Indicator mineral methods in mineral exploration

M. Beth McClenaghan
Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8, Canada (e-mail: bmcclena@NRCan.gc.ca)

ABSTRACT: Indicator minerals are mineral species that, when appearing as transported grains in clastic sediments, indicate the presence in bedrock of a specific type of mineralization, hydrothermal alteration or lithology. Their physical and chemical characteristics, including a relatively high density, facilitate their preservation and identification and allow them to be readily recovered at the parts per billion level from sample media such as till, stream sediments or soil producing large exploration targets. Another major advantage of indicator mineral methods is that grain morphology, surface textures or mineral chemistry may be examined to obtain information about transport distance and bedrock source. Indicator minerals have become an important exploration method in the past 20 years and now include suites for detecting a variety of ore deposit types including diamond, gold, Ni–Cu, PGE, porphyry Cu, massive sulphide, and tungsten deposits. One of the most significant events in the application of indicator mineral methods in the past 10 years was the explosion in diamond exploration activity in the glaciated terrain of Canada and the resultant changes in sampling and processing methods and improved understanding of kimberlite indicator minerals. At the same time, technological advances have led to increased sophistication of determining indicator mineral chemistry for all indicator minerals. This paper provides an overview of indicator mineral methods and their application in a variety of terrains in the past 20 years, focusing on gold and diamond exploration.

KEYWORDS: *indicator minerals, drift prospecting, gold grains, kimberlite indicator minerals, stream sediments*

INTRODUCTION

Indicator minerals are mineral species that indicate the presence of a specific mineral deposit, alteration or rock lithology. Ideal indicator minerals are found in few if any rocks other than the host deposit or lithology. Their physical and chemical characteristics allow them to be readily recovered from exploration sample media (e.g. stream, alluvial, glacial or aeolian sediments or soils) and make them sufficiently abundant. The characteristics include: visual distinctiveness, moderate to high density, silt or sand size, and ability to survive weathering and/or clastic transport. Most often, only indicator mineral abundance in a sample is reported; however, grain morphology, surface textures or mineral chemistry also may be determined. Indicator mineral methods differ from traditional geochemical methods for soil, stream sediment or till sampling in that the indicator grains reflect mechanical dispersion/dispersal and the individual grains are visually examined and counted. The greatest advantage of indicator mineral methods over traditional geochemical analysis of the heavy mineral, or some other fraction, is that the mineral grains are visible and can be examined. The resulting benefits of using indicator minerals are: (1) the ability to detect haloes or plumes much larger than the mineralized target including associated alteration; (2) physical evidence of the presence of mineralization or alteration; (3) the ability to provide information about the source that traditional geochemical methods cannot, including nature of the ore, alteration, and proximity to source; (4) sensitivity to detect only a few grains, equivalent of ppb-level indicator mineral abundances, even in regions where regional rocks dilute concentrates with non-indicator heavy minerals; and (5) the ability to visually identify and remove anthropogenic contamination (Brundin & Bergstrom 1977; Averill 2001).

Indicator mineral methods have been used for thousands of years, most notably to search for deposits of gold, copper and precious stones (Ottensen & Theobald 1994). Today, the methods can be used to explore for a broad range of commodities, rock types and geological terranes, some of which are summarized by Friedrich *et al.* (1992); Stendal & Theobald (1994). For example, scheelite and wolframite can be indicative of tungsten deposits (e.g. Lindmark 1977; Stendal 1982; Toverud 1984; Johansson *et al.* 1986), cinnabar is an indicator of mercury (Plouffe 2001) or gold mineralization (Stendal & Theobald 1994), and cassiterite has been used to trace tin deposits (e.g. Zantop & Nespereira 1979; Ryan *et al.* 1988). Fluorite may be an indicator of tungsten mineralization, skarn-type mineralization, Mississippi Valley type Pb–Zn deposits or of greisens, and topaz can be used to trace greisens, molybdenum or tin deposits (Stendal & Theobald 1994; Friske *et al.* 2001). Cr-spinel and Cr-garnet can be indicators of Cu–Ni deposits (e.g. Aumo & Salonen 1986; Peltonen et al.1992; Karimzadeh Somarin 2004) as well as kimberlite (e.g. Gurney 1984; Fipke *et al.* 1995), and Zn-spinel can be an indicator of polymetallic deposits in high-grade metamorphic terranes (e.g.

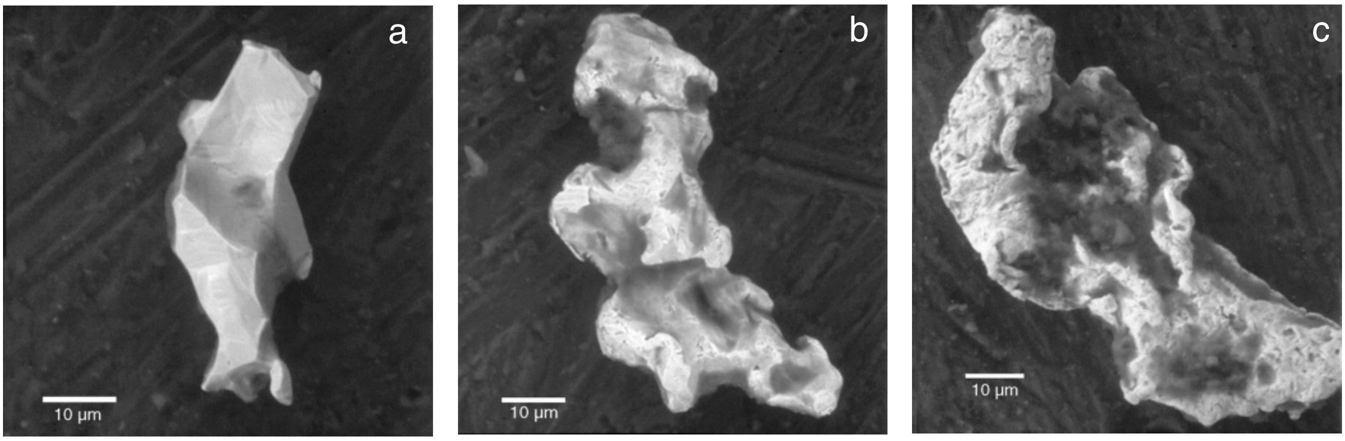

Fig. 1. Secondary electron images of gold grains from till showing the three conditions routinely documented for gold grains: (a) *pristine* gold grain with equant molds suggestive of former quartz–feldspar–carbonate–sulphide gangue; (b) *modified* gold grain with vestiges of equant gangue molds and edges that are slightly curled; and (c) *reshaped* gold grain showing pitted surfaces and well curled edges (from McClenaghan 2001).

Allard & Carpenter 1988; Morris *et al.* 1997). The focus of this paper is the application of indicator mineral methods to gold and diamond exploration as these indicator mineral methods are well established, widely used in different terrains, and have seen significant increases in their application in the last 20 years.

SAMPLING METHODS

Indicator mineral abundance in sediments will depend on the primary indicator mineral content of the source rock, degree of post-emplacement/post-formation weathering of the indicator mineral source, and dispersion/dispersal transport mechanisms (i.e. fluvial, glacial or aeolian). All of these factors must be considered when planning sampling strategies (i.e. sample medium, size and spacing).

