ERCB/AGS Open File Report 2009-21

Compositions of Low-Chromium Garnet Xenocrysts from Selected Ultramafic Bodies in the Northern Alberta Kimberlite Province

Energy Resources Conservation Board

AGS
Alberta Geological Survey

ERCB/AGS Open File Report 2009-21

Compositions of Low-Chromium Garnet Xenocrysts from Selected Ultramafic Bodies in the Northern Alberta Kimberlite Province

D.R. Eccles

Energy Resources Conservation Board
Alberta Geological Survey

November 2009

ISBN 978-0-7785-8623-4

Eccles, D.R. (2009): Compositions of low-chromium garnet xenocrysts from selected ultramafic bodies in the northern Alberta kimberlite province; Energy Resources Conservation Board, ERCB/AGS Open File Report 2009-21, 20 p.

Published November 2009 by:
Energy Resources Conservation Board
Alberta Geological Survey
4th Floor, Twin Atria Building
4999 – 98th Avenue
Edmonton, Alberta
T6B 2X3
Canada

Tel: 780-422-1927
Fax: 780-422-1918
E-mail: AGS-Info@ercb.ca
Website: www.ags.gov.ab.ca

Contents

Tables

Figures

Acknowledgments

Thanks to I. Graham (formerly of Kennecott Exploration Inc.), and T. McCandless and C. Hood (formerly of Stornoway Diamond Corporation) for donating the garnet xenocrysts used in this report. Their willingness to participate is a great example of how government-industry collaboration can continue to improve the geology of Alberta. Thanks also go to Overburden Drilling Management Ltd. of Nepean, Ontario for kimberlite-indicator mineralogy processing and picking; to D. Resultay, S. Matveev and G. Chen of the University of Alberta for their roles in preparation of the microprobe mounts, electron microprobe analytical work and laser-ablation inductively coupled plasma–mass spectrometry analytical work, respectively; and to T. Stachel of the University of Alberta for technical comments that improved the manuscript.

Abstract

To date, nearly half of the single-phase syngenetic diamond inclusions recovered and documented from the Buffalo Head Hills kimberlite field are eclogitic in paragenesis. Despite this predominance of eclogitic diamond inclusions, previous mantle xenolith and xenocryst studies in northern Alberta are limited primarily to peridotitic assemblages.

The goal of this study, therefore, is to provide a comprehensive set of low-chromium (Cr) garnet xenocryst compositions for selected ultramafic bodies from the Buffalo Head Hills (K1A, K6, K11, K14, K252 and K300) and Birch Mountains (Kendu and Legend) fields in north-central and northeastern Alberta, respectively. More than 30 kg of material from the Mountain Lake body in northwestern Alberta yielded no low-Cr garnets. Electron microprobe analysis and laser-ablation inductively coupled plasma–mass spectrometry provided quantitative major- and trace-element results for 150 low-Cr xenocrysts.

With the exception of the K300 body, which yielded only four garnets, all of the bodies sampled yielded more than one type of low-Cr garnet. Megacrystic (G1) garnet is dominant in the K1A, K14 and Legend bodies. Eclogitic (G3), group I eclogitic (G3D) and pyroxenitic-websteritic-eclogitic (G4) garnet dominate the Kendu, K11 and K6 bodies, respectively. Kendu eclogitic (G3) garnet compositions correlate well with those from a previous mafic granulite xenolith study of the same body, where P-T estimates are substantially shallow in comparison to those from the diamond-stability field. The diamondiferous K11 body has the highest number of G3D and G4D diamond-facies eclogitic garnets (14 of 16 grains), with sodium content of between 0.07 and 0.09 wt. % Na_2O.

Lastly, the low-Cr garnet obtained in this study bears little resemblance to the published Buffalo Head Hills diamond-inclusion eclogitic garnet data. This might be related to one or more of the following factors:

- With the exception of K11, diamondiferous eclogitic garnet was not present in our sample set.
- Of the bodies sampled in this study, the predominant protolith for diamonds is peridotitic, not eclogitic.
- The low-Cr garnet xenocrysts in this study have undergone a complex history of melt depletion and subsequent enrichment relative to the diamond-inclusion eclogitic garnets, which are encased in diamond such that ancient mantle conditions are preserved.

1 Introduction

Fifty-one occurrences of ultrabasic (non-archetypal kimberlite) to kimberlite rock are known from three separate areas of northern Alberta: the Mountain Lake ultramafic cluster (2 bodies), and the Buffalo Head Hills (41 bodies) and Birch Mountains (8 bodies) kimberlite fields (Figure 1). These occurrences collectively define the northern Alberta kimberlite province (Eccles et al., 2004).

In their rapid ascent to the Earth's surface from depths of tens to hundreds of kilometres, alkaline and kimberlite melts in northern Alberta ubiquitously entrained xenoliths (fragments) derived from mantle peridotite and eclogite, Archean and Proterozoic lower to upper crustal material, and overlying Phanerozoic rock formations. These entrained xenoliths provide a unique opportunity to view the nature of otherwise inaccessible geological environments. When xenoliths are disaggregated syn- or post-eruption, resistant mantle xenocrysts (mineral grains), such as garnet, chromite, ilmenite and chrome diopside, can serve as a proxy for the original mantle rock from which they were derived.

