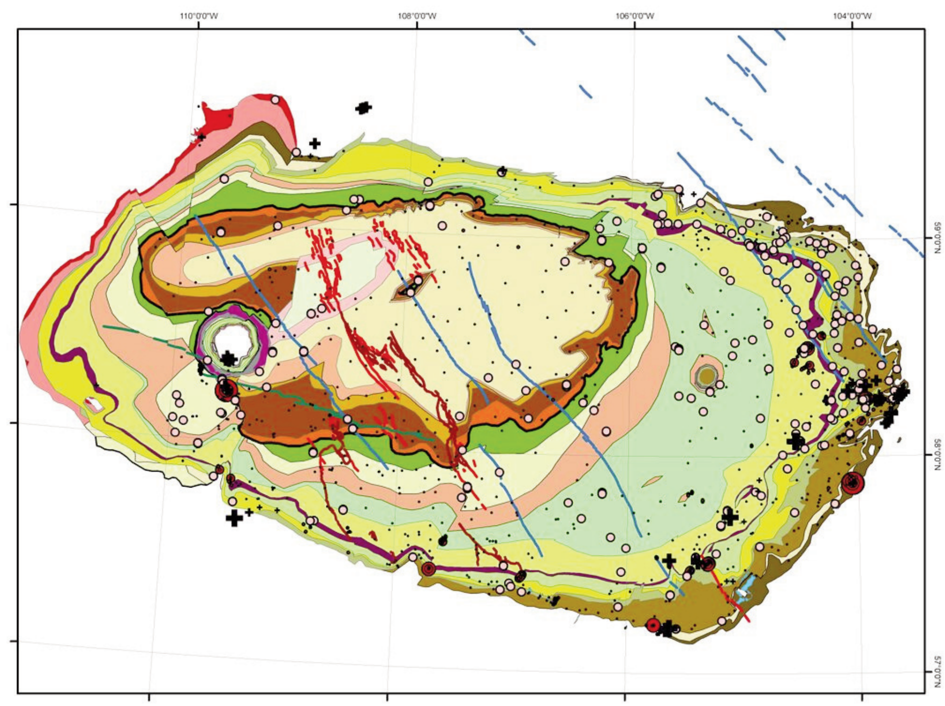

Figure 10: STRATDEPO mobile metal (F2; red) factor for drill hole and outcrop samples. Pale red circles= samples with negative F2 scores; dots= values above median but not anomalous; red circles=anomalous values denoted by progressively larger circles.

ation minerals developed (Jefferson et al., 2007). Lower level anomalies occur in the pebbly units low in the section, where in places autunite, a Ca-U phosphate is present. The autunite occurrences served to first focus exploration attention on the Athabasca Basin (e.g. Kermeen, 1955). Low values for this component are evident around the large U deposits in the southern 2/3 of the Ahenakew Deposystem, also previously shown in Figure 7.

Figure 13 shows where mobile metals Cu, Co, and Ni accumulated in outcrop. Anomalies are widely present through the basin, except in the areas of known large ore zones. High scores show a similar distribution as the mobile U (Figure 6). This suggests that this component is the one more or less equivalent to the mobile metals and U component in the STRATDEPO study, with the lack of U in it due to the strong leaching in the outcrops. High component scores are widely present in the central part of the basin, but much less so elsewhere, especially in the Ahenakew Deposystem, which are equally clean and silicified sandstones.

Figure 14 shows the distribution of the main U related component scores in the outcrop samples. It again shows some major divisions in the Athabasca Basin alteration patterns. Of note is the lack of HV minerals associated with the HREE and main mobile U F4 components in the Wolverine Point and Locker Lake formations. It suggests that metals and U in the Wolverine Point Formation were brought into the basin in other ways, perhaps, and in part, in the form of volcanic glass (ash), but also, and perhaps more importantly, in solution by the rivers flowing into the basin, to be recovered in the redox traps provided by the bacterial mats in both the fluviatile environments (red, white specs) and in the inland sabkhas in the Wolverine Point Formation (evidenced by haloturbation, displacive nodules, thin siltstones, pseudomorphed evaporite minerals). Such traps would hold the metals until remobilization during deep burial with the aid of evaporite- and diagenetic-derived brines.