Sampling media

The choice of sample media will depend on the climate, topography and size of area to be sampled. Typically, at least 10 to 20 kg (*c.* 5 to 10 litres) of sediment are collected for heavy mineral surveys. In glaciated terrain, till is most often used for indicator mineral surveys due to its simple transport history and widespread distribution, although glaciofluvial sediments may be sampled to obtain a preliminary regional overview. Stream sediments are commonly sampled in glaciated, tropical and arid terrains. As material is transported downstream, the heavy minerals are concentrated into what Fletcher & Loh (1996) refer to as 'mini placers', which increases the anomaly contrast and extends the length of the heavy mineral dispersion train downstream, thereby making the target larger and allowing for lower sampling densities to be used during reconnaissance surveys. In arid regions, stream sediments occur mainly as sheetwash deposits in broad alluvial fans and plains rather than in organized drainage channels, and these deposits are the optimal sample medium. Aeolian sediments may also be sampled in arid terrain where stream sediments are not available. Lateritic soils may be sampled in tropical and subtropical terrains.

Sampling methods

Sampling procedures used in glaciated terrain have been summarized by Hirvas & Nenonen (1990); Kauranne *et al.* (1992); McMartin & McClenaghan (2001). In areas of thin glacial cover, till can be collected from hand-dug holes, backhoe-excavated trenches, sections along river or lake shorelines or road cuts. Where cover thickness exceeds 5 m, overburden drilling is required to access till below the surface. Stream sediment sampling procedures for heavy minerals have been reviewed by Ottensen & Theobald (1994); Stendal & Theobald (1994). Stream sediments include sediments in active streams, in alluvial deposits on the floodplains adjacent to active channels and sheetwash deposits in broad alluvial fans and plains (Ottensen & Theobald 1994). First- or second-order streams are sampled immediately upstream of their confluences. Butt & Zeegers (1992) describe sampling procedures for lateritic soils (Fe- and Al-rich), which form in tropical and subtropical climates.

Sample spacing will depend on the type and size of the mineral deposit or district sought, the access and availability of samples sites, and cost of collecting the samples. Regional indicator mineral surveys, designed to determine background trends and sediment provenance, use a sample spacing of 1 to 50 km to obtain an overview of an area depending on the nature of mineral transport. In glaciated terrain, elongate dispersal trains are most likely to be intersected by a series of sample transects perpendicular to ice flow, with till sample spacing along lines (10 m to 1 km) much closer than spacing between lines (100 m to 100 km).

LABORATORY METHODS

Sample preparation

Indicator mineral samples are disaggregated, typically by agitation in a dispersant, and the gravel fraction (>2 mm) is removed for lithological analysis (pebble counts). Prior to disaggregation, a 500 g (*c.* 0.25 litre) subsample may be set aside for geochemical analysis and archiving. The <2 mm fraction is then preconcentrated using density methods (e.g. jig, shaking table, spiral, dense media separator or pan). Density preconcentration may be combined with the use of a heavy liquid such as tetrabromoethane (SG = 2.9 g/cm^3), prior to final concentration. Final density concentration is completed using heavy liquids such as methylene iodide (SG = 3.3 g/cm^3). The ferromagnetic fraction is removed using a hand magnet or roll separator, then weighed and archived. The non-ferromagnetic heavy mineral concentrate is then examined for indicator minerals and sometimes analysed geochemically.

Indicator minerals are picked from samples during a visual scan, in most cases of the 0.25–0.5 mm and 0.5–2.0 mm fractions, and then analysed using an electron microprobe

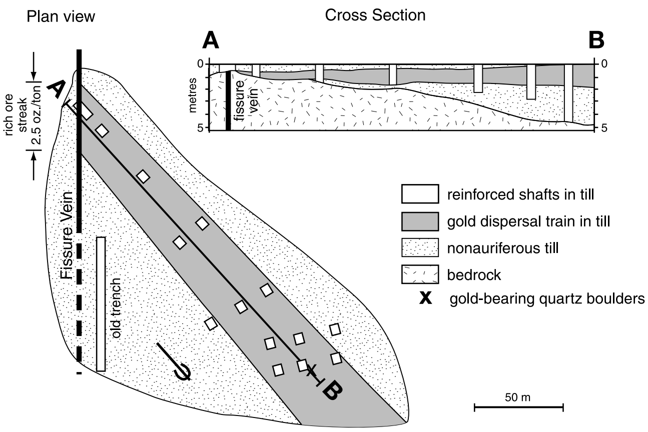

Fig. 2. Location of till samples collected by Prest in 1896 to trace the source of gold-bearing quartz boulders (indicated by x) and define a ribbon-shaped gold grain dispersal train in Nova Scotia, Canada (modified from Stea & Finck 2001).

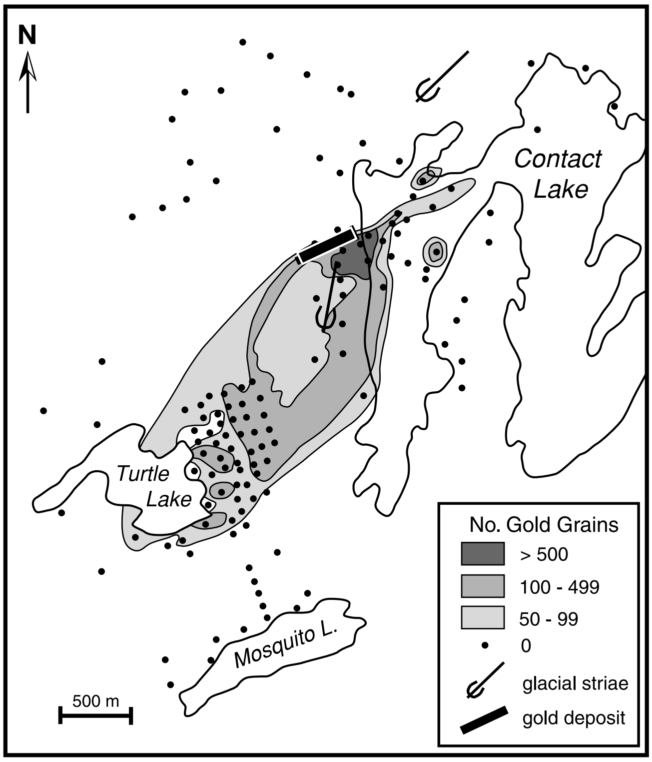

Fig. 3. Abundance of gold grains in 6-kg till samples around the Bakos gold deposit in northern Saskatchewan, Canada (modified from Chapman *et al.* 1990) showing a well developed dispersal train extending 2.75 km SW of the deposit.

to confirm their identification. Scheelite and zircon in the concentrate may be counted under short-wave ultraviolet light. Depending on the mineralogical composition of regional rocks and derived sediments, paramagnetic sorting may be required, especially for the 0.25–0.50 mm fraction, in order to reduce the volume of concentrate to be scanned. Gold and PGE minerals may be panned, counted, and classified with the aid of optical or scanning electron microscopy after density pre-concentration, or concentrates may be examined after non-destructive geochemical analysis using the Au or PGE results as a guide.

Indicator mineral analysis

Indicator minerals are visually recovered from heavy mineral concentrates and examined using a binocular microscope to obtain information that will aid in determining transport distances and nature of the bedrock source (e.g. Perttunen & Vartiainen 1992; Peuraniemi 1990; Peltonen *et al.* 1992). Analysis by electron microprobe, scanning electron microprobe (SEM), laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) or secondary ion mass spectrometry (SIMS) may then be carried out to determine major, minor and trace element contents of specific indicator minerals, as often mineral chemistry is used to confirm the identity and establish mineral paragenesis (e.g. Fipke *et al.* 1989; 1995; Ramsden *et al.* 1999; Belousova *et al.* 2002; Scott 2003; Lawrie & Mernaugh 2003).

