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KIMBERLITE INDICATOR MINERAL CHEMISTRY OF THE BUCKE AND GRAVEL KIMBERLITES AND ASSOCIATED INDICATOR MINERALS IN TILL, LAKE TIMISKAMING, ONTARIO

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ABSTRACT

A well documented glacial dispersal fan of kimberlite indicator minerals extends southward from the region of the Late Jurassic Bucke and Gravel kimberlites in the Lake Timiskaming kimberlite field of northeastern Ontario. The Geological Survey of Canada collected and analyzed a sample of kimberlite from both pipes and re-examined and analyzed indicator minerals from archived heavy mineral concentrates of till samples from the dispersal fan. The Bucke kimberlite contains more than 30,000 indicator mineral grains per 10 kg sample in the 0.25 to 0.5 mm fraction, which consists of, in decreasing order of abundance, Cr-pyrope>>Mg-ilmenite>chromite>Cr-diopside. The Gravel kimberlite is three times as indicator mineral rich, containing more than 100,000 grains per 10 kg sample in the 0.25 to 0.5 mm fraction, which consist of Mg-ilmenite>>Cr-pyrope>chromite>Cr-diopside. No olivine was recovered from either sample. Till samples within the fan contain 100s to 1000s of indicator minerals per 10 kg sample, mostly Mg-ilmenite, with Cr-pyrope and chromite, and lesser amounts of Cr-diopside and minor olivine. Indicator minerals are most abundant to the southwest to southeast of the two kimberlites and form a fan-shaped dispersal pattern that extends at least 6 km, and potentially 30 km down-ice. The results presented here demonstrate how ice-flow mapping can be combined with indicator mineral abundance, mineral chemistry, and relative abundance data to define dispersal patterns from kimberlite.

INTRODUCTION

The Bucke and Gravel kimberlites are located in the central part of the Lake Timiskaming kimberlite field, in northeastern Ontario (Fig. 1). The existence of a glacial dispersal fan of Mg-ilmenite, Cr-pyrope, chromite, and Cr-diospide grains in till extending at least 12 km south of the kimberlites (Fig. 2; Kjarsgaard et al., 2003) has been recognized by diamond exploration companies for more 20 years (D. Boucher, pers. comm., 2007). At least two companies identified a fan-shaped distribution of kimberlite indicator minerals in till down ice from the Gravel kimberlite, and potentially the Bucke kimberlite, through regional till sampling programs (Fig. 2). The eastern edge of this indicator mineral fan was detected during detailed till sampling in 1999 by the Geological Survey of Canada (GSC) around the Peddie kimberlite (McClenaghan et al., 1999, 2002a), approximately four kilometres southeast of the Gravel kimberlite (Fig. 2).

The GSC was given the opportunity to collect kimberlite samples from the Gravel and Bucke kimberlites (via De Beers Canada Exploration Inc.) to document their mineralogical signatures, as well as analyze indicator minerals from archived heavy mineral concentrates from till samples collected within the dispersal fan by Sudbury Contact Mines (currently Stornoway Diamond Corp.). The purposes of this GSC study were to document the indicator mineral signature of the kimberlites, and the existence and character of the kimberlite dispersal pattern. These objectives were achieved

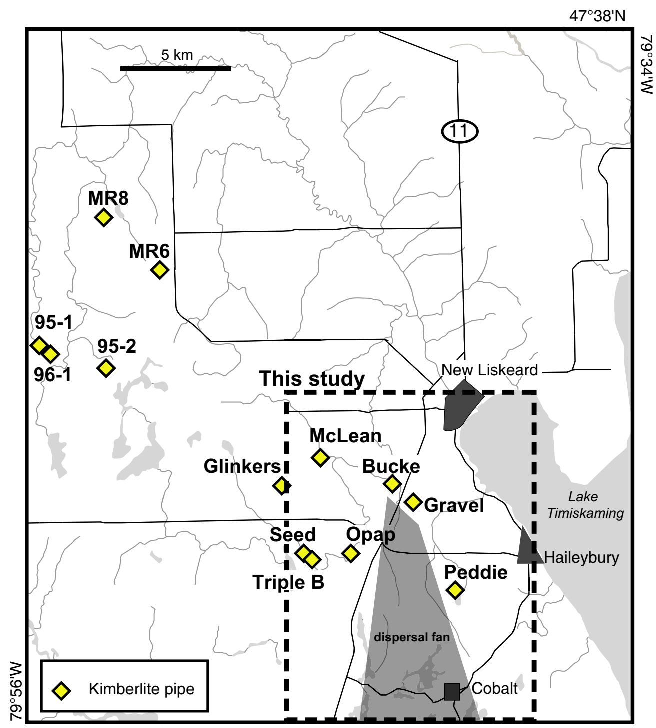


Figure 1. Location of the Bucke and Gravel kimberlites within the Lake Timiskaming kimberlite field in northeastern Ontario, and the outline of the kimberlite indicator mineral dispersal fan (dark grey) as was reported in Kjarsgaard et al. (2003).

by examining selected archived till concentrates both within and outside (north, east, and west) of the disper-

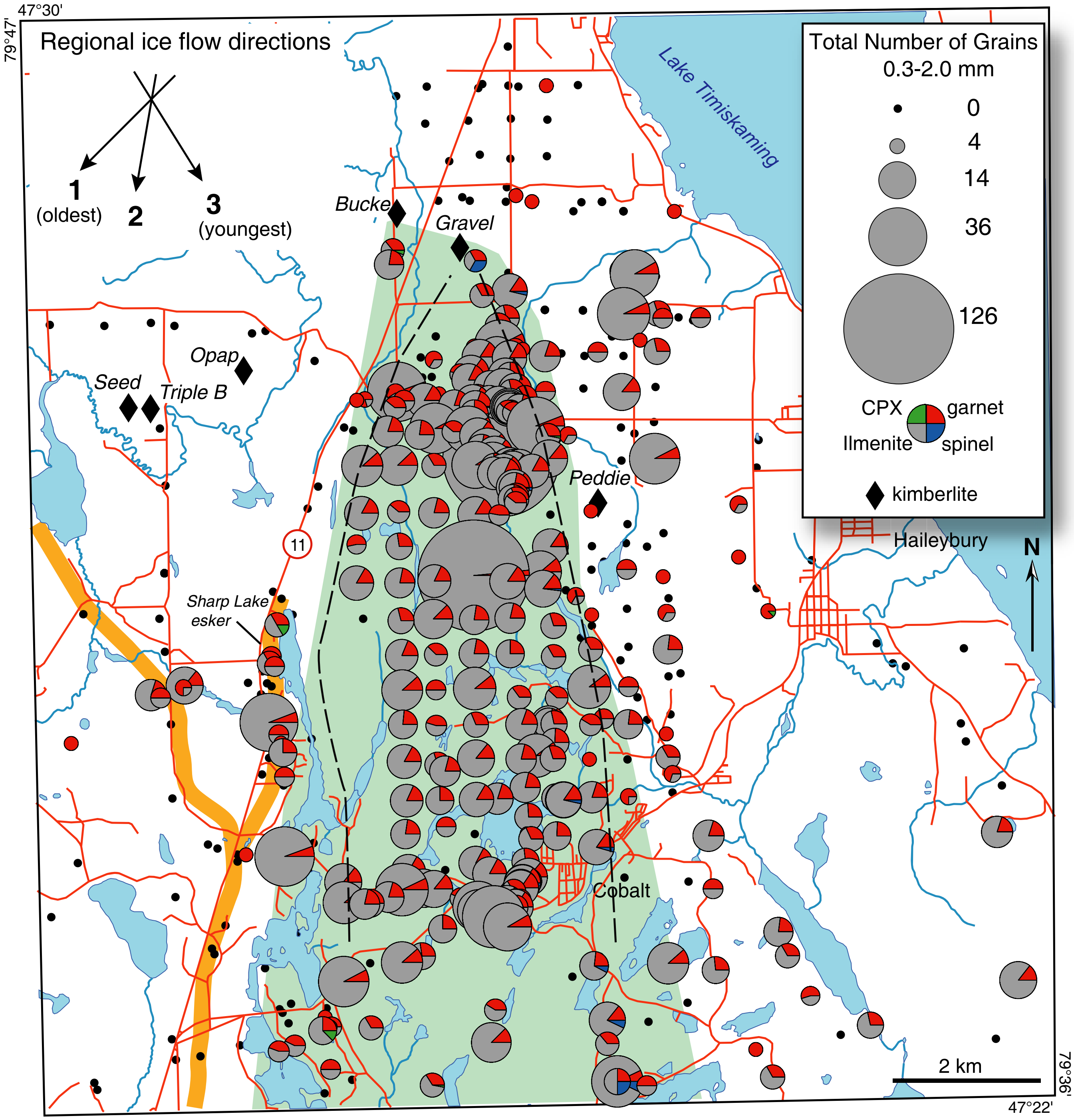


Figure 2. Abundance of kimberlite indicator minerals in till samples around the Bucke and Gravel kimberlites (unpublished data from De Beers Canada Inc., 2003) plotted as proportional pie diagrams. A fan-shaped dispersal train (shaded green) down ice of the Bucke and Gravel kimberlites has been outlined using these data (from Kjarsgaard et al., 2003). Black dashed lines outline the dispersal train from the Gravel kimberlite that has been interpreted from unpublished Sudbury Contact Mines indicator mineral data (2005). Regional ice-flow data are from Veillette (1996).

sal fan. This report describes the results of the GSC investigations.

Location and Access

The Bucke kimberlite is located four kilometres southwest of New Liskeard, at Easting 596650 and Northing 5258925 (UTM Zone 17, NAD27) in Bucke Township. The site can be accessed by a gravel road that extends west from Highway 11. The Gravel kimberlite is one kilometre to the southeast, at Easting 597500 and Northing 5258450 (UTM Zone 17, NAD27) (Fig. 3), also in Bucke Township. This kimberlite is in a farmer’s field, east of Highway 11.

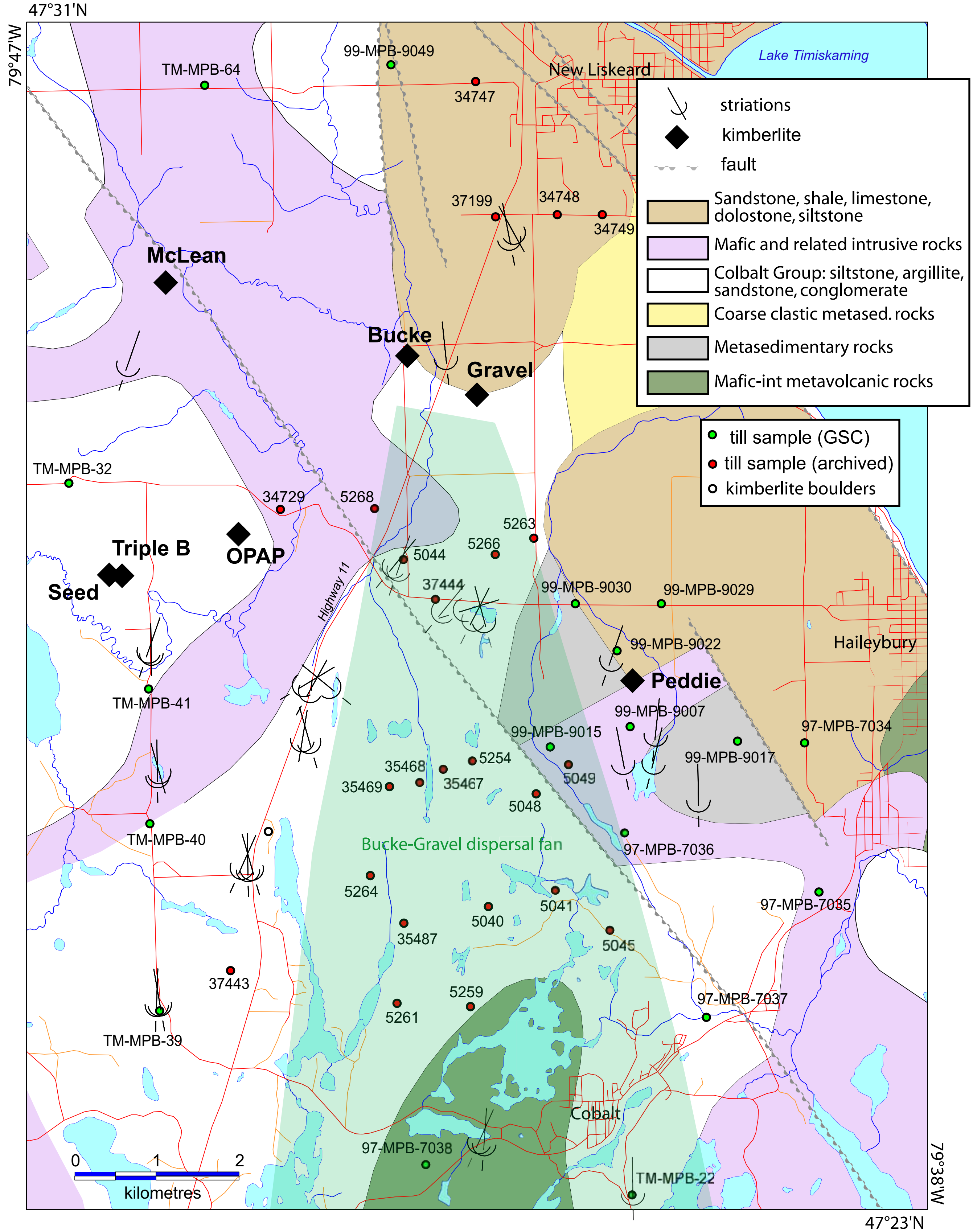


Figure 3. Bedrock geology in the study area (geology modified from Ontario Geological Survey, 1991), with location of archived till heavy mineral concentrates examined in this study and Geological Survey of Canada till samples from previous studies (McClenaghan et al., 1999, 2001, 2002a). Striation data are from McClenaghan and Veillette (2001).

GEOLOGY

Local Bedrock Geology

The bedrock geology in the immediate area of the Bucke and Gravel kimberlites consists of Archean metaconglomerate of the Timiskaming Formation, and Paleoproterozoic divaricate and argillite of the Gowganda Formation (Young and Nesbitt, 1999), which are cut by Paleoproterozoic Nipissing diabase sills (Lightfoot et al., 1993). Just to the north of the kimberlites are the Paleozoic limestones of the Ferrar Formation (Fig. 3), which are part of the Lake Timiskaming outlier (Grant and Owsiacki, 1987).

Kimberlite Geology

The Bucke kimberlite was discovered in the early 1980s by De Beers Canada Inc. (formerly Monopros Ltd.) following up airborne and ground geophysical surveys. It was subsequently restaked and drilled by several companies, including LAC Minerals Ltd. in 1987-1988 (Brummer et al., 1992), KWG Resources Ltd. in 1992-1993 (Sage, 1996), and NovaWest Resources in 2000. The Bucke kimberlite has a circular, positive magnetic signature (Brummer et al., 1992) and is at least 230 m in width. Brummer et al. (1992) report that the kimberlite consists of tuffisitic kimberlite breccia with country rock xenoliths of diabase, limestone, mudstone, and volcanic rocks. Macrocryst minerals include olivine, orange and purple garnets, ilmenite, and phlogopite. U/Pb age determinations on perovskite separates yielded an age of 155.4 ± 1.5 Ma for the kimberlite (Heaman and Kjarsgaard, 2000). Brummer et al. (1992) and Sage (1996) report recoveries of a few micro- and macrodiamonds from the kimberlite by the various companies that have evaluated the pipe.