The study of inclusions in xenocrystic diamond provides a realistic snapshot of the chemical conditions that were present in the mantle at the time of diamond formation. Davies et al. (2004) and Banas et al. (2006) documented 32 single-phase syngenetic diamond inclusions in diamonds sampled by the K10, K11, K14, K91 and K252 kimberlites in the Buffalo Head Hills kimberlite field of north-central Alberta. Diamond-inclusion grains include garnet, olivine, clinopyroxene, ferropericlase, spinel and rutile that span eclogitic (44%), peridotitic (41%), ultradeep (6%), websteritic (3%), wehrlitic (3%) and unknown (3%) parageneses. Despite a predominance of eclogitic diamond inclusions, previous mantle xenolith and xenocryst studies in northern Alberta are limited to peridotitic assemblages (e.g., Aulbach et al., 2004; Davies et al., 2004; Hood and McCandless, 2004; Eccles and Simonetti, 2008). One reason for this focus on peridotitic mantle is that there is abundant literature available on peridotitic versus eclogitic rocks, and mantle petrologists are now able to determine pressure-temperature (P-T) conditions from single grains of peridotitic mantle. Conversely, eclogitic mantle studies are often restricted to advanced stages of kimberlite exploration and evaluation of diamond potential.

The goal of this study is therefore to provide a comprehensive set of low-Cr garnet xenocryst compositions to complement the peridotitic garnet xenocryst data mentioned above. Electron microprobe analysis and laser-ablation inductively coupled plasma–mass spectrometry (LA-ICP) provided in situ quantitative data on low-Cr xenocrysts from selected ultramafic bodies of the Buffalo Head Hills and Birch Mountains kimberlite fields. Mountain Lake was not included because this body appears to lack low-Cr garnet. The results provide new information on the chemical nature of the eclogitic and pyroxenitic lower-crust and mantle components of north-central to northeastern Alberta.

2 General Overview of the Northern Alberta Kimberlite Province

Since 1990, 51 occurrences of ultramafic rocks have been discovered in northern Alberta. Physical and geochemical characteristics of the northern Alberta bodies have been reported by Wood et al. (1998), Aravanis (1999), Carlson et al. (1999), Skelton et al. (2003), Eccles et al. (2004), Hood and McCandless (2004), Boyer (2005), Eccles et al. (2008) and various Government of Alberta assessment reports.

The occurrences have large, geophysically inferred, near-surface areas of up to and possibly much larger than 45 ha. At least five bodies are known to crop out (Mountain Lake, K2, K5, K6 and K14), and approximately 65% of the bodies lie beneath less than 40 m of Cretaceous sediment and/or surficial deposits. To date, none of the bodies has been drill-tested to depths below 250 m, limiting our knowledge of their morphologies at depth. Atkinson and Pryde (2006) reported that the seismic images of seven Buffalo Head Hills bodies have diameters of 350–600 m at depths of 400–700 m. However, drill-testing has shown that the kimberlites are generally characterized by tabular volcaniclastic layers, and no feeder zones have been unequivocally proven to date (Skelton et al., 2003).