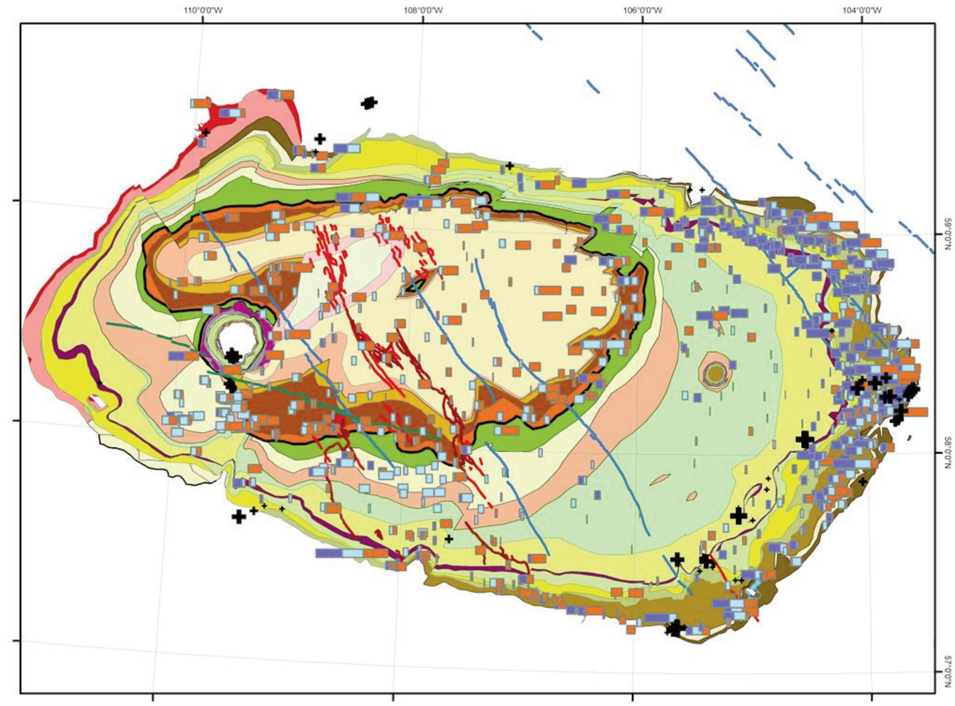

FIGURE 11: DF2930 HV minerals (F3; dark blue), altered HV minerals (LREE, Sr, ZBa, P, K with no Zr and low Th; F1; pale blue), hematite (Fe,V,Cr, Sb; F7; red)) factors for outcrop samples. Significance of each factor indicated by length of bar and only shown if scores are above average.

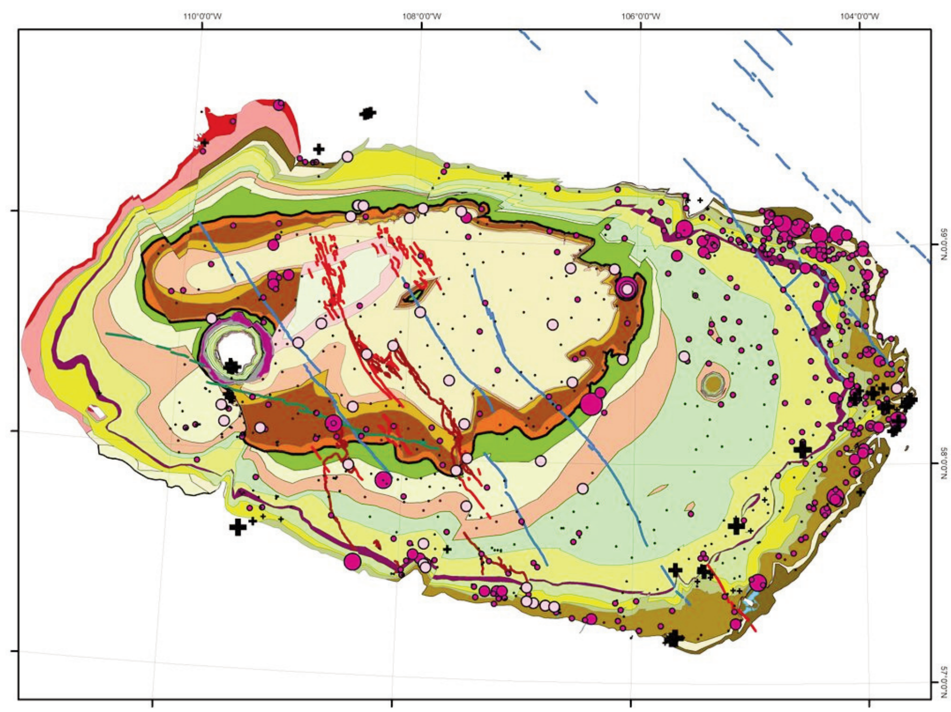

FIGURE 12: DF2930 mobile metals and phosphates (As, Sb, U1, Ca; F4) factor for outcrop samples. Pale red circles= samples with negative F4 scores below negative mode; dots= samples with negative F4 scores; violet circles=positive F4 values with anomalous values denoted by progressively larger circles.