The Gravel kimberlite was discovered by Falconbridge Ltd. in the 1990s through of its positive magnetic signature. It has since been restaked and drilled by other exploration companies. The kimberlite is of similar age to the Bucke kimberlite, as determined by a U-Pb perovskite age determination of 151.8 ± 2.2 Ma (Heaman and Kjarsgaard, 2000). At least four macrodiamonds (<0.5 mm diameter) have been recovered from the kimberlite (Sage, 1996).

Quaternary Geology

During the Wisconsinan, the Lake Timiskaming region was covered by the Laurentide Ice Sheet, which deposited a carbonate-rich grey silty sand till on top of bedrock. Till thickness varies from less than 1 m to occasionally more than 5 m. Where the till is thin, it is generally more locally derived. Striated bedrock in the area records evidence of three major ice-flow phases (Veillette 1996; McClenaghan and Veillette, 2001) during the Wisconsinan (Fig. 3). The oldest flow (Phase 1) was west-southwest and likely was associated with the main phase of the Laurentide Ice Sheet. During deglaciation, ice flow shifted counterclockwise (Phase 2) becoming southwest to south. During final deglaciation of the area, local ice tongues from the main ice sheet occupied the structural depressions of the Montreal River and Lake Timiskaming, giving rise to ice flow towards the southeast (Phase 3). All three phases of ice flow are associated with erosion and transportation of kimberlite debris in the region (Veillette, 1986, 1989, 1996; Veillette and McClenaghan, 1996; McClenaghan and Veillette, 2001) and deposition of till. Striated bedrock nearest the two kimberlites show evidence of all three phases of ice flow, but are dominated by Phase 2 and 3 striae (Fig. 3). Till in the local area is likely the product of both Phase 2 and Phase 3 ice flows.

As the glacier retreated northward approximately 9500 years ago, glacial Lake Barlow ponded in front of the ice sheet and thick sequences of fine-grained glaciolacustrine sediments were deposited on top of till and bedrock (Vincent and Hardy, 1979; Veillette, 1988, 1989, 1996). Glacial Lake Barlow receded from the New Liskeard area approximately 8000 years ago (Veillette, 1994) and surficial sediments have been exposed to normal postglacial weathering and soil-forming processes since that time. Quaternary sediments immediately around and overlying the Bucke and Gravel kimberlites are thick and consist of glaciolacustrine clay at surface. The Bucke kimberlite is overlain by approximately 40 m of glacial sediments consisting of clay, sand, and gravel (Brummer et al., 1992). Six diamond drill holes into the Gravel kimberlite intersected glacial sediments varying between 9.1 and 20. 5 m in thickness (Sage, 1996). Glaciolacustrine sediments generally thin southward of both kimberlites as the bedrock surface rises, such that approximately 2 km to the south thin till and bedrock are exposed at surface.

METHODS

Sample Collection and Preparation

Kimberlite samples were collected from diamond drill core provided by DeBeers Canada Inc. Sample KIA-03-77 was collected from a depth of 48.8 m in hole 01 in the Gravel kimberlite. Sample KIA-03-85-1 was collected from a depth of 23.5 m in hole 01 from the Bucke kimberlite. Both samples were processed by Overburden Drilling Management Ltd. (ODM), Ottawa, using procedures similar to those described in McClenaghan et al. (2003a,b). Samples were first crushed to <2 mm sized fragments and then processed using tabling and heavy liquids to prepare non-ferromagnetic heavy mineral concentrates. From these concentrates, the non-ferromagnetic 0.25-0.5 mm, 0.5-1.0 mm, and 1.0-2.0 mm heavy mineral fractions were sieved in preparation for picking. Weights for each fraction produced during sample processing of kimberlite are listed in Appendix B1.

Sudbury Contact Mines Ltd. (now Stornoway Diamond Corp.) collected till samples in the area around the Bucke and Gravel kimberlites between 1993 and 1996. These till samples were processed at the time of collection by ODM, who prepared non-ferromagnetic heavy mineral concentrates for the 0.25-0.5 mm, 0.5-1.0 mm, and 1.0-2.0 mm fractions of till. These samples were then visually examined by ODM and kimberlite indicator minerals (Cr-pyrope, eclogitic garnet, Mg-ilmenite, chromite, and Cr-diopside) abundances were determined. The concentrates were then archived. In 2003, the GSC selected 24 of the archived concentrates in order to study sample sites along east-west-oriented transects perpendicular to the dispersal fan at 4 km north (up-ice), 2 km north (up-ice), 2 km south, 4-5 km south, and 6-7 km south (Fig. 3). Location information for each sample site is listed in Appendix A. ODM weight data for till samples are listed in Appendix B2.

Kimberlite Indicator Mineral Identification

Three size fractions of the two kimberlite samples were examined by I. & M. Morrison Geological Services, Vancouver, and potential kimberlite indicator minerals were counted and set aside for electron microprobe (EMP) analysis. For the archived concentrates examined in this study, indicator minerals were originally picked by ODM and set aside in vials. The 0.25- 0.5 mm fraction of the concentrates were then examined by I & M Morrison Geological Services, the indicator minerals counted and added to the number of grains initially picked by ODM. From both picking groups, selected grains were mounted for EMP analysis. Visual grain counts for kimberlite and till samples are listed in Appendix C. Indicator minerals were visually selected on the basis of physical properties such as colour, grain morphology, and/or the presence of adhering kimberlite matrix material (e.g. McClenaghan and Kjarsgaard, 2007). Minerals picked included purple Cr-pyrope, red titanian Cr-poor pyrope (megacryst garnet), orange Mg-almandine garnet (eclogitic garnet), green Cr-diopside, black Mg-ilmenite, chromite, and pale yellow forsteritic olivine. Selected grains were mounted in 25 mm epoxy mounts and polished at Lakefield Research (now SGS Minerals), Lakefield, Ontario in preparation for EMP analysis to confirm their identity and further classify them using mineral chemistry. Most EMP analyses were carried out at GSC-Ottawa using operating conditions and mineral-sorting routines similar to those described in McClenaghan et al. (1999). EMP data are listed in Appendix D. Cr-diopside, as defined in this study, contains >0.5 wt.% Cr_2O_3.

EMP analysis of potential olivine grains was carried out at the Ontario Ministry of Northern Development and Mines (MNDM) Geoscience Laboratories, Sudbury, Ontario using a Cameca SX-100 Electron Probe Micro Analyzer (EPMA). Major elements were analyzed under normal operating conditions (20 kV and 20nA), whereas minor/trace element analyses were carried out using a higher beam current (20 kV and 200 nA) and where possible large surface area crystals (LLIF and LPET) were employed to improve the L.O.D.s.

For samples that contained hundreds to thousands of indicator minerals, a selection of indicator minerals were analyzed by EMP (Appendix C, part b) to establish the compositional range of each mineral species, as well as determine the success rate (correction factor) of the visual identification (Appendix C, part d). Indicator mineral counts were then corrected to reflect the number of grains for which identification was either confirmed by microprobe analysis or adjusted using the correction factors (Appendix C, part e). The correction factors were calculated by comparing the number of grains correctly identified and confirmed by microprobe analysis to the number picked and probed. Corrected counts were then normalized to a 10 kg sample weight (Appendix C, part f) and these normalized grain counts are reported in Table 1, plotted on maps, and discussed below.

In addition to the archived samples examined in this study, indicator mineral abundance and mineral chemistry data for proximal till samples from previously published GSC reports were included in indicator mineral distribution plots to provide a regional context for interpreting the dispersal fan data (Fig. 4, 5). Proximal GSC till samples include TM-MPB-22, -32, -39, -40, -41, -64 (McClenaghan et al., 2001); 97-MPB-34 to -38 (McClenaghan et al., 1999); and 99-MPB-15, -22, -29, -30, -49 (McClenaghan et al., 2002a). A designation as to whether each sample is within the dispersal fan identified by De Beers (*within dispersal fan*) or outside the fan (*background*) is listed in Table 1. These designations will be used when describing the results. Indicator mineral abundance data were plotted as proportional symbols and pie symbols in Figures 5 and 6 using Mapinfo Professional® Version 7.8.

KIMBERLITE INDICATOR MINERAL ABUNDANCE AND DISTRIBUTION

Kimberlites

The Bucke kimberlite contains several tens of thousands of indicator mineral grains per 10 kg (Table 1). Cr-pyrope garnet is the most abundant followed closely

Table 1. Kimberlite indicator mineral abundance data for the 0.25-0.5 mm fraction normalized to 10 kg sample weight for kimberlite and till samples around the Bucke and Gravel kimberlites (from Appendix C), till sample distance from kimberlites, and calculated proportions of indicator minerals

Sample	Location	Material	Source of the Data	Cr-Pyrope	E-Garnet	Mg-Ilmenite	Chromite	Cr-Diopside	Olivine	Distance Down-Ice from Gravel Kimberlite (m)	Within Dispersal Fan?	Total Number of Indicator Minerals	% Mg-Ilmenite	% Garnet	% Chromite	% Cr-Diopside	% Olivine
5040	dispersal fan 5-6 km	till	this study	114	0	392	31	6	0								
5041	dispersal fan 5-6 km	till	this study	1326	0	413	957	35	9	6.0	yes	2739	15	48	35	1	0
5044	dispersal fan 1.5-2.5 km	till	this study	600	0	6221	900	50	0	2.2	yes	7771	80	8	12	1	0
5045	dispersal fan 5-6 km	till	this study	41	0	242	125	9	1	6.6	yes	418	58	10	30	2	0
5048	dispersal fan 4-5 km	till	this study	849	0	5048	65	12	5	4.9	yes	5979	84	14	1	0	0
5049	dispersal fan 4-5 km	till	this study	983	1	2588	80	7	6	4.5	yes	3666	71	27	2	0	0
5254	dispersal fan 4-5 km	till	this study	105	0	626	18	20	4	4.4	yes	772	81	14	2	3	1
5259	dispersal fan 5-6 km	till	this study	32	0	87	7	2	0	7.4	yes	128	68	25	6	2	0
5261	dispersal fan 5-6 km	till	this study	218	0	711	203	10	10	7.4	yes	1154	62	19	18	1	1
5263	dispersal fan 1.5-2.5 km	till	this study	14	0	63	52	8	0	1.6	yes	136	46	10	38	6	0
5264	dispersal fan 5-6 km	till	this study	259	0	1363	184	5	3	6.0	yes	1814	75	14	10	0	0
5266	dispersal fan 1.5-2.5 km	till	this study	1169	0	6262	176	46	6	1.8	yes	7659	82	15	2	1	0
5268	background-west	till	this study	19	0	24	40	3	0	1.9	yes	87	28	22	46	4	0
34729	background-west	till	this study	1	0	4	9	0	0	2.8	no	15	27	9	64	0	0
34747	background-up-ice	till	this study	3	0	2	14	13	4	-3.8	no	36	5	8	38	37	12
34748	background-up-ice	till	this study	2	0	4	23	18	4	-2.4	no	50	8	4	45	35	8
34749	background-up-ice	till	this study	1	0	14	14	23	0	-2.6	no	52	27	2	27	44	0
35467	dispersal fan 4-5 km	till	this study	113	0	393	24	7	1	4.5	yes	538	73	21	5	1	0
35468	dispersal fan 4-5 km	till	this study	1361	0	2554	971	49	34	4.7	yes	4970	51	27	20	1	1
35469	dispersal fan 4-5 km	till	this study	396	0	892	21	23	0	4.8	yes	1332	67	30	2	2	0
35487	dispersal fan 5-6 km	till	this study	217	0	619	75	18	13	6.5	yes	942	66	23	8	2	1
37199	background-up-ice	till	this study	3	0	2	8	9	1	-2.0	no	23	8	12	36	40	4
37443	background-west	till	this study	1	0	3	10	1	5	7.6	no	21	16	6	48	6	24
37444	dispersal fan 1.5-2.5 km	till	this study	156	1	254	70	6	7	2.5	yes	494	51	32	14	1	1
97-MPB-7834	background-east	till	McClenaghan et al. 1999	3	0	23	46	10	0	5.6	no	82	28	4	56	12	0
97-MPB-7835	background-east	till	McClenaghan et al. 1999	3	0	6	1	1	4	7.0	no	15	40	20	7	7	27
97-MPB-7836	dispersal fan 4-5 km	till	McClenaghan et al. 1999	16	0	57	3	7	0	4.8	yes	83	69	19	4	8	0
97-MPB-7837	background-east	till	McClenaghan et al. 1999	3	0	2	1	0	2	7.7	no	8	25	38	13	0	25
97-MPB-7838	dispersal fan 8 km	till	McClenaghan et al. 1999	2	0	0	1	1	8	8.2	yes	12	0	17	8	8	67
99-MPB-9007	background-east	till	McClenaghan et al. 2002a	0	0	3	0	0	0	4.5	no	3	100	0	0	0	0
99-MPB-9015	dispersal fan 4-5 km	till	McClenaghan et al. 2002a	143	0	1321	16	13	0	4.0	yes	1493	88	10	1	1	0
99-MPB-9017	background-east	till	McClenaghan et al. 2002a	1	0	12	4	4	0	5.5	no	21	57	5	19	19	0
99-MPB-9022	background-east	till	McClenaghan et al. 2002a	0	0	6	8	6	0	3.5	no	20	30	0	40	30	0
99-MPB-9029	background-east	till	McClenaghan et al. 2002a	0	0	4	4	0	0	3.0	no	8	50	0	50	0	0
99-MPB-9030	dispersal fan 1.5-2.5 km	till	McClenaghan et al. 2002a	13	0	75	13	15	0	2.7	yes	116	65	11	11	13	0
99-MPB-9049	background-up-ice	till	McClenaghan et al. 2002a	6	0	0	0	0	0	-3.0	no	6	0	100	0	0	0
TM-MPB-32	background-west	till	McClenaghan et al. 2001	3	0	4	1	4	0	4.7	no	12	33	25	8	33	0
TM-MPB-39	background-west	till	McClenaghan et al. 2001	2	0	9	11	6	0	7.0	no	28	32	7	39	21	0
TM-MPB-40	background-west	till	McClenaghan et al. 2001	0	0	31	29	4	0	5.5	no	64	48	0	45	6	0
TM-MPB-41	background-west	till	McClenaghan et al. 2001	0	0	5	8	3	0	4.8	no	16	31	0	50	19	0
TM-MPB-64	background-up-ice	till	McClenaghan et al. 2001	1	0	0	22	10	0	-2.0	no	33	0	3	67	30	0
TM-MPB-22	dispersal fan 9 km	till	McClenaghan et al. 2001	0	0	6	8	6	0	9.0	yes	20	30	0	40	30	0
K1A-03-77	source kimberlite	Gravel kimberlite	this study	16017	197	108426	156	109	0	0.0	yes	124905	87	13	0	0	0
K1A-03-85-1	source kimberlite	Bucke kimberlite	this study	18032	72	12857	1125	149	0	0.0	yes	32235	40	56	3	0	0
97-MPB-7810	4 km southeast	Peddie kimberlite	McClenaghan et al. 1999	685	0	1131	241	269	·5000	4.0	no	2330	9	6	2	2	81
MPB-SD-013	5 km southwest	Seed kimberlite	McClenaghan et al. 2004	133	0	3653	5	59	0	5.0	no	3855	95	3	0	2	0
MPB-02-1006	5 km southwest	Triple B kimberlite	McClenaghan et al. 2004	409	0	3557	34	300	23	5.0	no	4328	82	9	1	7	1
99MPB9050	3 km northwest	McLean kimberlite	McClenaghan et al. 2003a	30	0	8	3	30	·2000	3.0	no	74	1	2	0		95

