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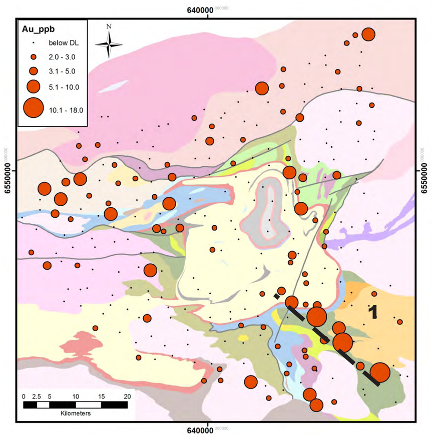
Statistical analysis as a viable method for exploration and mapping

by N. Yavorskaya, C.O. Böhm, and S.D. Anderson

Manitoba Geological Survey

GOLD

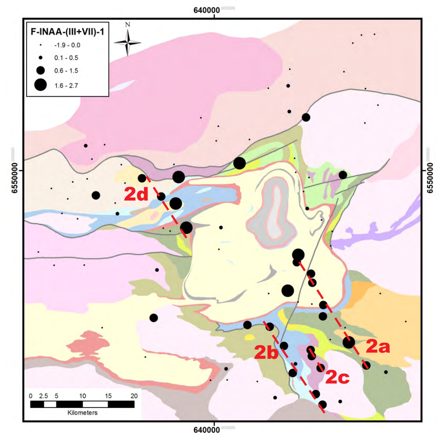


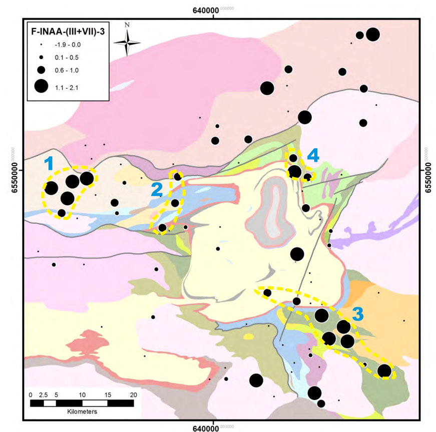
Analysis for Au was included in the INAA analytical suite which was performed for the samples located in the western part of the study area.
Analytical results for Au are shown on the map. Black dots indicate the sample sites where Au values are less than detection limit (DL).

There is a very distinct northwest trending anomaly (1) in the south-eastern part of the survey area. The rest of the anomalous values are scattered on the map without any clear anomaly pattern.

Ninetyone samples from the INAA data with Au values that are more than half of the DL were the subject of the first factor analysis.
Factor analysis of INAA analytical data (FA-INAA-I) resulted in 7 factors which explain 78 % of total element variability. The table shows the factors that influence Au distribution. Factor F-INAA-I is a typical clastic component and has negative correlation with Au and LOI. This suggests that Au accumulates in forms that are different from the clastic component of lake sediment -- probably in various forms of adsorption. Factors F-INAA-III and Factor F-INAA-VII support this assumption as Au associates with Sb, Fe and LOI and probably indicates As-Sb, Fe-Mn and organic adsorption.

Au associations from FA-INAA-I		
Factor	% of variance explained	Element association
F-INAA-I	47%	Ba-Rb-Ti-Na-Hf-Cs-Ta-Sc LOI / Au
F-INAA-III	8%	As-Sb / Cr-Fe / Au
F-INAA-VII	3%	Au / Sb-Fe-LOI

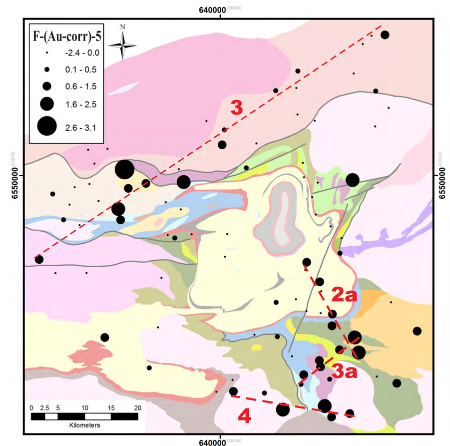


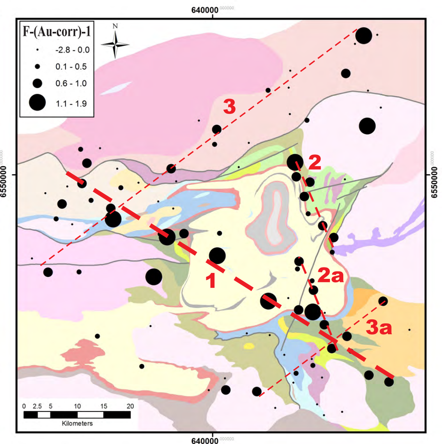


The second run of factor analysis **(FA-INAA-(III+VII))** was performed using the elements that significantly contributed to the factors F-INAA-II and F-INAA-III. This resulted in 3 main factors that explain 83% of the total element variability. Gold contributes to two factors.
Factor **F_INAA-(III_VII)-1** is assumed to identify mafic-ultramafic rocks as there are significant contributions of Cr and Fe to this factor. Gold probably occurs in sulfides as As and Sb loadings are very strong. This factor creates 4 parallel north-west trending linears on the map (red dashed lines), mainly in the south-eastern part of the INAA survey area. The trend of these linears is parallel to gabbro dykes (Sap4) as inferred by magnetics.
Factor **F_INAA-(III_VII)-3** is influenced mainly by Au with strong negative Cr loading. It is assumed that this factor is responsible for disseminated free Au that can concentrate in carbonate veins as LOI loading is also high in this factor. This factor shows 4 multi-element anomalous zones (yellow dashed lines) in different geological environments. Zone 3 spatially correlates with mafic volcanic unit (Sa9) situated in the south-east of the INAA survey area.