GOLD GRAINS

Gold grains are the best indicator mineral for detecting the presence of gold deposits, although other heavy minerals such as pyrite, arsenopyrite and jamesonite (e.g. Boyle & Gleeson 1972; Gleeson & Boyle 1980) may also be useful in specific locations. Background abundance will depend on the terrain and sample media, but typically exceeds a few grains. Till and stream sediments are the most effective media for using gold grain methods, which include documenting gold grain

Table 1. *Selected examples of the use of indicator minerals for gold exploration in various terrain types.*

Indicator mineral	Sample medium	Location	Terrain	Reference
Gold	Stream sediments	Antena District, Chile	Temperate (tropical in Miocene)	Townley *et al.* (2003)
Gold	Till	Abitibi region, Canada	Glaciated	McClenaghan (2001, 1994, 1992)
Gold	Stream sediments	Leadhills area, Scotland	Glaciated	Leake *et al.* (1998)
Gold	Till	Abitibi region, Canada	Glaciated	Bajc (1996)
Gold	Stream sediments	Yukon, Canada	Glaciated	Knight *et al.* (1994)
Gold	Aeolian sediments	Xinjiang-Uygur, China	Semi-arid to arid	Smith *et al.* (1993)
Gold	Till	Ilomantsi, Finland	Glaciated	Huhta (1993)
Gold	Till, glaciofluvial sediments	Ilomantsi, Finland	Glaciated	Nikkarinen (1991)
Gold	Glaciofluvial sediments	Ivalojoki area, Finland	Glaciated	Saarnisto *et al.* (1991)
Gold	Till	N Saskatchewan, Canada	Glaciated	Chapman *et al.* (1990)
Gold	Till, glaciofluvial sediments	Ancocala-Ananea Basin, Peru	Glaciated	Hérail *et al.* (1989)
Gold	Till	Abitibi region, Canada	Glaciated	Averill (1988)
Gold, native copper, galena, pyromorphite	Till	N Saskatchewan, Canada	Glaciated	Averill & Zimmerman (1986)
Gold	Stream sediments	S British Columbia, Canada	Glaciated	Knight & McTaggart (1986)

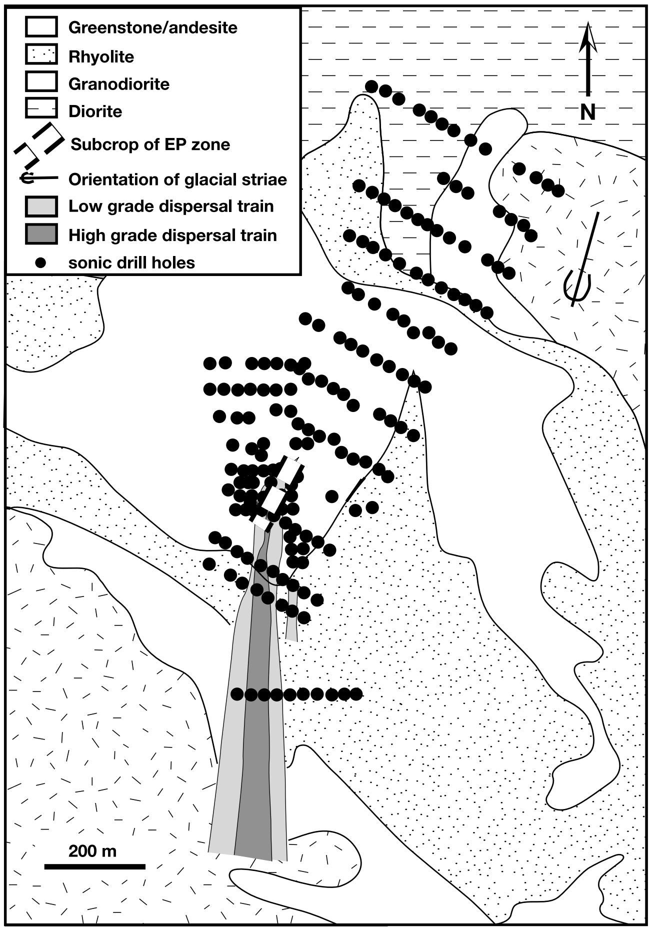

Fig. 4. Location of overburden drill holes used to collect till samples and the ribbon-shaped dispersal train defined by gold grains in till around the E-P Zone gold deposit in northern Saskatchewan, Canada (modified from Averill & Zimmerman 1986).

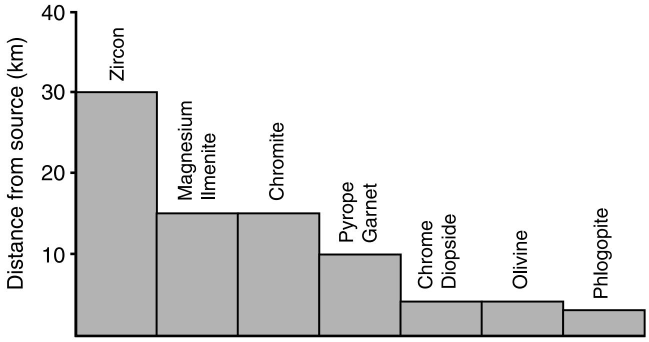

Fig. 5. Relative abundance of indicator minerals at varying distance from source in unglaciated Australian terrains (modified from Atkinson 1989).

abundance, size, shape and fineness (e.g. Grant *et al.* 1991). The optimal size range of grains that are recovered from these sample media is 0.01 to 2.0 mm. In glaciated terrain, till is a much more effective sampling medium than stream sediments because 90% of gold grains are silt-sized (<0.063 mm) and such fine grains are expelled rather than concentrated during stream sedimentation (Averill 2001). Although gold grains have been panned from stream sediments since Roman times, the systematic use of the combination of gold grain abundance, size, shape, flatness and fineness has only been used for the past 20 years. Much of what has been published on the use of gold grain characteristics in gold exploration relates to: (1) till sampling in glaciated terrain (e.g. Sopuck *et al.* 1986; Pronk & Burton 1988; Grant *et al.* 1991; Sibbick & Fletcher 1993; McClenaghan 2001); (2) exploration for, and sampling of, placer deposits (e.g. Giusti 1986; Minter *et al.* 1993; Knight *et al.* 1994; Youngson 1998); and (3) exploration in lateritic terrain (e.g. Grant *et al.* 1991; Porto & Hale 1996; Gedeon & Butt 1998; Freyssinet & Butt 1998).

Gold grain condition

The degree of rounding, polishing, bending and flatness of the gold grains may provide information about transport distance and mechanism (e.g. glacial, fluvial, alluvial) or provide insights into the style of gold mineralization (e.g. Averill 1988; Hérail *et al.* 1989; Nikkarinen 1991; Smith *et al.* 1993; Seeley & Senden 1994; Kinnunen 1996; Youngson 1998; Townley *et al.* 2003). The graphically descriptive classification scheme (pristine–modified–reshaped) of DiLabio (1990) for describing conditions and surface textures of gold grains recovered from glacial sediments builds on Averill's (1988) descriptions of gold grain shape related to transport distance. Although Averill and DiLabio's schemes were initially designed for gold grains recovered from till, they can also be applied to stream sediments in glaciated and other terrains. Their scheme is described in detail here as it is widely used and reported in some of the case studies presented below. The progression from pristine to reshaped grains represents increasing distance of transport. However, caution should be used when utilizing gold grain condition as an indication of transport distance because gold grain morphology can be quite variable in the bedrock source, and gold grains can be released from mineralized bedrock fragments at any distance during transport or during subsequent post-depositional weathering (Coker & Shilts 1991; Henderson & Roy 1995).