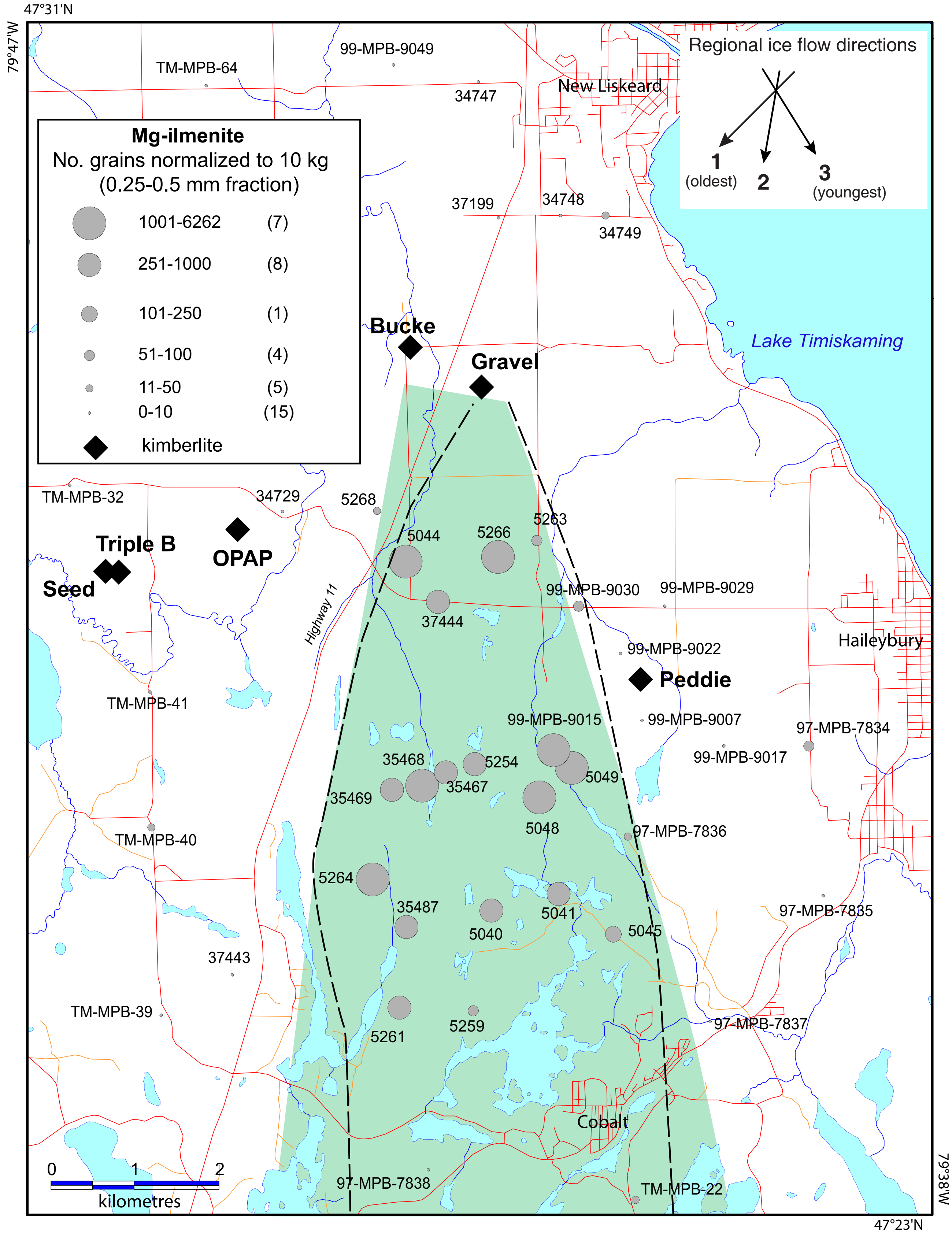


Figure 4. Proportional dot maps showing the distribution of indicator minerals in the 0.25 to 0.5 mm fraction of till down-ice from the Bucke and Gravel kimberlites. The fan-shaped dispersal train determined from DeBeers data (2003) is shown as green shading and from Sudbury Contact Mines data (2005) is outlined with black dashed lines. Regional ice-flow data are from Veillette (1996). Modified from Kjarsgaard et al. (2003). **a)** Distribution of Mg-ilmenite.

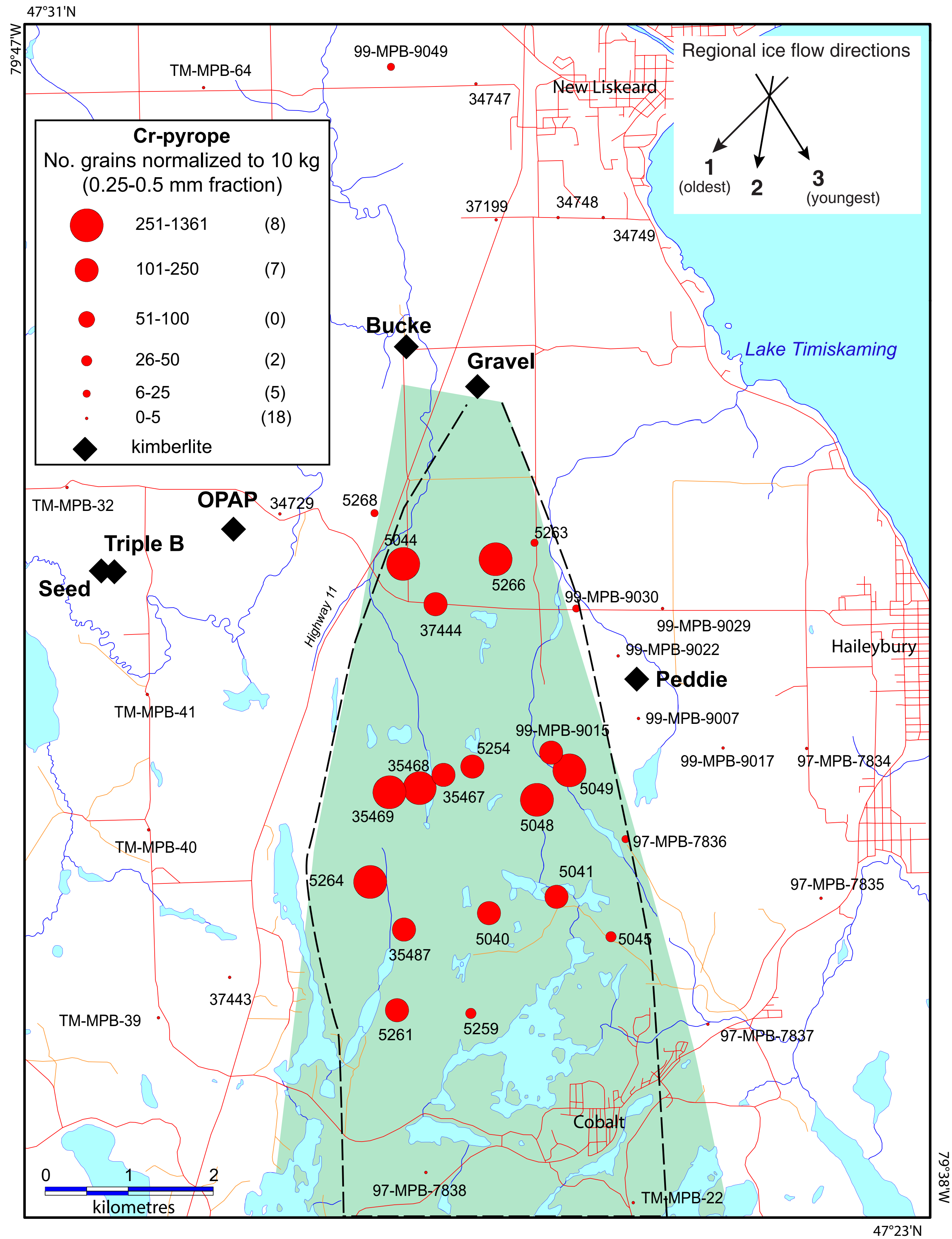


Figure 4 continued. b) Distribution of Cr-pyrope garnet minerals in the 0.25 to 0.5 mm fraction of till down-ice from the Bucke and Gravel kimberlites.

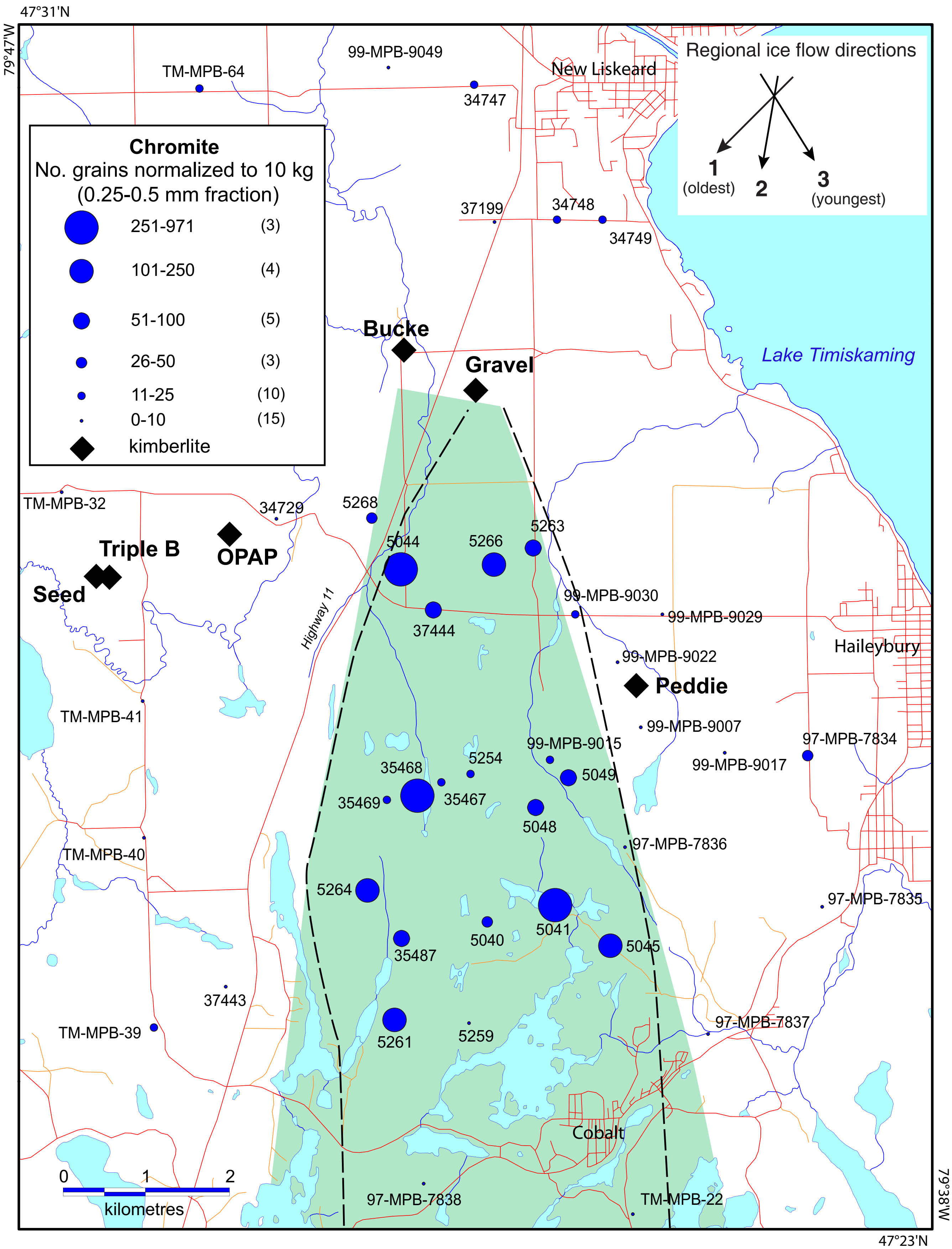


Figure 4 continued. c) Distribution of chromite minerals in the 0.25 to 0.5 mm fraction of till down-ice from the Bucke and Gravel kimberlites.

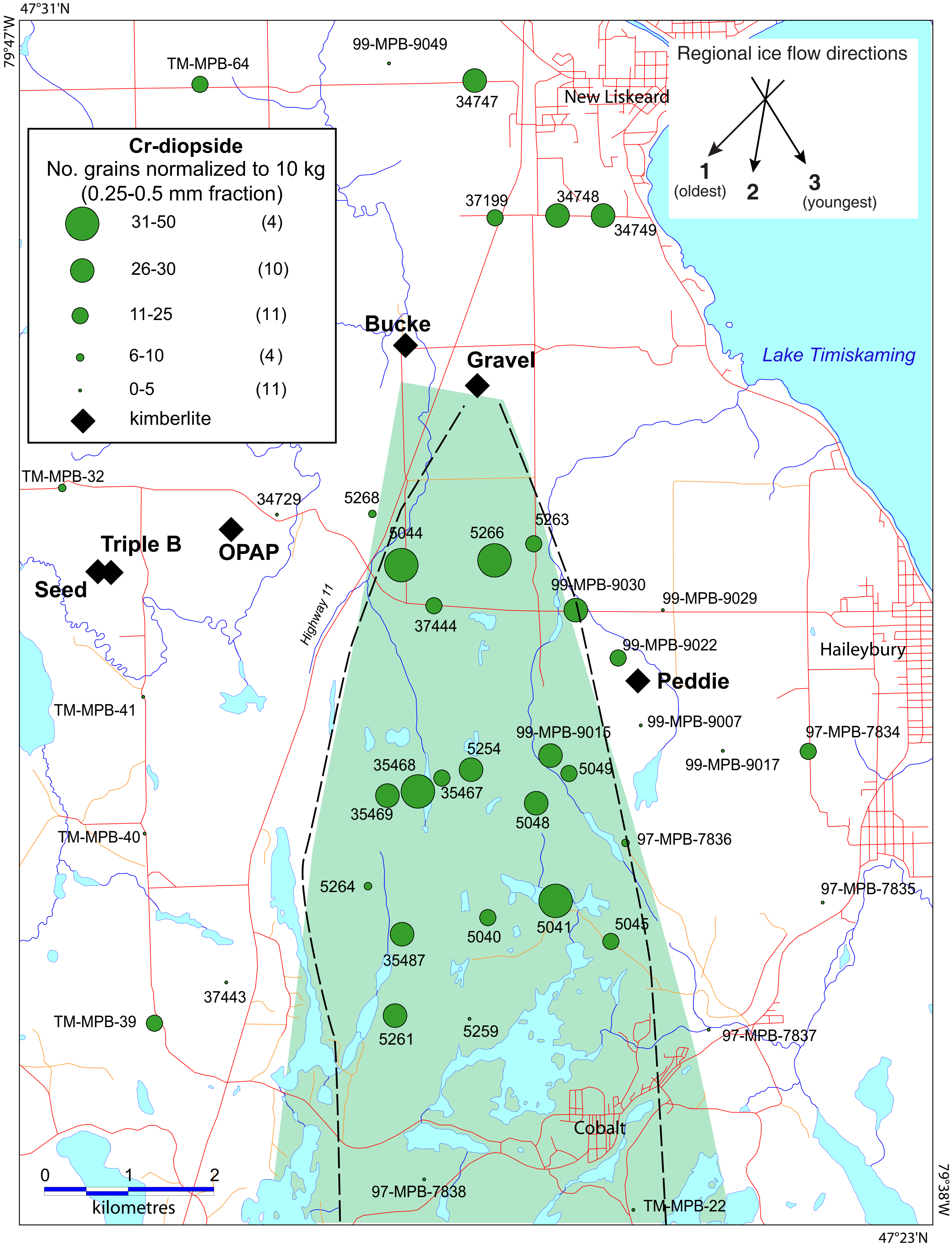


Figure 4 continued. d) Distribution of chromite minerals in the 0.25 to 0.5 mm fraction of till down-ice from the Bucke and Gravel kimberlites.