Geochemical facies in mineralized drill holes: Centennial deposit, ddh VR-018

Figure 15 shows the distribution of components F3 (HREE), F2 (Mobile metals, U), F6 (Resistate metals), and F5 (Heavy minerals) in ddh VR-018, one of the mineralized holes at the Centennial deposit. Figure 15(B) shows a close-up of the basal samples just above the regional unconformity. The main mineralization is carried by the HREE facies (brown). Above the deposit, the mobile metals component is dominant, but at greater distance above the deposit it is replaced again by low values of the HREE facies.

Geochemical facies in unmineralized surface and drill hole samples (Study ULT2PPM)

To find the more subtle anomalies and the trace of mineralizing solutions, samples with less than 2 ppm U were run through the PCA separately. Similar components were derived, except that the mobile metals components of the earlier studies seems to be split in two: a Ni, Mo, Cu, Co, Sb, W, V, Zn, Fe_2O_3 and mobile U component with the second highest, but relatively low mobile U loading, component F2, and a mobile Pb, Zn, U, V, Sb component, that had the highest mobile U loading, component F7.

Figures 16–18 show the distribution of the main U components. Figure 16 shows the main mobile metal component. The low mobile U loading suggests that it represents a somewhat oxidized remnant or remobilization of the near-ore, mobile-metal factor seen earlier. Large anomalies are, among others, in the magnetic low belt at the La Rocque Lake occurrence that is visible in the regional airborne data (Buckle et al., 2011), in the vicinity of the Phoenix deposit, and in the fault zone hosting the Patterson Lake South deposit.

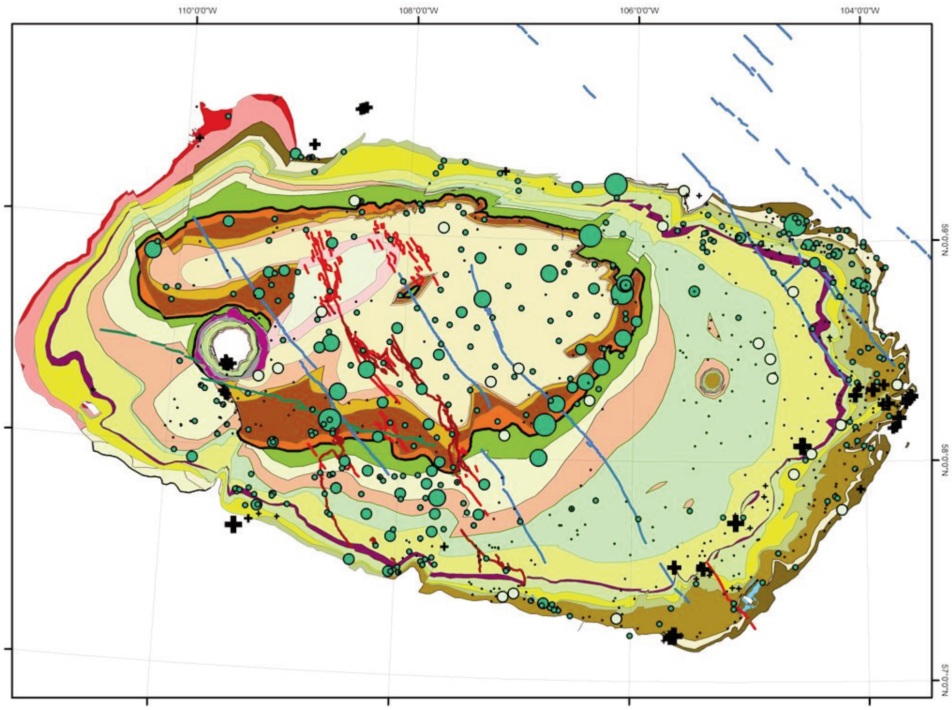

Figure 13: DF2930 mobile Cu, Co and Ni (F6) factor for outcrop samples. Pale green circles= samples with negative F6 scores below negative mode; dots= samples with negative F6 scores; dark green circles=positive F4 values with anomalous values denoted by progressively larger circles.