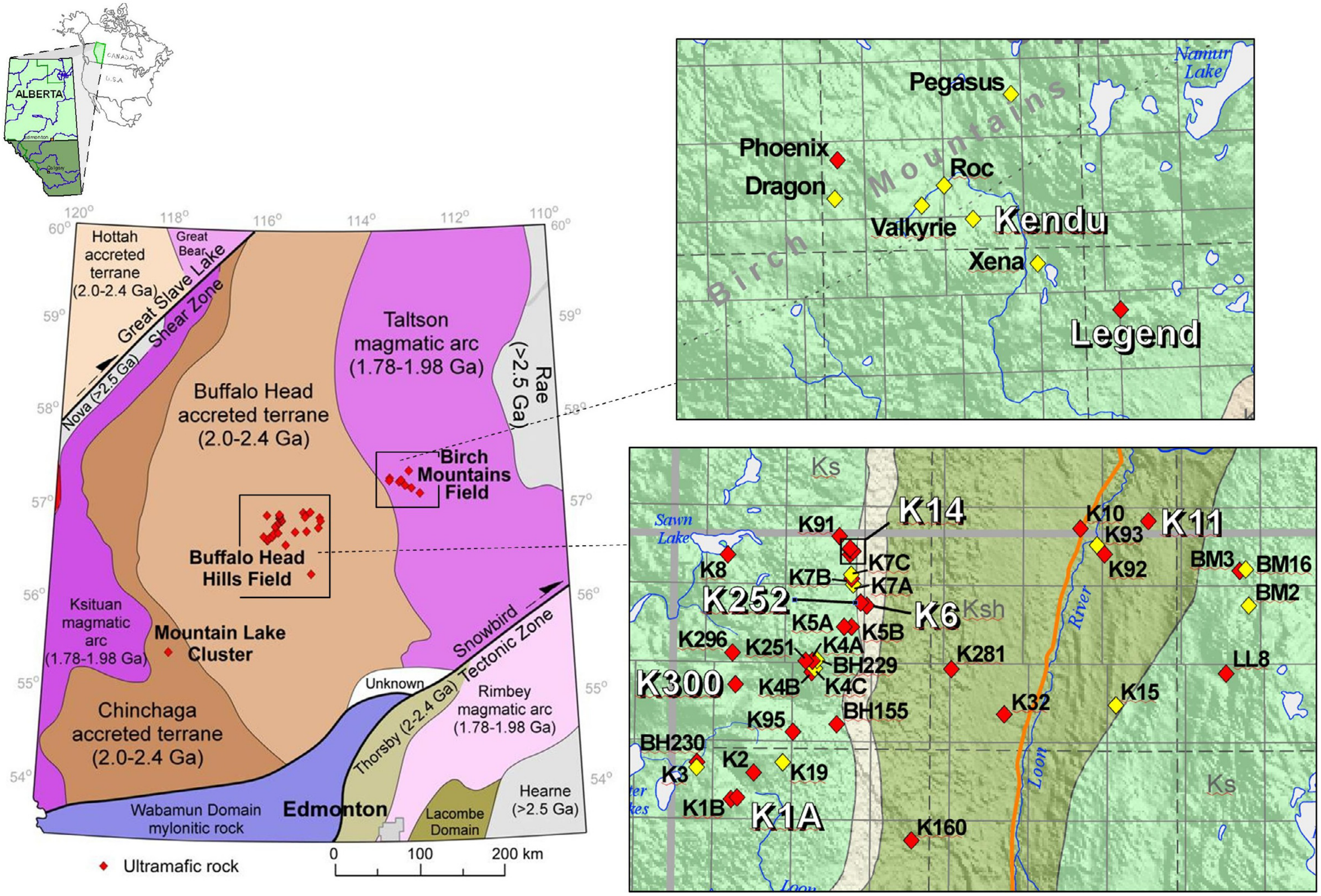


Figure 1. Ultramafic rock occurrences in the northern Alberta kimberlite province on the inferred basement domain map of Ross et al. (1994). Inset maps show the detailed location of individual ultramafic bodies in the Buffalo Head Hills and Birch Mountains kimberlite fields on the bedrock geology base map (Hamilton et al. 1999): bedrock abbreviations Ksh, Ks and Kd refer to the middle to Upper Cretaceous bedrock units Shaftesbury Formation (shale and silty shale), Smoky Group (shale and silty shale) and Dunvegan Formation (sandstone). On the inset maps, ultramafic bodies, from which garnet xenocrysts were used in this study, are in larger white-shadowed type. Diamondiferous and barren kimberlites are depicted by red and yellow diamond symbols, respectively. Mountain Lake is reportedly subeconomic.

The field is composed of pyroclastic, volcaniclastic, resedimented volcaniclastic and coherent kimberlite—the latter term is used to describe subvolcanic intrusive material (*after* Cas et al., 2008). In general, the kimberlites are juvenile, lapilli-bearing, olivine-crystal tuff. Ultramafic occurrences in the northern Alberta kimberlite province can be generally distinguished from one another by their non-archetypal kimberlite ultrabasic signature (Mountain Lake) or, in the case of kimberlite fields, primitive (Buffalo Head Hills) to evolved (Birch Mountains) magmatic signatures (Eccles et al., 2004). Intra-field anomalies are also evident. For example, the K1A body in the Buffalo Head Hills field is barren of diamond and has minerals (e.g., edenite-pargasite amphibole and sanidine) and geochemical compositions (e.g., flatter chondrite-normalized rare-earth element [REE] patterns with elevated heavy rare-earth elements [HREE]) that differ from archetypal kimberlite worldwide and bona fide kimberlite in the same field. Such bodies are therefore better referred to as hybrid ultrabasic-kimberlitic rocks (Eccles et al., 2008). Similarly, based on whole-rock, mineral-separate and isotopic geochemical evidence, Eccles et al. (2004) suggested that the Kendu body in the Birch Mountains field contains a contribution from a shallower, light rare-earth element (LREE)–enriched, low Sm/Nd lithospheric source.

Previous mantle xenolith/xenocryst studies are limited to peridotitic assemblages (e.g., Aulbach et al., 2004; Davies et al., 2004; Hood and McCandless, 2004; Eccles and Simonetti 2008). Aulbach et al. (2004) reported that mantle xenoliths from the K6, K11 and K14 Buffalo Head Hills kimberlites include spinel lherzolite, garnet-spinel lherzolite, garnet harzburgite, sheared garnet lherzolite and pyroxenite. Eccles and Simonetti (2008) inferred at least five lithological transitions for the lower crustal–sublithospheric mantle underlying northern Alberta. From low to high temperature, these are fertile lherzolite, chromite-clinopyroxene-garnet equilibrium and/or wehrlite (<870ºC); low-T lherzolite (870º–950ºC); melt metasomatized wehrlite (950º–1000ºC); depleted lherzolite and melt metasomatized lherzolite (1000º–1130ºC); and moderately fertile lherzolite and high-Ti melt metasomatized lherzolite (>1130ºC). A modelled conductive paleogeotherm for the Buffalo Head Hills corresponds to a heat flow of between 38 and 39 mW/m^2 (Aulbach et al., 2004) with equilibration temperatures of 1100º–1200ºC ±50ºC on a 40 mW/m^2 geotherm (Davies et al., 2004).

The Buffalo Head Hills kimberlite field has the best reported diamond contents in northern Alberta to date. Twenty-eight of 41 occurrences in the Buffalo Head Hills contain diamond. Five bodies (K6, K11, K14, K91 and K252), all of which are in the northwestern part of the field, have undergone mini–bulk sampling (14–616 tonnes). At least three kimberlites (K14, K91 and K252) in the northwestern part of the field contain estimated grades of >12 carats per hundred tonnes (cpht), with K252 having the highest estimated diamond content at 55 cpht from a mini–bulk sample of 22.8 t (Skelton et al., 2003).

3 Collection of Low-Cr Garnet Xenocryst Samples

We carried out heavy-mineral processing on selected ultramafic bodies using rock sample sizes that ranged between 1 and 10 kg, the sample size being a function of the amount of material available for this study. Indicator-mineral picking by Overburden Drilling Management Ltd. yielded low-Cr garnet from several Buffalo Head Hills (K1A, K6, K11, K14, K252 and K300) and Birch Mountains (Kendu and Legend) bodies (Table 1). The Mountain Lake body yielded no low-Cr garnet despite the processing of some 30 kg of material. Our low-Cr garnet coverage in the Buffalo Head Hills field does include both barren and diamondiferous bodies (Table 1). A total of 157 low-Cr garnet xenocrysts were mounted for analysis, as described below.