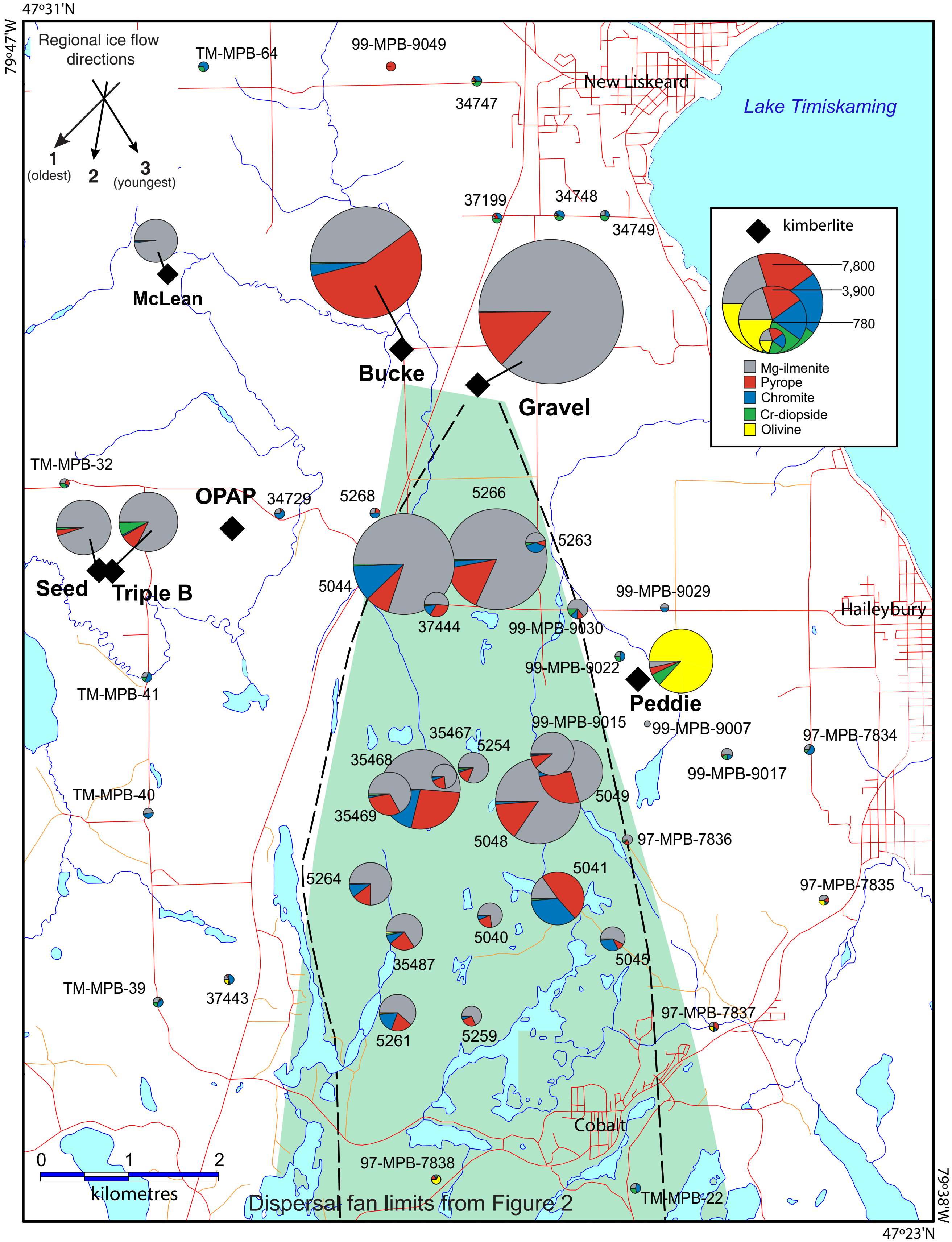
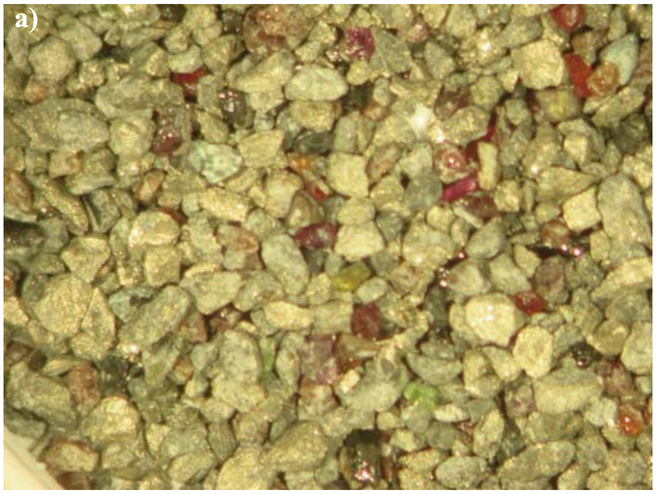


Figure 5. Proportional pie plots of the relative abundance of Mg-ilmenite, pyrope, chromite, Cr-diopside, and olivine in the 0.25 to 0.5 mm fraction of the kimberlite and till samples from this study, and selected kimberlite and till samples from previous Geological Survey of Canada studies (McClenaghan et al., 1999, 2001, 2002a).



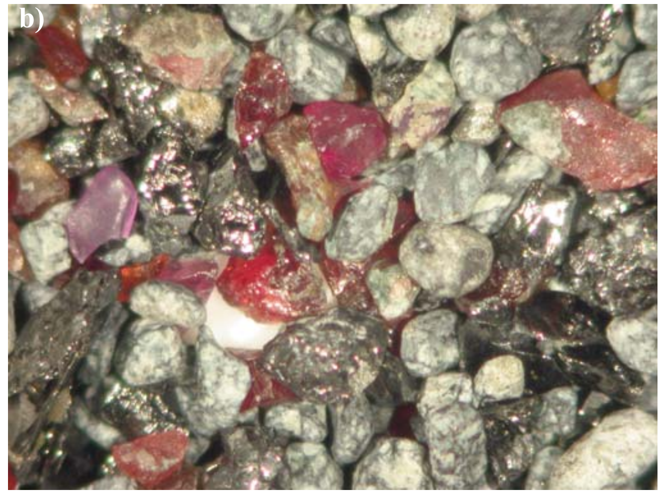


Figure 6. Photographs of 0.5-1.0 mm heavy mineral concentrates from **a)** the Bucke kimberlite and **b)** the Gravel kimberlite.

by Mg-ilmenite, with minor amounts of chromite and Cr-diopside, and rare eclogitic garnet (Fig. 6a). All grains visually selected as olivine (Appendix C, part a) were determined to be enstatite by EMP analysis. The Gravel kimberlite contains >100,000 indicator mineral grains per 10 kg consisting mostly of Mg-ilmenite and to a lesser extent Cr-pyrope (Fig. 6b), although the absolute abundance of garnet is similar to that of Bucke. Chromite and Cr-diopside abundances in the Gravel kimberlite are lower than in the Bucke kimberlite (Table 1). Cr-diopside and eclogitic garnet are rare in the Gravel sample.

Most indicator grains in the kimberlites occur in the smallest size fraction (0.25-0.50 mm) (Appendix C) with the exception of chromite in the Gravel kimberlite, which is most abundant in the 0.5 to 1.0 mm size fraction. Garnet in both kimberlites consists of approximately equal proportions of purple and red varieties, the latter due to large numbers of megacryst garnets, probably due to larger grains being crushed during processing.

Till Samples

The abundance of kimberlite indicator minerals was determined only for the 0.25-0.5 mm fraction of till samples (Appendix C), and these values have been normalized to 10 kg (Appendix Cf; Table 1). The distribution of Mg-ilmenite, Cr-pyrope, chromite, and Cr-diopside in till samples around the Bucke and Gravel kimberlites is shown in Figure 4 and total and relative abundances are shown as proportional pie symbols in Figure 5. Till samples contain 10s to 1000s indicator mineral grains. Background samples up-ice/north (samples 34747, 34748, 37749, 37199, TM-MPB64, 99-MPB-9049) and west (samples 34729, 37443, 5268, TM-MPB-32, -39 to -41) of the dispersal fan generally contain <60 indicator grains per 10 kg, of which most are chromite and Cr-diopside (Figs. 4c,d and 5). In contrast, till samples within the dispersal fan (Table 1) contain hundreds to thousands of grains per 10 kg and are typically dominated by Mg-ilmenite, with lesser amounts of Cr-pyrope and chromite (Fig. 4), minor Cr-diopside, and rare olivine. Indicator mineral abundances for individual mineral species in till are highest in samples between 2 and 7 km down-ice (Fig. 4). Total indicator mineral concentrations can be seen to decrease with increasing distance down-ice as shown in the proportional pie plots (Fig. 5). Sample 97-MPB-7838, 8 km south, and sample TM-MPB-22, 9 km south, contain background levels of indicator minerals.

Mg-ilmenite is by far the dominant indicator mineral in till samples within the fan, with abundance varying from 50 to >6000 grains per 10 kg sample. Background till samples generally contain <31 grains. The relative abundance of Mg-ilmenite within the dispersal fan varies from 50 to 88% of the total indicator count (Table 1, Fig. 5). One exception within the fan is sample 5041, 5.5 km south, which contains only 15% Mg-ilmenite. The highest Mg-ilmenite counts (>1000 grains) are in both western and eastern parts of the fan between 2 and 5 km down-ice (Fig. 4a).

Cr-pyrope abundance in the dispersal fan varies from 11 grains/10 kg on the eastern margin of the fan to 1361 grains/10 kg 4 km down-ice in the central part of the fan (Fig. 4b). Background samples up-ice and west and/or east of the fan contain between 0 and 19 garnet grains. The relative proportion of garnet in till varies between 8 and 33% within the fan, with the exception of sample 5041, which contains 48% garnet (Table 1). The highest Cr-pyrope counts (>250 grains) occur in both western and eastern parts of the fan between 2 and 5 km down-ice (Fig. 4b).

Chromite is not very abundant in either kimberlite (4% in Bucke and 0.3% in Gravel) and is proportionally more abundant in the till (Table 1). The Bucke kimberlite contains ~1100 chromite grains in the 0.25-

0.5 mm fraction. The Gravel kimberlite, in contrast, contains much less chromite (~150 grains). Three till samples within the fan (5041, 5044, and 35468) have high chromite abundances (900 to 971 grains), similar to that of the Bucke kimberlite. Background chromite counts in till vary from 0 to 42 grains whereas counts for till samples within the fan vary from 3 to 971 grains (Fig. 4c). Chromite in background till samples comprises a significant percentage (on average 39%) of the indicator minerals as compared to those within the fan. Most till samples within the fan contain between 1 and 14% chromite (Table 1). Samples 5045 and 5041 in the southeastern part of the fan are exceptions, containing 30 to 35% chromite. Sample 5263 on the eastern margin of the fan also contains a much higher percentage of chromite (38%). Sample 35468 contains 20% chromite.

Cr-diopside is the least abundant indicator mineral in the two kimberlites (109 and 149 grains/10 kg) and till samples both within and outside the dispersal fan contain even lower abundances (0 to 34 grains/10 kg). Similar to chromite, Cr-diopside is proportionally much more abundant (35-43%) in background till samples (Table 1) than in till samples within the dispersal fan (most <5%) or in the kimberlites (<1%). The highest Cr-diopside counts (>25 grains) occur within the fan or directly north of the fan (Fig. 4d).

Olivine was visually identified in several till samples, notably samples 35468 (34 grains/10 kg) and 35487 (13 grains), and eight other samples with 5 to 10 grains per 10 kg sample (Table 1). Seventy-eight yellow grains picked as olivine from till samples from the Bucke/Gravel dispersal fan were probed, and most were determined to be epidote (n=32) or enstatite (n=31) with only 14 grains confirmed as olivine. Olivine was confirmed in till samples 5041, 5048, 35468, 5254, and 35467 (Table 1).

KIMBERLITE INDICATOR MINERAL CHEMISTRY

Mg-Ilmenite

Kimberlites

Ilmenite EMP data for the Bucke and Gravel kimberlites are listed in Appendix D1. Figure 7 shows the range of Mg-ilmenite compositions from the Bucke and Gravel kimberlite as determined in this study as well as for data reported by Sage (1996) and Schulze et al. (1995). Mg-ilmenite from the Bucke kimberlite has a MgO concentration ranging from 7 to 16 wt.% and is predominantly Cr-poor (<1 wt.% Cr_2O_3), with some scatter towards higher Cr_2O_3 (up to 3.5 wt.%. in GSC data set, up to 5.5 wt.% in data from Schulze et al., 1995) at the high MgO end of the spectrum (Fig. 7a). Gravel kimberlite Mg-ilmenite compositions plot as a crescent shape in the MgO versus Cr_2O_3 concentration diagram (Fig. 7b) with many grains containing elevated Cr_2O_3 concentrations (up to 6.5 wt.%) at both ends of the MgO concentration spectrum from 7 to 16 wt.%. The high Cr/low Mg compositions are unique to the Gravel kimberlite, the other compositions overlap with those from the Bucke kimberlite. Previously published data for the Bucke and Gravel kimberlites show essentially the same distribution as data presented here, with the exception of a few more MgO- and Cr_2O_3-rich grains from the Bucke kimberlite reported by Schulze et al. (1995). The plot of TiO_2 versus MgO concentrations (after Wyatt et al., 2004; Fig. 8) shows that all Mg-ilmenite grains are from kimberlite and that Mg-ilmenite from the Bucke kimberlite are moderately oxidized (5-15% hematite component), with outliers reaching up to 25% hematite component. The Mg-ilmenite grains from the Gravel kimberlite are moderately oxidized and plot mainly between 5 and 13% hematite with outliers between 10 and 20% hematite.

Till Samples

Ilmenite EMP data for till samples are listed in Appendix D1. Mg-ilmenite compositions are plotted for selected till samples in Figure 7c-f (samples 37444, 5049, 5266, 35468) that represent varying locations with increasing distances down-ice within the fan. Figure 7g shows ilmenite compositions for background samples 34747, 37199, and 34748 up-ice of the kimberlites. Most till samples from the dispersal fan display crescent-shaped patterns (Fig. 7c-f) that are very similar to Mg-ilmenite compositions from the Gravel kimberlite (Fig. 7b), suggesting they are sourced from the Gravel kimberlite. Samples 37444 (Fig. 7c) and 35467 contain a few low MgO/low Cr ilmenite grains that are observed in the Bucke kimberlite but not in the Gravel kimberlite. However, three samples up-ice from the Bucke and Gravel kimberlites also contain low-Cr Mg-ilmenite with between 6.5 and 12 wt.% MgO (Fig. 7g), thus the source of the low Mg, low Cr ilmenite is not necessarily the Bucke kimberlite

Plots of TiO_2 versus MgO for Mg-ilmenite from the till samples identify them as kimberlitic and show a continuous spectrum of between 2.5 and >20% Fe_2O_3 (hematite) concentrations (Fig. 8c). Most grains, plot in the compositional range of the Gravel kimberlite (Fig. 8b), which is slightly less oxidized than that of Bucke (Fig. 8a).

