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Systematic variations in xenocryst mineral composition at the province scale, Buffalo Hills kimberlites, Alberta, Canada

Chris T.S. Hood*, Tom E. McCandless

Ashton Mining of Canada Inc., Unit 116-980 W. 1st Street, North Vancouver, BC, Canada

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Abstract

The Buffalo Hills kimberlites define a province of kimberlite magmatism occurring within and adjacent to Proterozoic crystalline basement termed the Buffalo Head Terrane in north-central Alberta, Canada. The kimberlites are distinguished by a diverse xenocryst suite and most contain some quantity of diamond. The xenocryst assemblage in the province is atypical for diamondiferous kimberlite, including an overall paucity of mantle indicator minerals and the near-absence of compositionally subcalcic peridotitic garnet (G10). The most diamond-rich bodies are distinguished by the presence of slightly subcalcic, chromium-rich garnet and the general absence of picroilmenite, with the majority forming a small cluster in the northwestern part of the province. Barren and near-barren pipes tend to occur to the south, with increasing proximity to the basement structure known as the Peace River Arch. Niobian picroilmenite, compositionally restricted low-to moderate-Cr peridotitic garnet, and megacrystal titanian pyrope occur in kimberlites closest to the arch. Major element data for clinopyroxene and trace element data for garnet from diamond-rich and diamond-poor kimberlites suggests that metasomatism of lithospheric peridotite within the diamond stability field may have caused destruction of diamond, and diamond source rocks proximal to the arch were the most affected.

Keywords: Mineral chemistry; Proterozoic mantle; Pyrope; Chromian spinel

1. Introduction

The Buffalo Hills kimberlite province is located approximately 350 km north of the city of Edmonton in north-central Alberta. A joint venture consisting of Ashton Mining of Canada, EnCana Corporation (formerly Alberta Energy Company) and Pure Gold Minerals discovered the first kimberlites in the region in early 1997 and exploration efforts since that time have led to the identification of a new diamondiferous kimberlite province in Canada (Carlson et al., 1999; Skelton et al., 2003). Thirty-eight bodies have been identified as of May 2003. The area of kimberlite magmatism extends over 6000 km^2, with most bodies concentrated in the core area of the province (Fig. 1).

The kimberlites of the Buffalo Hills are emplaced through Devonian and Cretaceous sedimentary sequences mantling a regionally significant, geophysically defined block of crystalline basement known as

* Corresponding author. Tel.: +1-604-983-7753; fax: +1-604-987-7107.
E-mail address: chris.hood@ashton.ca (C.T.S. Hood).

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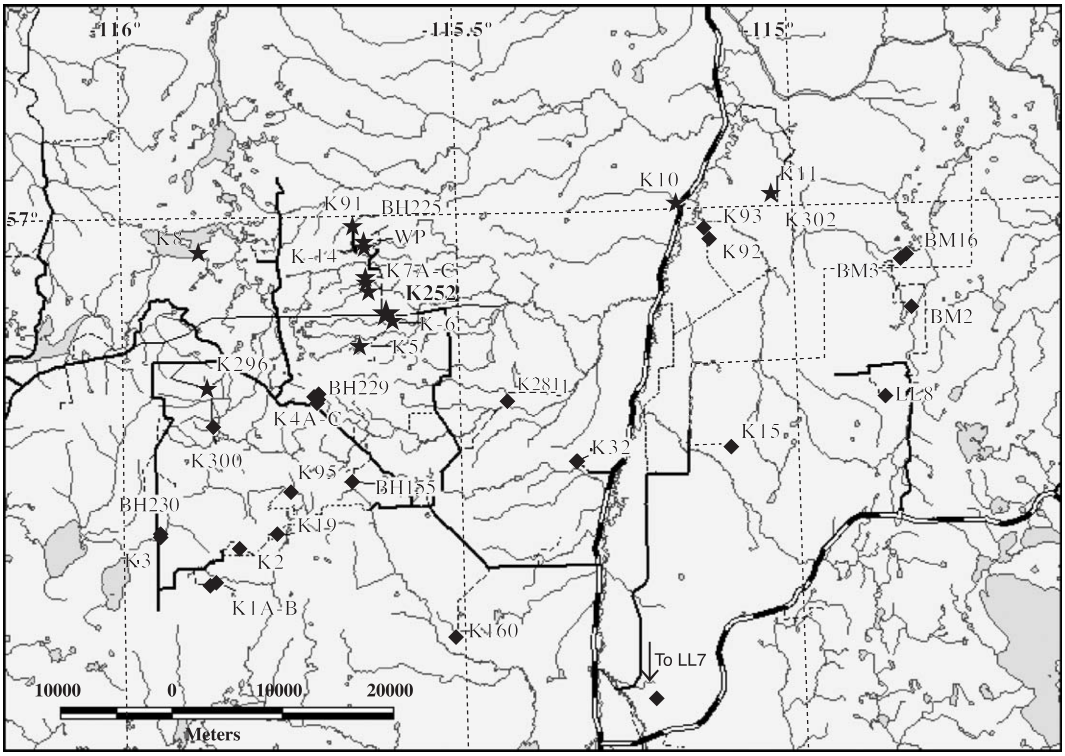

Fig. 1. Location map for the Buffalo Hills kimberlites. Stars represent northern group kimberlites; diamonds represent southern group kimberlites. The town of Red Earth Creek is situated just off the south-central boundary of the map.

the Buffalo Head Terrane. Samples of basement from oil company boreholes have generated Paleoproterozoic ages for the terrane (Ross et al., 1991), although Sm–Nd model ages for some samples have indicated a possible Archaean component (Villeneuve et al., 1993). The terrane is also considered a part of the tectonometamorphic Red Earth granulite domain of Burwash et al. (2000), with basement rocks interpreted to have experienced granulite facies metamorphism. A broad, northeast-trending upward known as the Peace River Arch bisects the southern part of the terrane and is associated with a long history of epei-orogeny.

Most of the kimberlites range from 1 to 40 ha in surface area and are presently established as crater facies to depths of 200 m (Boyer et al., 2003), with two groupings based on geographic position and diamond content. The northern group includes bodies containing higher diamond contents, typically with a sub-population of larger (+1 mm) stones. The southern/eastern group is dominated by barren to weakly diamondiferous kimberlites, usually with microdiamond results suggesting poor commercial diamond potential. The K252 kimberlite has the highest diamond content (55 carats per hundred tonnes, cpht) and is situated within the northern group.

Twenty-six of thirty-eight bodies are known to contain diamond as of mid-2003. Most of the kimberlites also contain a diverse xenocryst mineral assemblage, as discrete grains or as part of a rarer mantle nodule suite. The mantle nodule suite is well-represented in only a few bodies and is part of a separate study that suggests a Paleoproterozoic or reworked Archaean history (Aulbach et al., 2003). In this study, the xenocryst suites of representative kimberlites are characterized with respect to relative abundance, mineral compositions and parental mantle rock types, diamond cogenesis, and lithosphere evolution.