Rotated Component Matrix of FA_INAA-(III+IIV)			
	Factor		
	As-Sb-Cr-Fe		Au-LOI-U
	F_INAA-(III+VII)-1	F_INAAI-(III+VII)-2	F_INAA-(III+VII)-3
% of Variance	33%	21%	18%
As	.847	.127	.140
Sb	.838		
Cr	.642		-.628
U		.844	.263
Fe	.416	.739	-.188
sediment		-.672	
LOI	-.175	-.616	.577
Au	.284		.836

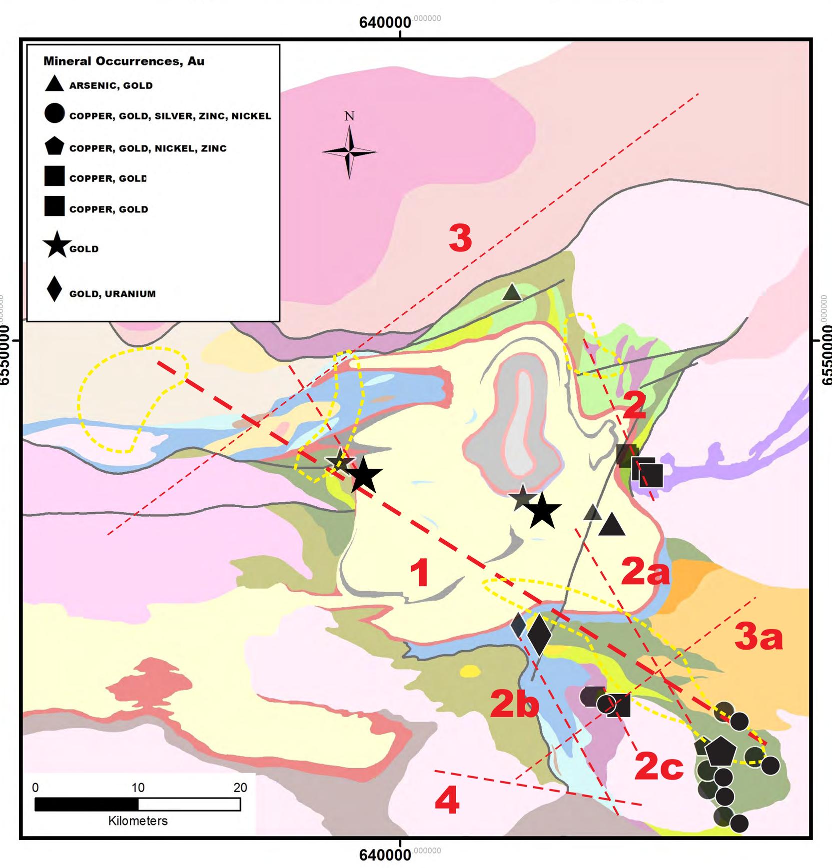
For the 91 samples with Au values that are more than half of detection limit Au analyses were merged with the ICP data. A correlation matrix created for this data set establishes that Au correlates with Ag, Hg, Mo, S, Sb, Se.



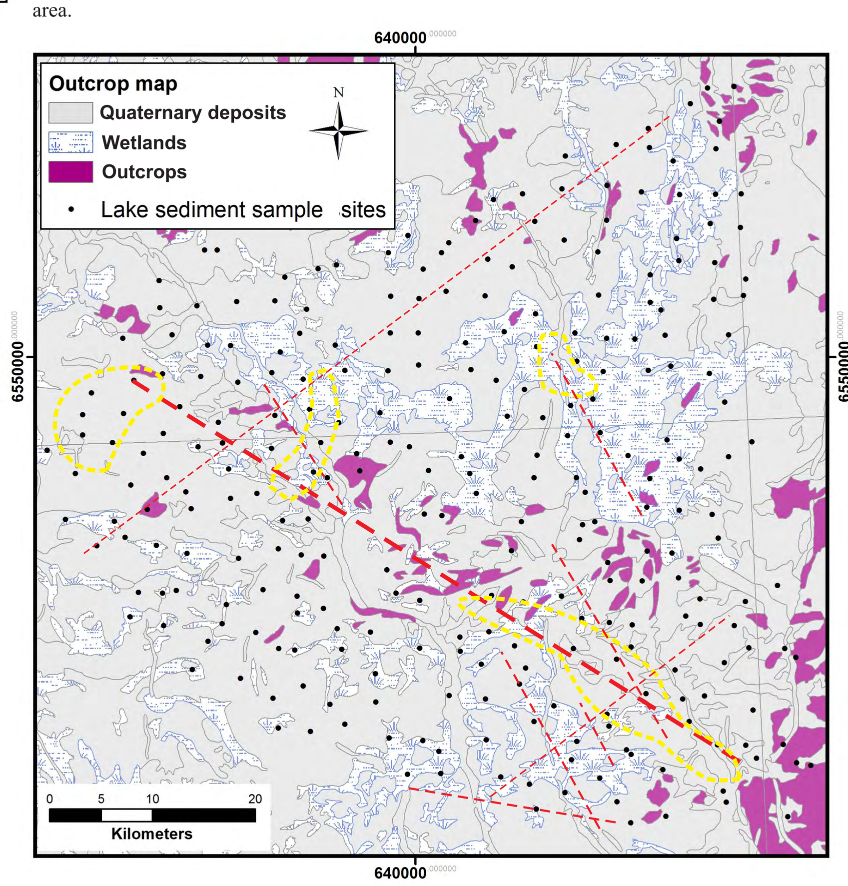


Factor analysis FA-(Au-corr) was performed with the elements that have positive correlation with Au (correlation coefficient > 0.3). It resulted in two factors that contain Au.
Mercury makes a strong contribution to the factor **F-(Au-corr)-1** which suggests that this is a fault factor. Spatial distribution of the factor supports this suggestion and indicates several linear trends (red dashed lines) with high factor scores. The longest and strongest trend (1) is located in the center of the survey area and crosses the map in a NW direction. It may indicate a regional fault. Two short, but strong, N-NW parallel linear trends (3 and 3a) are located in the eastern part of the survey area. There are also two very weak NE linear trends (3 and 3a) in the northern and southern parts of the map.
Factor **F-(Au-corr)-5** has the highest loading for S and a weak Hg loading that probably indicates the presence of sulfides in ffaults. F-(Au-corr)-1shows the same linear trends (2a, 3 and 3a) obtained for F-(Au-corr)-1. The trend 3a is more distinctive for F-(Au-corr)-5. In addition, there is a western trend (4) at the southern edge of the survey area.