Pristine gold grains (Fig. 1a) retain primary shapes and surface textures and appear not to have been damaged in transport. They occur as angular wires, rods and delicate leaves that once infilled fractures, as crystals with grain moulds, and as inclusions in sulphides. The transport history of pristine grains may be interpreted in two ways: (1) gold grains were eroded from a bedrock source nearby and transported to the site with little or no surface modification; transport distance is generally short; and (2) gold grains were liberated from rock fragments during *in situ* weathering of transported sulphide grains containing gold; the pristine shape and surface texture provide little information on transport distance, but do provide important information on style of gold mineralization, i.e. sulphide-hosted gold mineralization (Henderson & Roy 1995).

Modified gold grains (Fig. 1b) retain some primary surface textures but all edges and protrusions have been damaged during transport and they are commonly striated. Irregular edges and protrusions are crumpled, folded and curled. Grain moulds and primary surface textures are preserved only on protected faces of grains. Samples that contain elevated concentrations of modified grains are generally proximal to the bedrock source.

Reshaped gold grains (Fig. 1c) have undergone sufficient transport that all primary surface textures have been destroyed and the original grain shape is no longer discernible. Reshaped grains are flattened to rounded resulting from repeated folding of leaves, wires and rods. Grain surfaces may be pitted from impact marks from other grains. Surfaces are not leached of silver in glaciated terrain. Although these grains can have a complex transport history, the presence of large numbers of reshaped grains in discrete areas may be significant. Most

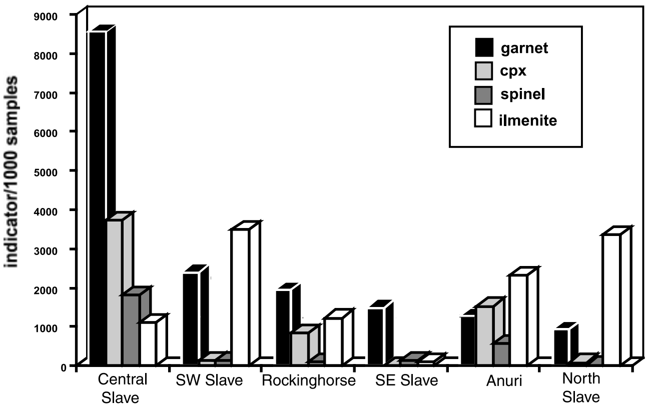

Fig. 6. Comparison of the relative abundance of kimberlite indicator minerals in till for six kimberlite fields in the Slave geological province, northern Canada (from Armstrong 2003).

background gold grains have a reshaped morphology (Averill 1988).

Case studies

In glaciated terrain, the presence of significant numbers of gold grains in till has led to much exploration (e.g. Hérail *et al.* 1989; Nikkarinen 1991; Saarnisto *et al.* 1991; Huhta 1988; 1993; McClenaghan 1992; 1994) and, in many cases, discovery of gold deposits (e.g. Sauerbrei *et al.* 1987; Thomson *et al.* 1987). One of the earliest published examples of utilizing gold grains to detect glacial dispersal trains, and ultimately mineralized bedrock, is from Nova Scotia, Canada. In 1896, W.H. Prest located the bedrock source of gold-bearing quartz boulders by panning gold grains from till samples collected from 5-m-deep pits (Stea & Finck 2001). Pits dug to follow the trend of gold-rich till eventually led to the discovery of a north-trending gold vein 200 m up-ice (NW) of the quartz boulders (Fig. 2). Several more recent examples of the application of gold grain methods to exploration are listed in Table 1.

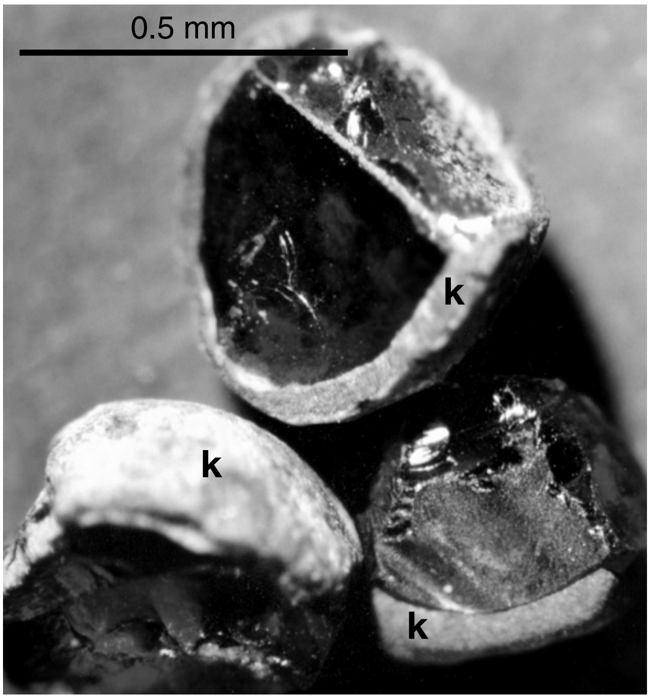

Fig. 7. Cr-pyrope grains from kimberlite with thick kelyphite rims, indicated by the letter **k**.

In northern Saskatchewan, Canada, till sampling to recover gold grains was used to explore the area around a lake sediment gold anomaly, and led to discovery of the Bakos gold deposit. Gold grains in till defined a well developed dispersal train, 2 km long by 0.5 km wide, SW (down-ice) of the deposit (Chapman *et al.* 1990). Gold grain content in 6-kg till samples varied from

Table 2. *Selected examples of the use of indicator minerals for kimberlite exploration in various terrain types.*

Indicator mineral	Sample medium	Location	Terrain	Reference
Kimberlite indicator minerals	Kimberlite boulders	Kirkland Lake, Canada	Glaciated	Kjarsgaard *et al.* (2004)
Kimberlite indicator minerals	Stream sediments	James Bay Lowland, Canada	Glaciated	Crabtree (2003)
Kimberlite indicator minerals	Till	Kirkland Lake and Lake Timiskaming, Canada	Glaciated	McClenaghan *et al.* (2003; 2002a,b; 1999a–c; 1998, 1996); McClenaghan & Kjarsgaard 2003
Kimberlite indicator minerals	Stream sediments, till	Buffalo Head Hills, Canada	Glaciated	Friske *et al.* (2003)
Kimberlite indicator minerals	Aeolian sand	southern Africa	Desert	Van Coller *et al.* (2003); Williams *et al.* (2003)
Cr-spinel	Till	Lapland, Finland	Glaciated	Lehtonen & Marmo (2002)
Kimberlite indicator minerals	Till	Lac de Gras, Canada	Glaciated	Dredge *et al.* (1995; 1996b; 1997); Kerr *et al.* (1995; 1996; 1999; 2000); Ward *et al.* (1995, 1997)
Kimberlite indicator minerals	Stream sediments	James Bay Lowland, Canada	Glaciated	Kong *et al.* (1999)
Kimberlite indicator minerals	Stream sediments	Wawa, Canada	Glaciated	Morris *et al.* (1998)
Kimberlite indicator minerals	Stream sediments	southeast Russia	Glaciated	Romashkin (1997)
Kimberlite indicator minerals	Till, glaciofluvial sediments	Lac de Gras, Canada	Glaciated	Mckinlay *et al.* (1997)
Cr-spinel, diamonds	Stream sediments	Kimberley, Australia	Arid	Sumpton & Smith (1997)
Kimberlite indicator minerals	Till, glaciofluvial sediments	Arkhangelsk, Russia	Glaciated	Golubev (1995)
Kimberlite indicator minerals	Till	Prairie region, Canada	Glaciated	Thorleifson *et al.* (1994)
Kimberlite indicator minerals	Till, glaciofluvial sediments	Kirkland Lake, Canada	Glaciated	Brummer *et al.* (1992)
Cr-spinel, diamonds	Stream sediments	Kimberley, Australia	Arid	Towie *et al.* (1991)
Kimberlite indicator minerals	Stream sediments	Wajrakarur, India	Tropical	Guptasarma *et al.* (1989)
Ilmenite, garnet	Stream sediments	Goiás region, Brazil	Tropical	Tompkins (1987)
Pyrope, magnetic minerals	Till	Michigan, USA	Glaciated	Stewart (1988)
Kimberlite indicator minerals	Stream sediments	Colorado, USA	Arid	Carlson & Marsh (1986)
Kimberlite indicator minerals	Aeolian sand	Botswana	Desert	Lock (1985)