2. Methodology

In comparing xenocryst minerals from different kimberlites, it is important that grains are selected such that the mantle sampled by the kimberlite is objectively represented. Grain selection for the Buffalo Hills kimberlites was accomplished by visual examination of non-magnetic mineral concentrates exceeding a 2.85 specific gravity in the 0.4–2.0 mm size fractions. Characterization of the overall mineralogical constituents was first completed and garnets were then removed as the first 100 encountered, or all grains were removed from the sample if less than 100 were present. Chromite was similarly removed on a "first 50" basis, while all picroilmenite grains were removed when present. Approximately 3500 grains were derived for the study, covering most of the Buffalo Hills kimberlites.

Subsequent to visual characterization of colour and morphology, grains were cast in resin and polished. Major and minor elements were analyzed by the IXION Research Group (Montreal, PQ), using a Jeol JXA-8900L microprobe, located at McGill University. Trace element abundances in a subsample of 254 garnets were determined by laser ablation ICP-MS using a Perkin Elmer/ Sciex Elan 6000 ICP-MS with a Cetac LSX-200 laser ablation module housed at the Department of Geological Sciences, University of Cape Town. Trace element abundances were internally standardized against SiO_2 and CaO (wt.%) concentrations of each garnet, previously determined through microprobe analysis. Relative variations are less than 10%, which is acceptable for trace elements discussed in this study.

3. The xenocryst mineral suite

3.1. Relative abundance and distribution

Most of the Buffalo Hills kimberlites contain some amount of the standard kimberlite xenocryst suite, which are in most cases visually distinctive. This includes peridotitic pyrope, eclogitic pyrope-almandine, titanian pyrope of the low-Cr megacryst suite, chromite/Cr-spinel, Cr-diopside/augite and forsteritic olivine. Magnesian ilmenite, kimberlitic zircon, enstatite, Cr-corundum, Mg–Al spinel, uvarovite and edenitic hornblende are also occasionally present. Olivine is by far the most abundant mineral in most concentrates, but is excluded from further consideration in this study. Xenocryst occurrence varies widely between bodies and appears uncorrelated with geographical location, pipe morphology or diamond content. Table 1 summarizes xenocryst abundance in typical bodies from the two defined groups and for the K252 kimberlite (included with the northern group).

The peridotitic suite of garnets is variously represented in concentrates from the Buffalo Hills province, ranging from forming an important indicator in pipes such as K14, K15 and K4B to only trace amounts in other bodies (K7C, K8, LL7). The suite is sourced from lherzolitic, wehrlitic, websteritic, pyroxenitic, dunitic and harzburgitic protoliths, with intact nodules of the parent rocks occasionally present in drill core samples (Aulbach et al., 2003). Grains occasionally contain small ($\ll$1 mm) euhedral inclusions of chromian spinel, suggesting an equilibrium relationship between the two phases. Compositions for individual garnet populations are dominated by species of lherzolitic

Table 1
Xenocryst mineralogy of representative kimberlites

Kimberlite	Grade (cpht)	P-pyrope, kg[a]	Low-Cr pyrope, kg[a]	Chromite, kg[a]	Mg Ilmenite, kg[a]	Cpx, kg[a]
Northern group						
K252	55.0	0.3	0.1	1.0	0	0.3
K14	11.8	63.7	21.2	148.7	0	26.8
K6	7.2	1.7	~ 0	13.1	0	1.8
K11	4.4	170.4	8.9	1049.0	4.5	5.4
K10	1–5	333.2	7.8	238.2	3.9	3.1
K5	0.36	0.6	0.1	22.6	0	0
K8	< 1	0	0	0.1	0	0
K7C	0	0	0	1.7	0	4.0
K7A	0	0	3.3	3.3	0	6.7
Southern group						
K2	< 1	31.8	2.5	43.6	2.5	8.0
K1B	< 1	3.2	0.4	0.4	0.2	9.8
K95	~ 0	75.9	6.5	12.0	0.7	2.1
K32	~ 0	0.5	1.1	5.4	0.5	2.2
K92	~ 0	6.6	1.3	60.4	1.3	0
K4B	~ 0	665.5	14.6	1167.5	1.4	1.8
K15	0	32.6	0.6	38.8	1.7	0.6
LL7	0	0.2	0	2.0	0	0
K3	0	0.1	0	2.0	0.1	0.2

[a] Based on standard 0.4–2 mm, non-magnetic concentrate. Grain abundances are per kilogram of kimberlite.

derivation, paralleling the rough trends defined by Sobolev et al. (1973) and Gurney (1984) as the line of calcium saturation.

Eclogitic garnets form a relatively minor component of most of the Buffalo Hills bodies, normally less than a few percent of the total garnet content. In some examples, such as the K160 and K7A pipes, orange (i.e. low-Cr) garnets form a significant portion of the total garnet content, and in the latter comprise the only easily recognizable mantle xenocryst phase. Orange, low-Cr garnets tend to be more abundant in the southern group kimberlites as a whole, particularly in the more indicator-rich examples. There is, however, a possible chemical distinction between the low-Cr suite from the northern and southern groups that is discussed in Section 3.2.

Chromite (and chromian spinel) is the most abundant and widely distributed xenocryst mineral in the Buffalo Hills province, occurring in at least trace amounts in all of the bodies for which indicator concentrates have been generated. Chromite tends to be the dominant indicator in the more xenocryst-poor kimberlites, including the LL7 and K6 kimberlites (Table 1). In most bodies, the mineral may form as much as 80% of the (non-olivine) xenocryst assemblage and is comprised of a range of morphologies showing varying degrees of resorption. No correlation of composition with morphology has been attempted, but grain morphology appears to be roughly consistent throughout the province. Individual grain sizes may be as much as several millimeters. The widespread occurrence of chromite makes it an ideal candidate to monitor compositional trends within the Buffalo Hills kimberlites.

Picroilmenite is a minor constituent of the Buffalo Hills kimberlites, with only seven bodies containing greater than trace amounts (K1A, K1B, K2, K3, K10, K11, and K15). The phase is interpreted to be xenocrystic or megacrystic in nature, with most grains occurring within the coarser fractions. Several other kimberlites, entirely within the southern group, contain small amounts of the mineral (Table 1), but limited recovery of grains restricts its application in evaluating diamond preservation potential (e.g. Haggerty, 1975; Gurney and Zweistra, 1995) to the few bodies where it is present in sufficient quantities.

Chromian clinopyroxene (diopside to augite) has been identified in most kimberlites from the province. The mineral is assumed to derive dominantly from disaggregated lherzolites and is most abundant in kimberlites from the southern cluster, where pyroxene alteration appears to be less severe. Orthopyroxene is much less abundant and is also believed to source from peridotitic and pyroxenitic mantle, based on comparable minerals in mantle xenoliths (Aulbach et al., 2003).