FA-(Au-corr)		
% of variance explained	33%	5%
Factor	F-(Au-corr)-1	F-(Au-corr)-5
	Loadings	
LOI	.876	.180
Se	.823	.161
Hg	.717	.301
Mo		.127
Ag	.389	
As		
Au	.212	.120
S	.422	.866
Sb	.373	.274



The compilation map for Au zones obtained from the factor analysis (FA), geology and Au mineral occurrences indicates that some of the known Au occurrences are situated in the vicinity of faults indicated from FA (red dashed lines). The areas where the Au linear trends (red dashed lines) cross the Au zones (yellow dashed lines) can be the **main areas of interest for Au exploration.**



Compilation of the outcrop map with Au zones obtained from FA (red and yellow dashed lines) shows that most of the INAA survey area is covered with Quaternary deposits and wetlands. Gold zones that are identified by FA occur mostly in areas with no outcrop. This indicates that FA is a valuable method for identifying blind mineralization from existing analytical data.

References

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Great Island - Seal River area, Manitoba (54L, 54M; 64I, 64P)

Regional lake sediment geochemical data

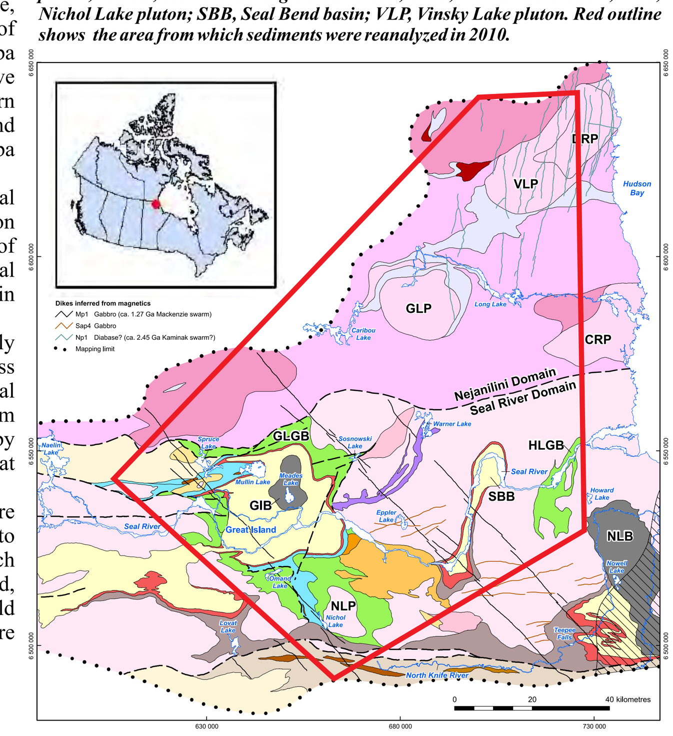
The National Geochemical Reconnaissance (NGR) program conducted by the Geological Survey of Canada (GSC) generated a regional geochemical database, comprising analyses of lake sediments and waters, covering a significant portion of the Canadian Shield. Over 18,000 lake sediment samples from northern Manitoba were collected between 1975 and 1991 and have since been stored in a GSC archive facility in Ottawa. Archived samples from the Great Island-Seal River area, northern Manitoba were re-analyzed in 2010 under the Geo-Mapping for Energy and Minerals (GEM) Program of Natural Resources Canada (NRCan) and the Manitoba Far North Geomapping Initiative of the Manitoba Geological Survey (MGS). Re-analysis of archived lake sediment samples, due to today's far superior analytical techniques, currently provides data for 65 elements, with much lower detection limits for most of the original 12 elements obtained in 1977. The main objective of the current study is to model the lake sediment geochemical data to identify regional geochemical anomalies, specifically to produce Au and U geochemical maps, in support of mineral exploration in the study area.
A total of 848 samples from 806 sample sites were re-analyzed by inductively coupled plasma emission spectroscopy and inductively coupled plasma mass spectroscopy (ICP-ES/MS). Analyses were carried out at Acme Analytical Laboratories Limited, Vancouver, British Columbia. In addition, 292 samples from 279 sample sites for the southwestern part of the survey area were analyzed by instrumental neutron-activation analysis (INAA), which was carried out at Becquerel Labs, Mississauga, Ontario.
In preparation of the ICP and INAA data for statistical analysis, values were subjected to log transformation, centering and scaling in order to create data close to normal distribution, resulting in the transformed data set. The elements with more than 50% of the analyses are below the analytical detection limit (Ge, In, Pd, Pt, Re, Ta, Te) are excluded from the data set. Lost on ignition (LOI) and field observations such as relief, lake area, lake depth, sediment color and suspension are included in the Seal River lake sediment data.

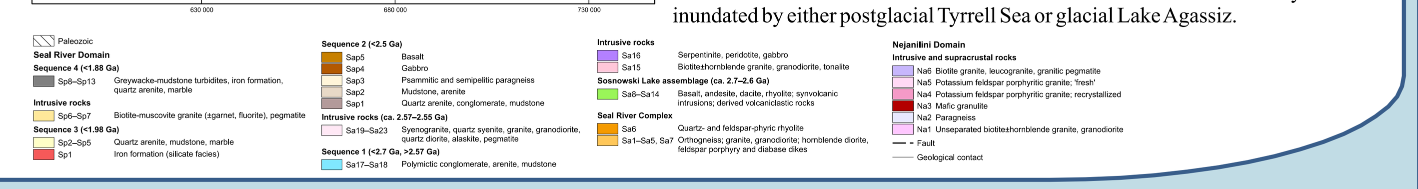
The composition of lake sediment depend on numerous factors that may influence elemental concentrations:

Geology	Surficial deposits	Other
- lithology	- amount of carbonate	- Fe-Mn adsorption
- mineralization	- direction of ice flow	- clastic and organic matter
		- water pH

Topography, drainage networks, lake depth, climate, vegetation and other factors control the amount of clastic and organic material in lake media and contribute to spatial patterns of sediment composition.