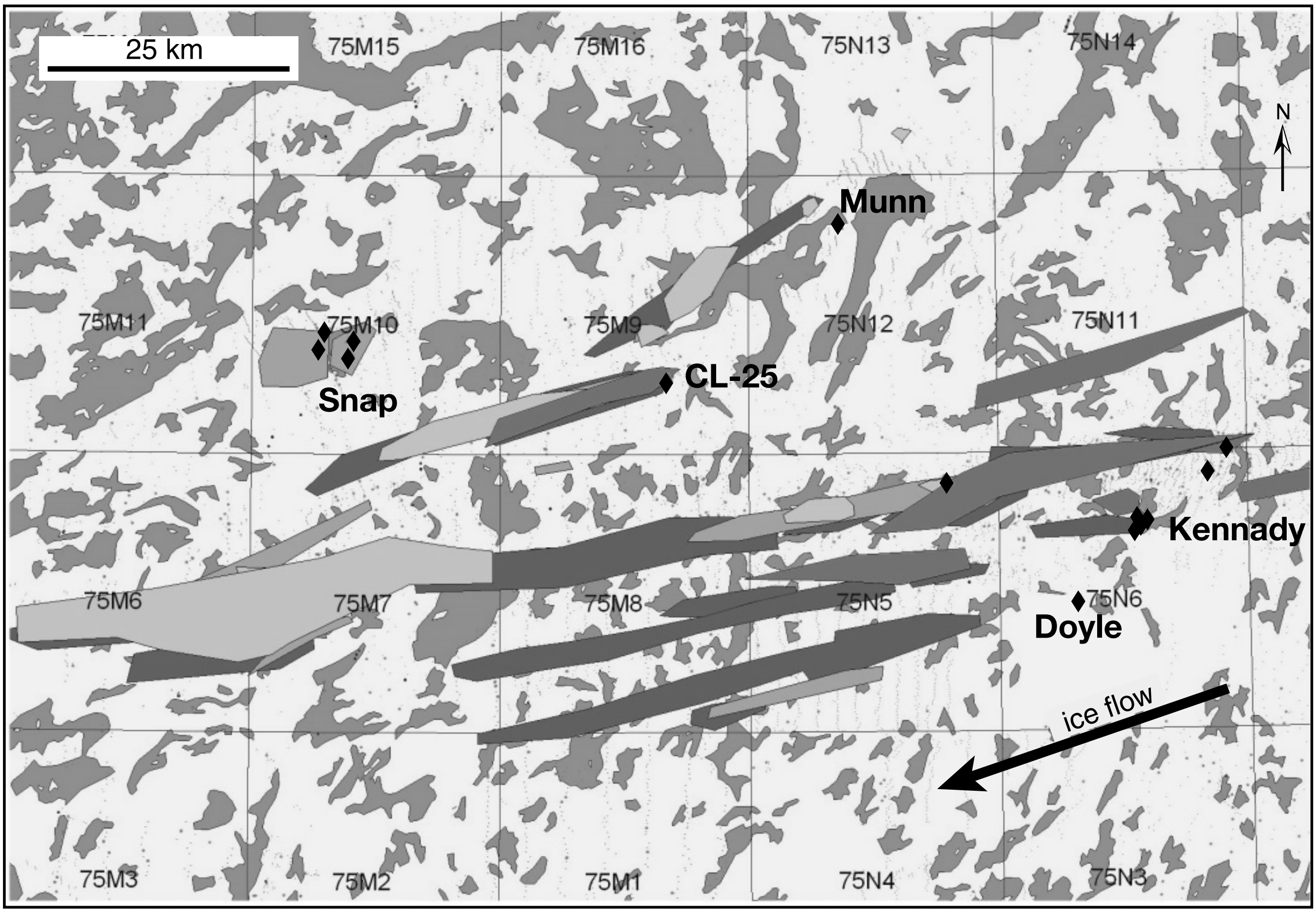

Fig. 8. Indicator mineral dispersal trains trending SW from kimberlites in the SE part of the Slave Province of northern Canada (from Armstrong, unpublished data). Black diamonds indicate the location of kimberlite pipes. Grey shades indicate the distribution of specific kimberlite indicator minerals: dark greys: Cr-pyrope, Cr-diopside; light greys: Mg-ilmenite, chromite.

background concentrations of zero grains to the highest value of 2751 grains (Fig. 3). At Waddy Lake, Saskatchewan, gold grains in combination with native copper, galena and chalcocite and pyromorphite grains in unweathered till were used to detect glacial dispersal trains and ultimately discover the E-P Zone. Gold grain abundance, as well as shape, were key factors in understanding the dispersal patterns and relative glacial transport distance, which was at least 600 m (Fig. 4). Anomalous till down-ice contained up to 10 000 gold grains in an 8 kg sample, with similar concentrations of native copper, galena and chalcocite, plus traces of pyromorphite (Averill & Zimmerman 1986).

Smith *et al.* (1993) examined gold grains in surface soils in the semi-arid to arid Hatu mining district of China, where the shape, trend and distribution of soil gold anomalies, with respect to known lode deposits, suggested they may have formed by aeolian dispersion. The most prominent soil anomaly was 30 km long and 5 km wide. Soil samples weighing 6 and 18 kg were sieved and panned to recover gold grains, which varied in abundance from zero to 378 grains, depending on distance from source. Using gold grain abundance, morphology, size and compositional features combined with the grains' areal distribution, Smith *et al.* (1993) concluded that the major component of the gold grains in the soil anomalies were not of aeolian origin, but were probably of fluvial origin.

The Wayamaga area, French Guiana, has a significant known upstream bedrock lode source defined, whereas the Cokioco area, after >US$1million of exploration expenditure, has no known lode source (Kelley *et al.* 2003). Gold grains were extracted from 10-litre stream sediment samples by panning, tabling and then micropanning and were classified according to size and degree of physical wear. In contrast, gold grains at Cokioco display: complete reshaping of all grains, coarser average grain size (125–200 μm), total leaching of any alloyed silver in cores and rims of grains, absence of unstable mineral inclusions, and possible presence of supergene gold in aluminosilicate inclusions. These characteristics suggest effective placer gold concentration but a lack of input from a proximal or preserved lode gold source. Gold grains may have travelled very far or the sources may have been totally eroded. In contrast, features of the gold grain population at Wayamaga suggest gold is being actively shed from a proximal lode source, and include: incomplete reshaping of some grains, finer average grain (50–125 μm), incomplete leaching of silver with average inner fineness of 953, and presence of unstable mineral inclusions.

