INDICATOR MINERAL AND SURFICIAL GEOCHEMICAL EXPLORATION METHODS FOR KIMBERLITE IN GLACIATED TERRAIN; EXAMPLES FROM CANADA

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Abstract

Diamond exploration in Canada focuses on kimberlite, the primary host rock for diamonds in this country. Kimberlite is a mineralogically and geochemically distinct point source that yields discrete dispersal trains in glacial sediments and dispersion fans in stream sediments. This paper provides a summary of selected diamond exploration techniques used in the glaciated terrain of Canada, focusing on indicator mineral methods. Kimberlite indicator minerals, in general, are able to survive long distance glacial transport. The relative abundance of specific minerals in till, and to a lesser extent in stream sediments, is a function of the mineralogy of kimberlite(s) in the source areas. Indicator mineral distributions observed at a regional scale define the net effect of glacial dispersal, often along different ice flow directions. Local scale distributions define individual dispersal trains. The 0.25 to 2.0 mm fraction of heavy mineral concentrates prepared from till and fluvial sediments is typically used for indicator mineral surveys, with the finer (0.25-0.50 mm) fraction often providing the best results. Till geochemistry is gaining popularity in diamond exploration because it is significantly cheaper than indicator mineral analysis and it can be performed quickly. Important kimberlite pathfinder elements include Mg, Ni, Cr, Co, Ca, Fe, Ti, Nb, Ta, REE, K, Rb, Sr, and Ba, but will depend on the composition of the country rocks versus the kimberlite. Soil selective leaches, soil gas, and hydrogeochemistry, still in the developmental stages for kimberlite exploration, may prove to be useful exploration techniques for application at a local scale.

Résumé

L'exploration à la recherche de diamants au Canada est centrée sur la kimberlite, la principale roche hôte des diamants au pays. La kimberlite est une source ponctuelle caractéristique des points de vue minéralogique et géochimique qui libère des traînées de dispersion distinctes dans les sédiments glaciaires et des cônes de dispersion dans les sédiments fluviaux. Dans la présente étude, on fournit un résumé de méthodes choisies d'exploration à la recherche de diamants utilisées dans les terrains anciennement englacés du Canada et en particulier des méthodes basées sur les minéraux indicateurs. En général, les minéraux indicateurs de kimberlite peuvent survivre au transport glaciaire sur de longues distances. L'abondance relative de minéraux spécifiques dans le till et, dans une moindre mesure, dans les sédiments fluviaux, dépend de la minéralogie de la (des) kimberlite(s) présente(s) dans les régions sources. La répartition des minéraux indicateurs observée à l'échelle régionale permet de définir l'effet net de la dispersion glaciaire, souvent dans différentes directions d'écoulement de la glace. La répartition à l'échelle locale permet de définir des traînées de dispersion individuelles. On utilise de manière caractéristique la fraction de 0,25 à 2,0 mm des concentrés de minéraux lourds extraits du till et des sédiments fluviaux dans le cadre des levés des minéraux indicateurs; la fraction plus fine (de 0,25 à 0,50 mm) fournit souvent les meilleurs résultats. Les méthodes géochimiques appliquées au till gagnent en popularité pour l'exploration à la recherche de diamants parce qu'elles sont beaucoup moins coûteuses et plus rapides à appliquer que l'analyse des minéraux indicateurs. Les éléments indicateurs importants pour la recherche de traînées de kimberlite sont Mg, Ni, Cr, Co, Ca, Fe, Ti, Nb, Ta, les terres rares, K, Rb, Sr et Ba, mais ceux à utiliser dépendront de la composition des roches encaissantes comparativement à celle de la kimberlite. Les méthodes fondées sur la lixiviation sélective des sols, sur les gaz présents dans les sols et sur l'hydrogéochimie en sont encore au stade de l'élaboration, mais pourraient s'avérer utiles pour l'exploration à l'échelle locale.

Introduction

Several major kimberlite fields in the world are located in glaciated terrain, including those in Yakutia, Archangel'sk, northern Finland, southwest Greenland, and Canada (Fig. 1). An understanding of the application of drift prospecting methods for glaciated terrain is essential for exploring for diamonds in these regions. In this terrain, glacial erosion is the principal means by which kimberlite has been dispersed, from a few tens of metres to tens of kilometres down-ice. Modern streams have also transported kimberlite debris, as boulders, cobbles, and discrete heavy mineral grains, up to several tens to hundreds of kilometres from source. As a result, boulder tracing, heavy mineral sampling using till or stream sediments and till geochemistry are the most common drift prospecting methods in glaciated terrain. Since the end of glaciation approximately 6000 to 10000 years ago, in situ weathering of kimberlite may have resulted in the geochemical transport of elements upwards from the kimberlites through overlying glacial sediments where they may be captured in surface soils and/or in groundwater. Thus, soil selective leaches, soil gas and hydrogeochemical methods, still in the developmental phase, may prove to be useful for kimberlite exploration in glaciated terrain.

In Canada, indicator mineral methods were first used to explore for kimberlites in the early 1960s and their continued application, in combination with geophysics, eventually led to the discovery of kimberlites fields in north and northeastern Ontario (Fig. 2) in the 1980s (Brummer et al., 1992a; Kjarsgaard and Levinson, 2002) and the highly diamondiferous kimberlites in the Lac de Gras field of the Northwest Territories (Fig. 2) in the early 1990s (Fipke et al., 1995a; Pell, 1997; J. Carlson et al., 1999). Since the discovery of the Lac de Gras kimberlites, many government agencies have undertaken regional diamond exploration surveys in Canada

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FIGURE 1. Areas of the northern hemisphere covered by Pleistocene ice sheets and location of major kimberlite deposits (modified from Eriksson, 1992).

(e.g. Dredge et al., 1995; Crabtree, 2003; Friske et al., 2003). Simultaneously, industry diamond exploration geologists conducted regional survey programs that led to the discovery of additional kimberlite fields in the Northwest Territories (Armstrong, 2001; Armstrong and Chatman, 2001), Nunavut, northern Quebec, and northern Alberta. A number of exploration case histories, describing the application of drift exploration methods in the discovery of kimberlites in glaciated terrain have been reported (e.g. Mckinlay et al., 1997; J. Carlson et al., 1999; S. Carlson et al., 1999; Doyle et al., 1999; Kong et al., 1999; Kirkley et al., 2003; Rikhotso et al., 2003). As well, case studies have been carried out around known kimberlites to document indicator mineral and surficial geochemical dispersal patterns in glacial sediments (e.g. McClenaghan et al., 1996, 1998, 1999a,b,c, 2002a,c, 2004; Fenton and Pawlowicz, 1997; Leckie et al., 1997; Eccles, 1998a,b; Kerr et al., 2000; McClenaghan et al., 2002a; Lehtonen et al., 2005) in order to refine existing and test new kimberlite exploration methodologies. In Canada, kimberlite indicator mineral methods are by far the most commonly used and successful of the surficial techniques

that can be applied to diamond exploration in glaciated terrain. Thus, the majority of the published literature describing kimberlite-related exploration case histories, regional till or stream sediment surveys, and orientation studies in Canada deals with the use of indicator mineral methods. As a result, the emphasis of this paper is on indicator mineral methods, with numerous Canadian examples. Other surficial sediment techniques that may be applied to kimberlite exploration in glaciated terrain are also mentioned in the paper, although their applications are largely untested and/or undocumented in the literature.

Kimberlite

Key Attributes

Kimberlites are CO₂- and H₂O-rich ultramafic rocks of magmatic origin, derived from limited partial melting of the mantle at very high pressure (>10 GPa, or >300 km depth). The rocks have a distinctive inequigranular texture, and often appear hybrid in nature as they may contain mantle xenoliths, mantle xenocrysts, macrocrysts (a non-genetic term for crystals 1 to 20 mm in size, i.e. megacrysts and xenocrysts), crustal xenoliths, and euhedral to subhedral phenocrysts set in a groundmass matrix crystallized from the kimberlite magma. Macrocrysts include minerals derived from disaggregated mantle xenoliths, plus the kimberlite megacryst suite of minerals (Mg-ilmenite, Cr-poor Tipyrope garnet, Cr-diopside, phlogopite, enstatite, zircon, and olivine). Primary minerals include euhedral olivine and phlogopite phenocrysts and microphenocrysts in a finegrained matrix of one or more of the following minerals: spinel, ilmenite, perovskite, monticellite, apatite, phlogopitekinoshitalite mica, carbonate, olivine, and serpentine.