Garnet

Garnets were classified according to the scheme of Grütter et al. (2004) into the following groups:

1) G01 garnet: red megacryst garnets (0 to <4 wt.% Cr_2O_3, TiO_2 > 0.4 wt.%, Mg-# between 70 and 85) with the following subgroups:

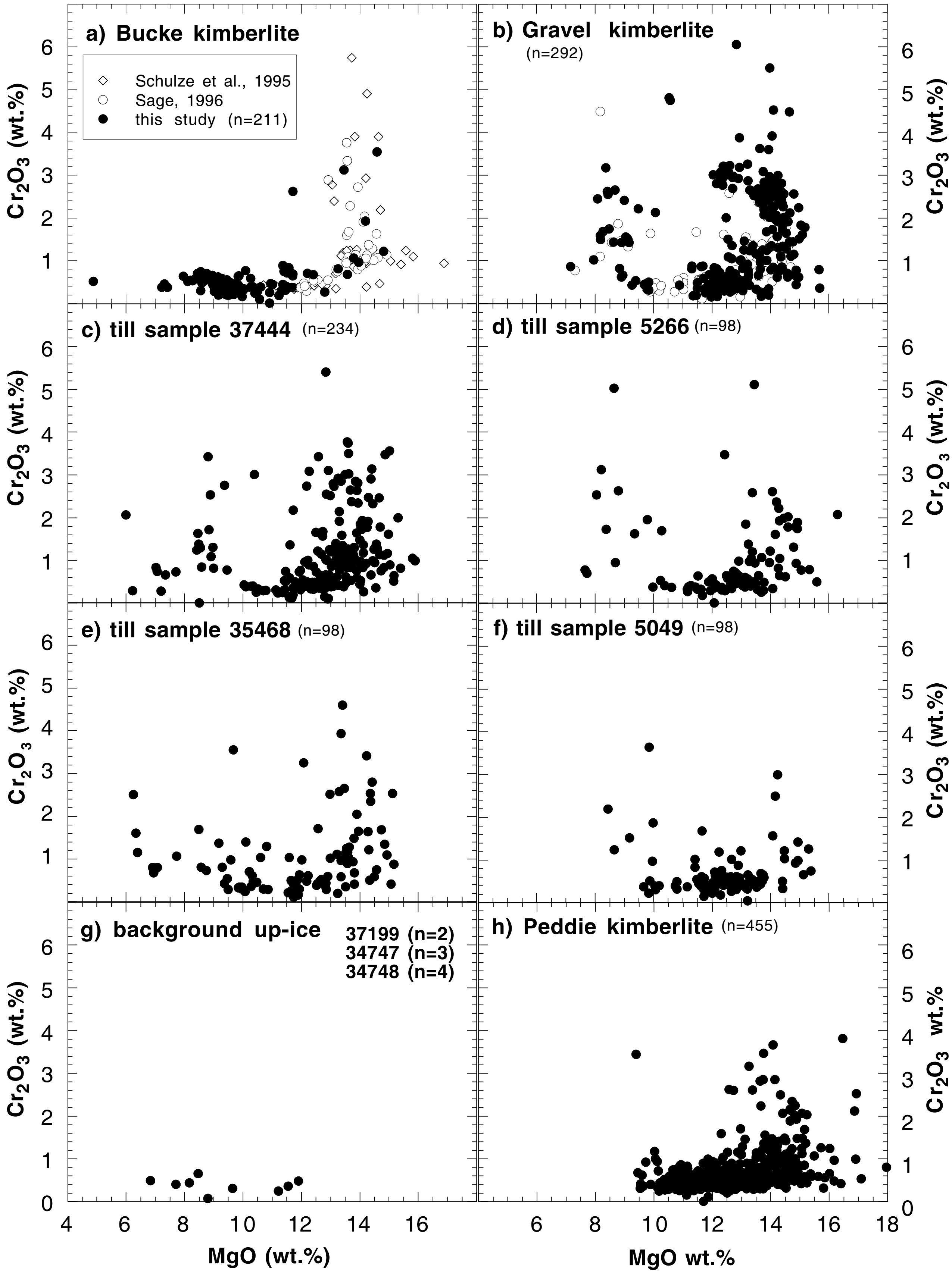


Figure 7. Plots of MgO versus Cr_2O_3 in Mg-ilmenite from **a)** Bucke kimberlite and **b)** Gravel kimberlite: both compared to previously published ilmenite data from Schulze et al. (1995) and Sage (1996); **c)** to **f)** selected till samples down-ice; **g)** background till up-ice from Bucke and Gravel kimberlites; and **h)** Peddie kimberlite (McClenaghan et al., 1999).

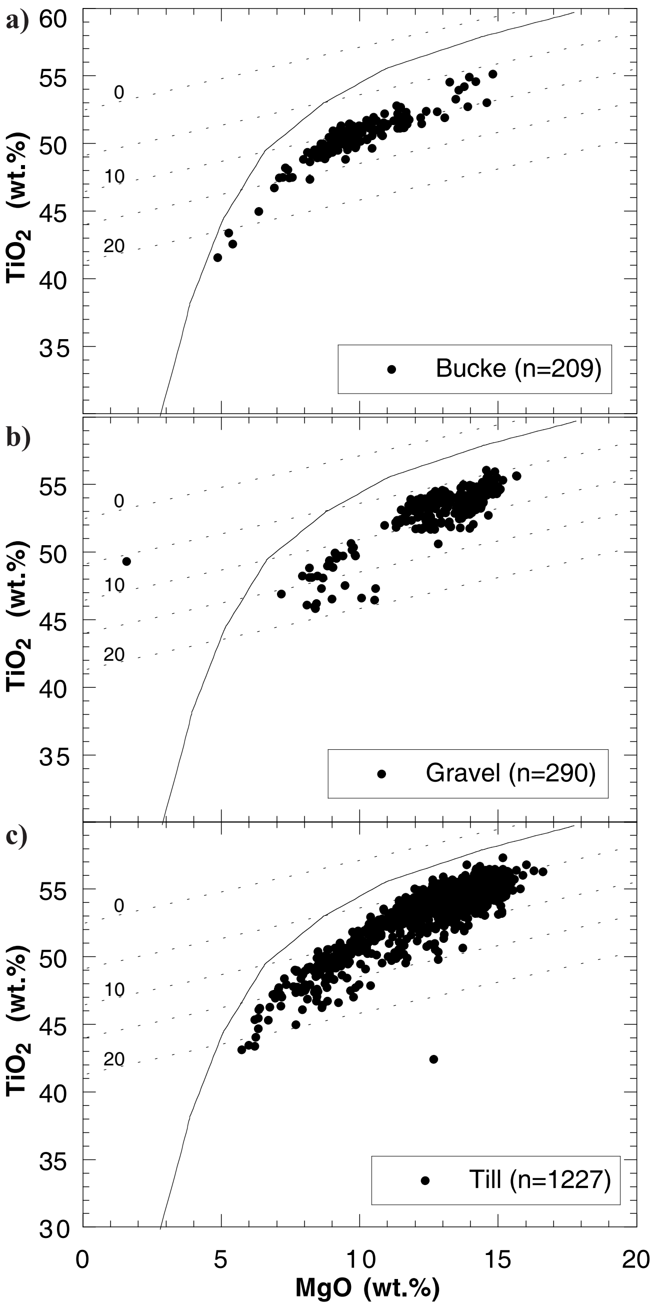


Figure 8. MgO versus TiO_2 concentrations in Mg-ilmenite from **a)** Bucke kimberlite; **b)** Gravel kimberlite; and **c)** till down-ice from the two kimberlites. The curve separates the kimberlitic (to the right) from the non-kimberlitic (to the left) Mg-ilmenite. Stippled lines indicate the degrees of oxidation (hematite content) after Wyatt et al. (2004).

G1a (Cr_2O_3 < 1 wt.%, CaO < 5.2 wt.%)
G1b (Cr_2O_3 < 1 wt.%, CaO > 5.2 wt.%, Mg-# > 80 (Bucke) or ~75 (Gravel)
G1c (Cr_2O_3 1 to 4 wt.%, CaO < 5 wt.%)

2) G3 garnet: orange eclogitic garnets (Cr_2O_3 < 1 wt.%, CaO > 6 wt.%, FeO_{tot} < 22 wt.%, Mg-# < 70), with subgroup G3D for garnets from potentially diamondiferous Group I eclogite (TiO_2 > 0.20 wt.%, Na_2O > 0.07 wt.%).
3) G4 garnet: orange websteritic, pyroxenitic, or eclogitic garnets (Cr_2O_3 < 1 wt.%, CaO < 6 wt.%, Mg-# < 85), with subgroup G4D for garnets from potentially diamondiferous Group I eclogite (TiO_2 > 0.20 wt.%, Na_2O > 0.07 wt.%).
4) G5 garnet: orange websteritic or pyroxenitic garnet (Cr_2O_3 > 1 wt.%, CaO < 6 wt.%, Mg-# < 85)
5) G9: purple Cr-pyrope from unmetasomatized lherzolitic assemblages (Cr_2O_3 > 1 wt.%, TiO_2 < 0.4, CA_INT between 3.375 and 5.40, Mg-# 70 to < 90)
6) G10: purple Cr-pyrope from subcalcic harzburgite (Cr_2O_3 > 1 wt.%, TiO_2 < 0.4, CA_INT < 3.37, Mg-# 75 to < 95)
7) G11: red to purple garnet from metasomatized (sheared) lherzolite (Cr_2O_3 > 4 wt.%, TiO_2 > 0.4, CA_INT > 3.0, Mg-# 65 to < 90)
8) G12: purple garnet from Ca-rich wehrlite (olivine-clinopyroxenite) (Cr_2O_3 > 1 wt.%, TiO_2 < 0.4, CA_INT > 5.40)
9) G13: orange to red pyrope (Cr_2O_3 < 1-3 wt.%, TiO_2 > 1 wt.%, CaO > 5.00 wt.%) that would classify as wehrlitic garnets (G12) with positive TI or as megacryst garnets (G1 with CA_INT > 5).

For the above classifications, CA_INT = CaO - Cr_2O_3 x 0.25, TI = TiO_2 - (2.13-2.1 x Mg-#/100), and Mg-# = 100 x Mg/(Mg+Fe)

The following modifications were made in this study when applying the Grütter et al. (2004) classification scheme:

1) because there is a gradual transition between megacryst (G01) and Ti-rich lherzolite garnets (G11) in this study, with only a slight difference in Mg-# between classifications G01 and G11, the cut-off between these two groups was set at 4 wt.% Cr_2O_3 since the strong clustering of the grains in this compositional range (up to 4 wt.% Cr_2O_3) and their colour and large grain size indicate abundant grain fragments from crushed or disintegrated megacrysts. However, some G11 garnets with <4 wt.% Cr_2O_3 might be contained in the group of G1c megacryst.
2) some moderately Ti-rich (> 0.4 wt.%), low Cr garnets classified as G04 (pyroxenitic/ websteritic/ eclogitic garnets) were added to the megacryst group (G01) because they form an extension of that group at slightly lower TiO_2 concentrations (0.3 to 0.4 wt.%, seethe examples in Figs. 9, 10, and 11).
3) the cut-off between Ti-poor G9 and Ti-rich G11 Cr-pyrope is defined by the value TI (see definition above) in the Grütter et al. (2004) nomenclature. The G11 group has positive TI values while the G9 has negative TI values. Since there is an almost

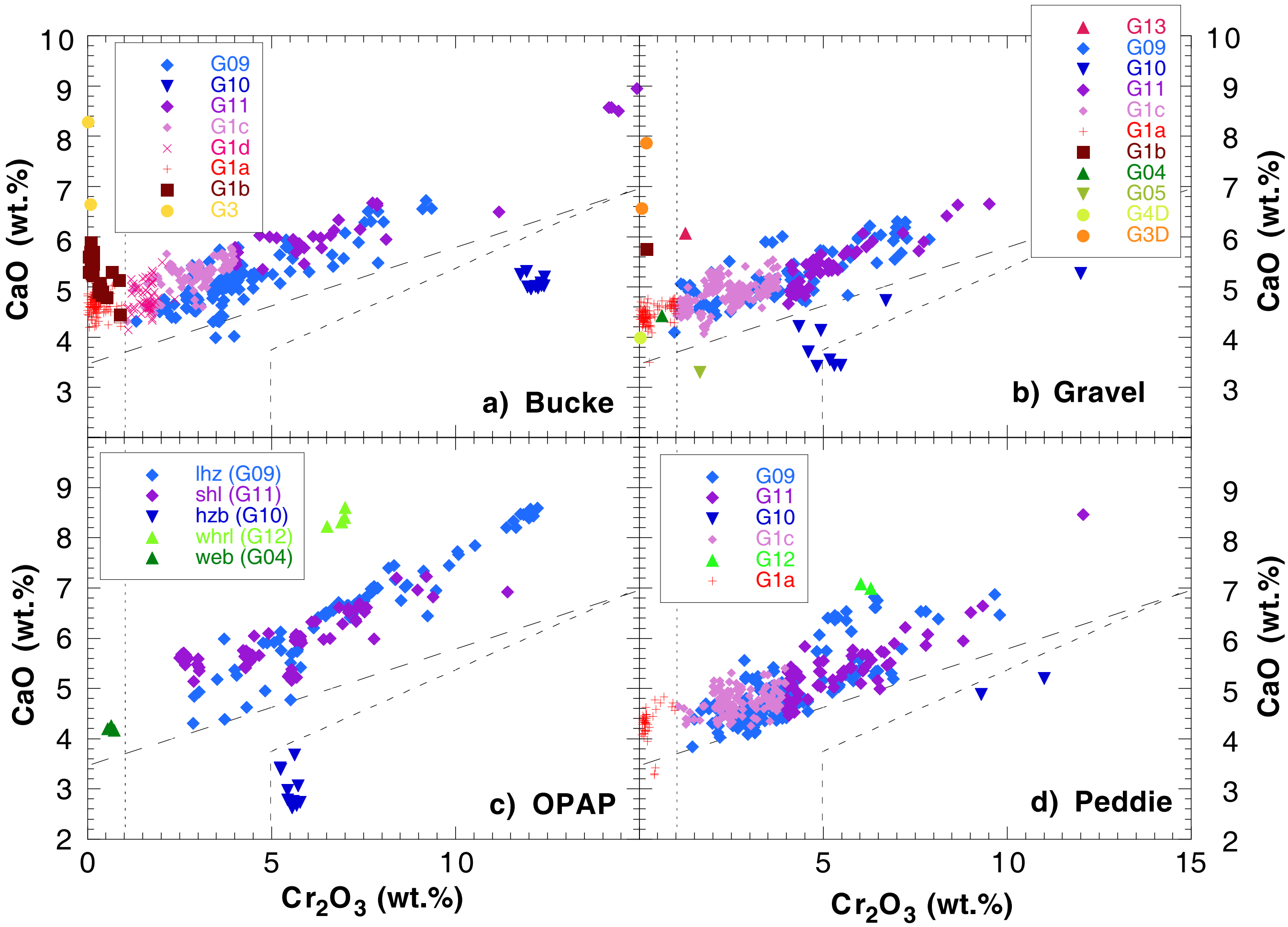


Figure 9. CaO versus Cr_2O_3 in garnet from local kimberlites: **a)** Bucke, **b)** Gravel, **c)** OPAP, and **d)** Peddie. and e) to h) surrounding till. Diagonal dashed line is the 85% line defined by Gurney (1984) and the dashed field below is the field of subcalcic garnet (Sobolev, 1977). A vertical line separates the Cr-poor (orange) eclogitic, websteritic, or pyroxenitic garnets from Cr-rich (red or purple) peridotitic garnets.

seamless transition from Ti-poor to Ti-rich lherzolitic garnets in the kimberlites studied here we have replaced the TI cut-off with a more "organic" TiO_2 cut-off of around 0.45 wt.% (depending on the individual kimberlite).

4) eclogitic garnets were classified as having <22 wt.,% FeOtot, <1 wt.% Cr_2O_3, >5 wt.% MgO, <1 wt.% MnO, and Mg-# <70. Group I eclogitic garnets in the sense of McCandless and Gurney (1989) have ≥ 0.25 wt.% TiO_2 and ≥ 0.07 wt.% Na_2O, Group II eclogitic garnets have < 0.25 wt.% TiO_2 and < 0.07 wt.% Na_2O but major element chemistry similar to group I eclogitic garnets. In the classification scheme of Grütter et al. (2004), both groups G03 and G04 can contain eclogitic garnets, although G03 garnets are by definition more Ca-rich (>6 wt.% CaO).