KIMBERLITE INDICATOR MINERALS

The unique mineralogical signatures of kimberlites enable the application of indicator mineral sampling for diamond exploration (Gurney 1984; Atkinson 1989; Jennings 1990; Fipke *et al.* 1995; McCandless & Nash 1996; McClenaghan & Kjarsgaard 2001). Minerals that indicate the presence of kimberlite, the primary host rock of diamonds, include: xenocrysts derived from disaggregated peridotite and eclogite mantle xenoliths (Cr-diopside, Cr-pyrope garnet, Cr-spinel, pyrope–almandine

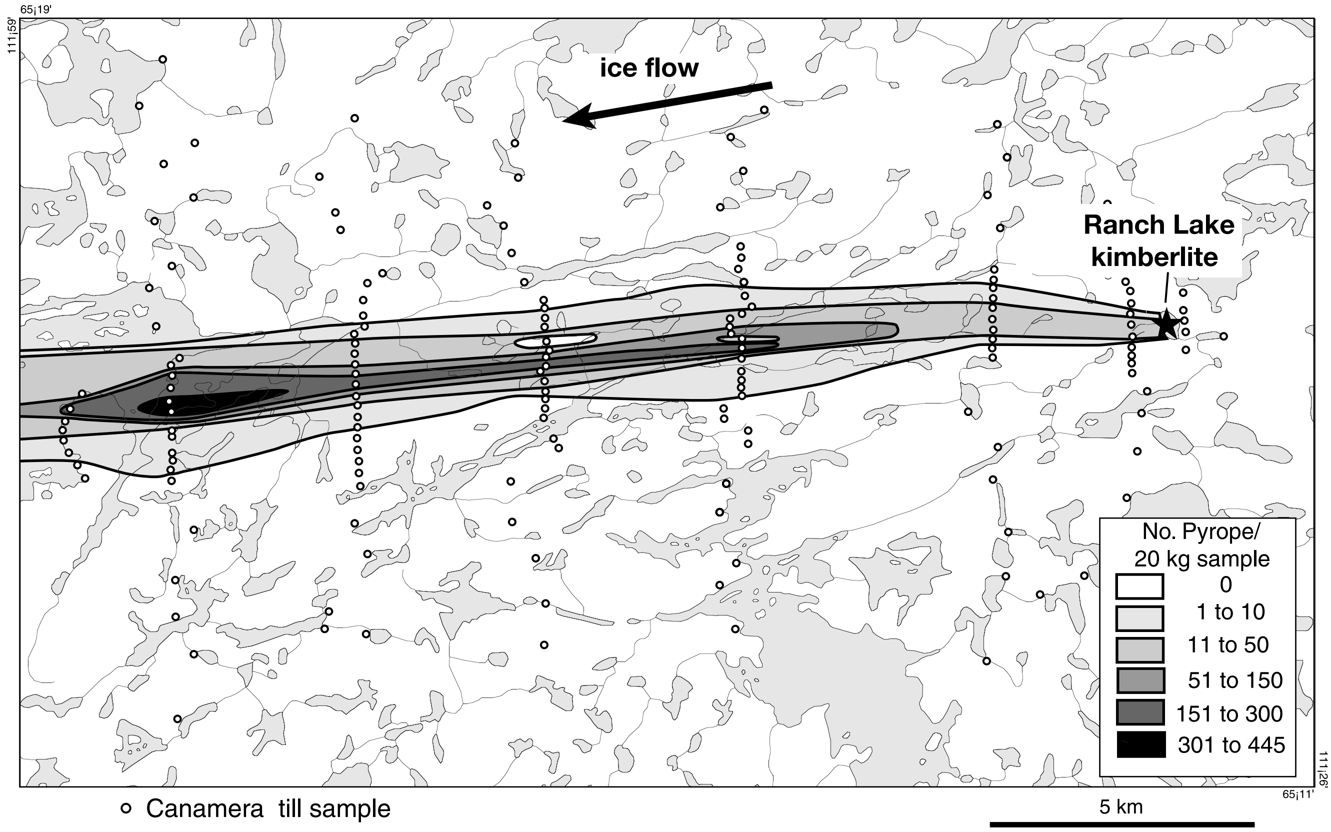

Fig. 9. Indicator mineral dispersal train (shaded grey) trending westward from the Ranch Lake kimberlite, Lac de Gras, central Slave Province, as defined by Cr-pyrope concentrations in 20-kg till samples (modified from McClenaghan & Kjarsgaard 2001).

garnet, olivine, enstatite, omphacitic pyroxene, and diamond); the associated megacryst suite of minerals (low-Cr Ti-pyrope, Mg-ilmenite, Cr-diopside, phlogopite, zircon and olivine); and kimberlite-derived phenocrystic olivine, spinel and ilmenite (McClenaghan & Kjarsgaard 2001). Because diamond is a rare mineral even in productive kimberlites, a subset of the kimberlite indicator minerals, termed 'diamond indicators', is used to indicate the *potential* presence of diamond in the kimberlite. These minerals include: subcalcic Cr-pyrope, commonly referred to as G10 pyrope (garnet-bearing harzburgite/dunite source rock); Cr-pyrope commonly referred to as G9 pyrope (garnet-bearing lherzolite source rock); high Na pyrope–almandine garnet (eclogite source rock); and high Cr-Mg chromite (chromite-bearing harzburgite/dunite source rock) (Sobolev 1971; Gurney & Switzer 1973; Sobolev *et al.* 1973; Gurney 1984; Fipke *et al.* 1989; 1995; Schulze 1999). A few other minerals may be useful as indicators in specific kimberlite fields, such as chromian corundum (e.g. Swanson & Gent 1993; Hood & McCandless 2003). Some kimberlite indicator minerals recovered from sample media can be identified visually, but some grains of Mg-ilmenite and spinel and all grains of eclogitic garnet as well as the diamond indicator minerals usually require electron microprobe analysis to confirm their identification and determine element concentrations for classification.

Background indicator mineral abundance will depend on sample media, but typically is zero away from kimberlite fields. Indicator minerals can be recovered from fine to very coarse sand-sized material; however, they are most abundant in, and cost effective to pick from, medium sand (0.25 to 0.5 mm). Till and glaciofluvial sediment in glaciated terrain, and stream sediments in glaciated and other terrains are the most effective media for using kimberlite indicator mineral methods (Atkinson 1989; McClenaghan & Kjarsgaard 2001), which include documenting overall mineral abundance, relative mineral species abundance, size, and surface textures. Lock (1985), and more recently, Van Coller *et al.* (2003), have reported using aeolian sediments to detect the presence of kimberlite in desert terrain and lateritic soils can be sampled in tropical terrains (Atkinson 1989; Gregory & Janse 1991).

Relative abundance

In unglaciated terrains, kimberlite indicator mineral abundance is the result of chemical and physical degradation of indicator minerals and primary abundance in the kimberlite source (Mosig 1980; Jennings 1990). In Australia, for example, Cr-spinel and Mg-ilmenite are more resistant to weathering and survive greater distances of fluvial transport (Fig. 5), followed by, in decreasing distance, Cr-pyrope, Cr-diopside, and olivine (Atkinson 1989). In glaciated terrain, all kimberlite indicator minerals survive long-distance glacial transport and are little affected by degradation or physical breakdown. Instead, the variations in relative abundance of indicator minerals in individual kimberlites controls the relative amounts of indicator minerals in glacial sediments down-ice. Decreases in concentrations of indicator minerals down-ice 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. In the Slave Province of northern Canada, for example, Cr-pyrope and Cr-diopside are the most abundant in kimberlite and till in the central part of the Slave region, while in the north Mg-ilmenite is the dominant indicator mineral (Fig. 6). Relative abundance of indicator minerals also may vary significantly between kimberlites within the same field. Where dispersal/