The basis for drift prospecting methods for kimberlites in glaciated terrain relies on two principles: 1) kimberlites contain a distinctive suite of resistant and abundant minerals known as kimberlite indicator minerals that includes Crpyrope garnet, pyrope-almandine garnet, Mg-ilmenite, Cr-



FIGURE 2. Kimberlite and selected ultrabasic locales in Canada, shown with a backdrop of the major geological terranes. Numbers refer to locations of kimberlite fields discussed in the text (modified from McClenaghan and Kjarsgaard, 2001).



FIGURE 3. Aerial photograph showing the glaciated landscape of the thin to moderately drift-covered bedrock in the Lac de Gras region and the location of the Point lake, Misery lake, Jaeger, and Jay kimberlites underlying glacially scoured lakes.

diopside, Cr-spinel, Mg-olivine, and enstatite and 2) kimberlites have a characteristic geochemical signature that is rich in both 'incompatible' elements Sr, Ba, LREE (La, Ce, Sm, Nd), Nb, Ta, Hf, Zr, P, and Ti and first order transition elements Mg, Ni, Cr, and Co of ultramafic affinity (Litinskii, 1961; Mitchell, 1986; Fipke et al., 1995b). These two distinctive features of kimberlite form the basis for indicator mineral and geochemical sampling of surficial sediments. Importantly, the distance of glacial dispersal down-ice for kimberlite indicator minerals and the kimberlite geochemical signature is related to the size of the kimberlite point source, the type of kimberlite being eroded (i.e, hypabyssal versus volcaniclastic) and the compositional contrast with the host rock. Note that kimberlites can be quite variable in size and may form thin dykes, sheets, and pipe-like bodies that can range from 50 to 1500 m in diameter.

Weathering

In Canada, kimberlites range in age from ca. 1123 to 45 Ma (Heaman et al., 2004) and were subject to significant weathering prior to Quaternary glaciation. At the time of kimberlite emplacement, or shortly thereafter, macrocrysts and primary groundmass minerals are commonly replaced by serpentine and calcite. Furthermore, the highly porous nature of volcaniclastic kimberlite (crater and diatreme zone kimberlite) makes these rocks highly susceptible to postemplacement alteration by weathering processes. Over time, this alteration leads to the development of a soft, friable, clay-rich regolith, often referred to as "yellow" or "blue" ground. Glacial erosion has removed varying amounts of the regolith and, in some cases, the more competent kimberlite below. For example, glacial erosion of the Peddie, McLean, and Seed kimberlites in the Lake Timiskaming kimberlite field in northeastern Ontario (Fig. 2) removed all regolith, leaving fresh glacially striated kimberlite beneath thick till. In contrast, glacial erosion of other kimberlites in the same field was less intense, leaving more than 6 metres of regolith at the top of some kimberlites (e.g. McClenaghan et al., 2004). Glacial erosion and entrainment of kimberlite debris was likely more robust where the preglacial regolith was thickest, thus the volume of regolith exposed to the glacier may have been a factor in determining the areal extent and abundance of kimberlite debris in glacial dispersal trains. Since kimberlite is commonly more susceptible to glacial erosion than the surrounding country rock, many kimberlites in glaciated terrain are found in bedrock depressions that are either in low, swampy ground under small lakes (Fig. 3) or covered by thick glacial sediments (Fig. 4). In the Buffalo





FIGURE 4. Schematic plan and cross-section views of clastic dispersal and chemical dispersion patterns in various media around a kimberlite in glaciated terrain.



FIGURE 5. Examples of typical colours and surface features of kimberlite indicator minerals: (**A**) purple and mauve Cr-pyrope, some retaining kelyphite (dark); (**B**) emerald green Cr-diopside; (**C**) opaque black Cr-spinel, some exhibiting slightly resorbed octahedral form; (**D**) black Mg-ilmenite, both single crystals and polycrystalline morphologies shown; (**E**) yellow Mg-olivine; (**F**) orange eclogitic pyrope-almandine garnets. Photos A to E from the Geological Survey of Canada, photo F from Mineral Services Canada.

Head Hills field, however, kimberlites are more competent than the surrounding Cretaceous sandstone and shale, and thus form topographic highs on the bedrock surface (Fenton et al., 2003; Skeleton et al., 2003).

Kimberlite Indicator Mineral Methods

The unique mineralogical signature of kimberlites enables the application of indicator mineral techniques commonly used for diamond exploration in southern Africa, Australia. and Russia to glaciated terrains of Canada and Fennoscandia. Several minerals that occur in kimberlite are useful indicators of the presence of this rock type (Gurney et al., 1993; Fipke et al., 1995b). These indicator minerals are visually (Fig. 5) and chemically distinct, mostly sand-sized (0.15-2.0 mm), sufficiently dense to be concentrated by gravity methods, and can typically (but not always) survive preglacial weathering, subsequent glacial transport, and postglacial weathering (Dummett et al., 1987; McCandless and Nash, 1996; Averill, 2001). Kimberlite indicator minerals include 1) xenocrysts derived from disaggregated peridotite and eclogite mantle xenoliths (olivine, enstatite, Crdiopside, Cr-pyrope garnet, Cr-spinel, eclogitic pyropealmandine garnet, omphacitic pyroxene, and diamond), 2) the associated megacryst suite of minerals (low-Cr Tipyrope, Mg-ilmenite, Cr-diopside, phlogopite, zircon and olivine), and 3) kimberlite-derived (i.e. phenocrystal) olivine and spinel. The physical characteristics of the kimberlite indicator minerals commonly used in glaciated terrain are summarized in Table 1. A subset of these indicator minerals (those derived from disaggregated peridotite and eclogite xenoliths) also can be used for a preliminary evaluation of the diamond potential of an area or a kimberlite body. The use of Cr-pyrope, pyrope-almandine garnet, Cr-diopside, Mg-ilmenite, and Cr-spinel in regional- and local-scale till and stream sediment sampling programs for kimberlite exploration is well established (J. Carlson et al., 1999; S. Carlson et al., 1999; Kong et al., 1999). However, few examples of glacial dispersal patterns for kimberlitic olivine have been published. In contrast to arid and tropical terrains, kimberlitic olivine easily survives glacial transport and it is visually distinct from olivine derived from other rock types (e.g. Afanase'ev et al., 1984; McClenaghan et al., 2004) and should be used along with the more common indicator minerals.

Indicator Mineral Chemistry

Various types of indicator minerals recovered by visual sorting from surficial media samples can be more precisely characterized by measuring the concentrations of major oxides and some trace elements by SEM-EDS or electron microprobe analysis (e.g. Sobolev, 1977; Fipke et al., 1989). Mineral analysis is undertaken in order to correctly differentiate indicator minerals from kimberlite versus those associated with other bedrock sources that can be visually similar. Simple identification of kimberlite-derived ilmenite, for example, utilizes a minimum threshold of 4 wt.% MgO (Fig. 6A). A more sophisticated crustal versus kimberlite ilmenite discrimination diagram using TiO₂ versus Cr_2O_3 (Fig. 6B) has recently been published by Wyatt et al. (2004).

Indicator Mineral and Surficial Geochemical Exploration Methods for Kimberlite in Glaciated Terrain; Examples from Canada

TABLE 1. Summary of physical features of kimberlite indicator minerals (modified from Muggeridge, 1995). These features can be used to visually identify and distinguish kimberlite indicator minerals from other minerals in heavy mineral concentrates produced from kimberlites and surficial sediments.

