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Influence of till thickness and texture on till geochemistry in the Lac de Gras area, Northwest Territories, with applications for regional kimberlite exploration

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Abstract

Although the Lac de Gras area hosts numerous kimberlite pipes, continued exploration success depends on the development of a kimberlite exploration model for this region. This paper presents preliminary analyses of the use of till geochemistry for kimberlite exploration.

Elements whose concentrations are higher in kimberlite than in the bedrock of this region were identified as Ba, Ce, Cr, La, Mg, Nb, and Ni. For these elements, the geochemical composition of regional clay and clay+silt size fractions of till was compared to that of the clay+silt+sand size fraction from a detailed survey to determine the compositional variation of the till in the various till size fractions. High concentrations of Ba, Cr, Mg, and Ni in the *thick till are apparently due to differences in the derivation of entrained debris. To identify a kimberlite geochemical signature in the till, different anomaly thresholds must be selected for discrete till sample populations based on till thickness.*

Résumé

Bien que la région du lac de Gras renferme de nombreux pipes de kimberlite, le succès continu de l'exploration dépend de l'élaboration d'un modèle de recherche de la kimberlite pour la région. Le présent article comprend des analyses préliminaires portant sur l'utilisation de la géochimie du till appliquée à la recherche de la kimberlite.

Les éléments dont les concentrations sont plus élevées dans la kimberlite que dans le substratum rocheux de la région étudiée sont les suivants : Ba, Ce, Cr, La, Mg, Nb et Ni. Pour ces éléments, la géochimie régionale des fractions granulométriques de l'argile et de l'argile+silt a été comparée à la fraction argile+silt+sable obtenue lors d'une étude détaillée afin de déterminer la variation de la composition du till dans ses différentes fractions.

Il semble que les concentrations élevées de Ba, Cr, Mg et Ni présentes dans le till de forte épaisseur soient imputables aux différences dans la provenance des débris entraînés. Pour mettre en évidence la signature géochimique de la kimberlite dans le till, il faut sélectionner différents seuils de détection d'anomalies pour les populations distinctes d'échantillons de till basés sur l'épaisseur du till.

INTRODUCTION

The Lac de Gras region of the Slave Province, in Canada's Northwest Territories, is home to the recently opened Ekati diamond mine, with a second diamond mine (Diavik) slated to open in 2003. Exploration in the Lac de Gras region of the Slave Province has been ongoing since 1991, with over

150 kimberlites pipes currently known (J. Armstrong, pers. comm., 2000). Despite the impressive number of pipes discovered to date, exploration success in finding new kimberlite continues, albeit at a reduced rate compared to the early to mid-1990's. The two most widely used exploration methods in the Lac de Gras area are indicator-mineral sampling of till and other sediments and geophysical methods (both airborne and ground). For regional-scale studies, both of these techniques can be relatively expensive. Till geochemistry, on the other hand, is comparatively inexpensive and is commonly carried out for metallic mineral exploration programs, to which kimberlite could be added as a secondary objective. This paper explores some of the preliminary issues concerning the use of till geochemistry for kimberlite exploration.

The application of till geochemistry to mineral exploration, or any geochemical method for that matter, is not trivial. Which elements should be used? Should the element concentrations be used as point data sources (e.g. proportional symbol plots), or should the data be interpolated to make a continuous surface map? Although glacial erosion and transport may produce a large exploration target (dispersal train), how does one find an individual kimberlite target within a kimberlite field? Which size fractions of till should be chemically analyzed?

In this paper, we identify pathfinder elements for the application of till geochemistry to kimberlite exploration in the Lac de Gras area, and examine the role of till thickness on the concentration of the pathfinder elements in different size fractions of till. The geochemical composition of clay (<0.002 mm) and clay+silt (<0.063 mm) fractions of regional-scale till samples, collected by the Geological Survey of Canada (GSC), are compared to the clay+silt+sand (<0.177 mm) fraction till samples from a detailed survey conducted by Kennecott Canada Exploration Ltd., to determine the compositional variability of the till in the various till size fractions.

This study, part of Project #81, ‘Understanding the diamondiferous Lac de Gras kimberlite field, Northwest Territories’, of the GSC, is run jointly by the Mineral Resources and Continental Geoscience divisions of GSC-Ottawa and by GSC-Calgary. Other government partners include Indian and Northern Affairs Canada, Canada Centre for Remote Sensing, and the Government of the Northwest Territories. Industry partners include Monopros, BHP, Kennecott Canada Exploration Inc., and Diavik. As a multiagency and multidisciplinary effort, this project aims to establish a baseline for kimberlite exploration in the Lac de Gras area, and to establish exploration criteria that can potentially, be applied to other regions of Canada and the world.