Minor components of the xenocryst population include edenitic amphibole, which has been identified in minor amounts in some barren and near-barren bodies of the southern group (Table 1), as well as trace amounts in a few kimberlites in the northern group. The formation of edenitic amphibole has been linked to hydrous metasomatism of lherzolitic mantle (Field et al., 1989). Kimberlitic zircon is relatively rare in the Buffalo Hills and is most frequently encountered in the southern group kimberlites, where it occurs as large, generally colourless and highly resorbed grains. The mineral is believed to be related to the Cr-poor megacryst suite and is thought to be the result of fractionation in an incompatible element-enriched melt (LeCheminant, 1998). Corundum and Mg–Al spinel have also been identified in a number of kimberlites in the Buffalo Hills, including the diamondiferous K252 kimberlite. Corundum and spinel are present in the essentially barren K7A and 7B kimberlites, implying a distribution that is controlled by lateral rather than vertical variations in the source region. Chromian corundum is present throughout the Buffalo Hills kimberlites, although the highest concentrations are found in the northern part of the province. The presence of the mineral in both diamondiferous (K6) and essentially barren (K7A) pipes is indicative of a source that is unrelated to diamond-bearing lithosphere. Xenocrystic Mg–Al spinel is an important phase in the K6 kimberlite complex in the northern cluster and is commonly associated with chromian corundum Trace amounts of corundum, Mg–Al spinel, and white, Cr-free pyrope have been identified within concentrates from the southern group; these grains may be similar to the aluminous mantle assemblages described by Mazzone and Haggerty (1989) within the Jagersfontein kimberlite.

In summary, the xenocryst mineral suite is dominated by species characteristic of peridotitic mantle, with some amount of eclogitic and pyroxenitic mantle also represented. The presence of both orthopyroxene

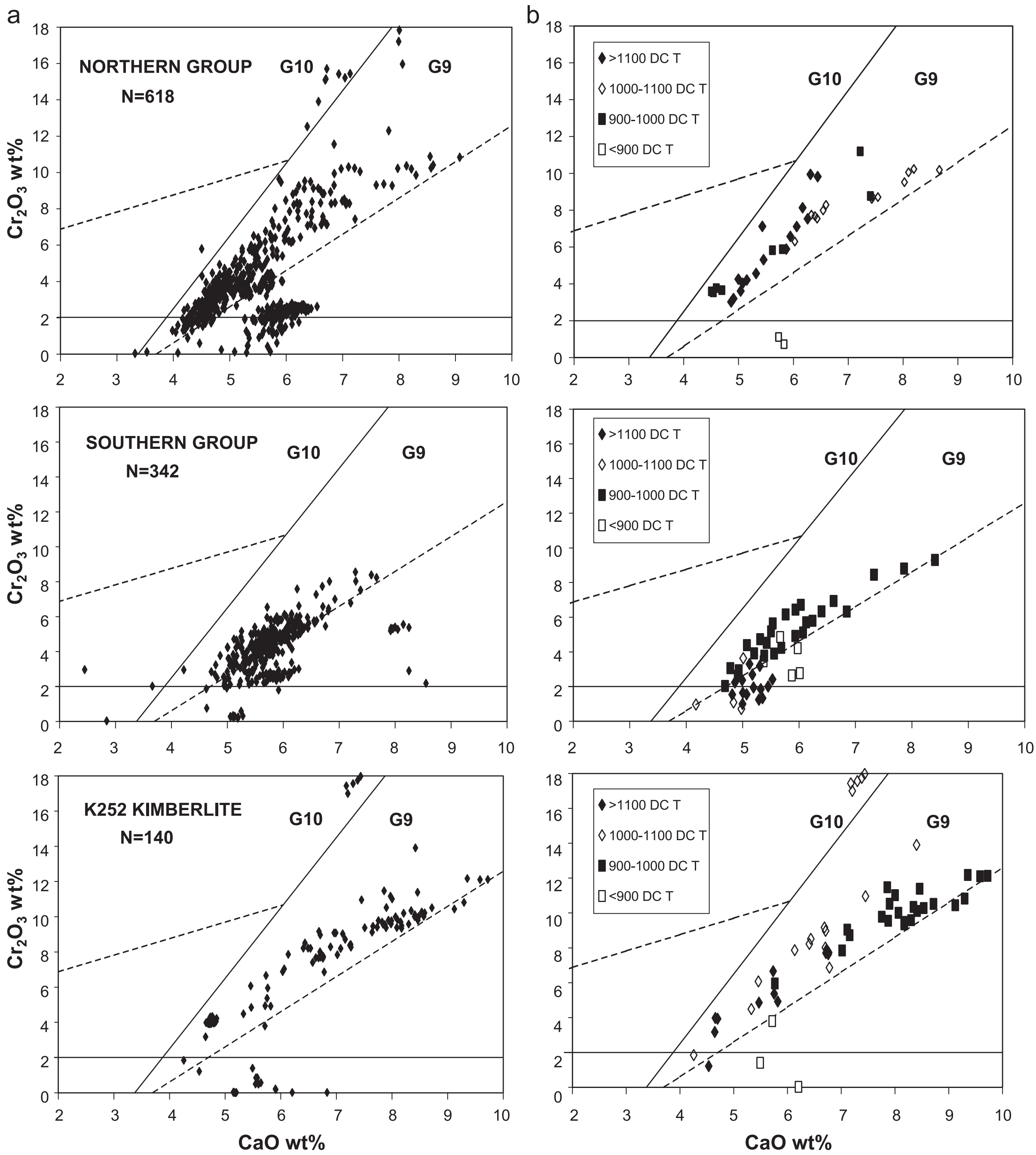

Fig. 2. (a) Cr–Ca diagrams for peridotitic garnet populations from the northern and southern groups, and the K252 kimberlite. Superimposed fields are G9/G10 (Gurney, 1984), with dashed lines for spinel–garnet equilibrium (Kopylova et al., 2000) and graphite–diamond (Grutter and Sweeney, 2000). (b) Temperature distribution for representative northern group, southern group and K252 garnets in Cr–Ca space. Ni-in-garnet temperature calculated according to method of Canil (1994).

and clinopyroxene is additionally suggestive of a possible lherzolitic character to the peridotite. These xenocryst data are matched by xenolith and diamond studies that also demonstrate a dominantly lherzolitic mantle in the area (Aulbach et al., 2003; Davies et al., 2003). Mineral abundance does not appear to parallel diamond content, as some diamond-rich kimberlites contain relatively low concentrations of peridotitic xenocrysts, while a few diamond-poor kimberlites contain large numbers of xenocrysts. The presence (or absence) of some species, such as magnesian ilmenite, may correlate with diamond content.

3.2. Mineral compositions in the northern and southern groups

3.2.1. Peridotitic garnets

In addition to relative abundance, the northern and southern groups can also be defined on the basis of contrasting xenocryst mineral compositions. Peridotitic garnets from the Buffalo Hills kimberlites are plotted in CaO–Cr_2O_3 space, using the traditional division of Gurney (1984) for "G10" subcalcic pyrope for reference (Fig. 2). A few pyrope lie within the G10 field, but the grains are not strongly subcalcic and form a very small percentage of the total population, suggesting that subcalcic harzburgite is very rare beneath the Buffalo Hills. Garnets from the northern pipes display lherzolitic trends with a closer proximity to the 85th percentile line of Gurney (1984) (Fig. 2). Also present in these diamondiferous kimberlites are sparsely distributed greenish, knorringitic grains containing up to 20 wt.% Cr_2O_3. Data for the northern group resolves into a number of distinct clusters and trends (Fig. 2), implying a diversity of bulk composition and possibly depth of the source lithosphere. The extent of this diversity is more pronounced than is evident in the southern group kimberlites.