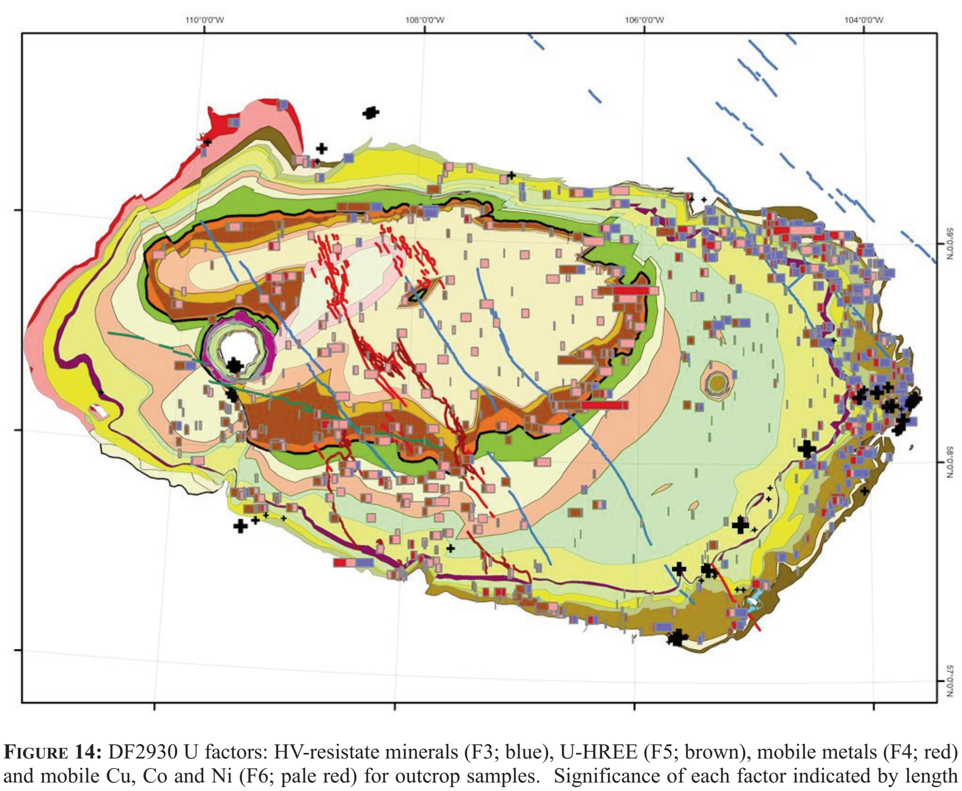

Figure 14: DF2930 U factors: HV-resistate minerals (F3; blue), U-HREE (F5; brown), mobile metals (F4; red) and mobile Cu, Co and Ni (F6; pale red) for outcrop samples. Significance of each factor indicated by length of bar and only shown if scores are above average.

Figure 17 shows the HREE component, here with only low U loadings. Anomalies are again near some of the known ore zones, but some of the largest are in the major fault zones such as the Grease River, the Virgin Lake-Black Lake shear zone, and the Harrison Fault near the Carswell structure. Others are from samples taken very close to some of the Cree Lake area mafic intrusive rocks. These may record the pathways of mineralizing solutions that, by and large, lacked a reducing environment to precipitate the contained U at the sampling level, but perhaps not necessarily at the unconformity-level in the structure.

Figure 18 shows the distribution of the mobile Pb, Zn, U, V, Sb component F7, the one with the highest loading for mobile U. The anomaly distribution correlates with pebbly units in the Moosonees deposystem, less so in the Karras deposystem, and not with the pebbly units in the southern Ahenakew deposystem, where the large orebodies are located. Other large anomalies are present in faulted areas in the Carswell, Patterson Lake, Virgin River, and Cable Bay fault zones. As an initial hypothesis to be further investigated, it is here suggested that this pattern may represent a late, possibly Paleozoic intrusion of brines into the basin and its effect both on existing mineralization and still in place disseminated U.