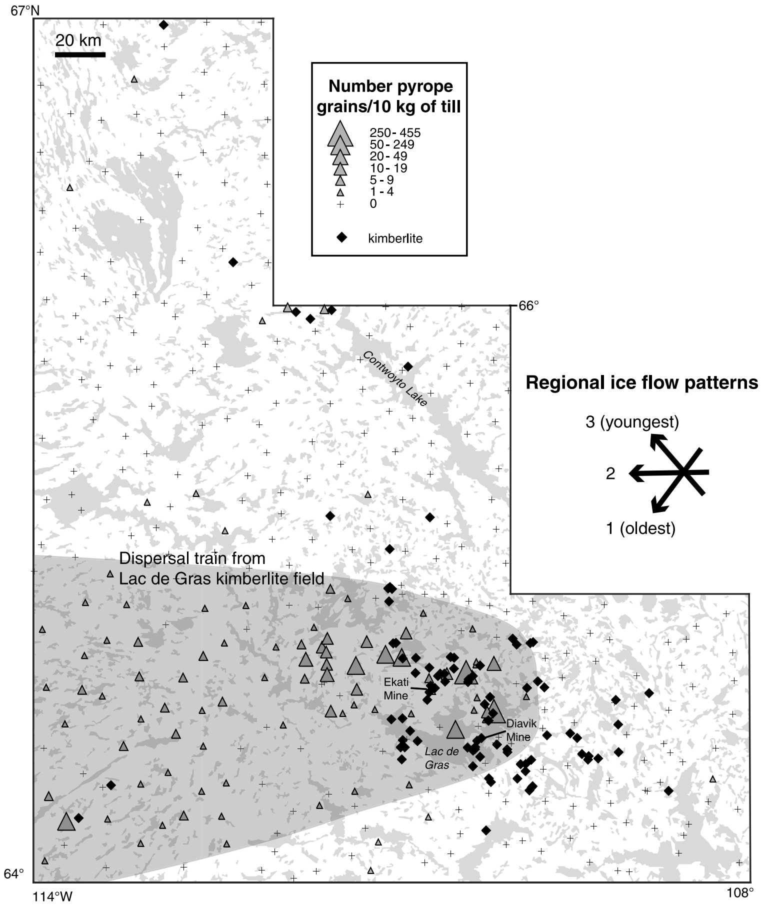

Fig. 10. Abundance of Cr-pyrope in the 0.25 to 0.5 mm heavy mineral fraction of 10-kg surface till samples collected by the Geological Survey of Canada across the Lac de Gras kimberlite field in the central Slave Province (from McClenaghan & Kjarsgaard 2001). Cr-pyrope grains have been dispersed by three phases of ice flow to the SW, west and NE. The highest concentrations are overlying and just down-ice from the kimberlite field centered around Lac de Gras.

dispersion trains from two kimberlites overlap, the relative abundance of minerals may aid in distinguishing between the trains. For example, the Diamond Lake kimberlite near Kirkland Lake, central Canada, contains >5000 Mg-ilmenite grains in a 10-kg sample (McClenaghan *et al.* 1998). In contrast, the C14 kimberlite, 20 km to the NW, is Mg-ilmenite poor and contains <10 grains per 10 kg (McClenaghan *et al.* 1999a). The large differences in relative abundance of Mg-ilmenite in these two kimberlites are reflected in the glacial sediments down-ice.

Surface features

Examination and comparison of surface features on kimberlite indicator minerals can provide information about distance of transport and nature of the transport medium (e.g. glacial versus fluvial) after the grains were liberated from the kimberlite source (Mosig 1980; Afanase'ev et al. 1984; McCandless 1990; Averill & McClenaghan 1994; Golubev 1995; Dredge *et al.* 1996a; Garvie 2003). Abrasion of indicator minerals during transport can result in changes to primary features such as crystal faces on chromite, resorbed surfaces, kelyphite rims on garnets and perovskite overgrowths on Mg-ilmenite. For example, garnet may be partially covered with up to 2 mm of thick greenish-black kelyphite reaction rims (Fig. 7) composed mainly of pyroxene with spinel, phlogopite or serpentine. The garnet rims possibly form during a decompression reaction with the high-temperature kimberlite magma during ascent (Reid & Dawson 1972; Garvie & Robinson 1984). Because of its soft nature, kelyphite layers break off or wear down readily during abrasion (McCandless 1990) and therefore the presence/absence and the thickness of kelyphite on individual pyrope grains may give some indication of the relative distance of transport.

Case studies

In glaciated terrain, exploration companies and government agencies have identified numerous indicator mineral dispersal trains down-ice of kimberlites (Table 2). In the Slave Province, the trains often extend for tens of kilometres in the direction of ice flow (e.g. Mckinlay *et al.* 1997; Carlson *et al.* 1999; Doyle *et al.* 1999; Graham *et al.* 1999) and are sharp-edged linear ribbons (Fig. 8) (Armstrong 1999; 2003). The linear shapes of the dispersal trains and their orientation parallel to the main ice flow direction indicate that they were formed during a single phase of flow in one direction. The Ranch Lake kimberlite train is an exceptional example of a ribbon-shaped dispersal train and is best defined by the abundance of Cr-pyrope (Fig. 9) and Cr-diopside, containing between 1 and 545 Cr-diopside and 1 and 445 Cr-pyrope grains in 20-kg till samples (McClenaghan *et al.* 2000a,b).

In contrast to dispersal trains for individual kimberlites, indicator minerals often define broader glacial dispersal trains for kimberlite fields that are many times larger than the fields. The fan-shaped glacial dispersal train down-ice of the Kirkland Lake kimberlite field extends 30 km south of the kimberlites (Brummer *et al.* 1992). The fan-shaped glacial dispersal train for the much larger Lac de Gras kimberlite field in the central Slave Province extends at least 180 km down-ice (west) reflecting three phases of ice flow. It is best defined by Cr-pyrope concentrations in till, an example of which is shown for 10-kg till samples collected 10 to 15 km apart (Fig. 10). Till in background areas outside the dispersal fan contains no Cr-pyrope whereas the concentration is between one and 455 grains inside the fan. In the James Bay Lowland of central Canada, indicator minerals in stream sediments clearly show the presence of the Attawapiskat kimberlite field. At a reconnaissance scale, the signature of the field is best defined by

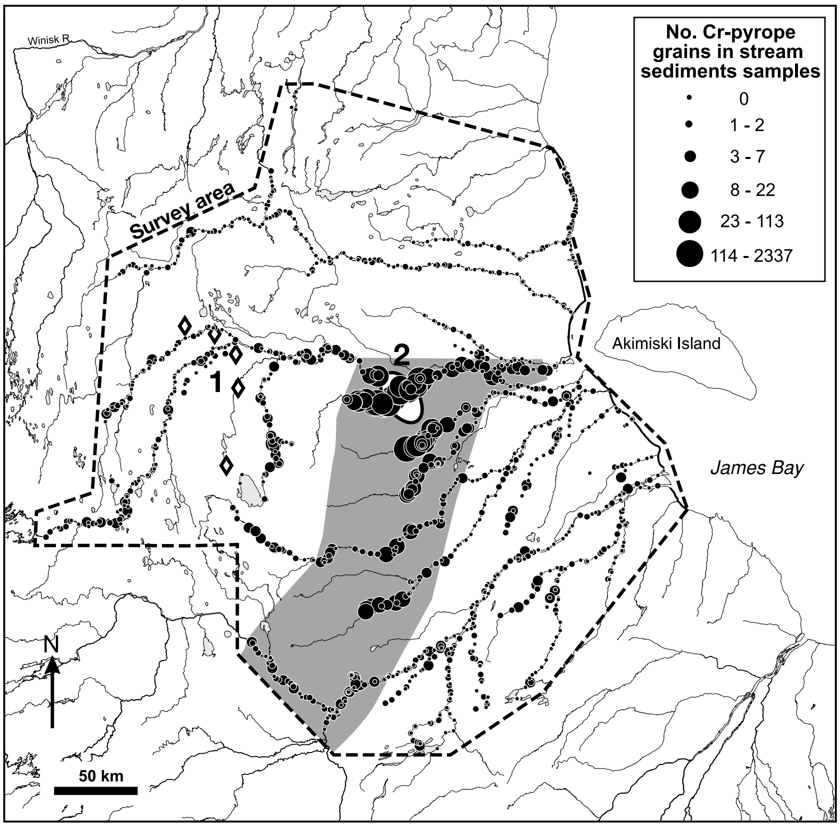

Fig. 11. Abundance of Cr-pyrope in the 0.25 to 2.0 mm heavy mineral fraction of 8 to 13 kg stream sediment samples around the Attawapiskat kimberlite field in northern Ontario, Canada (modified from Crabtree 2003). White diamonds (1) indicate location of Kyle Lake kimberlite cluster; white oval (2) indicates location of Jurassic age kimberlite cluster. The dispersal fan, highlighted in dark grey, is the net effect of glacial transport from the Jurassic age kimberlite cluster to the SW and subsequent fluvial transport to the NE and east.