4 Analytical Methodology

A JEOL8900 electron microprobe (EMPA) at the University of Alberta provided quantitative chemical analyses of major elements on mineral grain separates. The silicate grains were analyzed using an accelerating voltage of 20 kV, beam diameter of 1–10 µm and beam current of 20 nA. Peak and background counting times were 20 and 10 seconds, respectively. Standards were natural minerals from the Smithsonian microbeam set of standards (Jarosewich, 2002) and were regularly analyzed to ensure the calibration remained valid throughout the probe session. A $\phi(\rho Z)$ correction routine (Armstrong, 1988) was used in data reduction.

Table 1. Summary of the ultramafic bodies with low-Cr garnet xenocrysts selected for this study. Diamond contents from Creighton and Eccles (2002), Skelton et al. (2003) and Eccles et al. (2008).

Ultamafic body	Area/field	Rock type	Location (NAD82)			DMS (cpht)[1]	Weight (kg)	Microdiamond testing[2]	
			Easting	Northing	Zone			Macros (>0.5 mm)	Micros (<0.5 mm)
K1A	Buffalo Head Hills	Non-archetypal kimberlite	569483	6284979	11		184	0	2
K6	Buffalo Head Hills	Kimberlite	585184	6308955	11		23 762	14+	81+
K11	Buffalo Head Hills	Kimberlite	619596	6320345	11	4.4	22 000		
K14	Buffalo Head Hills	Kimberlite	582822	6315364	11	11.7	479 000		
K252	Buffalo Head Hills	Kimberlite	584176	6309418	11	55.0	23 000		
K300	Buffalo Head Hills	Kimberlite	569119	6299027	11		208	0	121
Kendu	Birch Mountains	Non-archetypal kimberlite	368503	6353633	12		170	0	0
Legend	Birch Mountains	Kimberlite	386142	6340825	12		407	0	4

[1] Dense media separation mini–bulk sample results (carats per hundred tonnes)

[2] Diamonds >0.1 mm are reported as number of stones

An ELAN6000 quadruple ICP-MS coupled to a UP213 nm laser ablation system at the University of Alberta provided in situ trace-element analyses. Complete details for this technique are available in Schmidberger et al. (2007) and summarized here. The garnet grains were ablated using a 150 μm beam diameter, 5 Hz repetition rate and energy density of approximately 13 J/cm^2. Ablation runs were conducted in a mixed He/Ar atmosphere (ratio of 0.5:0.1 L/min), and mixed with Ar (1.03 L/min) prior to entering the torch assembly. The laser-ablation cell was flushed with a higher flow rate of He (up to 0.9 L/min) for approximately 1 minute between laser ablation runs to ensure adequate particle washout. A typical analysis consisted of an approximately 25-second background measurement followed by ablation for approximately 40 seconds. The National Institute of Standards and Technology (NIST) SRM 612 glass standard was used as the external calibration standard. Calcium oxide concentration, which was also measured by EPMA, was used as the internal standard. Data reduction and concentration determinations were obtained using GLITTER® (XP version, Macquarie University) laser-ablation software. Schmidberger et al. (2007) reported relative standard deviations (2σ) for most elements measured in the garnet grains ranging from 3% to 15%, with detection limits for most trace elements varying between 0.01 and 0.05 ppm.

5 Results

Table 2 summarizes the low-Cr garnet species analyzed in this study. The major- and trace-element data, totalling 157 and 146 analyses, respectively, are presented in Tables 3 and 4, and discussed in this section.

5.1 Classical Garnet Classification

The updated garnet classification scheme of Grütter et al. (2004) builds upon multivariate statistical analysis (e.g., Dawson and Stephens, 1975) and diamond-inclusion data (e.g., Gurney, 1984), and was used to separate EMPA data from the 157 garnet analyses into seven distinct groups (Table 2). These groups are megacrystic (G1, n = 60), eclogitic (G3, n = 44), diamond-facies eclogitic (G3D, n = 15), pyroxenitic-websteritic-eclogitic (G4, n = 34), diamond-facies eclogitic (G4D, n = 1), lherzolitic (G9, n = 1) and unclassified garnet composition (G0, n = 2). With the exception of K300, all of the bodies yielded more than one type of low-Cr garnet (Table 2, Figure 2). Megacrystic (G1) garnet dominates the K1A, K14 and Legend bodies. Eclogitic (G3), group I eclogitic (G3D) and pyroxenitic-websteritic-eclogitic (G4) garnet dominate the Kendu, K11 and K6 bodies, respectively. K300 has only eclogitic (G3; n = 4) garnet, which may be a function of the low total number of low-Cr garnets obtained and analyzed.

Table 2. Summary of low-Cr garnet classification, with the number of electron microprobe and laser-ablation inductively coupled plasma–mass spectrometry (LA-ICP-MS) analyses for each group.

Ultamafic body	Area/field	Garnet Group															
		G0		G1		G3		G3D		G4		G4D		G9	
		EMPA	LA-ICP	EMPA	LA-ICP	EMPA	LA-ICP	EMPA	LA-ICP	EMPA	LA-ICP	EMPA	LA-ICP	EMPA	LA-ICP
K1A	Buffalo Head Hills	1	1	17	17	1	1	1	1						
K6	Buffalo Head Hills			1	0	3	2			18	11				
K11	Buffalo Head Hills					3	3	13	13	2	2	1	1		
K14	Buffalo Head Hills			17	17	2	2			7	7				
K252	Buffalo Head Hills			1	0					1	1				
K300	Buffalo Head Hills					4	4							1	1
Kendu	Birch Mountains	1	1			29	29	1	1	2	2				
Legend	Birch Mountains			24	23	2	2			4	4				

However, the classification of low-Cr garnet into eclogitic, Cr-poor megacrystic and crustal affinities is not always straightforward. Not only are there physical similarities between these orange-coloured garnets, but there is also compositional overlap. In our dataset, for example, there is considerable overlap in Cr-Ca space between megacrystic (G1) and pyroxenitic-websteritic-eclogitic (G4) garnets on Figure 2. Further explanation and discussion of these garnet types is important to diamond exploration, so we examine the EMPA data in greater detail below.