Mineral	Composition ^a	Crystal system	Colour	Typical grain size (mm) normal (to rare)	Response to electromagnet (paramagnetism)	Specific gravity	Hardness (Moh)	Streak colour	Visible diagnostic features ^b	Main source rocks
Pyrope garnet	Mg Fe Ca Al silicate, <i>Cr, Ti</i>	Isometric	purple, crimson red, mauve	1-5 (to 100)	nonparamagnetic to very weakly paramagnetic	3.51	7.5		anhedral, kelyphite rim, characteristic colours, orange peel surface	Peridotite, kimberlite, lamprophyre (certain basic volcanic rocks)
Pyrope almandine garnet	Mg Fe Ca Al silicate, <i>Ti, Na</i>	Isometric	orange	1-5 (to 25)	nonparamagnetic to very weakly paramagnetic	3.7 to 3.8	7.5		anhedral, kelyphite rim, characteristic colours, orange peel surface	Eclogite
Mg-ilmenite (picroilmenite)	Mg Fe Ti oxide <i>Cr, Mn, Al</i>	Trigonal	black	1-20 (to 100)	strongly paramagnetic	4.5 to 5.0	5 to 6	black	anhedral, rounded or blocky, white porcellaneous leucoxene coating, perovskite overgrowth, glassy lustre on broken surfaces, conchoidal fracture	Kimberlite (certain basic volcanic rocks)
Cr-diopside	Ca Mg silicate, Fe, Cr, Al, Na	Monoclinic	emerald green	1-5 (to 50)	nonparamagnetic to very weakly paramagnetic	3.2 to 3.6	5 to 6		anhedral, blocky, cleavage in 2 directions, characteristic colour	Peridotite, kimberlite, (certain ultrabasic rocks)
Cr-spinel	Mg Cr Al Fe oxide, <i>Mn, Ti</i>	Isometric	black, reddish brown	0.5-1 (to 8)	moderately paramagnetic	4.3 to 4.57	5.5	dark brown	octahedral to irregular shape, reddish brown on edges of broken grains, glassy surface on broken grains	Peridotite, kimberlite, lamproite, carbonatite, various ultramafic plutonic and volcanic rocks
Forsteritic olivine	Mg silicate, <i>Fe,</i> <i>Ni, Mn</i>	Orthorhombic	pale yellow to green	2-10 (to 50)	nonparamagnetic to very weakly paramagnetic (non- kimberlitic grains with magnetite inclusions are strongly paramagnetic)	3.2 to 3.33	6 to 7		characteristic colour, irregular crystal apices, vermiform etching	Peridotite, kimberlite, lamproite, carbonatite, various ultramafic plutonic and volcanic rocks
Diamond	C native (N, B)	Isometric	colourless, pale colours (especially yellow and brown)	0.5-10 (to 30)	nonparamagnetic	3.52	10		adamantine lustre, crystal form, resorption features, step layering	Kimberlite, lamproite (certain lamprophyres and high grade metamorphic rocks)

a minor and trace elements listed in italics

b by naked eye, hand lens, or binocular microscope

The discrimination and classification of mantle-derived garnet versus crustal-derived garnet versus kimberlite megacryst garnet has been improved substantially since the early studies of Dawson and Stephens (1975), Sobolev (1971; 1977), Sobolev et al. (1973), Gurney and Switzer (1973), and Gurney (1984). Recently, Grütter et al. (2004) published a simple, easy to use garnet discrimination/classification scheme, based on a large dataset, using sound petrological principles. This classification allows for discrimination of: "G12" or wehrlite garnet; "G11" or high-Ti peridotite garnet; "G10" or harzburgite/dunite subcalcic garnet; "G9" or lherzolite Ca-saturated garnet; "G4" or pyroxenite –

websterite – eclogite garnet; "G3" eclogite garnet, and "G1" megacryst garnet. Grütter et al. (2004) unfortunately retained the use of "G5" terminology in their updated garnet classification system. In the early 1990s in Canada, a number of sampling studies reported the occurrence of high iron "eclogitic G5" (nomenclature of Dawson and Stephens, 1975) garnets. Subsequently, Schulze (1995) suggested that many of these garnets are in fact of crustal origin. More recently, Fipke et al. (1995b) and Schulze (1997) have published a threshold of 22 wt.% FeO to separate mantle-derived garnets from Fe-rich crustal garnets.



FIGURE 6. (A) Cr_2O_3 versus MgO bivariate plot for ilmenite from the A4 kimberlite, Kirkland Lake kimberlite field. Note that ilmenite from kimberlite contain >4 wt.% MgO and elevated Cr_2O_3 ; (B) TiO₂ versus Cr_2O_3 bivariate plot for ilmenite for the same data set (modified from McClenaghan et al., 1996). Curve separating kimberlitic from non-kimberlitic ilmenite is from Wyatt et al. (2004).



FIGURE 7. (A) Cr_2O_3 versus Mg[#] (100Mg/(Fe+Mg)) in diopside from kimberlite boulder SD-040, Lake Timiskaming kimberlite field; (B) projection of SD-040 kimberlite boulder clinopyroxene compositions into the pyroxene quadrilateral. The coloured ovals indicate the approximate compositional fields of diopside from eclogite, websterite, megacryst and peridotite lithologies. Data from McClenaghan et al. (2006b).

Minerals that are more difficult to chemically classify as kimberlite-derived include olivine, spinel, and diopside. These minerals form phenocrysts in a wide variety of ultrabasic and basic rocks, and may also have primitive mineral chemistry, i.e. elevated Mg/(Mg+Fe) and Cr/(Cr+Al) ratios and high MgO and Cr₂O₃ concentrations. Kimberlite olivine phenocrysts are MgO-rich (forsteritic; Mg#>84) and contain variable, but high Ni concentrations (Mitchell, 1986; Fipke et al., 1995b) as do olivine from a variety of other rocks. However, olivine from disaggregated mantle peridotite typically has Mg#>91.5 with high Ni concentrations. Kimberlites and mantle xenoliths are the only rocks that contain very Cr-rich diopside with >1.5 wt.% Cr₂O₃, (Deer et al., 1982; Fipke et al., 1989, 1995b). But kimberlites also may contain diopside with <1.5% wt.% Cr₂O₃. Hence, Crdiopside grains containing <1.5% wt.% Cr₂O₃ identified in surficial media require further discrimination to determine their bedrock source. A variety of discrimination plots are utilized (Boyd and Nixon, 1972; McCandless and Gurney, 1989; Nimis, 1998; Morris et al., 2002). Most use a combination of Mg[#] and Cr₂O₃ and Ca-Mg-Fe and Na-Al-Cr ternary relationships (e.g. Fig. 7).

Because diamond is a rare mineral in kimberlite (usually <<1.4 ppm), a subset of the kimberlite indicator minerals, termed "diamond indicators", is used to indicate the *potential* presence of diamond in these rocks. This subset is based on studies of silicate and oxide inclusions in diamond and minerals from diamond-bearing mantle xenoliths (e.g.



FIGURE 8. CaO versus Cr_2O_3 bivariate plot for garnet from the SD40 kimberlite boulder, Lake Timiskaming kimberlite field. Dashed diagonal lines between G9-G10 and G9-G12 garnets, dashed vertical line at 1 wt.% Cr_2O_3 , and G10D-G10 discriminant line are from Grütter et al. (2004). Data from McClenaghan et al. (2006b).

Sobolev, 1971; Gurney and Switzer, 1973; Sobolev et al., 1973; Gurney, 1989; Fipke et al., 1995b). Specific diamond indicator minerals include subcalcic Cr-pyrope, "G10" garnet (harzburgite/dunite source rock), high Cr-Mg picrochromite (chromite-bearing harzburgite/dunite source rock), and high Na-Ti pyrope-almandine garnet (eclogite source rock). Many diamond inclusion peridotitic garnets have low-Ca, high-Cr compositions and these garnets are sought in diamond exploration (Gurney and Switzer, 1973; Sobolev et al., 1973; Fipke et al., 1989, 1995b). In the recent Grütter et al. (2004) classification system, discrimination of diamond subclass "G10" garnets is done on the CaO versus Cr₂O₃ bivariate plot (Fig. 8). In eclogitic garnet, elevated Na (and lesser Ti) contents are viewed as being diamond favorable (Fipke et al., 1989, 1995b; Schulze, 1997; Grütter and Quadling, 1999), and discrimination of diamond subclass eclogite "G3" garnet is still best accomplished by use of a TiO₂ versus Na₂O discriminant diagram (Fig. 9).



FIGURE 9. TiO_2 versus Na₂O bivariate plot for Cr-poor orange garnets from SD40 kimberlite boulder, Lake Timiskaming kimberlite field (fields from Schulze, 1997). Garnet nomenclature modified from Grütter et al. (2004). Data from McClenaghan et al. (2006b).



FIGURE 10. Plots for Cr-spinel from the Peddie kimberlite, Lake Timiskaming kimberlite field (N=505): (A) Cr_2O_3 versus MgO bivariate plot (diamond inclusion and intergrowth fields are from Fipke et al., 1995b); (B) Al₂O₃ versus Cr_2O_3 bivariate plot (diamond inclusion field is from Sobolev, 1977); (C) TiO₂ versus Cr_2O_3 bivariate plot (modified from McClenaghan et al., 1999a).