Influence of Athabasca Basin Mafic Intrusive Rocks

Many component scores and element distributions are affected by proximity to the Athabasca Basin mafic intrusive rocks, with the two generations (Mackenzie dykes versus Moore and Cree Lake intrusions) showing different responses for some element and components. A few components show anomalously high component scores, while others show antipathetic behaviour. As an example, the Sr/Ce ratio is shown in Figure 19, which shows Ce greater than Sr in nearly all samples associated with intrusive rocks, as well as in the Grease River and Virgin River/Black Lake shear zones. The Sr/Ce ratio is suggested to be indicative of proximity to mineralized zones when in the form of aluminum phosphate sulphate (APS) minerals (the LREE component). Whether the relation is to mineralized zones or simply to areas of high heat needs to be investigated with further work.

Future Work

This short orientation study points to structural zones, stratigraphic units, and hydrologic units that can and should be further investigated, initially with PCA of the geochemical data, and then followed up with petrographic, SEM and

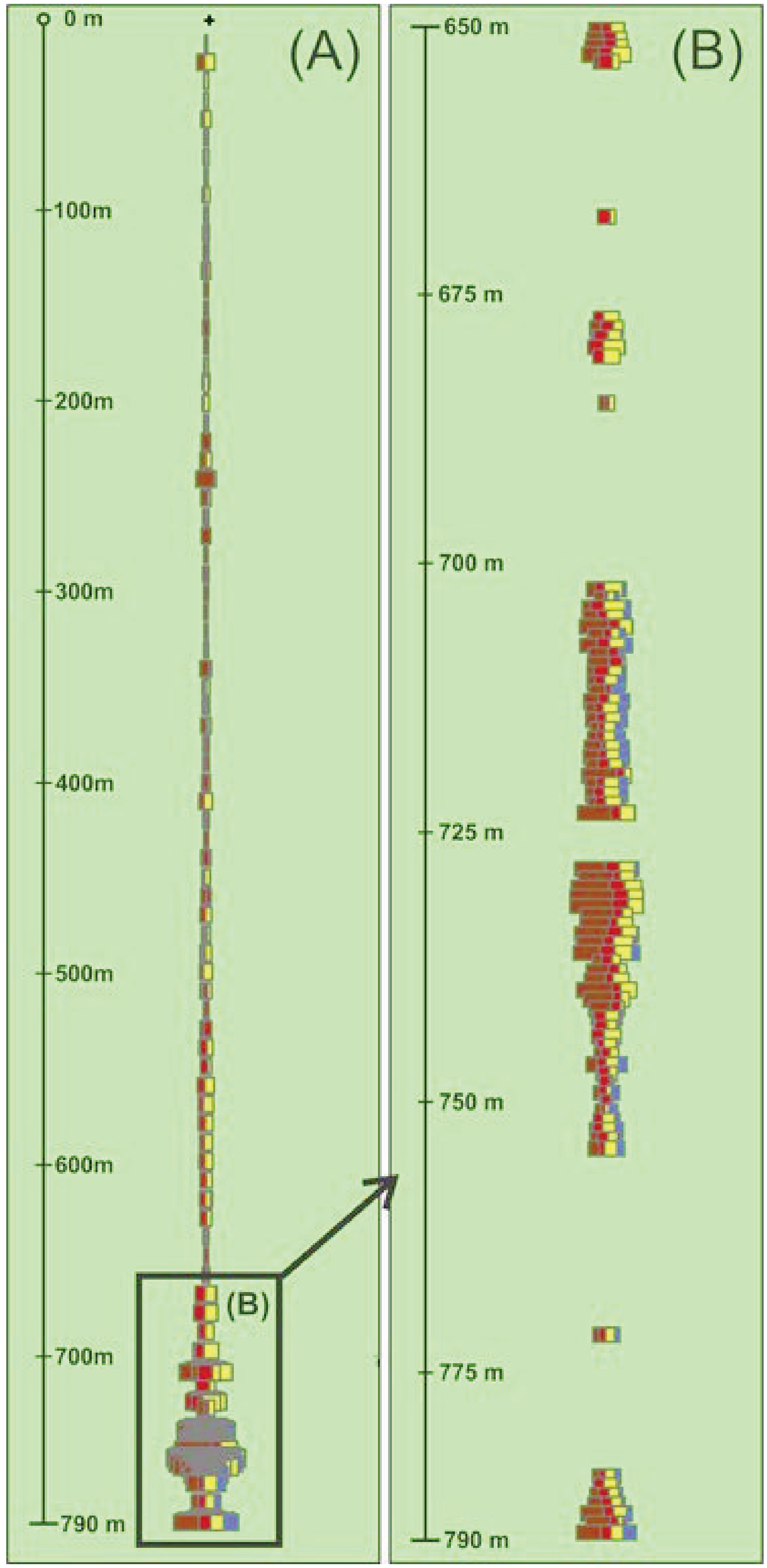

Figure 15: Geochemical facies within the Athabasca Group, from DDH VR-018 (Centennial deposit). (A) 0–790 m, (B) 650–790 m. Factors shown: U-HREE (F3; brown), mobile metals (F2; red), resistate minerals (F6; yellow) and HV minerals (F5; blue). Significance of each factor indicated by length of bar and only anomalous values shown.