5) a new group (G13) is proposed here for Ca-rich titanian pyrope at the lower end of the Cr-spectrum (0.5 to 2 wt.% Cr_2O_3) that contains high TiO_2 (1.5-2.2 wt.%) and would classify as both wehrlitic (due to high CaO) and megacryst garnet (due to high TiO_2) in the Grütter et al. (2004) classification.

Kimberlites

Garnet EMP data for kimberlites are listed in Appendix D2. Both the Bucke and Gravel kimberlites contain garnet with a broad compositional range, from Cr-poor eclogitic, websteritic, pyroxenitic, and megacryst compositions through lherzolitic garnets to very Cr-rich calcic and subcalcic harzburgitic garnets (Figs. 9 to 11). Purple Cr-pyrope is predominant in both kimberlites, but in both cases garnets from coarse granular Ti-poor lherzolite (G09) are outnumbered by Ti-rich compositions thought to be from sheared metasomatized lherzolite (G11) and Cr-rich megacrysts (G01; Fig. 9). The transition between these groups is gradational with TiO_2 values increasing from 0.0 to 1.3 wt.% in the Bucke kimberlite and to 1.15 wt.% in the Gravel kimberlite (Fig. 10a,b). The most Cr-rich garnet compositions, with almost 15 wt.% Cr_2O_3 (Fig. 9a), occur in the Bucke kimberlite (which are also very Ti-rich (~1.5

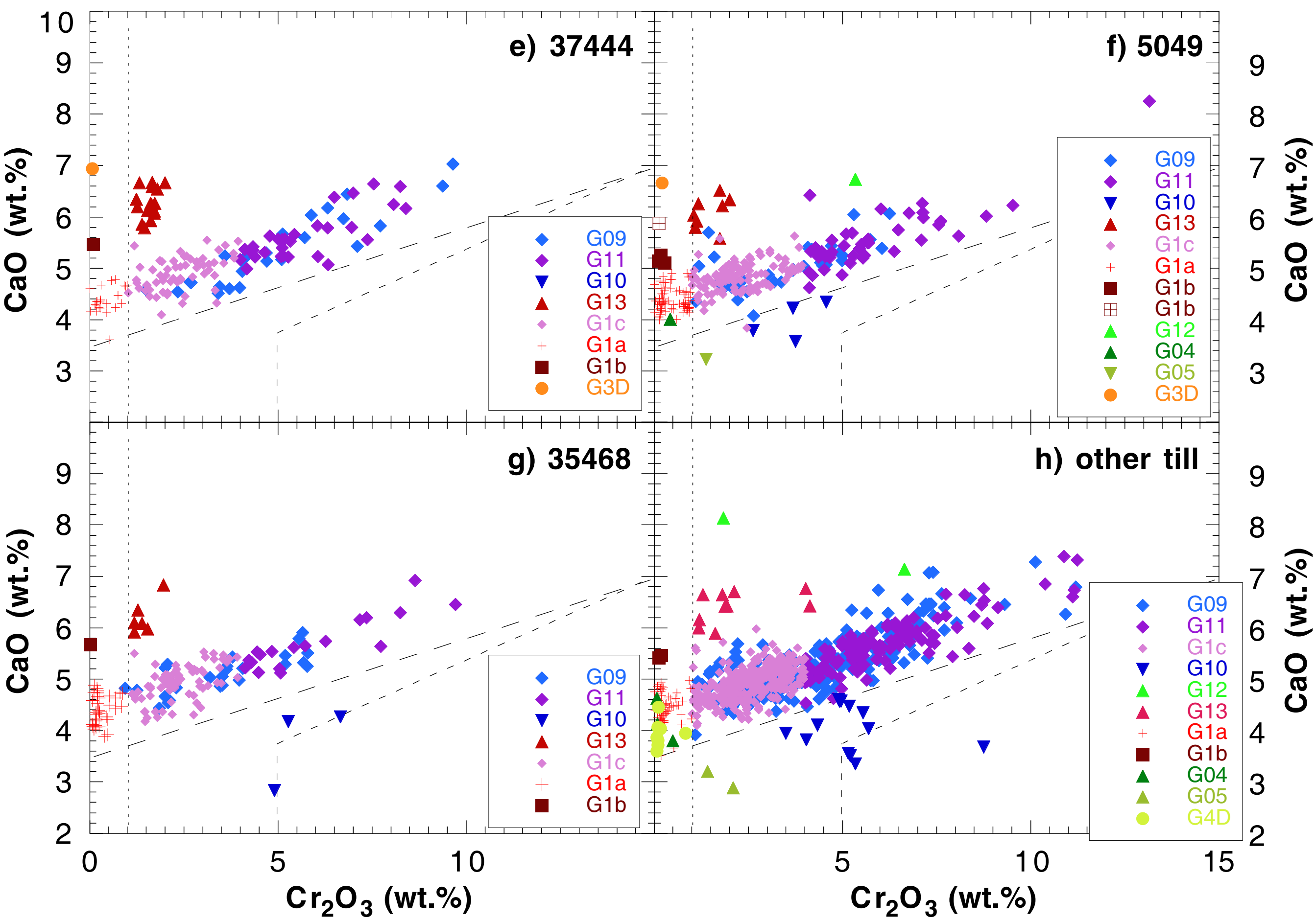


Figure 9 continued. CaO versus Cr_2O_3 in garnet from surrounding till for samples **e)** 37444, **f)** 5049, **g)** 35468, and **h)** other till. Diagonal dashed line is the 85% line defined by Gurney (1984) and the dashed field below is the field of subcalcic garnet (Sobolev, 1977). A vertical line separates the Cr-poor (orange) eclogitic, websteritic, or pyroxenitic garnets from Cr-rich (red or purple) peridotitic garnets.

wt.% TiO_2, Fig. 10a) and probably represent an extension of the G11 group (sheared lherzolites) (Fig. 9a). Subcalcic harzburgitic garnets (G10) containing 12 to 13 wt.% Cr_2O_3 were found in both the Bucke and Gravel kimberlites, but they are more numerous in the Bucke kimberlite. Both kimberlites also contain a group of less Cr-rich G10 subcalcic garnets with approximately 5 wt.% Cr_2O_3 (Gravel, Fig. 9b), and <4 wt.% Cr_2O_3 (Bucke, Fig. 9a), respectively.

An approximately equal number of purple and orange garnets were picked from heavy mineral concentrates of both kimberlites. The purple garnets fall into the G09 to G11 groups discussed above. The orange garnets can be divided into crustal almandine (or spessartine) with FeOtot of more than 22 wt.%, several groups of megacryst garnet (G01) (eclogitic (G3), websteritic (G04) and pyroxenitic (G05)), and garnet, as well as an enigmatic group of high Ti/high Ca garnets (G13) with between 1 and 2 wt.% Cr_2O_3 (Figs. 9, 10, and 11). Megacryst garnets are abundant in the Bucke kimberlite and form several distinct populations: 1) a Cr-poor megacryst group (G1a) with between 4 and 5 wt.% CaO and Mg-# < 75, similar to megacrysts found in most other kimberlites of the Lake Timiskaming kimberlite field; 2) a group of Ca-rich and Cr-poor megacrysts with 5 to 6 wt.% CaO and Mg-# > 80 (Figs. 9a, 10a, and 11a) but comparatively low TiO_2 concentrations (Figs. 10a and 11a); and 3) a group of more Cr-rich megacrysts (G1c) with > 1 wt.% Cr_2O_3 and Mg-# > 76 that grade into sheared lherzolite compositions (G11). The Ca-rich G1b garnets are unlikely to be from eclogites and, because of their high Mg-# (>80) and high TiO_2 concentrations (Fig. 11a), they were classified as megacrysts.

Megacrysts from the Gravel kimberlite generally have less than 1 wt.% TiO_2 (compared to <1.3 wt.% for Bucke) and are slightly different in composition from those of the Bucke kimberlite. The group with low Cr concentrations (G1a) have Mg-#s that range from 75 to 79 with less spread in TiO_2 concentrations; the Ca-rich group (G1b) has only one representative and a much lower Mg-# (75) than those from Bucke. In addition,

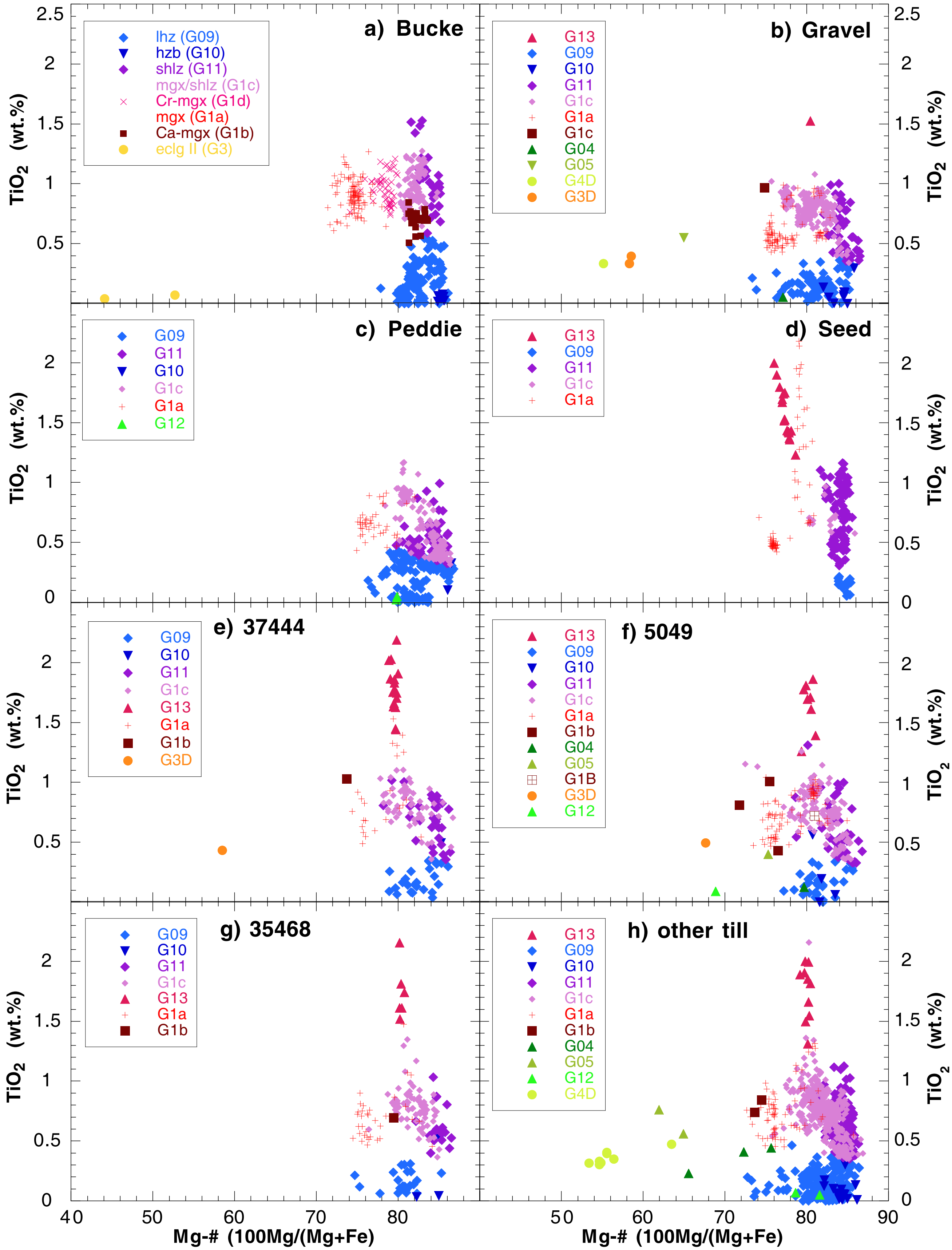


Figure 10. Plots of TiO_2 versus Mg number in garnet from **a)** the Bucke kimberlite; **b)** the Gravel kimberlite; **c)** the Peddie kimberlite, and **d)** the Seed kimberlite (from Sage, 1996) and from selected garnet-rich till samples **e)** 37444, **f)** 5049, **g)** 35468; and **h)** all other till samples.

Gravel contains one Cr-rich high-Ti/high-Ca pyrope (G13) with just over 1 wt.% Cr_2O_3 and an Mg-# of 80. It might represent a third group of megacryst or a highly titanian wehrlite (Figs. 9b, 10b). This composition is more numerous in till (Fig. 9b, 10b,c, 11b) and similar to garnets found in the Seed kimberlite (Fig. 10d). The Gravel kimberlite also contains two garnets that classify as websteritic or pyroxenitic garnet (G04 and G05). The G04 garnet is most probably from websterite since it has a fairly high Mg-# and low Ti content. The G05 garnet is more Cr-rich (1.59 wt.% Cr_2O_3), and subcalcic, but has a low Mg-#, which makes it difficult to assign to any group.

Bona fide eclogitic garnets are rare but do occur in both the Bucke and Gravel kimberlites. However, in each kimberlite they represent a different type of eclogite. The Bucke kimberlite yielded two Ca-rich, Ti- and Na-poor garnets interpreted to be from Group II (non-diamondiferous) eclogite (classification of McCandless and Gurney, 1989) (Figs. 9a, 10a, 11a). The Gravel kimberlite contained two grains that were equally Ca-rich but are also enriched in Ti and Na and were classified as being from Group I (potentially diamondiferous) eclogite (Figs. 10b, 11b). A third possibly eclogitic garnet from the Gravel kimberlite has lower CaO content (3.99 wt.%) but is similar to the other two grains in Mg-#, Ti and Na content, and plots in the Group I eclogite field in Figure 11b. It was classified as a G4D garnet.

Till samples

Garnet EMP data for till samples are listed in Appendix D2. Similar to the kimberlite concentrates, the proportion of red and purple garnets picked from till samples is about equal. Garnets in till comprise all the different garnet populations found in the Bucke (Fig. 10a) and Gravel (Fig. 10b) kimberlites with the notable exception of the Group II eclogitic garnets, Cr-poor/Ca-rich megacrysts, and high Cr/high Ti garnets from the Bucke kimberlite (Fig. 10e-h). In addition, the till contains several difficult to classify garnets (G00), a few Ti-poor wehrlitic garnets (G12), and a group of G04 garnets that plot in the field of diamondiferous eclogitic garnets (Fig. 11c) that have no match in either kimberlite. Individual till samples within the fan that have high garnet counts (e.g. samples 37444, 5049, and 35469) display garnet compositions that are similar to the Gravel kimberlite: they have a wider spread in Mg-#s for their peridotitic garnets than those in the Bucke kimberlite, contain megacryst, websteritic, and Group I eclogitic garnet compositions identical to those from Gravel, and contain G13 garnets (i.e. high Ti, high Ca, low Cr pyropes) with TiO_2 contents of up to 2.15 wt.% (Fig. 10e-h) as well as G10 garnets with 4 to 6 wt.% Cr_2O_3.