Simplified geological map of the Great Island-Seal River region (Anderson et al., 2010). Abbreviations: CRP, Caribou River pluton; DRP, Dickins River pluton; GIB, Great Island basin; GLGB, Garlinski Lake greenstone belt; GLP, Gross Lake pluton; HLGB, Howard Lake greenstone belt; NLB, Nowell Lake basin; NLP, Nichol Lake pluton; SBB, Seal Bend basin; VLP, Vinsky Lake pluton. Red outline shows the area from which sediments were reanalyzed in 2010.





Geological overview

The figure on the left shows the bedrock geology of the study area. Manitoba's far northeast forms part of the southeast margin of the Hearne craton, which comprises a heterogeneous basement of Archean orthogneiss, granitoid intrusions and rare supracrustal rocks overlain by latest Archean and Paleoproterozoic siliciclastic cover sequences, all of which have been variably overprinted by tectono-thermal and magmatic activity associated with the Paleoproterozoic Trans-Hudson orogeny (Anderson et al., 2010). The lake sediment samples cover two lithotectonic domains of the Hearne craton: the Seal River domain southern part of the survey area and the Nejanilini domain in the northern part as detailed in Schledewitz (1986).
The Nejanilini domain is dominated by variably deformed Neoarchean metaplutonic rocks with minor enclaves of early Paleoproterozoic metasedimentary rocks, and Paleoproterozoic calc-alkaline granitic intrusions. Metamorphic grade increases to the northwest up to granulite facies.
The Seal River domain is characterized by a dome-and-basin structural geometry, with the 'domes' defined by Meso- to Neo-Archean metaplutonic and metavolcanic rocks, and the 'basins' defined by synforms of latest Archean and Paleoproterozoic continental and marine siliciclastic rocks. Metamorphic grade in the Seal River domain reached middle amphibolite grade in Archean rocks, whereas Paleoproterozoic sedimentary rocks are at upper greenschist facies.
Northern Manitoba was repeatedly covered by the Laurentide Ice Sheet (LIS). The ice predominantly flowed southward across Manitoba from the Keewatin Ice Sector, but also was affected multiple times by ice flowing westward from or across Hudson Bay (Campbell et al., 2012). Tills of Keewatin provenance are derived primarily from Precambrian Shield rocks and tend to have a sandy, non-calcareous matrix. The relatively thin silty-sandy tills of Keewatin provenance are locally-derived and transported over short distances. This means that geochemical values in glacial sediments should reflect concentrations in nearby bedrock. Tills of Hudsonian provenance appear to be farther traveled and comprise both Precambrian and Paleozoic carbonate bedrock fragments. The southeast of the map area may have been within the zone of confluence between the Keewatin and Labradorean ice sheets. Much of the study area was inundated by either postglacial Tyrrell Sea or glacial Lake Agassiz.

Mapping

Factor Analysis

To determine the relation between all variables in the data set, factor analysis (FA) was carried out. FA explains data structures and correlation patterns in a data set. Multivariate lake sediment data are decomposed into factors which represent various processes that acted on the sediment. Each factor is characterized by loadings. Loading values of a factor indicate the strength of a process that influences the correlation between chemical elements in the factor. Loadings vary between -1 and +1 representing respectively negative and positive influence of a factor on the elements. Factor scores plotted on a map represent information about the extent of a process that has influenced an individual sample.
In the current study, lake area, lake depth, sediment color and suspension were coded and merged with the analytical data. **The first run of FA (FA-I)** resulted in seven factors that account for 71% of the total variability of the data. The elements strongly contributed to the factor F-I-1 (in which loading values exceed 0.5) show similar inter-correlations of the clastic-sediment association compared to those from other parts of the Canadian Shield, even though the number of elements that were involved in statistical analysis of data from Labrador, Alberta and Saskatchewan is less than from Manitoba data.

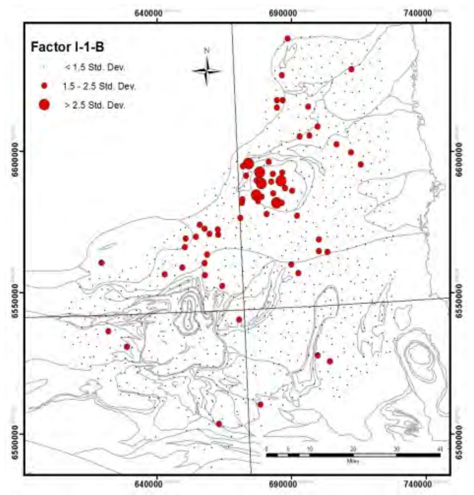
Comparison of element associations in the clastic component of lake sediment data from different areas of the Canadian Shield Amor, 2014; Yavorskaya and Amor, 2015

area	Element association in a clastic factor
Universal in Labrador	Al, Ba, Hf, K, Li, Mg, Na, Nb, Rb, Sc, Ti
SW Labrador	Al, Ba, Be, Cr, F, Fe, Hf, K, Li, Mg, Mn, Na, Nb, Pb, Rb, Sc, Sr, Th, Ti, V, Zr, (LOI)
NE Alberta and N Saskatchewan	Ba, Cr, Cs, Hf, Na, Rb, Sc, Th, (LOI)
NE Manitoba	Al, Ba, Be, Bi, Ce, Co, Cr, Cs, Cu, Fe, Ga, Hf, K, La, Li, Mg, Na, Nb, Ni, Pb, Rb, Sc, Sn, Th, Ti, Tl, V, Y, Zn, Zr, (LOI, Ca)