isotope methods. For example, the component structure in the DF2930 (outcrop) and STRATDEPO studies is influenced by the contrast between the Wolverine Point and Douglas formations and the rest of the strata: this obscures lesser distinctions. Follow up work needs to be done to find the mineralogy of the elements in the various components and the paragenetic sequence. These might vary within the same STRATDEPO derived component.

Conclusions

Two important general conclusions can be reached from this preliminary description of the PCA results. The first is that multi-element PCA can distinguish between a small hydrothermal signal and a larger immobile U signal in the same sample. Even with near-total digestions, immobile U is the dominant component of U in the outcrops and thus till samples, and this immobile U may mask the signal of hydrothermal U enrichment. This means that interpretations based on a limited number of elements in isolation, e.g. U/Th ratios, can be mistaken. Using only a few elements has the obvious benefits of decreased cost and increased speed, but it may miss the hydrothermal signature and important clues to mineralization. This same finding means that in the Athabasca Basin, airborne spectrometer surveys results can be misleading (too many false positives), unless they are done at high enough resolution to detect individual high-grade mineralized boulders and distinguish the latter from the not uncommon basement material with high radioactivity and low Th values such as basement boulders with pre-Athabasca basin pitchblende veins. These require ground follow-up studies; a need widely recognized by Fortin et al. (2015) and others.

The second general conclusion is that there are indications

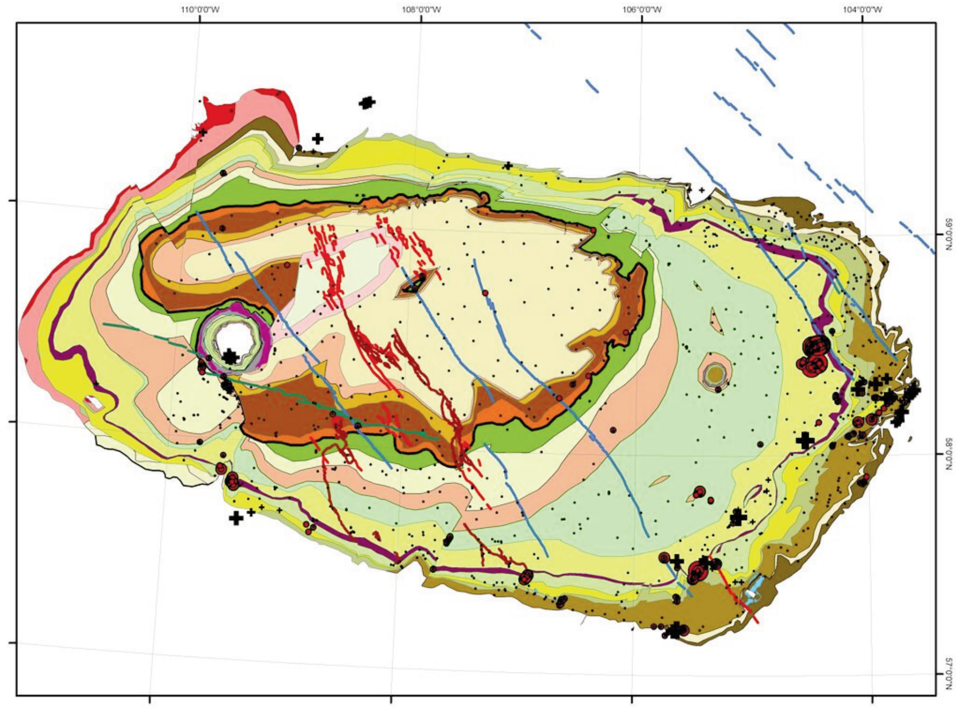

Figure 16: ULT2PPM mobile metals (F2) factors from DDH and outcrop samples with less than 2 ppm U_p (partial digestion). Dots=less than average value of F2, circles= positive F2 scores, with anomalous values denoted by progressively larger circles.