REGIONAL GEOLOGY

In the Lac de Gras area, the oldest known rocks consist of foliated granodioritic to tonalitic rocks and related granitoid gneiss, termed the ‘Central Slave Basement Complex’ (Bleeker and Davis, 1999). Immediately overlying the Central Slave Basement Complex is a thin, ca. 2.8 Ga cover sequence, which in turn is (structurally) overlain by post-2.72–2.66 Ga volcanic and turbiditic sedimentary rocks belonging to the Yellowknife Supergroup (McGlynn and Henderson, 1972; Villeneuve et al., 1997). In the Lac de Gras region, Yellowknife Supergroup rocks consist dominantly a of thinly bedded (1–10 cm), graded psammite–pelite sequence, with volumetrically insignificant volcanic rocks found only in the southwest part of the study area (Kjarsgaard and Wyllie, 1994). Plutonic rocks intruded the lithological units of the Central Slave Basement Complex, the Central Slave Basement Complex cover sequence, and the Yellowknife Supergroup during the time interval 2.71 to 2.58 Ga (Villeneuve et al., 1997). The Lac de Gras area is characterized by two phases of folding, each associated with a regional cleavage. High-strain zones parallel regional lineaments and are associated with fold limbs (Kjarsgaard and Wyllie, 1994). With the exception of some of the youngest granitoid rocks, all rocks have been variably folded, faulted, and metamorphosed. The region is transected by a variety of unmetamorphosed Proterozoic diabase dykes. Over 150 Eocene to Cretaceous kimberlite pipes (Kjarsgaard and Heaman, 1995; Davis and Kjarsgaard, 1997) intrude the Precambrian bedrock (**Fig. 1**).

Most of the area is overlain by till (**Fig. 2**) thought to be a single unit deposited by the Late Wisconsinan Laurentide Ice Sheet (Dredge et al., 1994). The till is characterized by a silt and sand to sand matrix with low percentages of clay, and contains 5 to 40% gravel. The upper 0.5 to 1 m has been modified by solifluction and cryoturbation, and organic material has been incorporated to depths of up to 80 cm. Till thickness varies from very thin <2 m (T1, veneer), to 2 to 10 m (T2, blanket), and to 5 to 30 m (T3, hummocky) (*see* Fig. 2). Numerous eskers occur in the Lac de Gras region and relief is generally low (Dredge et al., 1994). Other surficial materials in the area include glaciolacustrine deposits, organic deposits, and alluvial deposits. For the sake of simplicity and since all regional geochemical samples were taken from till, all nontill units were assigned to a single map unit (Other — *see* Fig. 2). Areas of exposed bedrock are also indicated on Figure 2.

Although the till deposits appear to be attributable to the most recent event, regional ice-flow patterns are complex and indicate several different flow events (Fig. 2). Some evidence shows that ice initially flowed southwestward across part of the study area, although the extent of this event is unknown. A progressive rotation of ice flow followed, first westward in the southern and northern regions, followed by northwestward in the south central and eastern regions with a shift to west-northwestward and westward in the west central regions. A final, very localized ice flow was also recorded in a few localities such as southwestward in the northern Aylmer Lake area, westward in the northwest Winter Lake area, and north-northwestward north of Contwoyto Lake. However, the dominant ice flows most responsible for transport of till and kimberlitic debris were the northwestward flows near Lac de Gras, Contwoyto Lake, and the region north of Point Lake. Westward flows dominated in the Winter Lake and southern Point Lake and Contwoyto Lake areas. These dominant directions of glacial transport are represented by abundant striae, as well as large-scale ice-flow landforms such as drumlins. Transport distances in the study area vary, with up to 30 to 40% of the gravel fraction being derived from distances of 5 to 30 km or more.

GEOCHEMICAL SURVEYS

Lithogeochemistry

A total of 557 whole-rock geochemical samples were compiled for the Lac de Gras area (B. Kjarsgaard, unpub. data, 2000; Kennecott Canada Exploration Inc., unpub. data, 1999; Diavik Diamond Mines Inc., unpub. data, 2000) and provide major- and trace-element geochemical data for most rock types in the area, including kimberlite (253 samples). Results reported as below the detection limit were assigned values of half the detection limit for the calculation of population statistics.

The whole-rock data were not screened for altered samples, on the assumption that fresh samples were selected for geochemical analysis for the purpose of lithological classification. The presence of a few altered samples is unlikely to affect the overall compositions of large numbers of samples, particularly since median values were used for the comparison of populations.

Till geochemistry

Survey information is summarized in **Table1**. For details on survey methods and analytical techniques, *see* references provided in Table 1.

For the GSC regional clay and clay+silt surveys, 1 kg of unoxidized till was obtained from mudboils (a region within the active layer, but excluding organic horizons) at depths of 20 to 100 cm. All clay size fraction till samples were digested in an aqua regia solution prior to ICP-AES analysis. Digestion may be incomplete for Al, Ba, Be, Ca, Cr, Ga, La, Mg, K, Sc, Na, Sr, Tl, Ti, and W. All silt+clay size fraction till samples were dry sieved and analyzed using INAA on approximately 30 g aliquots. Standards were inserted into the sample set at regular intervals, and duplicate field samples were also run to assess data precision and accuracy.