Mg-ilmenite (Fig. 11) and Cr-pyrope, 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 kimberlites (Kong *et al.* 1999). The 300-km-long dispersion fan of indicator minerals in stream sediments SW of the Attawapiskat field is a product of two modes of transport, glacial transport to SW and subsequent fluvial transport to the NE and east in modern streams.

Kimberlite indicator minerals in stream sediments have long been used to explore for diamonds in the warmer climates and areas of higher rainfall (Table 2). For example, diamonds and Cr-spinel (Fig. 12) in stream sediments in the Kimberley region of NW Australia led to the discovery of the Aries kimberlite (Towie *et al.* 1991). Kimberlite indicator minerals in stream sediments also can be used in glaciated terrain where there is sufficient topographic relief (e.g. Afanasev & Yanygin 1983; Afanase'ev et al. 1984; Dummett *et al.* 1987; Romashkin 1997; Steenfelt 2001; Morris *et al.* 1998; Friske *et al.* 2003) or where surface sediments such as peat or glaciolacustrine sediments mask the underlying till, as illustrated by the Attawapiskat example (e.g. Wolfe *et al.* 1975; Kong *et al.* 1999; Crabtree 2003).

Indicator mineral methods have also been applied to the aeolian sediments in the arid terrain of southern Africa, including several kimberlites in the Kalahari region of southern Botswana. Lock (1985) reported that Mg-ilmenite and Cr-pyrope were effective pathfinder minerals in identifying the location of several kimberlites in the Jwaneng area of Botswana, which is covered by thick Kalahari sediments and overlain by sand deposits. The presence of indicator minerals at surface was likely the product of bioturbation by termites; however, there had been some reworking by wind action as some anomalies tended to be displaced to the SW, in the direction of the prevailing wind.

SUMMARY

Indicator mineral methods have expanded to become a very important exploration method, most notably for gold, diamonds and base metal deposits. Their physical and chemical characteristics, which include distinct colour and crystal form, high density, sand to silt size and durability, allow them to be readily recovered from exploration sample media and identified, and make them sufficiently abundant. The choice of sample media will depend on the climate, topography, and size of area to be sampled. In glaciated terrain, till is most often used for indicator mineral surveys due to its simple transport history. Stream and alluvial sediments are sampled in glaciated, temperate, tropical and arid terrains. Aeolian sediments can be sampled in arid terrain when other media are not available. Sample spacing will depend on the size of the mineral deposit or district sought, the access and availability of samples sites, and cost of collecting the samples.

Examples from gold- and diamond-focused regional surveys and exploration case histories have been used in this paper to demonstrate the importance of grain abundance, grain morphology and mineral grain chemistry in determining the nature of dispersal and dispersion in till and stream sediments. These methods are now well established, widely used around the world, and have led to significant discoveries, particularly for diamonds in the last 10 years.

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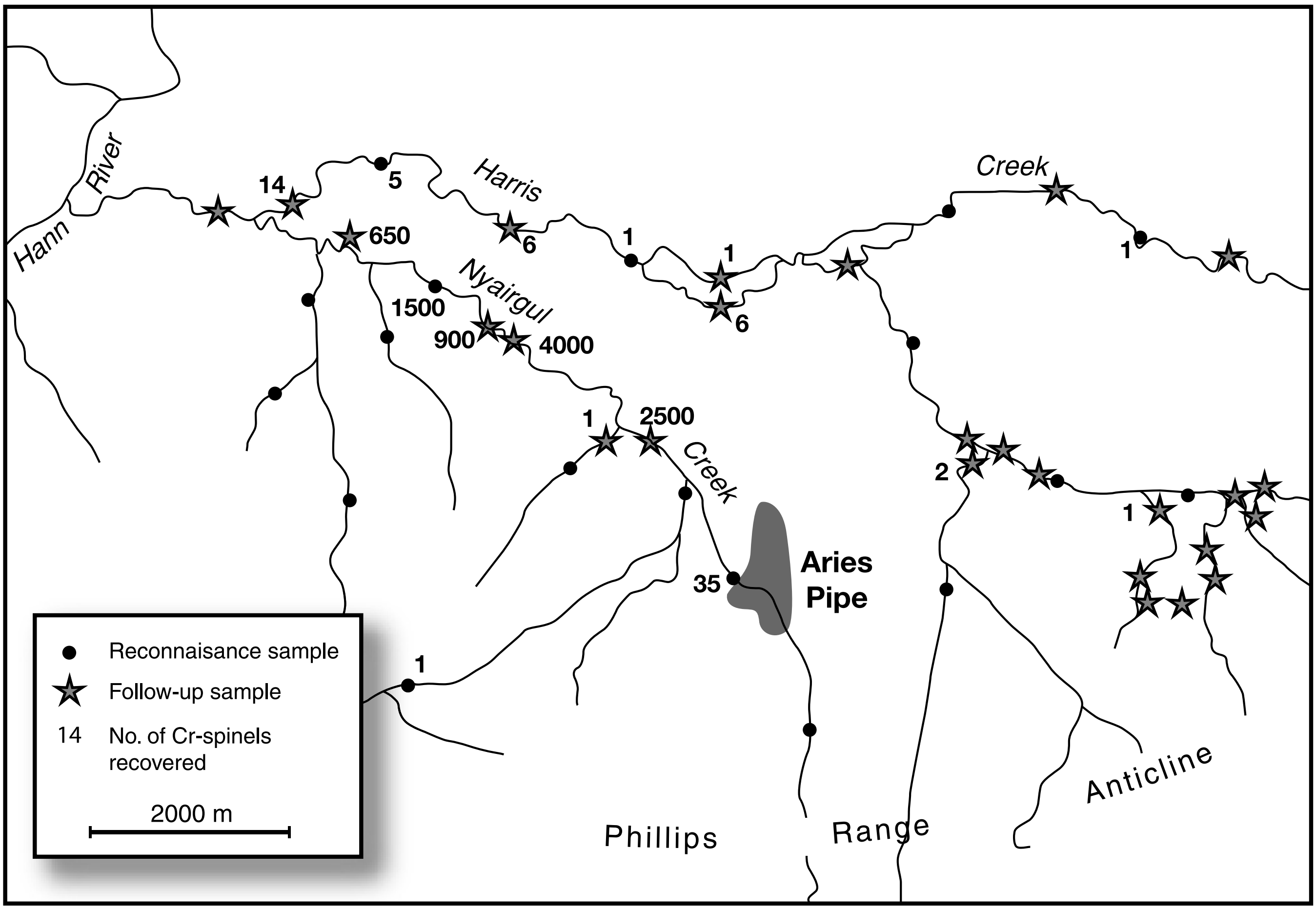

Fig. 12. Distribution of Cr-spinel in stream sediment samples around the Aries kimberlite, northern Australia (modified from Towie *et al.* 1991).

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