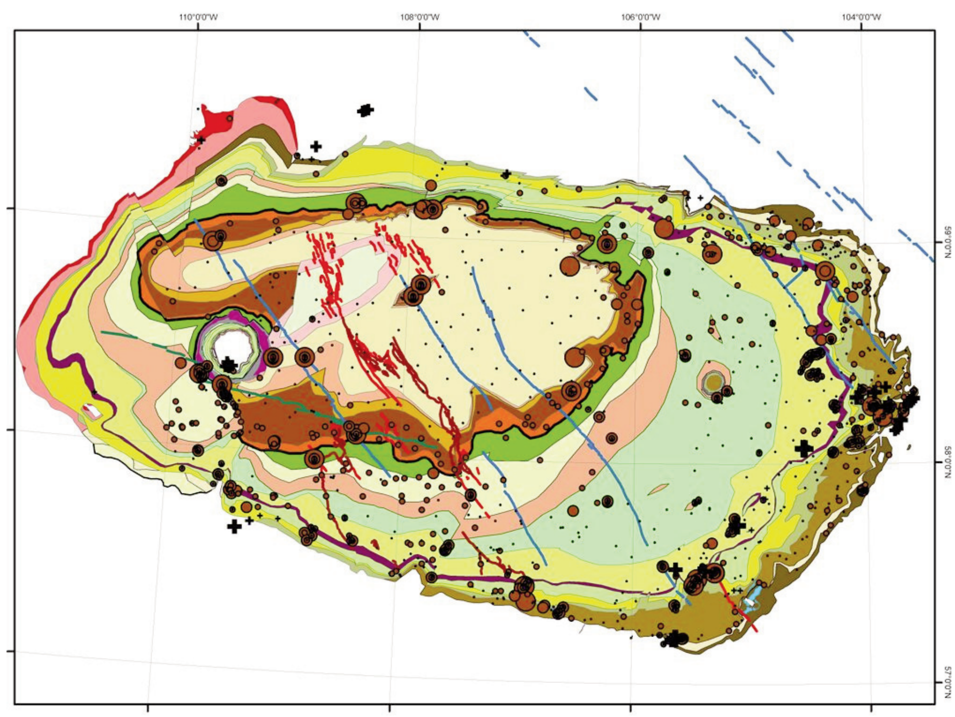

Figure 17: ULT2PPM HREE (F4) factors from drill hole and outcrop samples with less than 2 ppm U_p (partial digestion). Dots=less than average value of F4, circles= positive F4 scores, with anomalous values denoted by progressively larger circles.

of large depletion zones around the major orebodies, also noted by Dann et al., (2013) from the Phoenix deposit and consistent with recent fluid-flow modelling (Li et al., 2015). This means that the interpretation of the low raw data element values or low U component scores in a regional context is as important as that of any particular high values. The latter seem to identify areas where the U is still largely in its original position or close to it, and ore bodies are small or absent.

Many component scores and element distributions are affected by close proximity to the mafic intrusive rocks, with the two generations (Mackenzie swarm versus Moore and Cree Lakes) showing different responses. A few components show anomalously high component scores, while others show antipathetic behaviour. This suggests that the intrusive bodies generated hydrothermal systems of limited extent.

The differences in component scores above and below the Wolverine Point Formation for a number of the components indicate that the Wolverine Point Formation acted as an aquitard. In addition, the HREE component, especially in background U areas, may be a useful tool to map the path of mineralizing solutions in areas where they moved in an oxidizing environment. At least three episodes capable of transporting U seem to be recorded by the PCA.