DATA PROCESSING

Kimberlite pathfinder elements

In this paper, we assume that till geochemistry can be directly related to the composition of the underlying bedrock, although the bedrock signature in the till may be muted in the thicker till unit (*see* Ward et al., 1996). To determine and assess the source of variations in element concentrations in the till, it is necessary to first assess the variation of element concentrations in the underlying bedrock units. Ideally, elements naturally occurring in much higher concentrations in kimberlite than in other bedrock units will occur in higher concentrations in till that has a large kimberlitic component. Such an element can then be defined as a positive kimberlite pathfinder element.

Each whole-rock sample was assigned to one of seven rock types, kimberlite, diabase, felsic intrusive, metasedimentary, mafic volcanic, ultramafic volcanic, or pegmatite. To identify potential kimberlite pathfinder elements, major- and trace-element concentrations were compared for the bedrock units (304 analyses) and kimberlite (253 analyses) using box-and-whisker plots. Median values were used rather than mean values, as the median values are less sensitive to outliers (Garrett, 1993). Notches in the boxes represent the 95% confidence limits around the median value, and populations whose notches overlap are not significantly different. For these elements, it is impossible to distinguish concentrations in kimberlite and host bedrock. Alternatively, elements whose median value is much higher or lower in kimberlite than in the surrounding rocks can be considered as kimberlite pathfinder elements. Element concentrations were log transformed to ensure normally distributed populations so that parametric statistical procedures could be applied.

Element concentration as a function of till thickness

The presence of recessive kimberlite pipes in the Lac de Gras area suggests that a significant amount of kimberlite material has been eroded and transported by glaciers, and therefore is likely to be present in the till in a down-ice direction. The thicker (5–30 m) hummocky till occurs in a northwest-trending corridor, parallel to the dominant ice flow and hence till-dispersal direction and roughly parallel to the long axis of the Lac de Gras kimberlite field (*see* **Fig. 2**). Only nine kimberlite pipes have been found within the mapped thick till unit (T3), whereas the rest have been found within the thinner till units (T1, T2, and bedrock). This raises the question of whether the thick till has been an impediment to kimberlite exploration.

To test the relationship of till thickness to till geochemistry, data for samples from the thick till unit (T3) were compared to that for samples from the other till units (T1, T2, and areas mapped as >75% exposed bedrock and/or discontinuous, very thin till). Samples sites outside the area mapped by the GSC (*see* Fig. 2) were excluded from this comparison.

RESULTS

Kimberlite pathfinder elements

Elements whose concentration was significantly higher in kimberlite than in other local bedrock types, i.e. positive kimberlite pathfinder elements, include Ba, Ce, Cr, La, Mg, Nb, and Ni (**Fig. 3**). Also plotted on the box-and-whisker diagrams of Figure 3 are compiled global minimum and maximum element concentrations for archetypal Group I kimberlites (data *from* Mitchell, 1986).

Elements whose concentration in kimberlite was not statistically different from concentration in other lithological units include As, Cu, Dy, Er, Eu, Gd, Hg, Ho, Lu, Mo, P, Pb, Pr, Sb, Se, Sm, Sr, Tb, Th, Ti, Tm, U, Y, Yb, Zn, and Zr. In the case of Lu, however, outliers distort the overall population and may have resulted in the unnecessary elimination of Lu as a negative kimberlite pathfinder element. The concentration of elements Bi, Ca, Fe, K, Mn, Nd, and Rb overlapped only with that of diabase dykes, whereas the concentration of Co overlapped only with that of ultramafic rocks. In addition, for a number of elements (including S, V, Hf, Ta, Br, Be, Sc, Tl, and W), the number of samples was insufficient for a valid statistical comparison. Elements for which no bedrock chemical data were available (e.g. F, Cl, Li, Pr, Dy, Ho, Er, Tm, and Ga) could not be evaluated for their potential as kimberlite pathfinder elements.

Table 2 lists the kimberlite pathfinders available for each till geochemical survey and fraction. Not all kimberlite pathfinder-element data are available in each till geochemistry data set and, in particular, Ce data are available only in the regional clay+silt data set. Only Ba and Cr data are available in all five surveys and/or fractions.

Element concentration as a function of till thickness and fraction

Table 3 summarizes results of the comparison of kimberlite pathfinder-element concentration in the thickest till unit (T3) and in all other till units (T1, T2, and bedrock). However, since each survey used a different till size fraction, it is possible not only to assess trends in element concentration versus till thickness, but also to assess trends by size fraction.