Cr-spinel with >61% wt.% Cr₂O₃, 10 to 16% wt.% MgO, <0.60 wt.% TiO₂, <8 wt.% Al₂O₃ and <6 wt.% Fe₂O₃ are typical of diamond inclusion spinel compositions (Sobolev, 1971, 1977; Gurney, 1984; Fipke et al., 1989, 1995b; Griffin et al., 1997; Grütter and Apter, 1998; Kjarsgaard, 1998) although kimberlites also contain spinel with a broader range of Cr₂O₃ and MgO (Fig. 10A). Sobolev (1971; 1977) provided further refinement of spinel discrimination by examination of Al₂O₃ and TiO₂ concentrations in conjunction with Cr₂O₃ contents (Fig. 10B,C). Note that a stoichiometric recalculation of total iron into FeO and Fe₂O₃ is also an important additional criterion.

Relative Abundance of Indicator Mineral Species

In nonglaciated terrains, chemical and physical degradation of indicator minerals changes their relative abundances in soils, wind-blown sediments, sheet wash, and stream sediments, thus the relative proportions of indicator minerals will vary with proximity to the kimberlite source (Mosig, 1980; Jennings, 1990). In Australia, for example, Cr-spinel is most resistant to weathering followed by, in decreasing order of resistance, Mg-ilmenite, Cr-pyrope, Cr-diopside, and olivine (Atkinson, 1989). The relative abundance of indicator mineral species in individual kimberlites varies significantly (e.g. Smirnov, 1959; Mitchell, 1986; Schulze, 1993a,b) and it is these variations in the kimberlite mineralogy that largely control the relative amounts of indicator mineral species in glacial and stream sediments (e.g. Kong et al., 1999). Decreases in the concentration of indicator minerals downice from kimberlites are primarily the result of dilution.

The relative abundance of indicator minerals may vary between kimberlite fields and thus it is important to recover all indicator mineral species instead of focusing on just one or two. For example, Cr-pyrope and Cr-diopside are the most abundant indicator minerals in kimberlite and till in the Lac de Gras kimberlite field in the central Slave region, while in the Kikerk Lake kimberlite cluster, in the north Slave region. Mg-ilmenite is the dominant indicator mineral (Fig. 11). The relative abundance of indicator minerals may also vary significantly between kimberlites within the same field. Where dispersal/dispersion trains from two kimberlites coalesce, the relative abundance of minerals may aid in distinguishing between the trains. The Diamond Lake kimberlite near Kirkland Lake, for example, contains >5000 grains Mgilmenite grains in a 10 kg sample (McClenaghan et al., 1998). In contrast, the C14 kimberlite, located 20 km to the northwest, is Mg-ilmenite poor and contains <10 grains per 10 kg (McClenaghan et al., 1999c). The large difference in relative abundance of Mg-ilmenite grains in these two kimberlites is reflected in the glacial sediments down-ice of each.

Indicator Mineral Size

Indicator mineral size in glacial sediments is controlled by mineral-forming processes in mantle rocks or kimberlite magma. Cr-pyrope in kimberlite is commonly 0.1 to 1.0 cm in diameter (Smirnov, 1959; Mitchell, 1986) and is highly susceptible to fracturing during decompression and cooling (Garvie and Robinson, 1984; McCandless, 1990). As a gla-



FIGURE 11. Comparison of the relative abundance of garnet, Cr-diopside, spinel, and Mg-ilmenite in till for six kimberlite fields in the Slave geological province, northern Canada (from J. Armstrong, unpub. data, 2003).

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FIGURE 12. Colour photographs of indicator mineral grain surface textures from kimberlites: (**A**) Cr-pyrope with dark green-grey adhering kimberlite (k); (**B**) Cr-pyrope with dark green-grey kelyphite rims (kp); (**C**) Cr-pyrope displaying sub-kelyphite orange peel texture on surfaces, outlined by dashed line; (**D**) Cr-pyrope displaying sub-kelyphite frosted surfaces; (**E**) Cr-pyrope displaying fresh, angular broken surfaces; (**F**) Cr-diopside displaying rounded (r) to subrounded shape, adhering kimberlite (k), as well as broken angular surfaces (a).



FIGURE 12 CONTINUED. (G) chromite displaying octahedral to suboctahedral (resorbed) shapes.

cier entrains and transports kimberlite, Cr-pyrope preferentially breaks along the pre-existing fractures into angular grains that are dominantly sand sized (<2.0 mm). These grains appear to remain at this size regardless of glacial transport distance (Averill and McClenaghan, 1994).

Although indicator minerals occur in the fine sand (0.06-0.25 mm) fraction, grains in this size range are expensive and time consuming to recover due to their small size. Typically, indicator minerals are picked from the coarser sand (0.25-2.0 mm) sized material. Where extra grains are needed for indicator mineral chemistry studies, the fine sand fraction (0.125-0.25 mm) may also be processed and picked. Mg-ilmenite grains in sediments are commonly larger than other kimberlite indicator minerals because Mg-ilmenite occurs in kimberlite as a coarse mgeacryst phase and is intrinsically less susceptible to decompression fracturing. In sediment samples, especially coarse sorted gravel, it is not uncommon for Mg-ilmenite abundance in the 0.5 to 1.0 mm fraction to exceed abundance in the 0.25 to 0.5 mm fraction (S.A. Averill, pers. comm., 2006).

Indicator Mineral Shape and Surface Features

Surface features and textures on garnets (Table 1) may provide clues to a kimberlitic provenance, the type of transport medium (e.g. glacial versus fluvial), and the transport distance (Mosig, 1980; Afanase'ev et al., 1984; McCandless, 1990; Sobolev et al., 1993; Averill and McClenaghan, 1994; Golubev, 1995; McCandless and Nash, 1996; Garvie, 2003). Garnet may be partially covered with adhering kimberlite (Fig. 12A) or up to 2.0 mm of greenish black kelyphite reaction rims (Fig. 12B) composed mainly of pyroxene with spinel, phlogopite, or serpentine (Fediukova, 1977; Garvie and Robinson, 1984; Dredge et al., 1996). Kimberlite and kelyphite wear down or break off readily during abrasion (McCandless, 1990; McCandless and Nash, 1996) and therefore their presence/absence and thickness on individual grains may give some indication of the relative distance of glacial transport (Garvie, 2003). A finely pitted or microscopic "orange peel" textured surface underlies the kelyphite (Fig. 12C). This texture, formed on the surface of garnet,

consists of minute triangular or rhombic pits that are impressions of radially arranged pyroxene crystals (Garvie and Robinson, 1984). Garnets in kimberlite may also exhibit frosted surfaces (Fig. 12D). Similar to kelyphite, the presence or absence of orange peel textures or frosted surfaces on garnet may give some indication of relative distance of glacial transport. As kimberlite or kelyphite is eroded from pyrope, the amount of orange peel or frosted surfaces exposed on grains increases (Mosig, 1980; Averill and McClenaghan, 1994; Garvie, 2003). Additional abrasion, however, will ultimately remove any sub-kelyphitic (orange peel or frosted) textures.

Garnets in kimberlite occur as spherical nodules to subangular fragments (Fig. 12E) that break apart along pre-existing fractures. It is these fractures that govern the size and shape of garnet grains in till down-ice as the garnet grains suffer very little wear, rounding, or breakdown as a result of glacial or glaciofluvial transport. Therefore, the roundness of garnet grains cannot be used to estimate distance of glacial transport. Similar preservation of original indicator mineral shape has been reported for indicator minerals that have undergone fluvial transport in Siberia (Afanase'ev et al., 1984). In contrast, indicator minerals transported by sheet wash and soil creep in Australia show pronounced wear and degradation over short transport distances (Mosig, 1980; Atkinson, 1989).

Similar to garnets, the shape and surface features of other indicator minerals in till may provide clues to relative transport distance in glaciated terrain. Cr-diopside grains may display adhering kimberlite and rounded to subrounded shape (Fig. 12F). Mg-ilmenite grains may exhibit adhering kimberlite, perovskite mantles, or delicate overgrowths of microcrystalline ilmenite. Chromite grains commonly exhibit varying degrees of resorbed octahedral crystal faces (Fig. 12G) and may display distorted crystal shapes (Yannan and Matsyuk, 1991; Lee et al., 2003).