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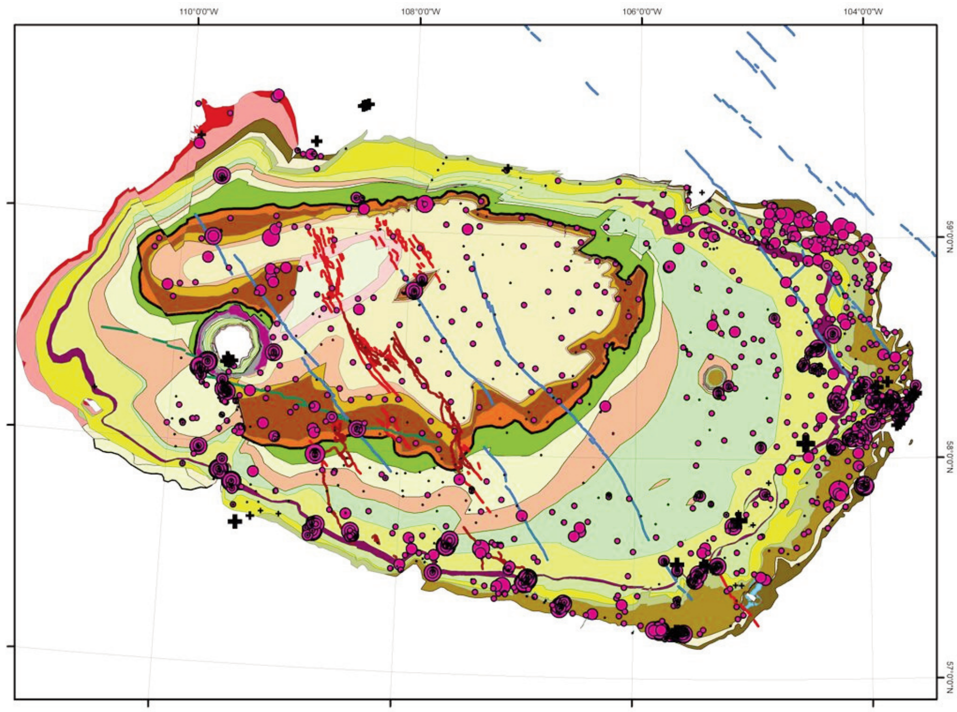

Figure 18: ULT2PPM Mobile Pb, Zn, V, Sb, U (F7) factors from drill hole and outcrop samples with less than 2 ppm U_p (partial digestion). Dots=less than average value of F7, circles= positive F7 scores, with anomalous values denoted by progressively larger circles.

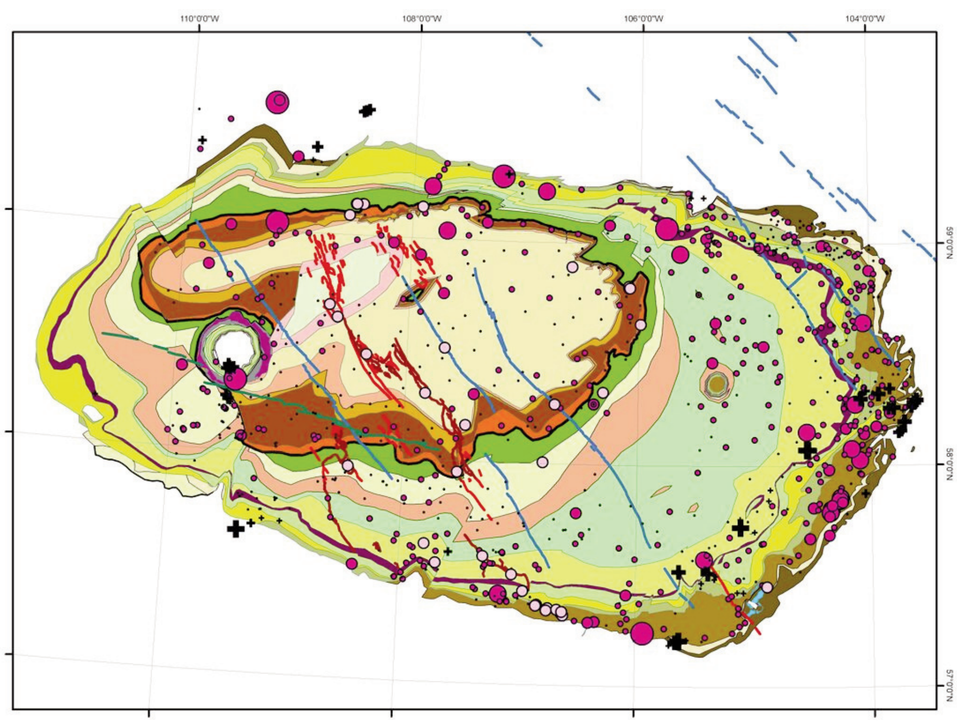

Figure 19: Raw data of Sr/Ce values from outcrop samples (DF2930 database). Pink circles Ce>Sr, dots=Sr/Ce < median, dark pink= Sr/Ce values above median, with anomalous values denoted by progressively larger circles.

Appendices (digital)

DF2930_Loadings.xlsx
DF2930_Raw-data.xlsx
DF2930_Scores.xlsx

STRATDEPO_Loadings.xlsx
STRATDEPO_Raw _data.xlsx
STRATDEPO_Scores.xlsx

ULT2PPM_Loadings.xlsx
ULT2PPM_Scores.xlsx

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