Each of the three surveys analyzed a different till size fraction (*see* **Table 3**). The thicker till unit is characterized by higher Ba and Cr concentrations, for all till size fractions (clay, clay+silt, clay+silt+sand), than the thinner till units (**Fig. 4**). Concentrations of Mg and Ni were also higher in the thicker till than in the thinner till, in both the clay and clay+silt+sand fraction. Analyses of Mg and Ni were not available in the clay+silt fraction. The concentration of La is lower in the thickest till unit in both the clay+silt and clay size fractions. The thickest till unit is also characterized by lower Ce values, although this could only be tested in the clay+silt fraction.

IMPLICATIONS FOR EXPLORATION

In Lac de Gras kimberlite bodies, the concentration of all identified kimberlite pathfinder elements (Ba, Ce, Cr, La, Mg, Nb, Ni) falls well within the global range for these elements in archetypal Group I kimberlite (*see* Mitchell, 1986). Global kimberlite ranges, however, overlap La, Ba, Cr, Mg, and Ni values in the Lac de Gras region. This indicates that La, Ba, Cr, Mg, and Ni may be useful kimberlite pathfinder elements in the Lac de Gras area, but globally this relationship may not be applicable, despite the common identification of Ba and La as elements whose high concentrations are more indicative of a kimberlite source (Gregory and Tooms, 1969; Muramatsu, 1983; McClenaghan, 1996; McClenaghan et al., 1999). The elements Rb, Th, Ta, Hf, and U (Gregory and Tooms, 1969; Mitchell, 1986;

McClenaghan, 1996; McClenaghan et al., 1999) have been reported as useful kimberlite pathfinder elements for separating kimberlite composition from ultramafic rock composition. In this study, whole-rock data for Ta and Hf were insufficient to assess their potential as kimberlite pathfinder elements. Concentrations of Th and U in kimberlite were not found to differ significantly from in other rock types in the area. The concentration of Rb in kimberlite overlaps that of Rb in diabase dykes in the Lac de Gras area. Other elements whose concentration in kimberlite overlapped only concentrations in diabase dykes included Bi, Ca, Fe, K, Mn, and Nd. These elements may be useful kimberlite indicators in regions not dominated by diabase or material of a similar composition. Likewise, Co, whose concentration in kimberlite overlapped only with that in ultramafic rocks, may be a useful kimberlite pathfinder element in regions without a significant component of ultramafic rocks.

The thickest till unit is characterized by higher concentrations of kimberlite pathfinder elements Ba, Cr, and likely Mg, and Ni, for all size fractions. The clay fraction is characterized by a well known tendency to concentrate metals primarily as a result of adsorption onto phyllosilicates and/or absorption into the structure of phyllosilicates (Klassen and Shilts, 1977; Shilts, 1995) and Fe and Mn scavenging (Ridler and Shilts, 1974). In Figure 4, it can be seen that absolute element concentration for Cr is higher in the clay size fraction samples than in the clay+silt and clay+silt+sand samples. Scavenging may thus be affecting the absolute value of the element concentration in the clay size fraction samples. However, the relative trends in element concentration between the thickest till unit (T3) and the other till units are identical to those for the clay+silt and clay+silt+sand size fraction samples. It is thus unlikely that the higher concentrations of Ba, Cr, Mg, and Ni in the thicker till are due to secondary surficial processes acting preferentially on the thicker till unit. Furthermore, a consistent sampling of till at 20 to 100 cm depth ensures uniformity in secondary surficial processes affecting the till (e.g. little variation in the effects of Fe and Mn scavenging).

In general, till composition is controlled by factors relating to bedrock source, namely the type and abundance of component minerals, the susceptibility of these minerals to weathering, and the area, relative topographic position, and resistance to erosion of the source rock (Shilts, 1996). The thicker unit, generally coincident with the area of mapped kimberlite pipes, may have entrained a larger volume of kimberlitic debris. It may also contain more distally derived material. This would suggest a kimberlite and/or ultramafic source of debris up-ice. There are few known ultramafic rocks in the Lac de Gras that may be this source. Alternatively, the higher values of Ba, Cr, Mg, and Ni in the thicker till may be a function of the volume of debris derived from metasedimentary and granitoid rocks of the Slave Province. A large volume of till debris derived from these rocks will have a high concentration of Ba due solely to the quantity of Ba-bearing debris in the till.

If kimberlite pathfinder-element concentrations in the thick till are masked by abundant, but distantly derived, sources of Ba and other elements, then it may be possible to screen the thickest till to reveal locally derived kimberlite anomalies. Continuous surface (contour) maps of each kimberlite pathfinder element could be generated and then a map made for each of the till units (i.e. for a map of the thickest till unit, mask out the areas of thin till, which become areas of no data). Separate anomalous thresholds could be calculated for each till unit using normal probability plots, and breakpoints reflective of kimberlite mineralization could be identified. The result would be separate element anomaly maps for each map unit. The spatial association of these anomalous areas could then be compared to the distribution of known kimberlites.

CONCLUSIONS

- Positive kimberlite pathfinder elements, identified from a comparison of whole-rock analyses of kimberlite and other lithological units, for the Lac de Gras area, include Ba, Ce, Cr, La, Mg, Nb, and Ni.