Heavy Mineral Sampling and Analytical Methods

The main sediment types used for indicator mineral and geochemical surveys in glaciated terrain are kimberlite fragments (boulder, cobbles, pebbles), till, glaciofluvial sediments, beach sediments, and stream sediments. Kimberlite fragments are the most obvious and direct indicators of the presence of kimberlite. In some kimberlite fields, fragments have been deposited down-ice of kimberlites within and on top of till (e.g. Stewart et al., 1988; Papunen, 1995; Melnyk, 1997; J. Carlson et al., 1999) or within poorly sorted pebble to cobble gravel facies of eskers (Fig. 13) (e.g. Baker, 1982; Brummer et al., 2004) and in modern fluvial sediments (Kong et al., 1999). Fragment distribution should be mapped systematically and sampled to determine indicator mineral chemistry and abundance.

Till is a first-cycle unsorted mixture of crushed rock and mineral fragments, from boulder to clay sized, transported by glaciers, blended with reworked sediments, and plastered onto the bed or released by melting at the base or surface of the ice (Klassen, 2001). Till is sampled to recover kimberlite indicator minerals and for geochemical analysis of its matrix (Fig. 4). Glaciofluvial sediments result from recycling of till by glacial meltwater, e.g. eskers, outwash, or beaches, and are sampled where sufficient sand-sized material is present. These sediments are useful at a regionalreconnaissance scale for detecting the presence of kimberlite (e.g. Golubev, Lee, 1965; 1995: McClenaghan, 2002) and are sampled to recover indicator minerals. Indicator minerals recovered from beach deposits formed from reworked esker deposits assisted in the initial discovery of the Lac de Gras kimberlites (Fipke et al., 1995a; Blusson, 1998). Glacial sediment sampling methods in permafrost and non-permafrost terrains are reviewed in Hirvas and Nenonen (1990), Kauranne et al. (1992), and McMartin and McClenaghan (2001).

Stream sediments, derived from erosion of bedrock and recycling of glacial sediments in modern day streams, are used at a reconnaissance scale to recover kimberlite indicator minerals (Fig. 4) in glaciated terrains having sufficient topographic relief (e.g. Dummett et al., 1987; Morris et al., 1994; Golubev, 1995; Morris et al., 1998; Steenfelt et al., 1999: Canil et al., 2005) or where surface sediments, such as peat or glaciolacustrine sediments, mask the underlying till (e.g. Brown et al., 1967; Wolfe et al., 1975; Kong et al., 1999; Crabtree, 2003; Friske et al., 2003). Because fluvial sediments may have undergone several cycles of transport from their bedrock source, it can be more difficult to trace indicator minerals found in



FIGURE 13. (A) Location of kimberlite boulders recovered from glaciofluvial sediments of the Munro Esker, relative to their source, the A1 kimberlite, which is 5 to 10 km upflow. Black arrows indicate approximate transport path of boulders in the esker (modified from Kjarsgaard et al., 2004); (B) highly weathered kimberlite boulder exposed in matrix-supported, poorly sorted, pebble- to small boulder-sized sediment in the Munro Esker.

them, as compared to indicator minerals in till that typically has a simpler transport history. Stream sediment sampling methods are reviewed by Maurice (1991), Ottensen and Theobald (1994), and Stendal and Theobald (1994).

For indicator mineral surveys, at least 10 to 20 kg (~5 to 10 litres) of sandy till, esker sediments, or stream sediments or 30 to 50 kg of clay-rich till are required to recover a sufficient weight of heavy minerals for visual sampling of indicator minerals (Averill, 1990, 2001; McClenaghan, 2005; Prior et al., 2005). An additional 1 kg (~0.5 litre) sample of till also may be collected for geochemical analysis of the till matrix. Indicator mineral concentrations should always be reported with respect to the weight of material sampled. To compare indicator mineral counts between till or stream sediment sampling programs, survey areas, or kimberlite fields, indicator counts should be standardized to a constant sample weight (Jennings, 1990). For example, McClenaghan et al.

(1999a,b,c, 2004) standardized indicator mineral counts to a 10 kg sample weight in order to compare results from till samples down-ice of kimberlites in the Kirkland Lake and Lake Timiskaming kimberlite fields.

Sampling Strategies

Once a glaciated region is selected for diamond exploration, reconnaissance- to regional-scale surveys are conducted to identify specific areas for more focused exploration, and then follow-up of specific targets. In the following section, a number of examples are cited, however, these are not the only, or necessarily the optimum approach. For example, in Russia field panning of various types of sample media is an integral aspect of the exploration process. If present, fluvial, glaciofluvial (esker), or beach sediments are sampled initially for indicator minerals instead of till (e.g. Fipke et al., 1995b; Mckinlay et al., 1997; Blusson, 1998;



FIGURE 14. Distribution of pyrope in 5 to 8 kg till and glaciofluvial sediment samples collected by the Ontario Geological Survey as part of the KLIP regional geochemical survey (1979-1984) and the location of the subsequently discovered kimberlites (modified from Brummer et al., 1992a). Kimberlite locations are from Zalnieriunas and Sage (1995). Note pyrope abundances are for a ~1 g split of the total <2.0 mm heavy mineral concentrate, not from the entire 0.2 to 0.20 mm heavy mineral fraction.

Crabtree, 2003), because a relatively small number of samples represents the bedrock composition of a large area and sample collection is relatively rapid. Systematic follow-up is then undertaken by sampling till (e.g. Fipke et al., 1995a; Cookenboo et al., 1998). Further follow-up in areas of interest could include sampling till at a higher density and/or airborne geophysical surveys (e.g. Brummer et al., 1992a,b; Jennings, 1995; Mckinlay et al., 1997; J. Carlson et al., 1999; Graham et al., 1999). Follow-up till sampling typically consists of grid sampling along several lines perpendicular to ice-flow direction, located down-ice of indicator mineral or geophysical anomalies (e.g. McClenaghan et al., 2000b, c). In areas with thick till units, thick cover of glaciolacustrine sediments, or organic deposits overlying till (e.g. Kong et al., 1999: Crabtree, 2003), stream sediments are sampled above stream confluences with a sample density dictated by survey area size.

Heavy Mineral Sample Preparation

Heavy mineral concentrates are prepared from large till samples to concentrate kimberlite indicator minerals by removing components such as quartz, feldspar, most ferromagnesian minerals, carbonates, and rock fragments that may mask or dilute the indicator mineral signature (Shilts, 1975). The combinations of processing techniques used by exploration companies or government agencies for recovering indicator minerals are quite variable (e.g. Gregory and White, 1989; Davison, 1993; Towie and Seet, 1995; McClenaghan and Kjarsgaard, 2001). Glacial or stream sediment is disaggregated and the >2 mm fraction is removed for lithological analysis (pebble counts). Because of the large weight (10-50 kg) of <2 mm material to be processed, laboratories first preconcentrate the sample by density, grain size, or magnetic susceptibility before final density separation. Density preconcentration, which may include jig, shaking table, spiral, dense media separator (DMS), or pan, may be combined with the use of heavy liquid separation methods (e.g. using tetrabromoethane), prior to final concentration. The tabling method has the advantages of speed and relatively low cost (Gregory and White, 1989), and provides the opportunity to capture indicators of other commodities such as gold, base metals, and PGEs (McClenaghan, 2005). However, tabling methods are not as efficient as heavy liquid or dense media separator techniques (i.e. they are potentially prone to the loss of indicator minerals), which can be critical in reconnaissance-scale sampling when the recovery of every indicator mineral grain is crucial. Furthermore, modern dense media separator techniques are rapid and efficient, but only for particles >0.3 mm. Screening to recover the medium to very coarse sand-sized fraction, or paramagnetic separation to separate oxides and silicates, may be used instead of density preconcentration if recovery of gold grains is not a priority. Final density concentration is completed using heavy liquids such as methylene iodide (diluted with acetone), or a Magstream® separator using a specific gravity threshold of 3.1 to 3.2 g/cm³ to ensure recovery of Crdiopside, the least dense of the kimberlite indicator minerals (Table 1). The ferromagnetic fraction, composed almost exclusively of magnetite, is then removed using a hand magnet or roll separator, weighed and stored. The final product is a non-ferromagnetic heavy mineral concentrate consisting of grains between 0.25 and 2.0 mm, for picking of kimberlite indicator minerals. The ferromagnetic fraction is sometimes examined for Mg-ilmenite or kimberlite spinel.