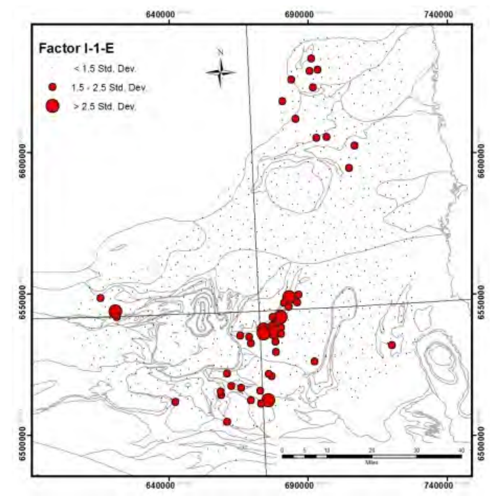
Because the clastic component can contain signatures from different geological processes, **the second run of factor analysis (FA-I-1)** was performed with elements from factor F-I-1 with loading values exceeding the threshold of 0.5. The elements that do not contribute significantly to the clastic component are considered geochemical "noise". This resulted in 5 factors that explain 83% of the total element variability and are assumed to identify different stratigraphy and mineralization:

1) **F-I-1-A : Cs,Ga,K,Li,Rb,Ti /Al,Be,Bi,Co,Cr,Mg,Na,Nb,Sc,Th,V**
2) **F-I-1-B: Ag,Cu,Mo,U,Ce,La,Y/W,Zn**
3) **F-I-1-C: Mn,Ba,Be,Co,Fe,Zn/Al,Bi (Na)**
4) **F-I-1-D: Hf,Zr,Th,Pb,(Fe,Mg,Ti,V)**
5) **F-I-1-E: Ni/Mg,Cu/Co,Cr**

The elements in an association are displayed in alphabetical order and are grouped in such a way as to emphasize their strength of correlation. The slash marker in an element association separates high loadings from moderate values. Elements in brackets are those with a weak correlation within a factor, but they can give an idea of which process is responsible for an element association. The figures illustrate the regional distribution of the factor



The highly anomalous **factor F-I-1-B** values that correspond with the Gross Lake granitic pluton (K-feldspar porphyritic granite, unit Na5) are situated in the northern part of the survey area. This factor has the highest loadings for Ag, Cu, Mo, U, Ce, La and Y association, which appears to represent a geochemicalcharacteristic of the pluton. Some of the other multi-element anomalies probably reflect granitic dykes that are similar in composition to the Gross Lake pluton.



Factor F-I-1-E has the highest loading for Ni (0.6) and weaker, but still significant loadings, for Mg,Cu,Co and Cr. The factor corresponds with a serpentinite-peridotite-gabbro body (unit Sa16). There is another linear cluster of high factor scores located near the south boundary of the survey area, to the north of the Nichol Lake pluton, that may indicate an unmapped ultramafic intrusion.

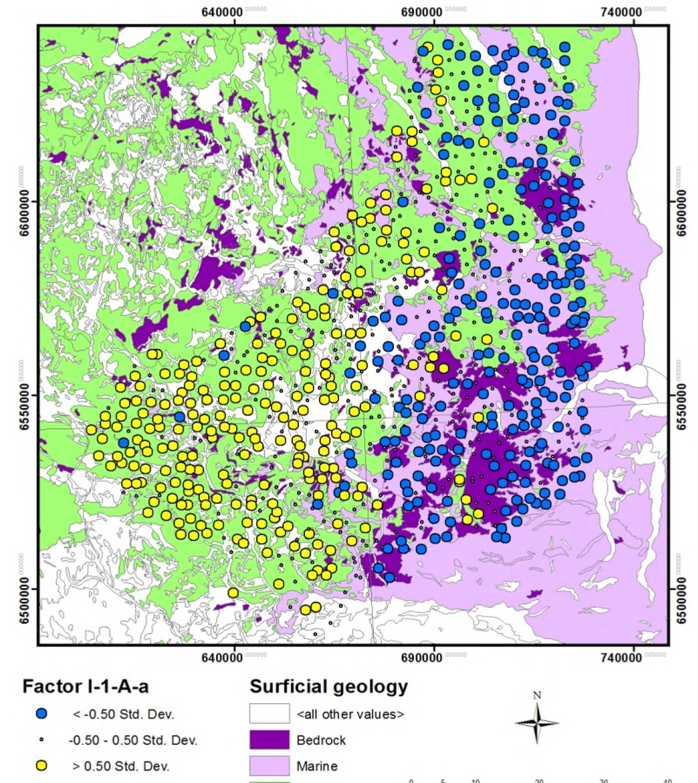
Both factors, I-1-B and I-1-E, suggest an unmapped NW trending units that crosses the Nejanilini Domain north of the Gross Lake pluton. These units suppose to be subparallel to the gabbro dikes (Mp1) that are inferred from magnetics in the central part of the geology map.

The third run of factor analysis (FA-I-1-A) was performed with elements that contribute to factor F-I-1-A (Cs,Ga,K,Li,Rb,Ti /Al,Be,Bi,Co,Cr,Mg,Na,Nb,Sc,Th,V) from the second run of FA (FA-I-1).
This resulted in two main factors that explain 33% and 30% of the element variability respectively and are assumed to identify different stratigraphy and mineralization:

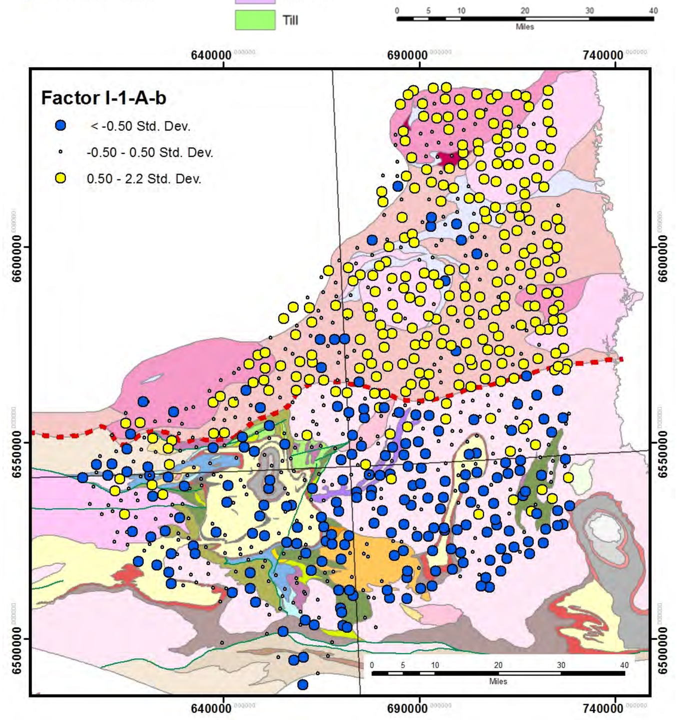
1) **F-I-1-A-a : Al, Be, Bi, Co / Cs, Ga, Sc**
2) **F-I-1-A-b: Th / Nb, Sc, Ti, V / Ga, K, Rb**

The elements in the associations are displayed in alphabetical order and are grouped in such a way as to emphasize their strength of correlation.

	Component	
Model	I-1-A-a	I-1-A-b
Variance explained	33%	30%
Al	0.8	0.4
Be	0.9	0.3
Bi	0.8	0.2
Co	0.7	0.4
Cr	0.5	0.5
Cs	0.6	0.5
Ga	0.6	0.6
K	0.5	0.6
Mg	0.2	0.2
Na		0.3
Nb	0.5	0.7
Rb	0.5	0.6
Sc	0.6	0.7
Th	0.2	0.9
Ti	0.4	0.7
V	0.5	0.7



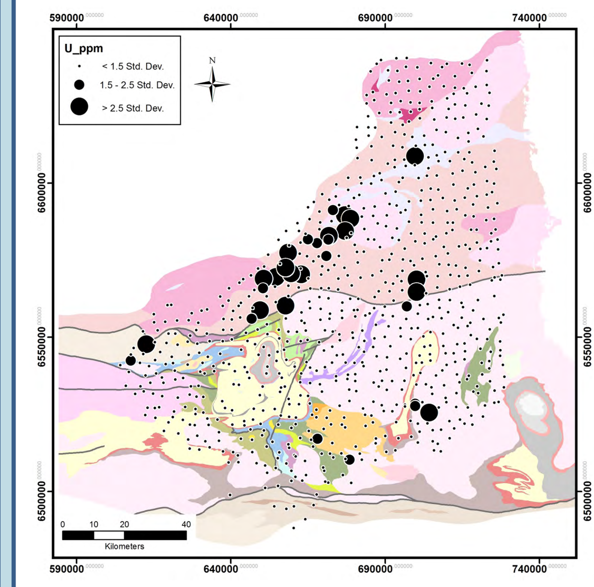
For FA-I-1-A, factor **F-I-1-A-a** is dominated by the association Al-Be-Bi-Co/Cs,Ga,Sc. The factor scores distribution roughly parallel to the Hudson Bay coast line. This factor is believed to reflect a contribution from surficial deposits to the lake sediment. Positive scores are located in the western part of the survey area that is covered by tills. In contrast the eastern part of the survey area , which is covered mostly by marine deposits, is characterized by negative loadings. The Figure on the left shows the distribution of the factor F-I-1-A-a.



Factor F-I-1-A-b is dominated by the association Th/Nb,Sc,Ti,V/Ga,K,Rb and reflects the difference in geochemistry between the two domains in the region. It clearly separates the Nejanilini domain from the Seal River domain; the boundary between the domains is shown as a red dashed line. The pattern for the Nejanilini domain, in the north is clearly visible and is characterized by positive scores, whereas negative scores indicate the Seal River domain.

URANIUM

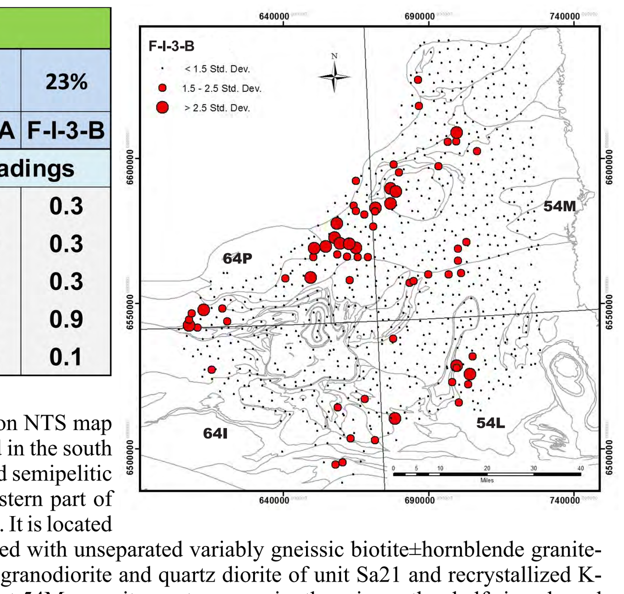
As U was of particular economic interest in the 1977 survey, U was chosen for investigation of its behavior in the reanalyzed lake sediment data. The spatial distributions of U in factors that contain this element were investigated. Factor F-I-3 from the first run of FA contains U with loading value of 0.6. Since factor F-I-3 is not correlated with lake depth, lake size and suspension, this factor was used in further analysis for uranium distribution. The next **factor analysis (FA-I-3)** was preformed with the Ce, Ge, La, U and Y association that have loadings higher than 0.5 in factor F-I-3.



Spatial distribution of **U** for **raw analytical data** defines two broad and strong anomalies in the muddle of the Nejanilini domain. Several one- to three sample anomalies are scattered over the study area

The results for FA-I-3 indicate that uranium significantly contributes to two factors, FA-I-3-A and FA-I-3-B (table on the right). These factors explain 74% of the total element variability.
Factor F-I-3-B extracts a significant geochemical signature from U (loading is 0.9) that is illustrated in the figure on the right. A chain of multi-sample anomalies occurs along the NW boundary of the survey area.