A somewhat diverse source is also implied by pyrope from the bodies in the K11 area of the northern group, where the lherzolitic trends have a broader range of Ca-values and, in the macrodiamond-bearing K10 and K11 pipes, relatively chromium-rich and calcium-poor ranges (Fig. 3). The K10 kimberlite (not included in Fig. 2) in particular is distinctive in that four recovered grains are classifiable as "G10's", with two of these showing probable affinity to a depleted, harzburgitic parent. The breadth of the

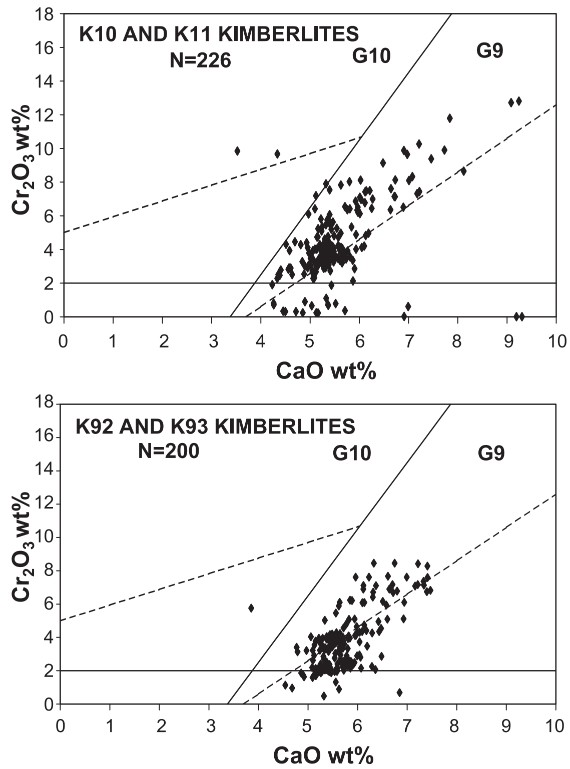

Fig. 3. Cr–Ca diagrams for garnet populations from the K10 and K11 kimberlites (northern group) and K92 and K93 kimberlites (southern group). Superimposed fields are G9/G10 (Gurney, 1984), with dashed lines for spinel–garnet equilibrium (Kopylova et al., 2000) and graphite–diamond (Grutter and Sweeney, 2000).

garnet compositions in Cr–Ca space may also define a contribution from a wehrlitic or websteritic source, or possibly a complex history for the mantle lithosphere from which they derive.

As with the northern group, garnet populations from the southern group are dominated by lherzolitic (calcic) compositions. In the southern bodies from the core area (K4A and B, K229, K2, and K95), the lherzolitic garnets are even more calcic and show an obvious lack of high-chromium compositions, although a few low chromium, subcalcic grains do occur within the G10 field (Fig. 2). Although the subcalcic grains are few in number, they may represent the contribution of a shallow (as implied by the low Cr content), depleted source within a dominantly lherzolitic population. A particular note may be made of the more calcium-rich lherzolitic pyrope of the barren K93 and weakly diamondiferous K92 kimberlites. In the same vicinity, the more diamondiferous K10 and K11 kimberlites define lherzolitic trends with lower average CaO values (Fig. 3).

The range of $CaO-Cr_2O_3$ analyses associated with the southeastern, "peripheral" bodies (K15, BM2, and LL8) is distinguished by densely clustered, low chromium garnets that may source from wehrlitic or websteritic lithosphere. The apparent shallow, fertile source material is expected to have a very low prospectivity for diamonds, confirmed by the essentially barren nature of these kimberlites. In most bodies from the southern group, garnet compositional trends follow the spinel–garnet equilibrium trend ("CCGE") defined for xenoliths from the Jericho kimberlite (Kopylova et al., 2000).

3.2.2. Low-Cr garnets

When plotted in Na_2O-TiO_2 space, low-Cr garnets from several bodies in the northern cluster reveal a number of unusual trends. The K10 and K11 kimberlites include distinct clusters of garnets with relatively high sodium contents, whereas garnets from the K5 and K14 kimberlites are dominated by very low sodium and titanium (Fig. 4). Application of the McCandless and Gurney (1989) model, using a cutoff of 0.09 wt.% Na_2O, would thus conclude that eclogitic diamond potential within the K10 and K11 kimberlites is relatively high, whereas the K14 area is dominated by peridotitic or perhaps "exotic" diamond protoliths. Davies et al. (2003) conversely recognized lherzolitic inclusions in one large diamond found in K10, with a number of diamonds containing eclogitic inclusions from K14. At present, the diamond data are too sparse to assess this apparent discrepancy.

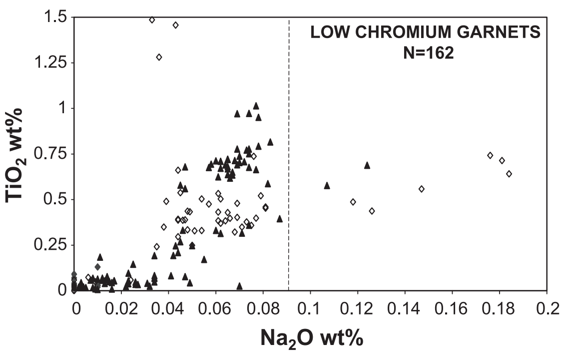

Fig. 4. Ti–Na diagram for low chromium garnet-bearing kimberlites from the Buffalo Hills. Open diamonds are northern group, filled triangles are southern group, filled diamonds are for K252. Field for diamond association compositions set at >0.09 wt.% Na_2O, as per McCandless and Gurney (1989).

Garnets that can visually be defined as low-Cr are also present in many pipes in the southern group, becoming an important component in a few bodies such as K2 and K95. Many of the grains contain elevated MgO and TiO_2 contents, suggesting that they are representative of the low-Cr megacryst suite rather than of true eclogitic mantle (Fig. 4). A subsidiary population of eclogitic grains is also present, with a small percentage containing elevated Na_2O (to ~ 0.12 wt.%). The diamond-poor nature of the southern group kimberlites suggests that the high-Na component of the eclogitic population is probably not associated with diamondiferous mantle, or that it is a minor contributor to the diamond population. Alternatively, the Na discriminant may not be useful in assessing the eclogitic diamond potential of this particular province (e.g. Grutter and Quadling, 1999).

3.2.3. Chromite/chromian spinel

Chromite Cr_2O_3 versus MgO plots have been generated for several pipes from the northern and southern groups (Fig. 5). A compositional field of "spinel inclusions in diamond" has been outlined (after Gurney and Zweistra, 1995) in order to apply a measure of diamond prospectivity for the spinel source region. Gurney (2000) and Griffin et al. (1994) note that compositional trends proposed to be associated with early stage fractional crystallization generally follow a positive slope, whereas xenocryst trends are normally negatively sloping in $MgO-Cr_2O_3$ space. Although the terminology assigned to these trends is questionable (McCandless and Dummett, 2003), the terms are used in the ensuing discussion.