Indicator Mineral Chemical Analysis

Visually selected indicator grains are counted and mounted on glass slides or in circular epoxy mounts. Mineral grains can be further screened at this stage by rapid qualitative analysis using an automated routine on a Scanning Electron Microscope (SEM) equipped with an EDS detector. Subsequently, mineral grains may undergo quantitative analysis by EDS on a SEM, or by EDS or WDS methods on an electron microprobe (EM) to determine their major and trace element composition. Mineral grains are then classified as being kimberlite-derived (or not) using the chemical criteria described above. Cr-pyrope, Cr-diopside, and olivine are the easiest minerals to identify visually and therefore the number of grains picked is usually equal to or only slightly more than the number confirmed by quantitative analysis. Mg-ilmenite may be visually similar to ilmenite from crustal rocks, as well as strongly resorbed Cr-spinel that has lost its octahedral form (Fig. 12G), thus, quantitative analysis may be required to confirm their identity (Wyatt et al., 2004). As a result, the number of Mg-ilmenite or chromite grains picked can be much greater than the number confirmed by quantitative analysis. Eclogite pyrope-almandine garnet identification must also be confirmed by quantitative analy-



FIGURE 15. Abundance of pyrope in the 0.25 to 0.5 mm heavy mineral fraction of 10 kg surface till samples collected by the Geological Survey of Canada across the Lac de Gras region, northern Canada. Pyrope grains have been dispersed by three phases of ice flow to the southwest, west, and finally to the northeast. The highest concentrations are overlying and just west of the kimberlites centred on Lac de Gras (modified from Dredge et al., 1997; Kerr, 2000).

sis, as these garnets are similar in appearance to crustalderived orange almandine or almandine-pyrope garnet.

Indicator Mineral Case Histories

The distribution of indicator minerals in till commonly defines broad fan-shaped patterns of dispersal from kimberlite fields that are many times larger than the fields themselves, and hence form large exploration targets. For example, the broad glacial dispersal fan (Fig. 14) that extends 30 km south (down-ice) from the Kirkland Lake kimberlite field (Fortescue et al., 1984; Brummer et al., 1992a,b) is the net result of three phases of ice flow to the southwest, south, and southeast. The glacial dispersal fan for the much larger Lac de Gras kimberlite field extends at least 180 km downice (west) reflecting three phases of ice flow (Dredge et al., 1995, 1997; Ward et al., 1995) across the field. At Lac de Gras, glacial dispersal from the field is best defined by high Cr-pyrope abundances in till (Fig. 15). Till in background areas contains no Cr-pyrope, whereas within the fan, Crpyrope counts vary between 1 and 455 grains. The lack of indicator minerals in till over the southeast part of the kimberlite field may be due to the presence of allochthonous till over this area, and/or thick till deposits that mask the underlying dispersal trains and/or the indicator-poor nature of these kimberlites. Indicator minerals in regional till and glaciofluvial sediment samples over large parts of the Canadian Prairie (Alberta, Saskatchewan, Manitoba) provide insight into the diamond potential of the region. Elevated Cr-pyrope concentrations in till form a broad, 300 km wide plume in western and central Saskatchewan (Fig. 16) derived from the Fort à la Corne and Candle Lake kimberlite fields. In contrast, elevated Cr-pyrope abun-



FIGURE 16. Abundance of Cr-pyrope in the 0.25 to 2.0 mm heavy mineral fraction of 25 kg surface till samples collected by the Geological Survey of Canada across the Canadian Prairie (Garrett and Thorleifson, 1996). The high concentrations of grains around Saskatoon, outlined by a solid black line, are derived from the Fort à la Corne kimberlite cluster and the high concentrations along southern border, outlined by dashed black line, are eroded from local Tertiary gravels.



FIGURE 17. Abundance of Mg-ilmenite in the 0.25 to 2.0 mm heavy mineral fraction of 8 to 13 kg stream sediment samples around the Attawapiskat kimberlite field in northern Ontario (modified from Crabtree, 2003). Red diamonds (1) indicate location of the Kyle Lake kimberlites; red oval (2) indicates location of Jurassic age kimberlite cluster. Yellow arrows indicate the orientation of linear ice flow features (Prest et al., 1968; Crabtree, 2003). The dispersion fan, highlighted in purple, is the net effect of glacial transport from the Jurassic age kimberlite luster to the southwest and subsequent postglacial fluvial transport to the northeast and east.



FIGURE 18. Regional ice-flow patterns and total kimberlite indicator mineral abundance in the 0.25 to 2.0 mm heavy mineral fraction of stream sediments normalized to 15 kg in the Buffalo Head Hills kimberlite field, northern Alberta. Yellow arrows indicate older ice flow directions during glacial maximum and green arrows indicate younger, late glacial ice-flow patterns. Red stars indicate the location of kimberlites (modified from Friske et al., 2003). Ice-flow arrows are modified from Paulen and McClenaghan (in press).

dances in southern Saskatchewan till are likely derived from local Tertiary gravels, which are suggested to contain fluvially derived material from rocks of the Montana Alkaline Province (Simpson, 1993; Kjarsgaard, 1995). In west-central Saskatchewan, a broad Cr-pyrope anomaly exists, but the source of the Cr-pyrope is unknown.

In the clay- and muskeg-covered terrain of the James Bay Lowland, indicator minerals in stream sediments clearly demarcate the presence of the Attawapiskat kimberlite field. At a reconnaissance scale, the signature of the field is best defined by Mg-ilmenite (Fig. 17), Cr-pyrope, and olivine, which are significantly more abundant in the stream sediments than Cr-diopside or spinel (Crabtree, 2003). The relative proportions of indicator minerals in the stream sediments reflect their relative abundance in the source Jurassic kimberlites to the north (Kong et al., 1999). The 300 km long dispersion fan of indicator minerals in stream sediments to the southwest of the field is the product of two modes of transport; glacial transport to the southwest and subsequent fluvial transport to the northeast and east in modern streams. In the thick (20-100 m), clav-rich drift covered terrain of the Buffalo Head Hills kimberlite field (Fig. 2), total counts of all indicator minerals in stream sediments indicate the presence of the kimberlites (Fig. 18). Indicator minerals have been glacially transported southwest and south from the kimberlites and then remobilized in small local streams flowing mainly to the east. The combined dispersal/dispersion of indicator minerals is detectable up to 30 km to the southwest



FIGURE 19. Summary of trends of the kimberlite indicator mineral glacial dispersal trains from individual kimberlites across the Slave Province (modified from Armstrong and Kjarsgaard, 2003). 1. Ranch Lake train (Fig. 20); 2. Potentilla train (Fig. 21); 3. Snap Lake train (Fig. 22).



FIGURE 20. Ribbon-shaped dispersal train trending westward from the Ranch Lake kimberlite, Lac de Gras, as defined by Cr-pyrope concentrations in 20 kg till samples. The train was formed by a single phase of ice flow towards the west (modified from McClenaghan et al., 2002a).

and is dominated by olivine in the north and by a combination of Cr-pyrope, Mg-ilmenite, and chromite in the southwest. In this field, other minerals such as Cr-corundum and zircon may also be useful indicators as they have been reported in the kimberlites as well as in the local stream sediments (Friske et al., 2003; Hood and McCandless, 2004).

In contrast to the large dispersal fans derived from kimberlite fields, glacial dispersal of indicator minerals from individual kimberlites can result in the formation of ribbon- to fan-shaped dispersal trains (Fig. 4). In the Slave Province, numerous narrow ribbonshaped dispersal trains have been identified (Armstrong and Kjarsgaard, 2003). These trains are sharp-edged linear features that often extend for tens of km down-ice and are interpreted to have formed by the last phase of ice flow across the region (e.g. Mckinlay et al., 1997; J. Carlson et al., 1999; Doyle et al., 1999; Graham et al., 1999; Armstrong and Kjarsgaard, 2003; Kirkley et al., 2003), which varies in direction within the Slave Province (Fig. 19). For example, the Ranch Lake train in the central part of the Slave



FIGURE 21. Ribbon-shaped dispersal train (outlined by dashed line) trending northwest from the Potentilla kimberlite in the North Slave kimberlite field of the north Slave Province. The train is defined by total indicator mineral abundance in the 0.4 to 1.25 mm fraction of 25 kg till samples, as well as the presence of kimberlite float and diamonds in till. A second train from an unknown kimberlite source is located to the east. The trains were produced by a single phase of ice flowing northwest (modified from Ashton Mining of Canada, unpublished data).



FIGURE 22. Short, wide dispersal train west of the Snap Lake kimberlite dyke and linear, ribbon-shaped dispersal trains trending west-southwest from the CL25 and CL174 kimberlites. Trains are defined by total indicator mineral counts in 25 to 50 kg till samples (Kirkley et al., 2003).