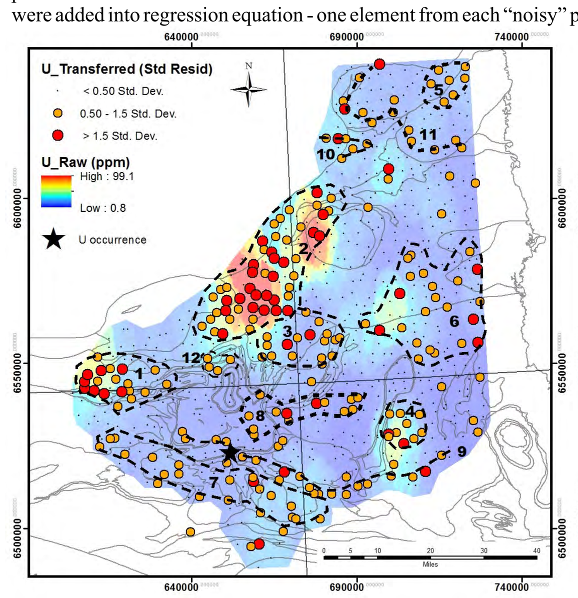
FA-I-3		
% variance explained	51%	23%
model	F-I-3-A	F-I-3-B
	Loadings	
Ce	0.9	0.3
La	0.9	0.3
Y	0.9	0.3
U	0.4	0.9
Ge	0.3	0.1



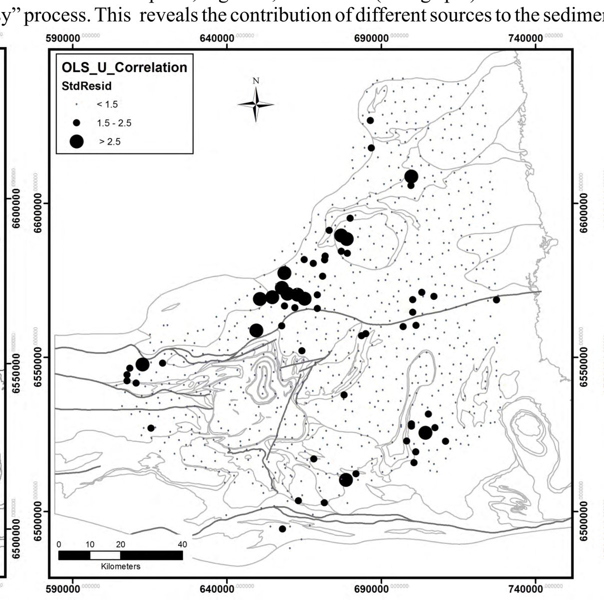
Two significant multi-sample anomalies are situated on NTS map sheet 64P. A strong half-ring shaped anomaly, located in the south western part of the survey area, overlies psammitic and semipelitic paragneiss (unit Sap3). A second anomaly in the eastern part of NTS sheet 64P is the largest and strongest in the region. It is located within the Nejanilini domain and is spatially associated with unseparated variably gneissic biotite±hornblende granite-granodiorite (unit Na1), and occurs between granite, granodiorite and quartz diorite of unit Sa21 and recrystallized K-feldspar porphyritic granite of unit Na4. On NTS sheet 54M, near its western margin, there is another half-ring shaped strong to moderate linear anomaly. It starts from the northern part of the Gross Lake pluton and continues to the SW into unit Na1. In the northern part of the survey area a three-sample moderate anomaly overlies paragneiss (unit Na2).
In the south-western part of NTS sheet 54M there is a moderate linear anomaly along the main domain boundary. It overlies both granite, granodiorite, quartz diorite unit (Sa21) in the Seal River domain and unseparated biotite±hornblende granite and granodorite (Na1) in the Nejanilini domain.

Regression Analysis

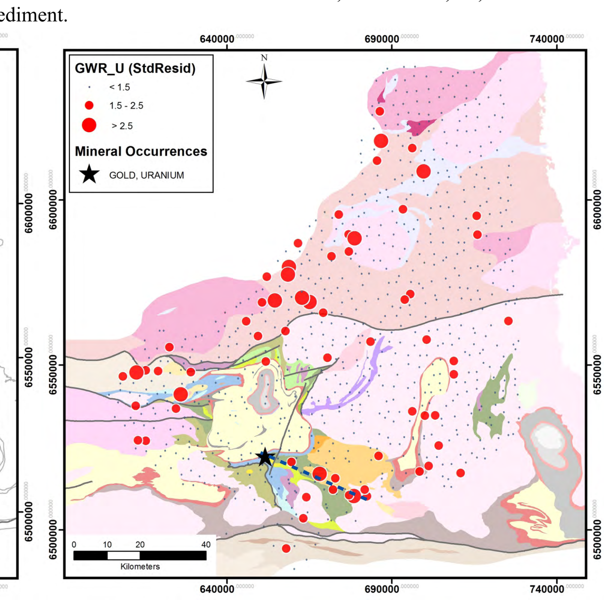
The second technique that was applied to the data is regression analysis. This method is based on multiple linear regressions in which the value of any element can be predicted, as a function of the values of other elements in a chosen model. Regression analysis calculates the differences between predicted and measured values in a regression model, which are commonly termed regression residuals. The processes being examined by regression analysis when applied to spatial data are assumed to be constant over an area. It creates a regression model and regression residuals from whole data set. For geochemical data a regression results in residuals which reflect regional difference in geology.
In order to avoid creating over-generalized regression equations, a geographically weighted regression (GWR) is applied. GWR allows the modeling of processes that vary over an area. It creates a regression equation (and regression residuals) for each sample, using a data set consisting only of the sample's neighbors, thus, the results reflect local, rather than global, element associations and deviations from them that can reflect mineralization in a given rock type. The application of the method to geochemical data is described in Yavorskaya and Amor (2015). Results for GWR model are summarized in the form of element residuals.
In the present study, the aim of the regression modeling is to remove the component of each sample's content that is attributable to the "noisy" content and then relate what is left (the residuals) to geology and possible mineralization. In lake sediment "noise" can be created from Fe-Mn-adsorption, organics, carbonates (change pH) and deviation of clastic contribution to a sediment, therefore Al, Ca, Mn and LOI were added into regression equation - one element from each "noisy" process. This reveals the contribution of different sources to the sediment.