- The elements Bi, Ca, Co, Fe, K, Mn, Nd, and Rb are additional potential kimberlite pathfinder elements in areas in which there is relatively little ultramafic volcanic and/or diabase debris in the till. The reported kimberlite pathfinder elements Th and U were not found to be useful in the Lac de Gras area because of high concentrations of these elements in granitoid rocks.
- The thicker till unit in the Lac de Gras area is characterized by higher values of Ba, Cr, Mg, and Ni. This pattern is evident in all three till size fractions (clay, clay+silt, and clay+silt+sand).
- High concentrations of Ba, Cr, Mg, and Ni in the thick till seem not to be due to secondary surficial processes, but rather to differences in the source (i.e. distance of derivation) and volume of the debris.
- To identify pathfinder elements more indicative of kimberlite than ultramafic rocks, more complete lithogeochemical data must be obtained. The potential of Be, Br, Cl, Dy, Er, F, Ga, Hf, Ho, Li, Pr, S, Sc, Ta, Tm, V, and W as kimberlite pathfinder elements could not be evaluated. Elements Hf and Ta have good potential as kimberlite pathfinders.
- The use of till geochemistry for kimberlite exploration requires an appropriate suite of high-quality geochemical analyses. Future research should examine whether aqua regia or other partial disolution techniques are appropriate, ideally including analysis for Ce, Ni, Mg, Nb, and Ni in all till size fractions. In addition, higher quality analyses are needed, particularly for Ni and La.

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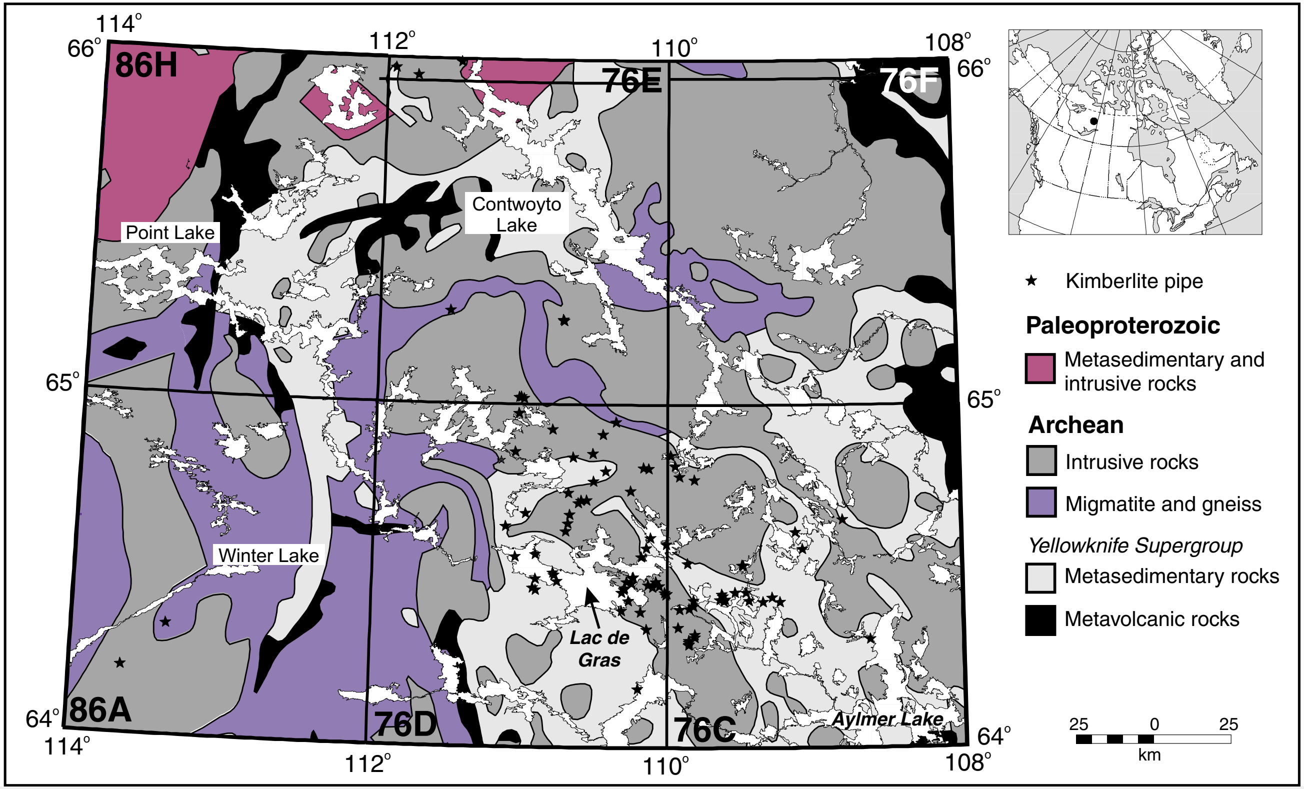


Figure 1. Generalized bedrock geology of the central Slave Province (*after* Kirkham et al., 1995). NTS 1:250 000 sheet areas are labelled.