Province is a 70 km long, west-trending, ribbon-shaped train (Cookenboo, 1996) that is best defined by the abundance of Cr-pyrope (Fig. 20) and Cr-diopside, which are the dominant indicator minerals in the source kimberlite. Till samples within the train contain up to 545 Cr-diopside and 445 Cr-pyrope grains in 20 kg samples, while background samples do not contain any indicator minerals (McClenaghan et al., 2000b,c). In the Kikerk Lake kimberlite cluster, ribbon-shaped dispersal trains trend northwest (e.g. Fig. 21), while in the southeast part of the Slave Province, indicator mineral trains trend southwest and vary from long (>100 km) narrow, linear ribbons derived from kimberlite pipes to wide, short (<10 km) trains (Fig. 22) derived from the kimberlite sheet at Snap Lake (Armstrong and Kjarsgaard, 2003; Kirkley et al., 2003).

Fan-shaped trains are interpreted to have formed as a result of two or more phases of ice flow. A good example of fan-shaped dispersal is the south-southeastward-trending dispersal of indicator minerals from the Bucke and Gravel kimberlites in the Lake Timiskaming field (Fig. 23). The fan-shaped pattern was formed by ice flow to the south followed by flow to the southeast, producing an indicator mineral anomaly that widens with increasing distance down-ice. The fan extends at least 12 km down-ice and is best defined by

Mg-ilmenite and Cr-pyrope, the most abundant indicator minerals in both kimberlites (Kjarsgaard et al., 2003). A second example, although not from Canada, has been documented by Lehtonen et al. (2005). They identified an indicator mineral fan extending down-ice from two kimberlites that was formed by two phases of ice flow to the east-southeast and southeast.

Geochemical Methods

Till Geochemistry

The use of till geochemistry in kimberlite exploration is increasing because of its versatility (regional- and local-scale surveys), initial low cost as compared to indicator mineral methods, and quick turnaround time. A kimberlite geochemical signature is detectable in till containing a minimum of hundreds of indicator minerals in a 10 kg sample (Fig. 24) (e.g. McClenaghan et al., 1996, 1999a, 2002a, 2004). Thus, this method is best used in conjunction with indicator mineral methods to identify kimberlite dispersal patterns (Gravel et al., 2005; Steenfelt et al., 2005) or for pre-screening/prioritizing bulk till samples prior to more costly and time consuming indicator mineral analysis. Because till geochemistry is already a well established method for precious and base metal exploration (McClenaghan et al., 2000a), its use in diamond exploration also allows for evaluation of a broad range of other commodities (e.g. gold and base metals). Till geochemistry also provides baseline environmental geochemical data for establishing prediamond mining soil conditions.

The application of till geochemistry to diamond exploration is based on the unusual major and trace element composition of kimberlites, thus elements such as Mg, Ni, Cr, Nb, Ta, Ti, Ba, K, Rb, Sr, P, and LREE should be the most useful kimberlite pathfinder elements (Atkinson, 1989; McClenaghan and Kjarsgaard, 2001). The presence of olivine in till will be reflected in elevated concentrations of Mg and Ni; high abundances of Cr-spinel, Cr-pyrope, and Cr-diopside will be reflected by high concentrations of Cr. Elevated values for Nb, Ta, and Ti reflect the presence of Mg- ilmenite and groundmass perovskite. Elevated Ba, K, and Rb are due to phlogopite; high levels of P and LREE are caused by apatite (and perovskite for LREE), and elevated Sr could reflect carbonate minerals and apatite. Because a set of pathfinder elements will depend on kimberlite composition as well as that of the surrounding bedrock, the diagnostic elements are region or location specific. For example, Cr, Ni, Ta, Nb, Sr, Ba, Co, Mg, Ca, K, Ti, P, and LREE serve a geochemical



FIGURE 23. Fan-shaped dispersal train of indicator minerals (shaded green) trending south-southwest from the Bucke and Gravel kimberlites in the Lake Timiskaming kimberlite field of northeastern Ontario (unpublished data from De Beers, 2003). The train is defined by visually identified abundance of Mg-ilmenite and garnet in the 0.3 to 2.0 mm fraction of till and glaciofluvial sediments and its shape is the result of two phases of ice flow, southwest followed by southeast (modified from Kjarsgaard et al., 2003).

pathfinder elements in the Lake Timiskaming and Kirkland Lake kimberlite fields (McClenaghan et al., 1999a,b, 2004), whereas in the Lac de Gras area, the incompatible elementrich nature of the granitoid host rocks reduces the list of pathfinder elements to Ni, Cr, Ba, Co, Sr, K, Mg, and Mn (Wilkinson et al., 2001; McClenaghan et al., 2002c). Typically, element concentrations in the kimberlite that are ten times greater than that of the host rocks will produce down-ice geochemical anomalies in the till matrix. Till geochemical analyses should be carried out using a total digestion method, such as LiBO₂ fusion, Na₂O₂ fusion, or fouracid digestion and not with aqua regia in order to digest both oxide and silicate minerals.

Case studies around known kimberlites in the Kirkland Lake and Lake Timiskaming fields indicate that the <0.063 mm fraction (silt + clay) provides a strong contrast between background and anomalous trace element concentrations related to kimberlite (Fig. 24). Anomalous elements in this fraction reflect silt-sized indicator minerals as well as claysized minerals from the fine-grained kimberlite matrix and its weathering products. Analyzing the -80 mesh (<0.177 mm) sand + silt + clay fraction of till is not recommended

because it includes abundant sand-sized quartz and feldspar grains (Saarnisto, 1990), which will dilute and mask the geochemical signature of the kimberlite.

Soil Selective Leaches and Soil Gas

Recently, interest has been growing in the application of selective extraction geochemical techniques capable of detecting the presence of kimberlites buried beneath thick glacial sediments (Hamilton, 1998; Burt and Hamilton, 2004; McClenaghan et al., 2006a). These methods may prove to be useful for prioritizing geophysical targets (i.e. determining which targets are most likely to be kimberlites) prior to drilling in areas of thick (>10 m) glacial sediment cover where till is extremely thick, not accessible (i.e. clay covered), or not present. During kimberlite weathering, elements may be mobilized, transmitted vertically through the overlying glacial sediments, and deposited on mineral grains or organic matter in surface soils (Fig. 4). Suggested transport mechanisms may include some combination of diffusion, electrochemical, gaseous, or groundwater transport (e.g. Hamilton, 1998; Cameron et al., 2004). The mobile ions in the soil are loosely bound and readily extractable by weak, selective chemical digestions, such as ammonium acetate at pH 5 (AA5), Mobile Metal Ion® (MMI-D), or Enzyme Leach® and detectable using ICP-MS techniques. As of yet, only two case studies have been published on the application of this technique to kimberlite exploration in glaciated terrain, thus the suitability of this method to kimberlite exploration has not been fully evaluated.

In contrast to soil profiles in older tropical and arid terrains that have been developing for more than 100,000 years, kimberlitic geochemical signatures in Canada have had less than 10,000 years to potentially migrate upwards through thick glacial sediments to the surface and accumulate in soil. Thus, relative to other terrains, soil geochemical anomalies in glaciated terrain are expected to be weaker (i.e. lower concentrations, fewer elements), and sample collection from a specific depth range below the surface is important. For soil selective leach methods in glaciated terrain, either mineral soils (Ae, B, C horizons), or organic soils (humus, peat), are collected using soil horizon-based or depth-based protocols between 5 to 25 cm from surface. Importantly, only one type of sampling medium is collected, i.e. either mineral soil organic soil. Kimberlite or pathfinder elements will depend on the geochemical contrast between the kimberlite and its host rocks, as well as the thickness and nature of overlying glacial sediments (till, clay, sand, or organics), the groundwater regime, and the specific

transport mechanism involved. Thus, some elements will be enriched in soil overlying kimberlites provided appropriate transport mechanisms were operative. Eccles (1998a) demonstrated that soil selective leaches using Enzyme Leach® were able to detect a geochemical signature in B horizon soil over the Mountain Lake ultrabasic diatreme hosted in Cretaceous sandstone. This case study, however, was conducted using soils developed on thin till enriched in clastically dispersed kimberlite debris. The kimberlite debris may have contributed to the selective leach signature. McClenaghan et al. (2006a) demonstrated that elevated concentrations of Ca. Sr. Na. Ni. Ba. Co. Mg. Mn. Pb. LREE. Ti. Cd, I, and U occur in mineral soils analyzed by ammonium acetate (pH 5) and MMI-D selective leaches over the 95-2 kimberlite in the Lake Timiskaming kimberlite field. This kimberlite, in contrast to the previous case study, is deeply



FIGURE 24. Indicator mineral abundance in the 0.25 to 0.5 mm fraction and concentrations of Ce, MgO, Ni, Ta, and Nb in four size fractions of till up-ice, overlying, and down-ice of the Triple B kimberlite, Lake Timiskaming field (modified from McClenaghan et al., 2004).

buried by up to 60 m of mostly glaciofluvial sediments (Fig. 25), which contain no kimberlite debris from the 95-2 kimberlite. For many of the elements in soil over the 95-2 kimberlite, the response is skewed to the south part of the kimberlite and its southern margin. The skewed responses may reflect the presence of zones of enhanced groundwater flow (common at some kimberlite margins) or kimberlite-rich till overlying bedrock on the down-ice (south) margin of the kimberlite.