As with the garnet populations, chromites from the northern and southern groups display distinct geochemical trends. In the northern group, low titanium chromite follow a prominent xenocryst trend, with the apex at high Cr_2O_3 content and in the diamond inclusion field. A possible fractionation trend is also expressed. Some bodies (ie. K14, K6, and K91) appear to contain multiple populations within the xenocryst trend, implying a diversity of mantle sources. In the diamondiferous K10 and K11 pipes, however, the fractionation trend is dominant, with few grains falling within the inclusion field. The distinctly indicator-and

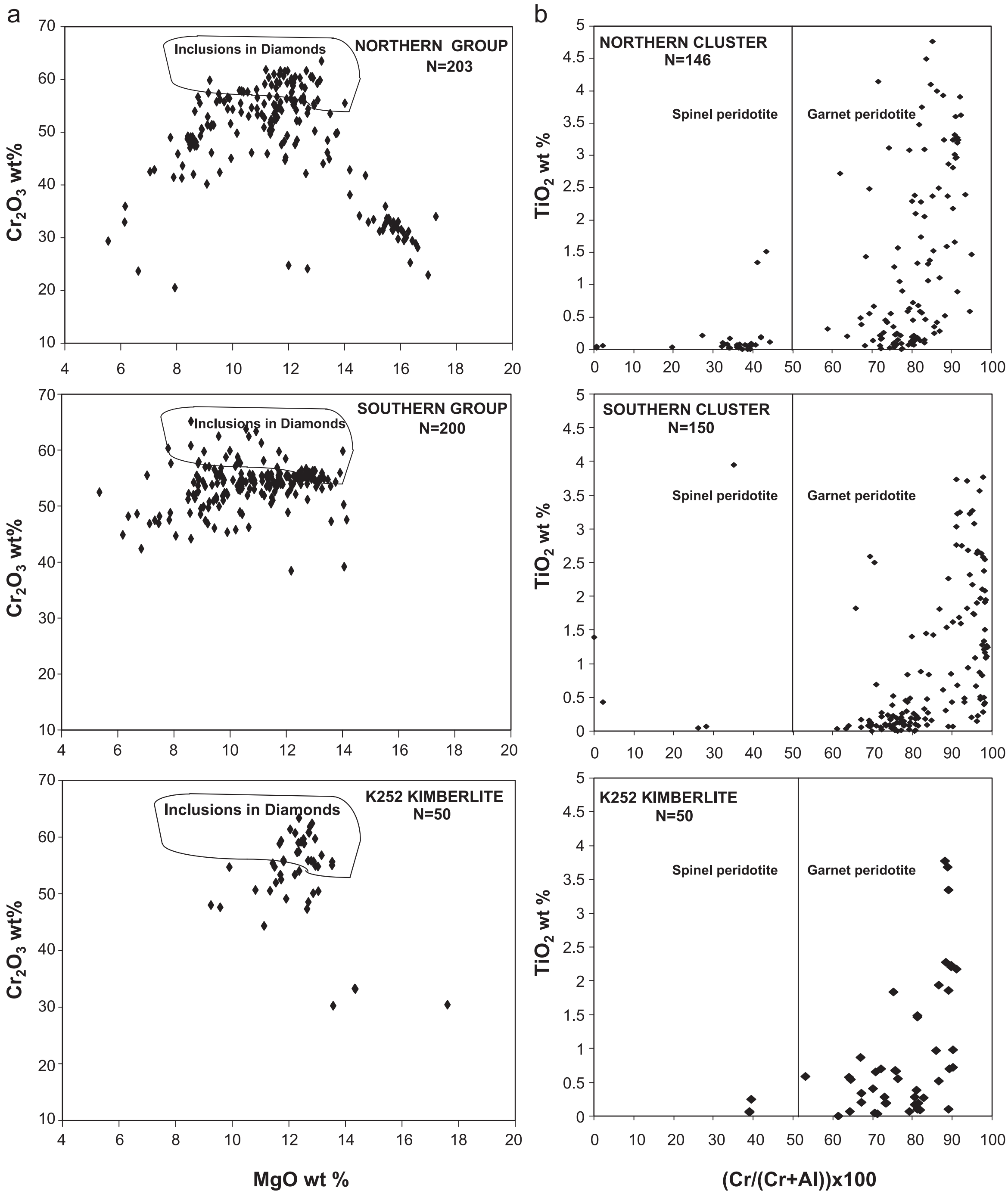

Fig. 5. (a) Cr–Mg diagrams for chromite populations from the northern and southern groups, and the K252 kimberlite, with added field for inclusions in diamond (after Gurney and Zweistra, 1995). (b) Ti–Cr# diagrams of chromite and chromian spinel grains from the northern and southern groups, and the K252 kimberlite.

diamond-poor K7A pipe has a prominent low chromium spinel population as the only feature of note. These grains probably represent xenocrysts derived from shallow-depth spinel lherzolites and are unusual in the Buffalo Hills indicator population.

The nearly barren kimberlites of the southern group include a few with chromites of the fractionation trend within the diamond inclusion field, but with an overall diffuse distribution that may imply a more complex geochemical history for the spinel protoliths (Fig. 5). These grains may represent a mix of xenocryst and fractionation trend chromites, as is apparent for TiO_2 contents within K2 chromites. Unlike the northern group, the fractionated phenocryst association is still the dominant paragenesis. The dominance of this trend in diamond-poor bodies is indicative of a negative association with diamond-bearing mantle in the Buffalo Hills kimberlites.

Many bodies of the southern group (eg. LL7, LL8, BM2, K15, and K32) also include grains within the diamond inclusion field, but with most analyses consisting almost entirely of tight clusters of grains associated with the fractionation trend, in agreement with the indicator-poor nature of these bodies and their associated low diamond content.

TiO_2 versus Cr/(Cr + Al) discriminant plots have been generated for chromite from several kimberlites in the northern and southern groups, after Ramsay (1992) (Fig. 5). The diagrams also define a narrow ‘‘diamond association field’’, as well as provide a rough division between chromian spinels derived from spinel or garnet peridotites. All northern pipes consist dominantly of high chromium populations with grains falling within the diamond-associated field. Interestingly, the diamondiferous K5 and K6 pipes have a lower percentage of grains within the prospective field, as well as lower overall Cr/(Cr + Al) ratios. These distinct populations within the spinel peridotite field are an additional feature of the diamondiferous bodies and hint at a complex mantle lithosphere beneath the K5 and K6 kimberlites, or a complex sampling process during kimberlite ascent.

Plots of TiO_2 versus Cr/(Cr + Al) from the southern group show a general similarity with results for the northern group, including numerous grains within the field for spinel inclusions in diamonds (Ramsay, 1992) (Fig. 5). Cr-number appears to be slightly higher for the southern group, with very few grains within the spinel peridotite field. The higher average Cr-number values, along with single defined paragenesis, may be produced through derivation from garnet peridotites dominated by low chromian garnet. As with the garnet, the existence of the positive trend may thus signal a shallower, less complex mantle source.