5.2 Low-Cr Crustal Garnet

Crustal garnets can be a major detriment in the assessment of surficial heavy-mineral sample media. Schulze (1997) differentiated between mantle eclogitic and low-Cr crustal garnet on the basis of their TiO_2 versus FeO_T content, where mantle garnet generally has higher TiO_2 and lower FeO_T than its crustal equivalent. Based on the Schulze (1997) cut-off of 22 wt. % FeO_T, the vast majority of these EMPA data do not exhibit a crustal garnet signature but plot on the 'eclogitic' side of the diagram (Figure 3). A single unclassified garnet (G0) from Kendu and five garnets classified earlier as eclogitic (G3), including two analyses from each of Kendu and Legend and a single analysis from K6, have between 22.5 and 28.0 wt. % FeO_T. The majority of the Kendu eclogitic (G3) garnet has high FeO_T (98% with >16 wt. % FeO_T).

5.3 Megacrystic Garnet

Determination of low-Cr megacrystic garnet is important because G1 garnet can occur in mantle-derived magmas other than kimberlite (e.g., alkali basalt; Schulze, 1987). Schulze (1997) suggested that garnet with >0.4 wt. % TiO_2 at low Cr_2O_3 and Na_2O could be classified as low-Cr megacrystic. With the exception of six analyses from Legend and K1A that have between 0.45 and 0.74 wt. % TiO_2, the majority of the eclogitic (G3/G3D) and pyroxenitic-websteritic-eclogitic (G4/G4D) garnets in this dataset have TiO_2 contents of <0.4 wt. %. Grütter et al. (2004), however, showed that, at any given Mg# (Mg/[Mg+Fe]), megacrystic garnet generally has a higher Ti content than garnet in eclogitic and pyroxenitic xenoliths. Based on Grütter et al. (2004), 60 garnets in this dataset, or 38%, are classified as megacrystic (G1; Figure 4). Megacrystic garnets are most dominant in the K1A (n = 17), K14 (n = 17) and Legend (n = 24) bodies and constitute >80% of the low-Cr garnet population in the K1A and Kendu bodies.

The REE patterns for megacrystic (G1) garnet, as demonstrated by garnets from K1A, K14 and Legend (Figure 5a, d, g), have moderately sloping patterns from depleted LREE with La_N of <3.2 (many are

Table 3. Summary of major-element analytical results for average low-Cr garnet cores from the northern Alberta kimberlite province.