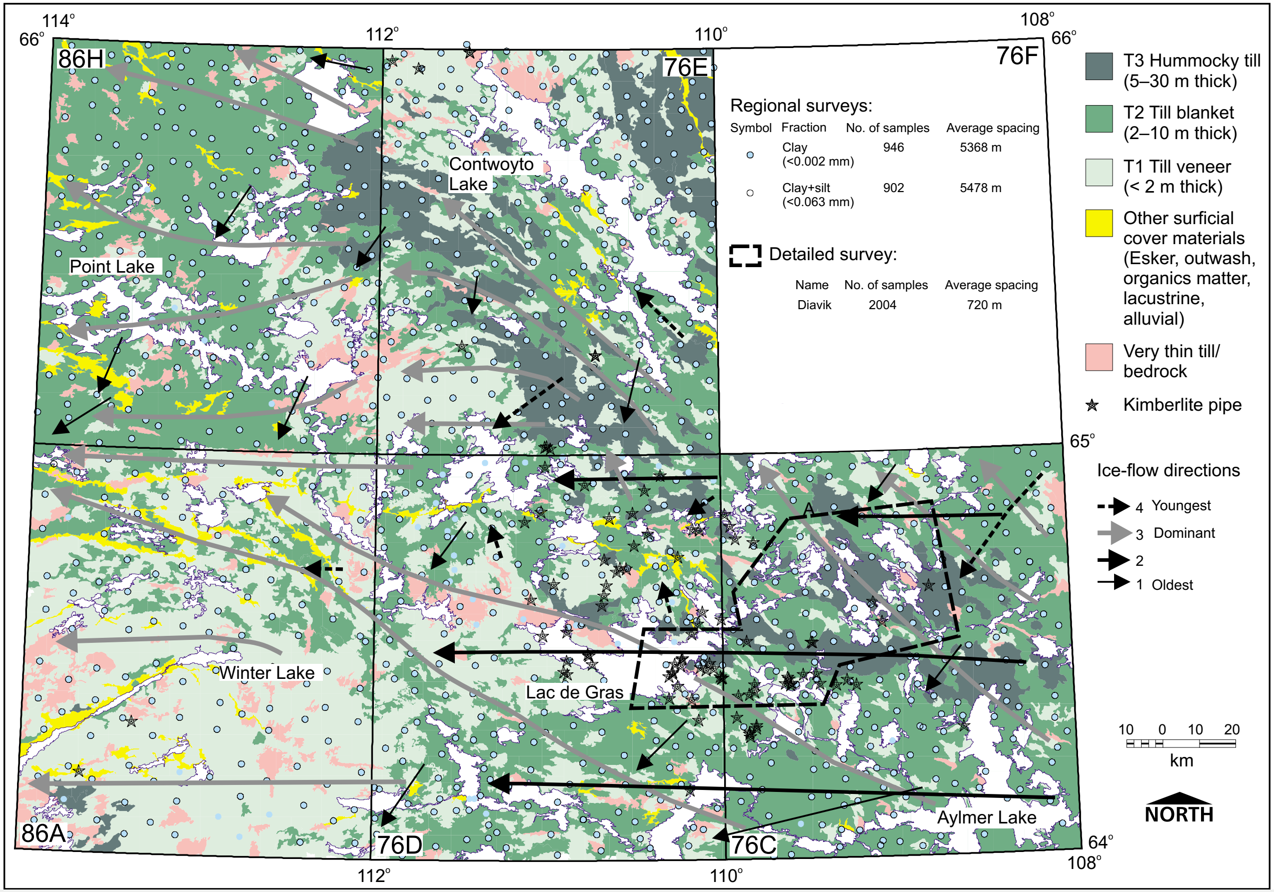