3.2.4. Picroilmenite

Picroilmenite has not been identified in the majority of pipes defined within the northern group, although the moderately diamondiferous K10 and K11 kimberlites both contain minor concentrations. Picroilmenite geochemical trends in these two pipes define a number of features (Fig. 6). Of particular interest is the elevated Nb_2O_5 in picroilmenite from the K10 kimberlite, with individual values up to almost 3 wt.%. This enrichment trend has been suggested to reflect increasing degrees of fractional crystallization in the source magma (e.g. Griffin et al., 1991). The lowest niobium contents are found in picroilmenite from the moderately diamondiferous K11 pipe. Most K10 and K11 ilmenites show a negative correlation between Cr and Nb, implying that fractional crystallization provides the most important control on ilmenite chemistry. The K10 pipe occupies an intermediate position in both diamond content and niobium values, suggesting a possible negative correlation between niobium and diamond content.

In the southern group, significant amounts of picroilmenite have been recovered from four pipes (K1A, K2, K3, and K15). Ilmenite from these bodies consistently contains elevated Nb_2O_5, with individual values up to almost 4 wt.%. The absence of a strong negative correlation with Cr content in the southern cluster bodies argues for an influence on ilmenite composition other than fractional crystallization (Fig. 6).

Evaluation of the mantle oxidation state and thus ‘‘diamond preservation potential’’ through plotting of Cr_2O_3 versus MgO (Haggerty, 1975) reveals a similar differentiation between the K11 and K2/K1A bodies (Fig. 6). Ilmenite data from both K11 and K10 cluster on the ‘‘reduced’’ limb of the parabola, indicating a relatively high degree of diamond preservation; K10 also contains some points plotting towards successively more oxidized compositions and therefore lower degrees of inferred diamond preservation. In the weakly diamondiferous K1A and K2 pipes, ilmenite compositions do not fall on a simple oxidation/reduction parabola, instead forming loose linear trends with

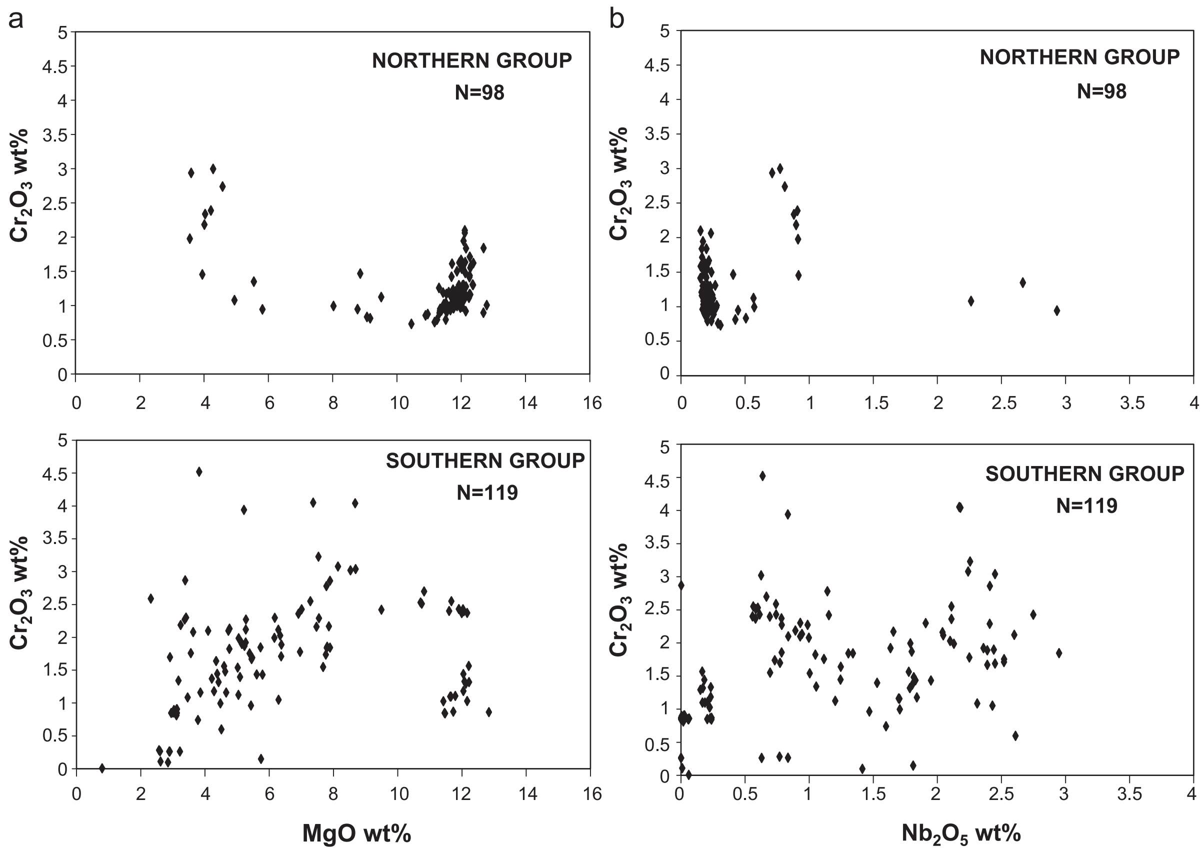

Fig. 6. (a) Cr–Mg plots for picroilmenite from the northern and southern group concentrates. Picroilmenite from the northern group is limited to two bodies (K10 and K11). (b) Cr–Nb plots for picroilmenite in northern and southern group concentrates.

positive slopes (Fig. 6). The association of these unusual trends with elevated niobium contents may be reflective of an additional metasomatic influence that disturbed host oxidation state and provided supplementary element contributions that affected overall Cr_2O_3 content. The overall implication for diamond potential is probably negative due to the implications of isobaric thermochemical modification of the source mantle lithosphere.

3.3. K252: a sample of diamond-bearing Proterozoic mantle?

The K252 kimberlite is geographically situated within the area encompassed by the northern group kimberlites and has the highest diamond content of the Buffalo Hills kimberlites: 55 carats per hundred tonnes from 22.8 tonnes of material. The xenocryst mineral assemblage present within K252 is consistent with other kimberlites nearby, but some chemical characteristics appear to be enhanced, implying a possible relation with diamondiferous mantle lithosphere. As with the other kimberlites, however, the mineral compositions are considered atypical for Archaean mantle.

3.3.1. Peridotitic garnets

In comparison with other kimberlites of the northern group, garnets from the K252 kimberlite are distinguished by a pronounced trend of elevated Ca and Cr, with some grains showing significant knorringite components (Fig. 2). As with the northern group kimberlites, a small proportion of grains with greenish tints contain Cr_2O_3 up to wt.%. The abundance of high-chromium garnet in the most diamondiferous kimberlite implies a relationship between this garnet population and diamond. The complete garnet population projects into the compositional region associated with wehrlites (Sobolev et al., 1973), but its proximity to the spinel–garnet equilibrium line of Kopylova et al. (2000) coupled with the implied high-chromium nature of the peridotite source may be associated with deeper mantle.

3.3.2. Low-Cr garnets

A small population of eclogitic garnets was identified in K252, with grains tending to contain very low TiO_2 and Na_2O (Fig. 4). No low-Cr megacryst-suite garnets were identified in concentrates.