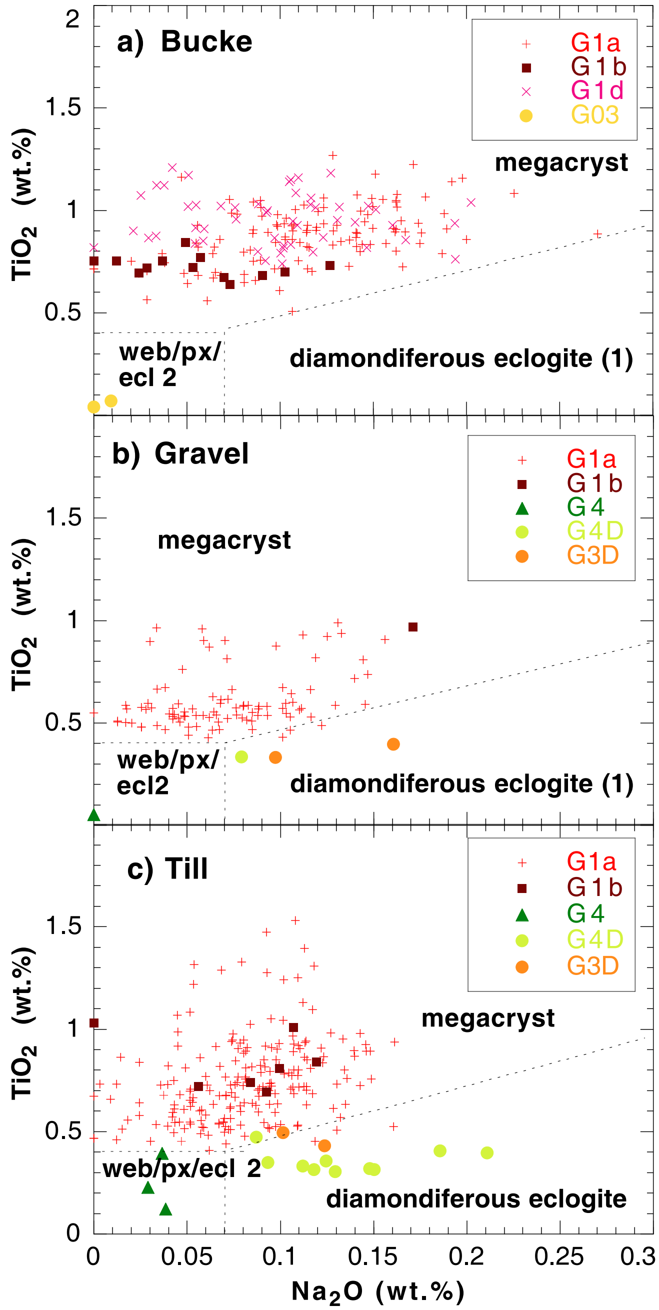


Figure 11. Plots of TiO_2 versus Na_2O in Cr-poor (<1 wt.% Cr_2O_3) garnet from **a)** the Bucke kimberlite; **b)** the Gravel kimberlite; and **c)** surrounding till. Boundaries after Schulze (1997).

Chromite

Kimberlites

Chromite EMP data for kimberlites are listed in Appendix D3. Chromite from the Bucke kimberlite forms a dense cloud of compositions below the diamond intergrowth and inclusion fields in Figure 12 with a slight diagonal trend from more Fe- and Cr-rich compositions to more Mg- and Al-rich but Cr-poor compositions. One chromite from the Bucke kimberlite contains sufficient Cr_2O_3 to plot in the overlap area of

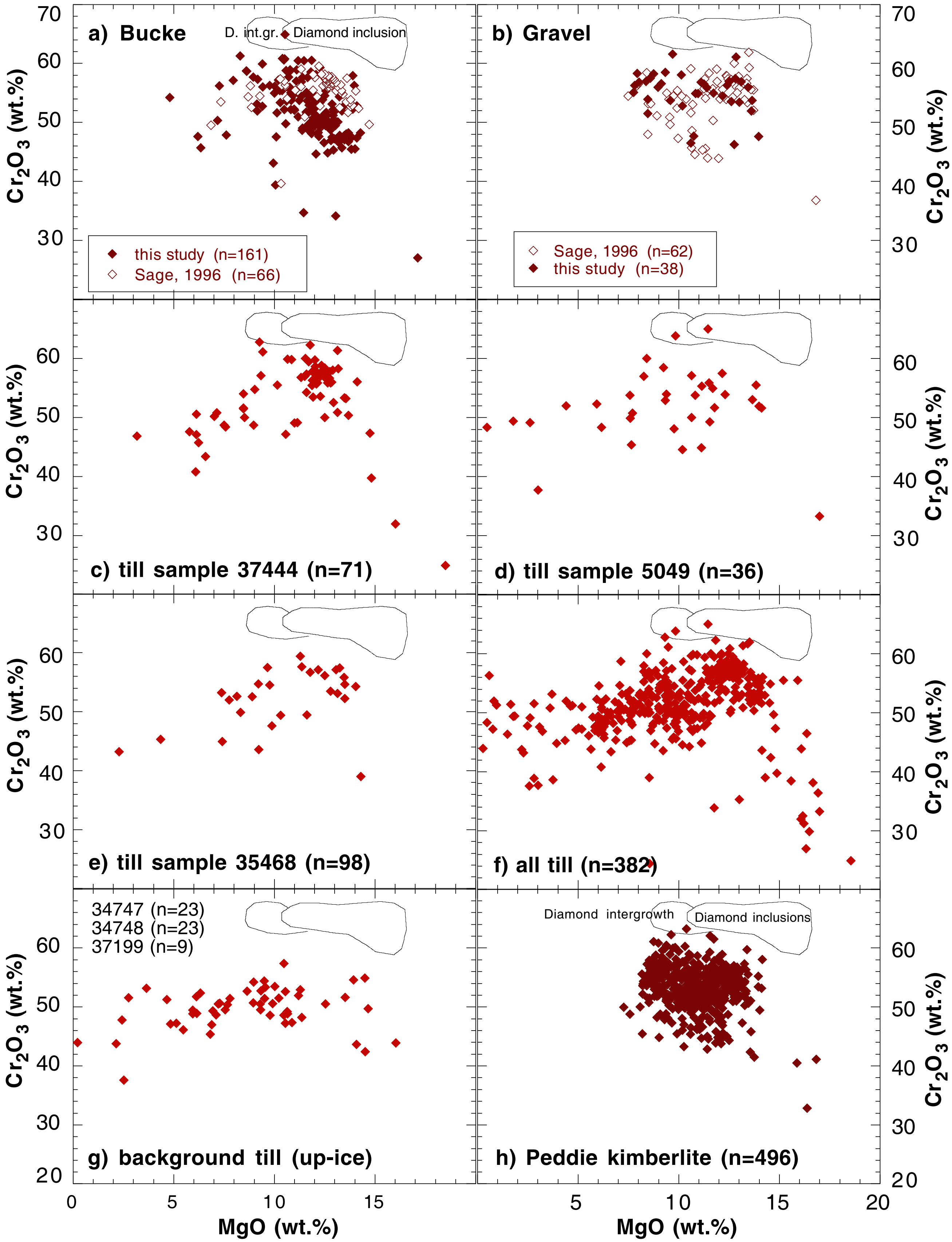


Figure 12. Plots of Cr_2O_3 versus MgO in chromite from **a)** the Bucke kimberlite; **b)** Gravel kimberlite; till samples **c)** 37444, **d)** 5049, **e)** 35468, **f)** all archived till samples, **g)** background samples 34737, 34748, 37199; and **h)** Peddie kimberlite. Diamond inclusion and intergrowth fields are from Fipke et al. (1995).

the diamond inclusion and intergrowth fields (Fig. 12a). Chromite grains from the Gravel kimberlite plot in a more restricted field below the diamond indicator and intergrowth fields. Both kimberlites contain chromite grains with Cr_2O_3 concentrations almost exclusively >43 wt.% and the most Cr-rich compositions straddling the lower edges of the diamond inclusion and intergrowth field. Chromite from the Peddie kimberlite, 4 km to the southeast, displays similar compositional variation as those from the Gravel kimberlite.

Till samples

Chromite EMP data for till samples are listed in Appendix D3 and plotted in Figures 12e to g. They show the same spread in Cr_2O_3 content as chromite in the Bucke and Gravel kimberlites but have a wider range in MgO concentrations. Grains that plot into the diamond inclusion and intergrowth field are from till samples 5048, 5049, and 5254, from the centre of the dispersal fan. Some chromite grains from till contain low concentrations of MgO (<6 wt.%) and plot outside the MgO range of the kimberlitic chromite. These compositions are particularly numerous in background till samples (Fig. 12g) and are thought to be derived from local ultramafic rocks and not from mantle xenoliths. It should be noted, however, that the background till samples also contain peridotitic chromite compositions together with minor amounts of Cr-pyrope and Mg-ilmenite, confirming the known presence of kimberlites up-ice from the Bucke and Gravel kimberlites (see Fig. 1).

Cr-diopside

Kimberlites

The few Cr-diopside grains that were analyzed (Appendix D4) from the Bucke (n=30) and Gravel kimberlites (n=8) range in Cr_2O_3 content from 0.5 to 2.8 wt.% and have Mg-#s from 85 to 96 (Fig. 13a). They plot in the compositional field of Cr-diopside from garnet lherzolite (Fig. 13b).

Till samples

Cr-diopside in the till samples (Appendix D4) also comprises the garnet-peridotitic compositions found in the kimberlites. A large number of the grains, however, have compositions with 0.6 to 1.4 wt.% Cr_2O_3, 0.5 to 1.5 wt.% Al_2O_3, and Mg-#s between 83 and 87, which is not found in the Bucke or Gravel kimberlites. These grains fall into the compositional field of Cr-diopside from GSC regional till samples from the Kirkland Lake (McClenaghan et al., 1993) and Lake Timiskaming regions (McClenaghan et al., 1999, 2001) and plot inside the black circle in Figure 13. These Cr-diopside grains are thought to be from non-kimberlitic regional

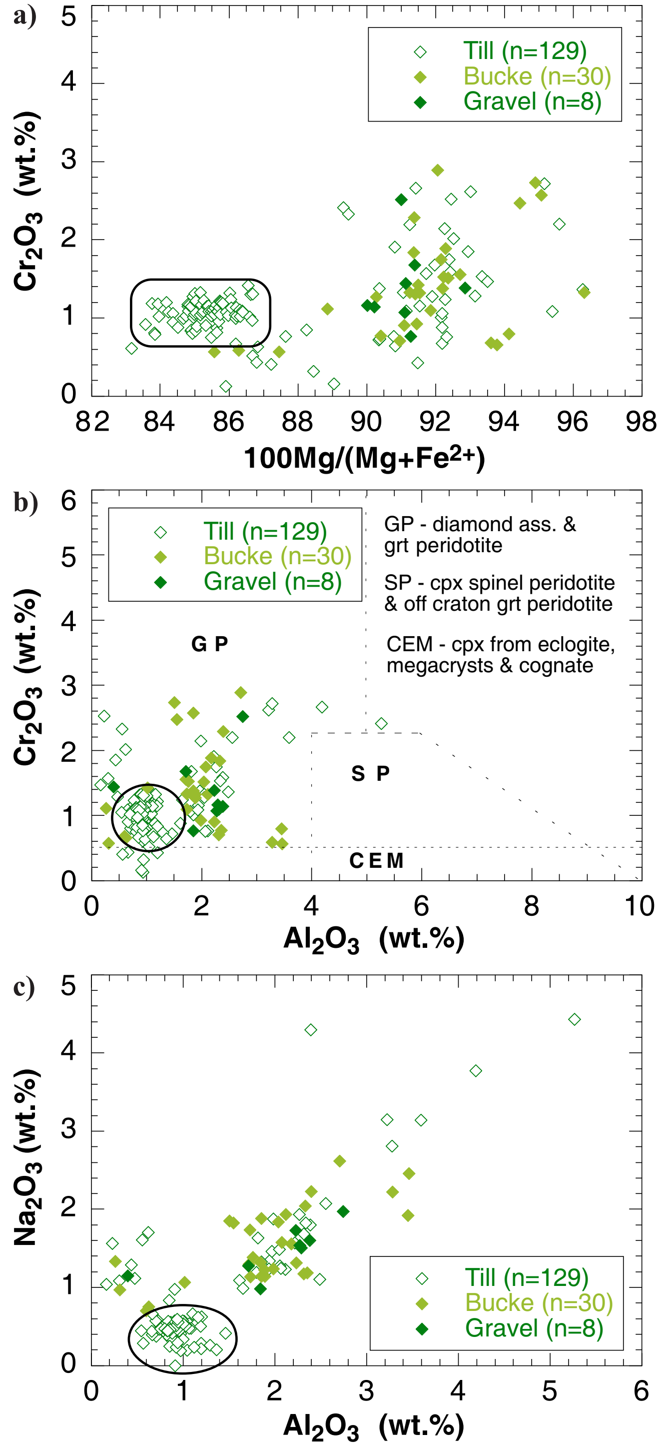


Figure 13. a) Cr_2O_3 versus Mg number; **b)** Cr_2O_3 versus Al_2O_3; and **c)** Na_2O_3 versus Al_2O_3 for Cr-diopside from the Bucke and Gravel kimberlites and surrounding till. Boundaries in (b) after Nimis (1998). The black circle indicates the compositional field of Cr-diopside from regional till samples from the Kirkland Lake and Lake Timiskaming area.

ultramafic rocks. In addition, a few Cr-diopside grains in till are enriched in both Na and Al, indicating a jadeitic component that is characteristic of omphacitic garnet from eclogite (Fig. 13c). However, they are also Cr-rich (>2 wt.% Cr_2O_3) and have high Mg-#s (>92).

Enstatite

Kimberlite

Enstatite grains found in the Bucke kimberlite concentrate form two slightly different groups chemically: 17 grains have low CaO concentrations (≤0.23 wt.%) and higher Mg-#s (91.77 to 93.83), 41 grains had higher CaO concentrations (1.18-1.47 wt.%) and slightly lower Mg-#s (89.9 to 91.1). Both are interpreted to be from mantle peridotite since they have Mg-#s ≥ 90, high Cr_2O_3 concentrations (0.21-0.41 wt.% in group I and 0.341-0.49 in the second group), and low Al_2O_3 concentrations (1.01-1.50 wt.%). These slight chemical differences are attributed to different levels of depletion of the host rocks (i.e. group I was possibly derived from harzburgite and group II from lherzolitic assemblages).

Till

The enstatite grains found in till do not differ greatly from those found in the Bucke kimberlite, although the Mg-#s are slightly higher, probably due to analytical bias. Most of the enstatite grains in till belong to the high CaO concentration group (i.e. are probably from lherzolitic xenoliths). Thus, till samples with high enstatite grain counts (e.g.samples 35487 (n=14), 5261 (n=7), and 37444 (n=5)) might indicate a higher component of material from the Bucke kimberlite. All three sample sites are due south of Bucke, but samples 35487 and 5261 are considerably farther south than sample 37444 (Fig. 3).

Olivine

Kimberlite

No fresh olivine was found in the two kimberlite samples. Sixty-one pale yellow grains picked from the Bucke kimberlite concentrate as olivine were determined to be enstatite when analyzed. However, fresh olivine is abundant in the Peddie kimberlite nearby and occurs in till samples in the immediate vicinity of Peddie (McClenaghan et al., 1999, 2002a).

Till

Seventy-eight yellow grains picked as olivine from till samples from the Bucke/Gravel dispersal fan were mostly epidote (n=32) or enstatite (n=31) with only 14 grains confirmed as olivine (occurring in samples 5041, 5048, 35468, 5254, and 35467; Appendix D7). The olivine grains that were found in till samples have, with one exception, Mg-#s ≥ 90 and NiO ≥ 0.29 wt.% indicating mantle provenance, either as part of a peridotitic assemblage or as kimberlitic high-pressure olivine megacrysts. Only one grain had a substantially lower Mg-# of 57.7 and is probably of crustal origin.