Body	K1A				K11				K14B				K252			K300		K6			Kendu				Legend		
Gar class[1]	G0	G1	G3	G3D	G3	G3D	G4	G4D	G1	G3	G4	DI-Ecl[2]	G1	G4	DI-Ecl[2]	G3	G9	G0	G3	G4	G0	G3	G3D	G4	G1	G3	G4
Anal. #	1	17	1	1	3	13	2	1	17	2	7	6	2	1	3	4	1	1	3	18	1	29	1	2	24	2	4
SiO_2	41.6	42.0	41.2	40.9	41.4	41.5	41.8	41.6	42.5	41.9	41.5	39.1	42.3	40.2	39.5	40.7	42.2	37.0	40.5	41.4	38.2	39.8	39.9	41.4	41.9	38.9	42.0
TiO_2	0.66	0.72	0.66	0.74	0.34	0.33	0.24	0.43	0.75	0.04	0.09	0.87	0.88	0.11	0.95	0.13	0.40	0.26	0.11	0.08	0.09	0.11	0.18	0.21	0.78	0.12	0.48
Al_2O_3	22.8	22.6	22.7	22.6	23.5	23.4	23.4	23.0	21.7	24.4	23.6	21.1	19.9	22.6	21.6	22.8	22.7	7.5	23.3	23.7	21.8	22.7	22.8	23.3	22.4	22.0	23.1
Cr_2O_3	0.15	0.63	0.10	0.08	0.11	0.11	0.38	0.39	1.68	0.08	0.28	0.03	3.64	0.69	0.11	0.26	1.29	0.02	0.03	0.30	0.08	0.04	0.01	0.28	0.46	0.08	0.22
FeO	11.6	10.4	12.5	13.5	11.0	11.0	12.0	12.0	8.5	10.9	12.7	19.5	7.8	18.2	19.9	15.5	10.6	20.3	15.3	13.7	28.1	19.2	16.8	13.6	10.1	23.6	10.8
MnO	0.28	0.29	0.36	0.29	0.21	0.23	0.40	0.24	0.29	0.31	0.35	1.35	0.30	0.77	0.49	0.56	0.31	0.32	2.99	0.46	0.72	0.39	0.42	0.38	0.38	0.66	0.41
MgO	16.6	18.9	15.7	13.8	15.5	15.6	17.5	16.5	20.6	17.1	16.5	9.5	20.4	12.2	10.5	13.5	19.0	0.1	11.9	15.8	5.9	10.3	12.4	17.4	19.7	7.3	19.3
CaO	6.9	4.8	7.2	8.4	8.3	8.1	4.8	6.0	4.4	6.1	5.6	8.2	5.1	5.6	7.6	7.0	4.0	32.9	6.6	5.4	5.6	8.5	7.9	4.7	4.8	8.3	5.1
Na_2O	0.07	0.07	0.05	0.14	0.07	0.08	0.03	0.09	0.08	0.01	0.02	0.27	0.08	0.01	0.34	0.01	0.08	0.01	0.02	0.01	0.01	0.04	0.11	0.03	0.07	0.01	0.06
K_2O	0.00	0.00	-0.01	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.03	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	-0.01
P_2O_5	0.02	0.03	0.01	0.02	0.04	0.02	0.02	0.03	0.03	0.00	0.01	/	0.03	0.01	/	0.01	-0.01	0.02	0.01	0.01	0.01	0.05	0.01	0.02	0.03	0.00	0.02
V_2O_3	0.04	0.04	0.05	0.04	0.03	0.02	0.04	0.03	0.04	0.01	0.02	/	0.06	0.04	/	0.03	0.03	0.07	0.03	0.02	0.08	0.03	0.02	0.03	0.06	0.04	0.05
NiO	0.00	0.01	0.03	0.01	-0.01	0.01	0.00	0.00	0.02	-0.01	0.00	/	0.02	0.00	/	0.00	0.02	0.00	0.00	0.01	-0.01	0.00	0.02	0.00	0.00	0.00	0.01
Total	100.7	100.6	100.5	100.5	100.5	100.5	100.6	100.3	100.5	100.9	100.7	100.0	100.4	100.4	101.0	100.5	100.7	98.5	100.9	100.9	100.5	101.2	100.5	101.3	100.8	101.1	101.5
Si	2.99	2.99	2.99	2.99	2.99	2.99	3.00	3.00	3.01	2.99	2.99	2.98	3.02	2.99	2.96	2.99	3.01	3.16	2.99	2.99	2.97	2.97	2.96	2.97	2.98	2.97	2.97
Ti	0.04	0.04	0.04	0.04	0.02	0.02	0.01	0.02	0.04	0.00	0.00	0.05	0.05	0.01	0.05	0.01	0.02	0.02	0.01	0.00	0.01	0.01	0.01	0.01	0.04	0.01	0.03
Al	1.94	1.90	1.94	1.95	1.99	1.99	1.98	1.96	1.81	2.04	2.01	1.90	1.68	1.98	1.91	1.98	1.91	0.76	2.03	2.02	2.00	2.00	2.00	1.97	1.88	1.98	1.93
Cr	0.01	0.04	0.01	0.00	0.01	0.01	0.02	0.02	0.09	0.00	0.02	0.00	0.21	0.04	0.01	0.02	0.07	0.00	0.00	0.02	0.00	0.00	0.00	0.02	0.03	0.00	0.01
Fe	0.70	0.62	0.76	0.83	0.66	0.66	0.72	0.73	0.50	0.65	0.77	1.26	0.46	1.13	1.25	0.95	0.63	1.45	0.96	0.83	1.83	1.20	1.04	0.81	0.60	1.51	0.64
Mn	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.02	0.09	0.02	0.05	0.03	0.03	0.02	0.02	0.20	0.03	0.05	0.02	0.03	0.02	0.02	0.04	0.02
Mg	1.78	2.01	1.69	1.50	1.66	1.68	1.87	1.77	2.18	1.82	1.77	1.07	2.17	1.35	1.17	1.48	2.01	0.01	1.28	1.70	0.69	1.14	1.37	1.85	2.09	0.84	2.03
Ca	0.53	0.37	0.56	0.66	0.64	0.62	0.37	0.46	0.33	0.47	0.43	0.66	0.39	0.45	0.61	0.55	0.31	3.02	0.52	0.41	0.47	0.68	0.62	0.36	0.37	0.68	0.39
Na	0.01	0.01	0.01	0.02	0.01	0.01	0.00	0.01	0.01	0.00	0.00	0.04	0.01	0.00	0.05	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.01	0.00	0.01
Sum	8.00	8.00	8.01	8.00	8.00	8.00	7.99	7.99	8.00	7.99	8.00	8.05	8.00	8.00	8.05	8.01	7.99	8.44	7.99	7.99	8.02	8.02	8.04	8.03	8.03	8.03	8.03
Ca/(Ca+Mg)	23.0	15.6	24.9	30.5	27.9	27.1	16.6	20.6	13.2	20.5	19.7	34.6	15.2	25.0	34.4	27.0	13.3	99.8	35.3	19.7	40.3	37.7	31.4	16.5	14.9	44.9	16.0
mg#	71.8	76.4	69.0	64.5	71.5	71.7	72.0	70.9	81.3	73.7	69.8	46.7	82.4	54.5	48.4	60.8	76.2	0.5	54.2	67.1	27.4	48.6	56.8	69.4	77.7	35.7	76.1
Cr/(Cr+Al)	0.43	1.82	0.31	0.25	0.32	0.32	1.07	1.13	4.93	0.21	0.80	0.10	10.89	2.01	0.35	0.76	3.68	0.14	0.07	0.85	0.25	0.13	0.04	0.80	1.37	0.24	0.62
Spess	0.56	0.58	0.73	0.60	0.42	0.46	0.81	0.49	0.58	0.63	0.73	2.93	0.60	1.62	1.00	1.16	0.63	0.70	6.64	0.95	1.57	0.81	0.86	0.75	0.76	1.40	0.81
Almand	22.5	19.9	24.5	27.2	22.1	22.2	24.1	24.3	15.0	22.0	25.5	39.0	13.2	37.9	39.6	31.5	21.1	7.0	32.4	28.0	60.3	39.3	33.8	26.3	18.1	49.1	19.8
Andr	1.0	1.2	1.0	0.4	0.0	0.0	0.3	0.0	2.7	0.0	0.3	2.7	3.5	0.0	1.3	0.1	0.0	61.1	0.0	0.0	0.0	0.1	0.0	0.6	2.6	0.3	1.6
Ti-Andr	1.8	1.9	1.8	2.0	0.9	0.9	0.6	1.2	2.0	0.1	0.2	2.5	2.3	0.3	2.7	0.4	1.1	0.8	0.3	0.2	0.3	0.3	0.5	0.6	2.1	0.3	1.3
Uvar	0.4	1.8	0.3	0.2	0.3	0.3	1.1	1.1	4.6	0.2	0.8	0.1	7.6	2.0	0.3	0.8	3.6	0.1	0.1	0.9	0.2	0.1	0.0	0.8	1.3	0.2	0.6
Knorr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gross	14.7	7.7	15.8	19.8	20.6	20.0	10.5	13.6	2.2	15.6	13.2	17.7	0.0	12.8	17.2	17.0	6.0	30.1	17.3	12.9	14.9	21.9	20.3	10.0	6.4	21.4	9.5
Pyrope	59.0	66.9	56.0	49.8	55.6	56.1	62.7	59.3	72.9	61.5	59.3	35.1	70.1	45.3	37.9	49.1	67.6	0.2	43.2	57.1	22.7	37.4	44.4	60.9	68.8	27.3	66.4