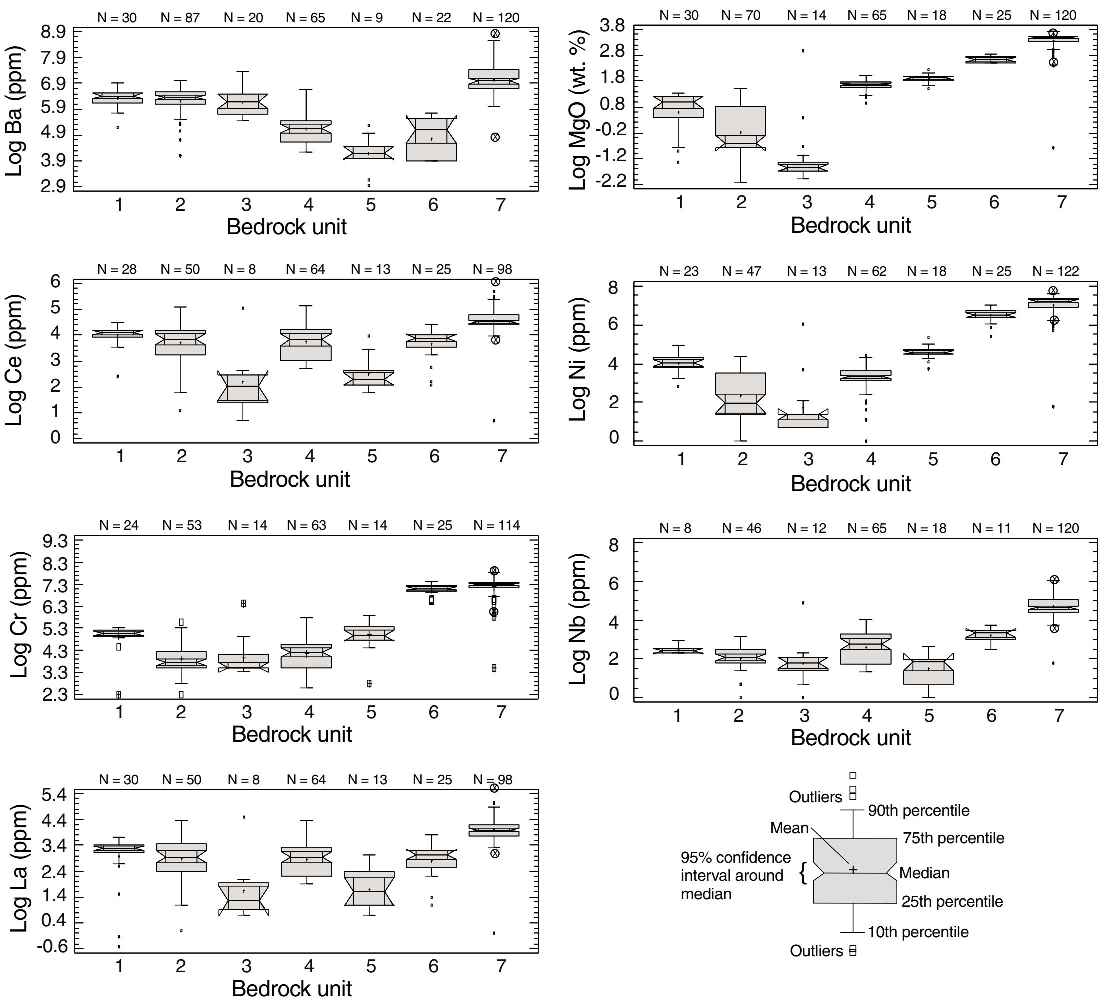