Since olivine easily succumbs to weathering under surface conditions it is likely that their source is close by and in this case the closest source of fresh mantle olivine is the Peddie kimberlite. Thus, till samples with fresh olivine (samples 5041 (n=5), 5048 (n=4), and 35468 (n=2)) could contain some material derived from the Peddie kimberlite. In light of prevailing ice-flow directions, this might be indeed the case for samples 5048 and 5041, which are located about 1 km southwest, and 1.3 km south-southwest from Peddie, but probably less likely for sample 35468, which is located about 2 km west-southwest from Peddie.

Perovskite

Perovskite was not systematically picked from the heavy mineral concentrate because it does not normally occur with grain sizes of more than 0.25 mm in kimberlite; it usually occurs in finer fractions of the heavy mineral concentrate. A few perovskite grains were picked as ilmenite or chromite from the Bucke kimberlite and from till sample 5266. Compositional data are reported in Appendix D6.

DISCUSSION

Source of Indicator Minerals in Kimberlites

The high abundance of Mg-ilmenite and Ti-rich Cr-pyrope garnet in the Bucke and Gravel concentrates is a reflection of the high proportion of megacryst-suite minerals in both kimberlites. Glacial fracturing and crushing of these large megacrysts likely contributed to the high indicator mineral grain counts in the two kimberlites. Compared to the abundance of megacryst grains, the contribution of cool, unmetasomatized mantle peridotite, as represented by Ti-poor Cr-pyrope, Cr-diopside, and chromite (and enstatite), is comparatively minor. Ti-poor Cr-pyrope compositions indicate the presence of both fertile lherzolite (G09) and much rarer subcalcic harzburgite (G10). The most Cr-rich garnets, however, are also Ti-rich (G11) and interpreted to be from sheared peridotites. Chromite compositions fall just below the diamond inclusion and intergrowth fields. In addition to megacryst suite and mantle peridotite minerals, there are also a few grains from eclogitic and pyroxenitic/websteritic assemblages. Both diamondiferous Group I and non-diamondiferous Group II eclogites are represented by rare eclogitic garnets in the Gravel and Bucke kimberlites, respectively. The Bucke and Gravel kimberlites both contain rare, but distinct subcalcic garnet harzburgite subpopulations that are not observed in the other kimberlites. The Gravel kimberlite contains rare Group I eclogite garnets that are not observed in the Bucke kimberlite.

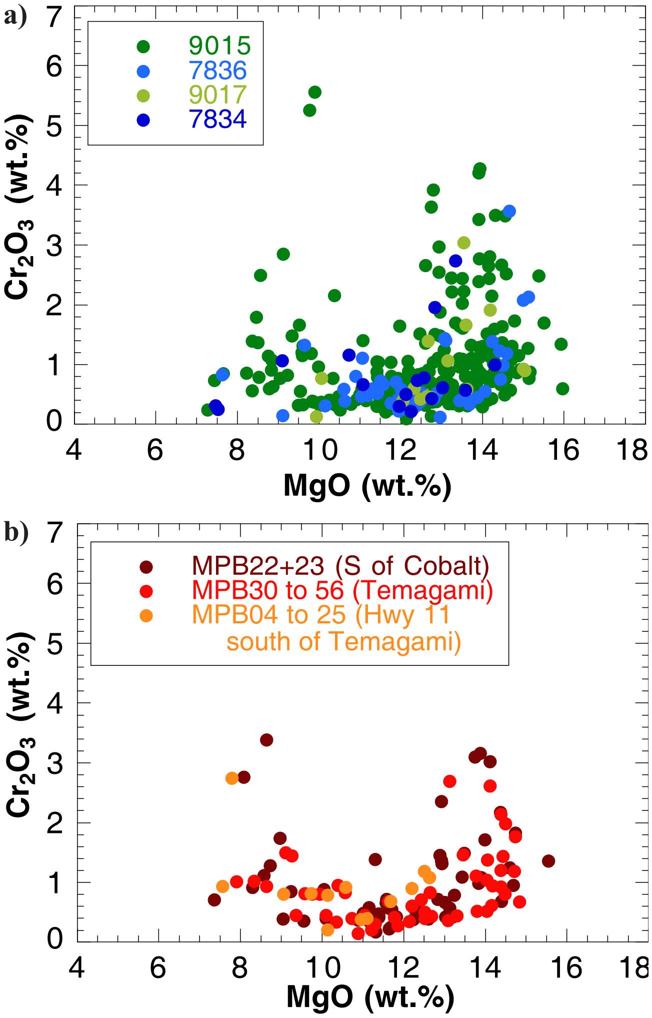


Figure 14. Plots of Cr_2O_3 versus MgO in Mg-ilmenite from regional till **a)** around Peddie kimberlite (McClenaghan et al., 2002a) and **b)** south of Cobalt and along Highway 11 (McClenaghan et al., 2001).

Indicator Mineral Abundance and Distribution

Both the Bucke and Gravel kimberlites are extremely indicator mineral rich compared to other kimberlites in the Lake Timiskaming field that have been studied in detail by the GSC (McClenaghan et al., 1999, 2002a, 2003a, 2004). The Bucke kimberlite contains >30,000 indicator mineral grains/10 kg in the 0.25-0.5 mm fraction. The Gravel kimberlite is three times as indicator mineral rich, containing >100,000 grains/10 kg in the 0.25-0.5 mm fraction. With such high indicator mineral counts in both kimberlites, it is not surprising that till down-ice contains 100s to 1000s grains/10 kg.

Three other kimberlites in the local area, McLean, OPAP, and Peddie, could also potentially have contributed indicator minerals to the till south of the Bucke and Gravel kimberlites because of these kimberlites' locations relative to the three phases of ice flow (southwest to southeast, see Fig. 2) that affected the area. The McLean kimberlite, 3.3 km northwest of the Bucke kimberlite, is unlikely to have contributed indicator minerals to the dispersal fan because this kimberlite is very indicator mineral-poor (<1500 grains/10 kg) (McClenaghan et al., 2003a), with olivine being the dominant indicator. The OPAP kimberlite, 3.5 km southwest of the Bucke and Gravel kimberlites, lacks Mg-ilmenite (Sage, 1996) and thus could not contribute Mg-ilmenite grains to the dispersal fan. It could, however, contribute chromite and garnet to the medial to distal part of the dispersal fan (Figs. 2, 5a). The Peddie kimberlite, 4 km southeast of the Gravel kimberlite, contains abundant fresh olivine as well as abundant Mg-ilmenite, garnet, and chromite and thus could have contributed some of these minerals to the till in the eastern part of the dispersal fan. Mg-ilmenite from the Peddie kimberlite has a compositional range that is similar to the Bucke kimberlite (McClenaghan et al., 1999, 2002a; Fig. 7g). The Peddie kimberlite is an olivine-rich kimberlite and the very low abundance of olivine in till to the southwest and within the dispersal fan south of Bucke and Gravel suggests that very little of the kimberlite debris derived from the Peddie kimberlite is present in till in the southeast part of the fan.

Indicator Mineral Chemistry

Indicator mineral chemistry reported here for the Bucke and Gravel kimberlites are for samples collected from drill core at 48.8 m and 23.5 m depths, respectively. These samples may not be similar in composition to the subcropping kimberlite phases that were eroded by the overriding glacier, although both samples are from just below the subcropping kimberlite surface.

Minerals in the two kimberlites representing (unmetasomatized) mantle peridotite, such as chromite, Cr-diopside, lherzolite garnets (G09), subcalcic harzburgitic garnets (G10), and wehrlitic garnets (G12), indicate the presence of lherzolite, harzburgite, and wehrlite xenoliths in the kimberlites. Low-Cr/low-Ti pyrope garnets with variable levels of CaO attest to the presence of websterite, pyroxenite, and eclogite. Eclogitic garnets are rare and notably different in composition between the two kimberlites: the Bucke kimberlite contains Group II eclogitic garnets and the Gravel garnets are from potentially diamondiferous Group I eclogite.

Mg-ilmenite megacrysts in the Bucke and Gravel kimberlites differ slightly in their compositional variability in that those from the Bucke kimberlite do not have oxidized (i.e. low MgO) Cr-rich compositions, whereas the Gravel kimberlite contains both oxidized and reduced Mg-ilmenites with >6 wt.% Cr_2O_3. Mg-ilmenite compositions in the till samples almost exclusively have compositional characteristics of the Gravel kimberlite ilmenites (Fig. 7b-g), although the Mg-ilmenite pattern of both the Bucke and Gravel kimberlites overlap. Few Mg-ilmenite compositions have been found in till that are unique to the Bucke kimberlite compared to the Gravel kimberlite (i.e. low MgO of <8 wt.% coupled with low Cr of <0.5 wt.%; compositions found for example in till sample 37444). Unfortunately such compositions are also typical of background till samples (Fig. 7g), so the contribution of debris from the Bucke kimberlite cannot be ascertained relying solely on Mg-ilmenite compositions. The Peddie kimberlite, just east of the dispersal fan, has a similar Mg-ilmenite compositions as the Bucke kimberlites, with a wide spread in MgO concentrations from 9.5 to 18 wt.% and increasingly Cr-rich (up to 3.5 wt.%) compositions towards the MgO-rich end of the spectrum (Fig. 7h). There is overlap with the Mg-ilmenite compositions from Gravel, with only the most MgO-rich (>16 wt.%) Mg-ilmenite compositions unique to the Peddie (and Bucke) kimberlite. The Peddie and Bucke kimberlites lack the moderate Cr /low MgO compositions (0.5-3 wt.% and 8-9.5 wt.%, respectively) found in the Gravel kimberlite. GSC till samples from further south, both around and south of Temagami (McClenaghan et al., 2001), display Mg-ilmenite compositions similar to those of the Gravel kimberlites. This similarity may indicate that debris from the Gravel kimberlites was transported at least 30 km to the south-southwest.

The indicator mineral chemistry of the Bucke and Gravel kimberlites is similar in that they both contain abundant Ti-rich Cr pyrope garnet megacrysts. In the garnet populations, there seems to be a seamless transition from megacryst garnets (G01) to garnets from sheared (metasomatized) peridotite (G11), which are also enriched in Ti. Both kimberlites also contain minor amounts of unusually Ca-rich megacrysts (G01c) as well as very Ti- and Ca-rich chromian pyrope (G13) that might be either from highly metasomatized wehrlite or represent a rare group of unusually Ca-rich chromian megacrysts. Similar garnet compositions have been reported for the Seed kimberlite (Sage, 1996), suggesting a wider occurrence in the Lake Timiskaming kimberlite field.

Other kimberlites in the vicinity of the Bucke and Gravel kimberlites, such as the OPAP (Fig. 9c) and Peddie (Fig. 9d) kimberlites, do not contain nearly as varied populations of red pyrope garnets. No megacryst garnets have been reported for the OPAP kimberlite, which is unusual for the Lake Timiskaming kimberlite field, however this lack of megacrysts could be due to a bias towards selecting purple garnets for study. The Peddie kimberlite only contains normal Cr-poor megacrysts with between 4 and 5 wt.% CaO, in addition to abundant Ti-rich lherzolitic garnets (G11). Both the Peddie and OPAP kimberlites lack eclogitic garnets but the OPAP kimberlite contains a few low Ti pyroxenitic or websteritic garnets. Both kimberlites also contain a few Cr- and Ca-rich garnets that were classified as wehrlitic and plot above the lherzolite trend.

High background counts and compositional differences between chromite and Cr-diopside in till and those found in the Bucke and Gravel kimberlites strongly suggests an additional non-kimberlitic source for these two minerals in the dispersal fan. The non-kimberlitic chromites are less MgO-rich but have similar Cr_2O_3 contents compared to those from kimberlite/peridotite. The non-kimberlitic Cr-diopsides form a distinct cluster around 1 wt.% Cr_2O_3 and 84 to 88 Mg-#.

Glacial Dispersal

A fan-shaped dispersal pattern best describes the widening of the area of elevated concentrations of indicator minerals with increasing distance down-ice (southwest to southeast) of the Bucke and Gravel kimberlites (Fig. 2). Fan-shaped dispersal fans are thought to reflect glacial dispersal during shifting ice flow (e.g. Shilts, 1996; Benn and Evans, 1998; Stea et al., 2009) and are in contrast to ribbon-shaped trains suggested to have formed by a single phase of ice flow (e.g. Batterson, 1989; DiLabio, 1990; McClenaghan et al., 2002b,c). The fan-shaped dispersal pattern south of the Bucke and Gravel kimberlites was likely produced during Phase 1, 2, and 3 ice flows, as indicated by the local striation orientations (Fig. 2). The trend of these three ice-flow events, combined with glacial erosion of the Gravel kimberlite (with possible additional input from the Bucke kimberlite), produced the dispersal pattern detected initially by De Beers. Within the fan, indicator mineral concentrations vary between thousands and tens of thousands of grains in the 0.25-0.5 mm fraction. Outside the fan, concentrations are only a few tens of grains. Within the fan, total concentration of indicator minerals decreases with increasing distance down-ice.

CONCLUSIONS

A glacial dispersal fan of indicator minerals derived from the Gravel kimberlite (with possible contribution from the Bucke kimberlite) extends at least 6 km down-ice towards the southwest to southeast. The southern limit of the fan is not known, but may extend further, as indicated by the presence Mg-ilmenite grains with compositions similar to the Gravel kimberlite in till up to 30 km south (McClenaghan et al., 2001). The fan-shape is a function of dispersal from one kimberlite (or possibly two kimberlites) in combination with southwest to southeast (190-165º) ice flow during three phases of ice flow that crossed the Lake Timiskaming region during the Wisconsinan. The

Gravel and Bucke kimberlites are both indicator-mineral-rich kimberlites, containing 10,000s to 100,000s of indicator minerals per 10 kg. Not unexpectedly, indicator mineral concentrations in till within the dispersal fan are high (10s to 1000s of grains) compared to background concentrations (1s to 10s of grains). Mg-ilmenite and garnet are the dominant indicator minerals from till samples within the dispersal fan. Background till samples outside the fan contain only a few to no grains of Cr-pyrope and Mg-ilmenite, and few grains of Cr-diopside and chromite. These few Cr-diopside and chromite grains are suspected of having been derived from non-kimberlitic rocks in the region.

The Bucke and Gravel kimberlites contain indicator minerals from the megacryst suite (Mg-ilmenite and Ti-rich Cr-pyrope), metasomatized and unmetasomatized lherzolite, minor subcalcic harzburgite, websterite and wehrlite and very rare eclogite. The Gravel kimberlite contains Group I eclogitic garnets whereas the Bucke kimberlite contains Group II eclogitic garnets. Both kimberlites also contain minor amounts of unusually Ca-rich megacrysts.

Mg-ilmenite and garnet in till samples within the fan have compositions consistent with derivation from the Gravel kimberlite. Although the Bucke kimberlite has a fairly high indicator mineral count compared to other nearby kimberlites, indicator minerals derived from the Bucke kimberlite are masked by compositional overlap with the Gravel kimberlite. Mineral compositions unique to the Bucke kimberlite (e.g. low MgO/low Cr Mg-ilmenites, Group II eclogitic garnets, high-Ca megacrysts, very Cr-rich high-Ca Cr-pyropes) are extremely rare or absent in the till samples in the fan. Background samples up-ice (north) of the two kimberlites have low but still significant abundances of both Mg-ilmenite and pyrope garnet, indicating the presence of kimberlites up-ice (e.g. Fig. 1).

The presence of fairly Cr-rich subcalcic garnets indicates there is diamond potential from harzburgitic material for both the Bucke and Gravel kimberlites. The diamond potential might be higher for the Gravel kimberlite since it also contains Group I eclogitic garnet. The increase in Cr content with increasing Mg in Mg-ilmenite from both the Gravel and Bucke kimberlites is considered positive for diamond preservation.

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