[1] Garnet classification based on Grutter et al. (2004)

[2] Diamond inclusion data for eclogitic garnet (DI-Ecl) from Banas et al. (2006) and Davies et al. (2004)

Table 4. Summary of trace-element (ppm) analytical results for average low-Cr garnet cores from the northern Alberta kimberlite province.

Body	K1A				K11				K14B				K252		K300		K6		Legend			Kendu			
Gar class[1]	G0	G1	G3	G3D	G3	G3D	G4	G4D	G1	G3	G4	DI-ecl[2]	G1	G4	G3	G9	G4	G3	G1	G3	G4	G0	G3	G3D	G4
Anal. #	1	17	1	1	3	13	2	1	17	2	7	4	3	1	4	1	11	2	23	2	4	1	29	1	2
Li	<0.28	0.31	0.50	0.35	BLD	0.31	0.97	0.46	0.53	0.32	0.38	/	0.47	0.37	0.09	<0.58	0.48	0.97	2.04	0.59	0.14	2.17	0.42	0.28	0.23
Sc	110	80	84	75	57	56	109	65	92	45	82	7	106	201	211	72	110	37	32	16	30	41	14	19	16
Ti	4855	4876	4358	5012	2183	2278	1769	2679	4977	462	577	13	6157	818	839	2759	510	474	1124	224	689	188	222	263	302
V	206	192	183	195	110	109	154	119	210	77	113	2	248	176	135	128	107	82	69	42	51	99	31	20	27
Cr	13042	2653	522	396	676	624	2131	2254	9185	979	1580	/	21225	4241	1507	6525	1518	283	625	108	268	59	58	50	343
Mn	1918	1835	2208	1860	1505	1510	2689	1668	2015	2372	2514	/	2055	5424	3938	2085	3027	1873	579	1035	616	1221	615	658	568
Ni_{60}	71.4	75.7	74.8	59.7	34.7	36.5	20.1	36.0	93.4	8.8	13.9	/	98.3	3.6	6.0	59.7	3.9	2.7	23.2	1.0	7.4	0.2	1.9	0.2	5.3
Ni_{62}	69.6	75.5	68.4	65.4	30.6	35.8	20.4	40.7	89.3	5.2	16.9	/	99.0	<6.55	7.6	58.1	6.4	7.2	25.0	1.4	5.8	0.9	3.3	<1.29	5.0
Zn	16.8	28.9	32.8	45.7	52.9	44.8	18.5	44.3	20.5	48.1	34.4	/	21.2	22.1	12.0	12.1	19.0	48.8	6.0	20.1	3.7	18.4	24.9	22.5	12.3
Ga	8.63	11.58	11.12	11.22	9.76	9.57	8.19	9.79	11.22	6.68	6.27	1.11	11.48	4.77	24.03	9.63	4.80	5.31	3.79	2.10	3.67	3.05	2.46	2.08	2.58
Rb	0.04	0.14	0.21	<0.04	BLD	0.07	BLD	<0.09	0.29	BLD	0.04	/	0.31	<0.10	0.16	<0.09	0.09	0.33	2.95	0.08	0.06	0.03	0.01	0.02	BLD
Sr	0.45	0.61	4.63	0.98	0.33	1.11	0.13	0.25	0.87	BLD	0.14	2.55	1.50	0.25	2.13	4.27	0.17	0.07	1.90	0.03	0.10	0.03	0.07	0.01	0.63
Y	24.7	26.8	30.9	31.7	10.0	9.8	26.6	11.8	24.6	6.4	13.4	16.9	22.9	45.2	26.5	20.6	19.9	6.6	6.4	12.9	6.3	119.6	6.4	2.8	3.5
Zr	65.5	49.5	31.9	44.8	5.5	9.0	16.6	7.1	62.9	1.3	8.1	33.4	125.3	17.8	137.2	22.6	10.3	3.2	43.4	1.8	33.2	11.5	1.7	0.8	8.7
Nb	0.21	0.17	1.29	0.12	0.15	0.51	0.11	0.16	0.63	BLD	0.24	9.16	1.07	<0.08	0.25	2.37	0.05	0.02	0.54	BLD	0.05	<0.02	0.06	<0.02	0.17
Cs	<0.05	BLD	<0.04	<0.04	BLD	0.02	BLD	<0.07	0.05	BLD	BLD	/	BLD	<0.05	BLD	0.06	0.02	BLD	0.07	BLD	0.01	<0.01	0.01	<0.01	BLD
Ba	0.04	0.28	3.87	0.03	0.03	9.47	0.23	<0.08	2.09	BLD	0.05	/	4.66	1.15	2.58	10.08	0.09	BLD	6.08	0.05	0.08	<0.01	0.05	<0.02	0.44