Figure 2. Generalized surficial geology and ice-flow directions of the central Slave Province (surficial geology compiled *after* Dredge et al., 1995b, 1996b; Kerr et al., 1996b, 2000; Ward et al., 1997). Ice-flow directions compiled *after* Dredge et al. (1994) and Kerr et al. (1995). Also shown are sample locations of regional till geochemical surveys and extents of detailed till geochemical surveys.



Legend

1 Metasedimentary rocks 2 Felsic intrusive rocks 3 Pegmatite 4 Diabase 5 Basalt
6 Basaltic komatiite-picrite 7 Kimberlite

⊗ Global kimberlite minimum and maximums for Type I kimberlites (compiled *after* Mitchell, 1986)

Figure 3. Box-and-whisker plots of positive kimberlite pathfinder-element concentrations in bedrock units of the Lac de Gras area.

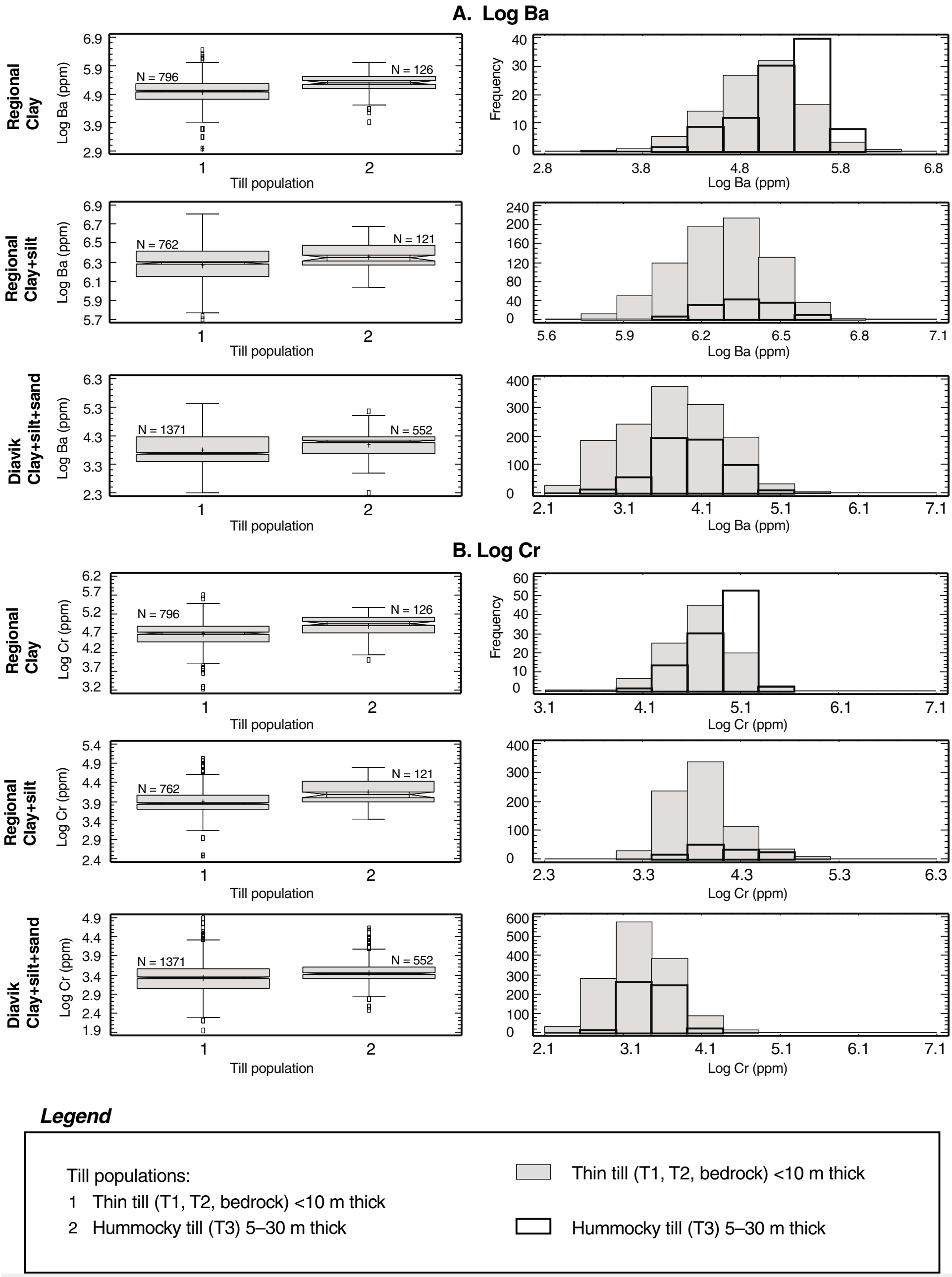


Figure 4. Comparison of Ba and Cr concentrations by till thickness, for each till size fraction. 'Bedrock' refers to till samples from areas of >75% bedrock exposure.

Table 1. Summary of till geochemical surveys. ICP-AES = inductively coupled plasma — atomic emission spectrometry; INAA = instrumental neutron activation analysis.

Fraction	No. of samples[1]	Analytical method	Sample spacing	Year of survey	Source
GSC: clay (<0.002 mm)	946 (944)	ICP-AES Aqua regia	5368 m	1995–1998	GSC[2]
GSC: clay+silt (<0.063 mm)	902 (900)	INAA	5478 m	1995–1998	GSC[2]
Diavik: clay+silt+sand (<0.177 mm)	2004 (1988)	ICP-AES Aqua regia	720 m	1993–1994	Kennecott Canada Exploration Ltd.

[1] The number of samples listed represents the total number of analyses available in each survey data set, the number in brackets represents the number of these samples that fell within the study area.
[2] Data compiled from Ward et al. (1996), Kerr et al. (1996a, 1998), Dredge et al. (1995a, 1996a, 1997).

Table 2. Summary of kimberlite pathfinder elements available for each survey and for each fraction. Elements in **bold** were eliminated from further statistical tests because of an insufficient number of analyses or problems with analytical precision.

Fraction/Survey	Elements
GSC: clay (< 0.002 mm)	Ba, Cr, La, Mg, Ni
GSC: clay+silt (<0.063 mm)	Ba, Ce, Cr, La, **Ni**
Diavik: clay+silt+sand (<0.177 mm)	Ba, Cr, **La**, Mg, Ni

Table 3. Comparison of kimberlite pathfinder-element concentrations in T3 and in other sampled till units (T1, T2, and very thin till in areas dominated by bedrock), by survey.

Fraction/Survey	Elements	Concentration in T3 versus other till units	No. of samples
GSC: clay (<0.002 mm)	Ba, Cr, La, Mg, Ni	Higher: Ba, Cr, Mg, Ni Lower: La	T3 = 126 Other = 794–796
GSC: clay+silt (<0.063 mm)	Ba, Cr, Ce, La	Higher: Ba, Cr Lower: La, Ce	T3 = 121 Other = 762
Diavik: clay+silt+sand (<0.177 mm)	Ba, Cr, Mg, Ni	Higher: Ba, Cr, Mg, Ni	T3 = 552 Other = 1371