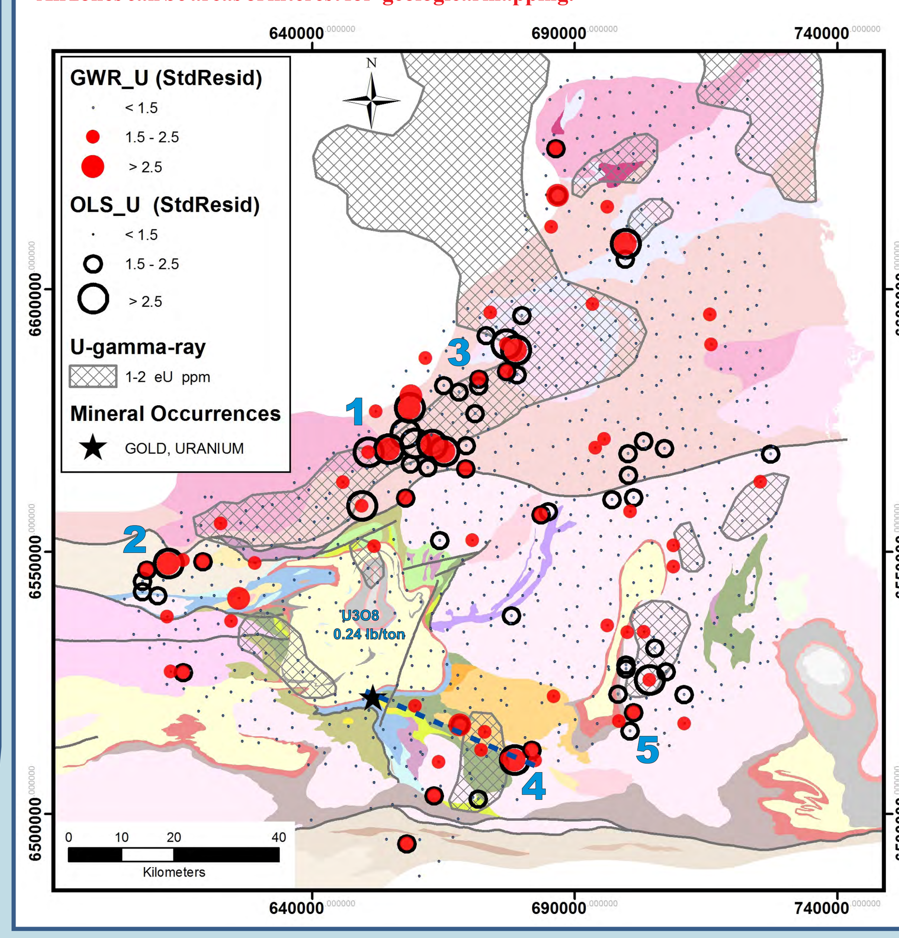
From the **U model, regressed against all elements in the data set,** 12 zones of elevated U residuals were defined. Zones 2 and 4 correspond with both gamma-ray and raw lake sediment anomalies, while zones 5, 6, 11 and 12 partly correspond only with gamma-ray anomalies (Geological Survey of Canada, 1976a). Zone 1 is much larger and stronger than the lake sediment anomaly defined from raw data. Zones 8 and 9 were not identified from previous investigations. **All zones can be areas of interest for geological mapping.**



This figure shows the **U regression model** for the elements that have a strong correlation (**Al, Ca, Cs, Cu, Mo, Pb, Sn, Th and Y**). Black bubbles indicate sample locations with anomalous values of U in comparison to average U concentration **calculated from all rock types within the study area.** For this model Mo and Y also have the strongest relationship with U.



Geographically Weighted Regression was performed for U with a 10 km window. Uranium is regressed against the same element suit as for OLS (**Al, Ca, Cs, Cu, Mn, Mo, Pb, Sn, Th, and Y**).
Red bubbles on the map indicate anomalous U values **in comparison with U concentration in the surrounding rocks within a 5 km radius from each sample location.**
There is only one U occurrence (black star) in the survey area indicated in the Manitoba Mineral Deposits Database. The occurrence is situated on a linear trend of elevated U residuals.



The compilation map with OLS and GWR analysis for lake sediment data, U-gamma-ray anomalies and regional geology shows the prospective areas for U-exploration.
A sample with elevated GWR and OLS residual values has an anomalous concentration of the element association in the rock type it represents.
The target areas with combined OLS and GWR multi-element anomalies are numbered according to their potential to contain undiscovered U mineralization. These locations are of the most interest for exploration.

Exploration target 4 is situated on the linear GWR trend (blue dashed line), the extent of which crosses the only U occurrence in the study area.
The occurrence lies at the margin of the Great Island basin structure. Within this structure, discontinuous belts of quartzite and interlayered schist, phyllite, paragneiss and migmatite define folds that trend east to northeast. The area is underlain by the Seal River volcanic rocks of Proterozoic or possibly Archean age. Radioactive pyritized quartz and quartzite pebble conglomerates contain low, but anomalous values in Au and U near the base of the sequence. Diamond drill hole returned assays of 0.005 oz Au/ton and 0.24 lb U_3O_8/ton over width of 5 m. Spectrographic analyses of samples anomalously high in Au and U were also moderately anomalous in Cr, Ti, Zr and Ce.
The GWR anomaly has maximum value at the south-eastern end of the trend suggesting that U mineralization at the occurrence is the weakest within the geological structure and **exploration target 4 may have better grades of U than in the known U mineral occurrence.**