3.3.3. Chromite/chromian spinel

Chromite and chromian spinel from the K252 kimberlite display a strong clustering at higher chromium (45–63 wt.%) contents, with approximately one-third of the analyzed grains falling within the "spinel inclusions in diamond" field of Gurney and Zweistra (1995) (Fig. 5). The population does not strongly follow either the xenocryst or phenocryst compositional trend, although a few grains approximate the xenocryst trend which is exhibited by the northern cluster kimberlites. Low chromium, aluminous spinels from K252 plot near the lower terminus of the xenocryst trend, suggesting a possible genetic relationship with the higher chromium population. The dominance of both high-chromium spinel and garnet in the K252 concentrate may reflect a possible co-genetic relationship, the result of either bulk-compositional differences or higher pressure regime.

Higher average Al contents are also implied from Cr numbers for the spinel population (Fig. 5), suggesting derivation from garnet peridotites containing garnet with elevated Cr. As with other kimberlites in the northern cluster, a subordinate population of spinel peridotite compositions is present. Overall, chromite compositions from K252 typify a "diamond favourable" mantle in the traditional interpretation of xenocryst mineral chemistry (Fipke et al., 1995).

4. Trace element analysis and geothermobarometry

Representative subsamples of garnet, chromite, and pyroxene populations from selected northern and southern kimberlites were subjected to a more rigorous analytical program for determination of trace element contents, including analysis of Ni in peridotitic garnet and Zn in chromian spinel for geothermometry (Ryan et al., 1996; Canil, 1999). Garnet populations from the highly diamondiferous K252 (northern group) and weakly diamondiferous K160 (southern group) kimberlites were examined in particular, for comparison of the two defined groupings. A comparison of the Ni-in-garnet temperatures to those obtained by application of the Mn-in-garnet geothermometer (Grutter et al., 1999) is illustrated in Fig. 7. The relatively good correlation allowed for an evaluation of Mn-temperature for garnets from other kimberlites for which Ni-data were not obtained.

Calculated Ni temperatures for the K6 (northern group), K160 (southern group) and K252 (northern group) kimberlites have been plotted in $CaO–Cr_2O_3$ space, allowing for closer examination of compositional changes associated with changing temperature of equilibration (Fig. 2). Garnet populations from the K252 kimberlite, and to a lesser extent the K6 kimberlite, include grains with relatively high Cr_2O_3 contents that also have calculated temperatures exceeding 1000 °C, the approximate position of the diamond stability field on a 40 mW/m^2 geotherm. These results compare well with inclusions from diamonds, in which lherzolitic garnet–clinopyroxene pairs give equilibration temperatures of 1100 to 1200 + 50 °C on a 40 mW/m^2 geotherm (Davies et al., 2003). In contrast, the

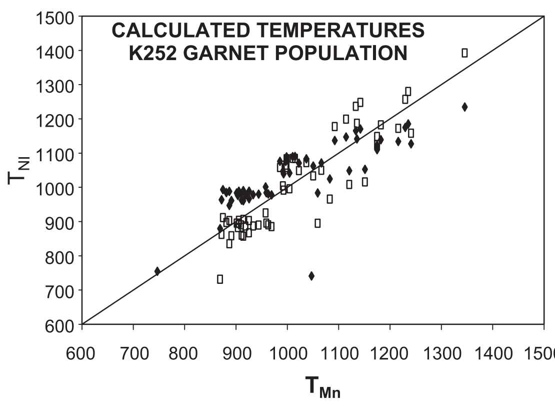

Fig. 7. Comparison of single garnet thermometric techniques for K252 garnets. Ni-in-garnet temperatures are calculated via the methods of Ryan et al. (1996) (open squares) and Canil (1994) (filled diamonds). Mn-in-garnet temperatures calculated according to method of Grutter et al. (1999).

K160 kimberlite consists primarily of temperatures below 1000 °C, with the higher temperature grains having much lower Cr_2O_3 contents. The coincident occurrence of lower Cr_2O_3 and higher temperature (e.g. >1000 °C) in the southern group kimberlite may indicate the presence of a thinner lithosphere, or more extensive thermal alteration at depths coincident with the diamond stability field. This trend has been observed in other kimberlites from the southern group.

The garnet populations also show distinct differences in their trace element composition. The K252 kimberlite consistently displays lower levels of the "metasomatic indicator" elements (Zr, Y) relative to temperature (Fig. 8). In contrast, the K160 kimberlite contains a well-defined population of higher Zr, Y and TiO_2 garnets over the calculated temperature spectrum, suggesting thermal and chemical modification at the base of the lithosphere (e.g. Griffin et al., 1999a,b). The metasomatized garnet population within a diamond-poor kimberlite may imply a thinner (shallower) lithosphere associated with the K160 garnets, or a diamond-destructive event that has altered the bulk of the lithosphere within the diamond stability field.

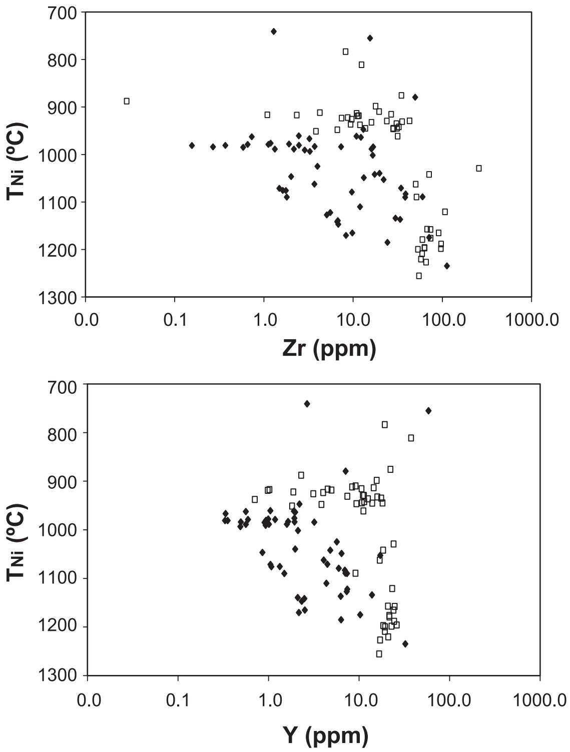

Fig. 8. Comparative trace element chemistry for peridotitic garnets from K252 (filled diamonds) and K160 (hollow squares). T_{Ni} is calculated using the method of Canil (1999).