Gases in soil, which have migrated upwards from deeply buried kimberlites and/or been released in soils near surface through bacterial activity, may also indicate the presence of underlying kimberlite (Fig. 4). Primarily hydrocarbons, but also sulphur, halogens, and some other miscellaneous compounds are detected in soils using one of two laboratory methods, soil desorption pyrolysis (SDP®, Thiede et al.,



FIGURE 25. Element distribution patterns in Ae + B horizon soil developed on thick glaciofluvial sand overlying the 95-2 kimberlite, Lake Timiskaming field, determined by two selective leaches, ammonium acetate (pH 5) (AA5) and MMI-D®: A) elements enriched; and B) elements depleted in soils overlying the kimberlite. Soil sample locations and cross-section showing the glacial sediment thickness over the 95-2 kimberlite are also shown (modified from McClenaghan et al., 2006a).

2005) or soil gas hydrocarbons (SGH®). For example, a kimberlite in the Lac de Gras field was distinguished from a geophysically similar granitic intrusion by its elevated counts and sum of CFCs, sulphur gases, and inorganic compounds using the SDP® soil gas method (Fig. 26).

Biogeochemistry

Similar to soil geochemical methods, biogeochemical methods are a local-scale exploration tool that may aid in prioritizing geophysical targets prior to drilling in areas of thick (>10 m) glacial sediment cover (Fig. 4). The few sitespecific studies that have been conducted over some Siberian kimberlites in the glaciated terrain of northern Russia indicate the potential of biogeochemistry for kimberlite exploration (e.g. Kobets and Komarov, 1958; Litinskiy, 1964; Buks, 1965; Komogorova et al., 1986). More recently, biogeochemical studies over kimberlites in Canada (Dunn, 1993: McClenaghan and Dunn, 1995; Dunn and McClenaghan, 1996; Eccles, 1998b) support the Russian observations of anomalous geochemical (Ni, Rb, Sr, Cr, Co, Nb, Mg, P, and LREE) signatures in vegetation growing on glacial sediments over kimberlite. In general, biogeochemistry is probably not a cost-effective exploration tool.

Hydrogeochemistry

Groundwater interaction with kimberlite may produce aqueous geochemical anomalies (Fig. 4) typical of low-temperature serpentinization reactions, which are characterized by high pH (up to 12), very low concentrations of Mg, and very high concentrations of K (e.g. Sader et al., 2003, 2007). The trace element signatures of these waters will depend on the

geochemical contrast between the kimberlite and its host rock. The identification of geochemical anomalies in groundwater and the unusual minerals that may precipitate from these groundwaters may be a potential exploration tool for the discovery of new kimberlites. Groundwater sampled from streams as part of regional stream sediment surveys or from seeps and springs as part of regional hydrogeochemical surveys will be the most useful media. In addition to the exploration benefits, groundwater geochemical data provide



Figure 26. (A) Airborne EM response and the location of soil gas sample sites (north and south lines) across the Kodiak kimberlite, Lac de Gras field; and (B) SDP® soil gas count and sum values for a combination of CFCs, sulphur gases, and inorganic compounds in the soil samples collected along the two sample lines (BHP Billiton unpublished data, 2003).

environmental baseline data on natural groundwater conditions prior to mining, as well as insights into the potential for alkaline mine drainage.

Summary and Conclusions

Kimberlite is a mineralogically and chemically distinct point source. In Canada, glacial dispersal of indicator minerals from kimberlite sources formed dispersal fan- and ribbon-shaped trains in till during the last glaciation. Subsequently, the indicator minerals were redistributed in streams producing dispersion anomalies. A kimberlite's variable size (50-1500 m) and competence influences the size and extent of the dispersal/dispersion patterns, and whether they can be detected using kimberlite fragments, indicator minerals, or trace element geochemistry. Understanding ice flow history, unravelling the genetic history of different glacial (till, glaciofluvial) and post-glacial (fluvial, beach) sediments sampled, and identifying multiple till sheets in thick drift areas, such as the Prairies, northeastern Ontario, and the southern Slave, are essential to successful sampling, interpretation, and follow-up of anomalies. The ability to detect kimberlitic geochemical signatures in till, soils, vegetation, or groundwater will depend on the size of the kimberlite body and the geochemical contrast between it and its host rock, and the extent to which the geochemical signature has been diluted by non-kimberlitic material.

In glaciated terrain, kimberlites have been subjected primarily to mechanical erosion with the debris transported away from the source by glaciers and/or streams. The resultant dispersal/dispersion of indicator minerals resulted in trains and fans that are much larger exploration targets than the kimberlites themselves. Thus, indicator mineral methods using till or stream sediments (Fig. 4) combined with geophysical methods are best suited to kimberlite exploration in glaciated terrain. Indicator mineral dispersal trains may be the result of one or more phases of ice flow, can vary from a few tens of metres to in excess of 100 kilometres in length, and are variable in width. Dispersal is typically mapped using the abundance of indicator minerals in the 0.25 to 0.5 mm fraction of till or stream sediments, although in some cases the finer (0.15-0.25 mm) fraction may be useful. The total concentration of indicator minerals varies from single grains to tens of thousands of grains and will depend on a number of factors, including the initial content in the kimberlite source and the amount of dilution. However, not all kimberlites will have indicator mineral dispersal trains. Dispersal trains or fans may not be evident or detected where kimberlite debris was glacially transported down-ice beyond the range of sampling. Alternatively, the kimberlite may not have been subjected to glacial erosion (e.g. the kimberlite is buried by thick till sheets or other glacial sediments, or by younger sedimentary or volcanic cover sequences), or more rarely the kimberlite may not contain a sufficient volume of indicator minerals to produce a detectable train. Some dispersal trains may have gaps or be missing the head or some part of the tail. Not all kimberlites display an obvious geophysical expression, thus some indicator mineral trains may appear to have no source (e.g. Fig. 21). Where kimberlites occur close together, their trains may coalesce or overlap (e.g. Fig. 23). In this circumstance, indicator mineral chemistry and relative abundance of each indicator species will be helpful in identifying and distinguishing between multiple dispersal trains.

Local-scale orientation studies around known kimberlites can provide crucial information on the geochemical, mineralogical, and lithological signatures of till and fluvial sediments, on appropriate sampling methods, the size fractions to examine or analyze, and on local glacial stratigraphy and ice-flow patterns (Jennings, 1990). As a significant proportion of an exploration budget is spent on the initial sample collection, especially in remote areas, it is cost effective to explore for other commodities, not just diamonds. This cost effectiveness can be accommodated if indicator minerals of other commodities such as precious or base metals also are recovered from the same heavy mineral concentrates that are prepared for kimberlite indicator mineral picking (Averill, 2001; McClenaghan, 2005). The use of till geochemistry in combination with indicator mineral methods will further increase the cost effectiveness by expanding exploration to a broad range of commodities and providing baseline environmental data.

Where potential kimberlites have been identified by geophysical methods, soil selective leaches and soil gas, still in the testing phase, may be helpful at a local scale for prioritizing targets for drilling (Fig. 4). Hydrogeochemistry, when included as part of a regional stream survey, may provide additional insights into the presence of kimberlites nearby (Fig. 4). Soil, vegetation, and groundwater geochemical techniques may also provide baseline environmental data, which document natural conditions prior to mining. Many more case studies need to be published that document the application of these new geochemical methods and their limitations with respect to kimberlite exploration in glaciated terrain.

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