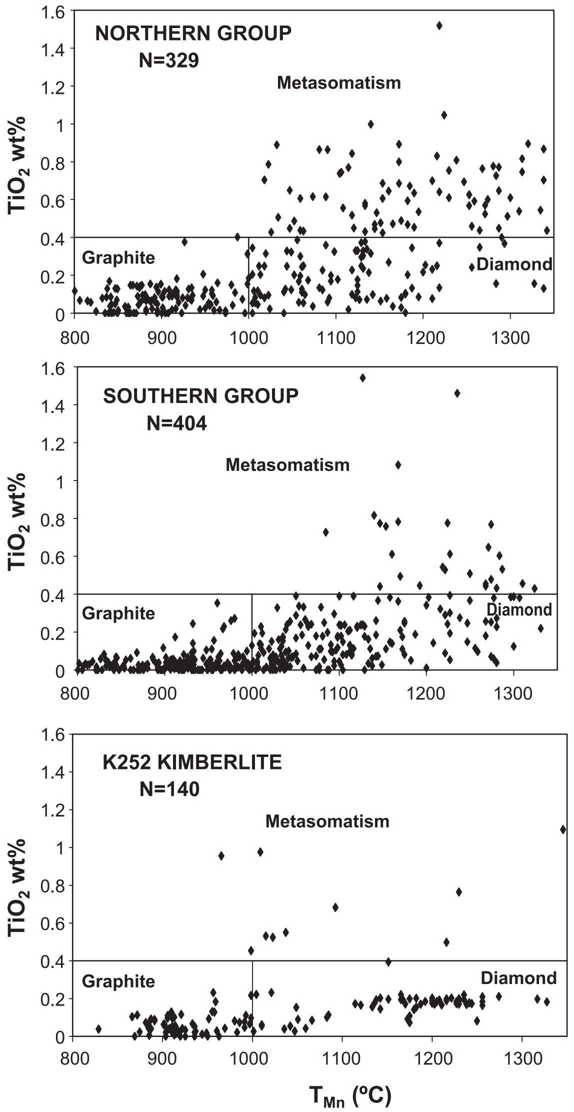

Fig. 9. T_{Mn}–Ti diagrams for peridotitic garnet populations from the northern and southern groups, and for peridotitic garnets from the K252 kimberlite. Fields defined according to a 40 mW/m^2 geotherm.

Garnet TiO_2 contents from kimberlites in the Buffalo Hills exhibit little apparent contrast between northern and southern group bodies when plotted against Mn-temperatures (Fig. 9). In the K252 pipe, however, garnet TiO_2 contents define a relatively narrow, even representation up to the upper limit of the Mn-thermometry method, including pronounced sampling from within the diamond stability field at T_{Mn}>1000 °C (Fig. 9). In other northern and southern group bodies, a large number of grains fall within the high-Ti field of metasomatism regardless of grouping. The implication is that the best potential diamond source has the highest number of low-Ti garnets with temperatures above ~1000 °C.

Although unaltered clinopyroxene grains are rare, single grain thermobarometry has also been applied to clinopyroxene grains from northern and southern kimberlites, using the method defined by Nimis and Taylor (2000). Results do not define a particular geotherm (e.g. Pollack and Chapman, 1977) and difficulties with the application limit use of the technique. Clinopyroxene has been identified in some Buffalo Hills diamonds (Davies et al., 2003).

5. Discussion and conclusions

A traditional assessment of xenocryst mineral compositions for the Buffalo Hills kimberlite province would conclude that it has poor economic diamond potential. All of the chemical plots, with the possible exception of those for chromite, imply that diamond from conventional parent rocks such as harzburgite and eclogite would be lacking. To some degree the assessment is correct, as most of the kimberlites for which tonnage-sized samples have been treated indicate diamond contents of less than 20 carats per hundred tonnes (Skelton et al., 2003). However, the interpretation would also extend to the K252 kimberlite, which based on its pyrope chemistry should have a diamond content comparable to or less than 10 carats per hundred tonnes (Fipke et al., 1995). With a grade of 55 carats per hundred tonnes and diamonds approaching one carat in size, K252 is distinguished by a singular lack of typical G10 pyrope, sodic eclogitic garnet, and exceptional numbers of favourable chromite. More elaborate assessments such as *P–T* constraints for garnets and clinopyroxenes also produce results that would indicate low diamond potential. An argument could be made that the xenocryst mineral suite does not represent the parent rocks from which diamond was derived. This may be true for clinopyroxene xenocrysts, if comparable to clinopyroxenes from xenoliths (Aulbach et al., this volume), but not for clinopyroxene inclusions in diamond (Davies et al., this volume). For the pyrope garnets, the Mn- and Ni-temperatures demonstrate that some could have derived from within the diamond stability field for a typical cratonic geotherm. Even though the pyrope are lherzolitic in composition, that they could have derived from the diamond stability field is supported in part by the fact that the only pyrope inclusion found in a Buffalo Hills diamond to date is lherzolitic in composition (Davies et al., this volume).

Although the xenocryst mineral chemistry for the Buffalo Hills kimberlites in many ways contradicts conventional thought regarding diamond co-genesis, this study indicates that some regional variations can be related to diamond content, and to geographic position. In the latter context, this has implications with respect to lithosphere evolution beneath the Buffalo Head Terrane. The mantle xenocryst compositions support a variably metasomatised lithosphere, also supported by xenolith studies (Aulbach et al., 2003) and by inclusions of disparate origin in single diamonds (Davies et al., 2003). The most significant feature in the Buffalo Head Terrane is the absence of typical Archaean material, either as xenocrysts, xenoliths, or inclusions in diamond. This combined evidence suggests either that Archaean mantle is missing beneath this terrane, or that chemical evidence of its existence has been completely obliterated from the geologic and geochemical record.

Closer examination of garnet, chromite, and picroilmenite data from various bodies from the Buffalo Hills indicates that a number of subtle trends are present within the more diamondiferous pipes. High chromium populations and slightly lower average calcium lherzolitic trends distinguish the peridotitic garnet populations from all of the more diamond-rich bodies, with an eclogitic component implied by data from the K10 and K11 kimberlites. Chromite data highlight the importance of identifying the trend of interest, particularly when considering its dominance in the diamond-bearing pipes of the northern group and K252. An additional significance may be attached to the presence of a complex mantle lithosphere, as implied by both garnet and chromite populations from bodies within the northern group. Picroilmenite is of more limited application due to its restricted occurrence, but a rough association may be made between low niobium contents and higher diamond content in the pipes where it is present.

The presence of the high-chromium, slightly subcalcic garnets within the northern kimberlites may be a high-pressure analogue of peridotitic mantle. Coexistence with chromian spinel implies that garnet chromium content can be qualitatively linked with depth (Doroshev et al., 1997; Grutter et al., 1999), suggesting that the grains may represent the deeper, potentially diamond-favourable mantle lithosphere.

Two external influences on the Buffalo Head mantle lithosphere may be reflected in the xenocryst data. The first control is defined by the history of the terrane itself, with a crystalline block of probable Paleoproterozoic age forming the core area and represented by lherzolitic, wehrlitic and websteritic garnet compositions. Development of compressional regimes during formation of the Ksituan and Taltson-Thelon magmatic arcs (Ross et al., 1991) allowed for accretion of eclogitic material to the base of the lithosphere, with associated volatile release affecting the margins of the block. Further melt-generated, incompatible element-rich metasomatism associated with inflation of the Peace River Arch and related structures also appears to have affected the vicinity of the arch, producing a diamond-destructive event in lithosphere sampled by the southern kimberlites. The association of higher temperature, Cr-rich pyrope (and, to a lesser extent, xenocrystic Mg–Al spinel) with the more diamondiferous northern cluster bodies may be related to the first event, defining a thicker, more complex section of lithosphere favourable for the formation of diamond. The absence of highly depleted mantle signatures throughout the Buffalo Hills xenocryst suite, and in the least metasomatized northern group kimberlites argues for an overall Proterozoic age for the mantle lithosphere, suggesting that similar, relatively stable crystalline blocks can potentially host diamond-bearing kimberlite.

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