La	<0.10	0.08	0.28	0.04	BLD	0.26	0.08	<0.07	0.24	BLD	0.05	15.35	0.47	0.79	15.03	0.62	0.05	BLD	0.23	0.02	0.02	0.00	0.07	<0.01	0.16
Ce	0.36	0.25	0.66	0.30	0.10	0.41	0.23	0.08	0.72	0.06	0.14	10.14	1.39	2.65	22.80	1.02	0.11	BLD	0.31	0.04	0.05	0.07	0.15	<0.01	0.17
Pr	0.13	0.09	0.16	0.16	0.11	0.14	0.05	0.06	0.20	0.02	0.07	9.82	0.31	0.28	2.16	0.09	0.16	BLD	0.05	0.01	0.03	0.11	0.03	<0.01	0.04
Nd	1.61	1.04	2.18	1.13	0.44	0.62	0.84	<0.30	1.44	BLD	0.43	14.86	2.66	1.63	7.13	0.53	0.75	BLD	0.34	0.12	0.17	4.99	0.33	0.10	0.15
Sm	0.92	0.89	1.23	1.42	BLD	0.68	0.89	<0.73	1.24	1.03	0.89	24.58	1.57	1.19	2.47	<0.78	1.63	BLD	0.23	0.24	0.18	9.98	0.49	<0.01	0.16
Eu	0.48	0.47	0.47	0.59	0.22	0.33	0.25	0.21	0.48	0.27	0.29	24.33	0.60	0.56	1.08	0.15	0.25	0.21	0.12	0.19	0.10	0.29	0.22	0.10	0.08
Gd	2.10	2.26	2.01	2.77	1.07	1.07	1.57	0.76	2.26	0.46	1.33	22.75	2.63	2.39	4.14	1.15	1.56	0.76	0.57	0.67	0.48	16.43	0.75	0.14	0.31
Tb	0.54	0.49	0.56	0.59	0.21	0.20	0.44	0.16	0.50	0.22	0.30	/	0.50	0.67	0.62	0.40	0.33	0.13	0.13	0.18	0.12	2.68	0.14	0.06	0.07
Dy	4.09	4.15	4.64	5.66	1.74	1.67	3.65	1.81	4.04	1.83	2.21	20.45	4.15	5.27	4.85	3.45	3.23	1.15	1.07	1.94	0.97	19.26	1.10	0.49	0.53
Ho	0.84	0.99	1.31	1.27	0.41	0.39	0.95	0.46	0.96	0.25	0.61	17.98	0.90	1.70	1.06	0.77	0.83	0.27	0.26	0.48	0.26	4.33	0.25	0.12	0.12
Er	2.82	3.13	4.54	3.67	1.08	1.10	3.05	1.10	2.92	0.86	1.83	17.64	2.65	6.34	3.61	2.11	2.33	0.76	0.80	1.64	0.81	13.03	0.74	0.36	0.40
Tm	0.33	0.51	0.61	0.44	0.18	0.18	0.42	0.27	0.47	0.16	0.41	/	0.39	1.10	0.58	0.39	0.38	0.26	0.13	0.28	0.13	2.11	0.11	0.06	0.07
Yb	3.21	3.50	4.62	3.20	1.24	1.23	2.95	1.52	3.13	0.79	2.07	19.38	2.96	10.41	4.07	2.70	2.58	1.38	0.87	2.03	0.92	15.46	0.83	0.36	0.46
Lu	0.50	0.55	0.81	0.44	0.19	0.17	0.59	0.25	0.51	0.13	0.48	18.42	0.45	2.00	0.64	0.31	0.49	0.25	0.13	0.30	0.14	2.07	0.13	0.08	0.08
Hf	1.60	1.17	0.65	1.17	0.21	0.25	0.32	<0.26	1.73	BLD	0.41	33.80	3.33	<0.23	2.95	0.30	0.42	0.09	1.13	0.04	0.87	0.21	0.06	<0.03	0.23
Ta	0.08	0.03	0.10	<0.06	0.03	0.05	BLD	<0.09	0.09	BLD	0.04	12.67	0.11	<0.10	0.02	<0.12	0.02	BLD	0.05	0.01	0.01	0.01	0.01	<0.01	BLD
W	<0.23	0.05	0.04	0.03	0.03	0.06	0.03	<0.30	0.08	0.10	0.03	/	0.08	<0.34	BLD	<0.23	0.10	0.05	0.01	0.02	BLD	<0.07	0.01	<0.09	BLD
Pb	<0.16	0.18	0.33	<0.12	0.23	0.38	BLD	<0.18	0.52	BLD	0.32	/	1.52	<0.12	0.45	2.19	0.16	BLD	0.36	0.03	0.05	<0.02	0.03	0.01	BLD
Th	0.05	0.03	0.10	0.02	BLD	0.10	BLD	<0.09	0.13	0.04	0.02	49.08	0.20	0.18	8.53	0.27	0.03	BLD	0.14	0.00	BLD	<0.02	0.02	0.01	0.02
U	<0.04	0.02	0.06	0.02	BLD	0.04	BLD	<0.05	0.05	0.02	0.01	34.43	0.08	<0.10	0.34	<0.08	0.03	0.01	0.02	0.00	0.01	<0.02	0.00	<0.01	0.01

[1] Garnet classification based on Grutter et al. (2004).

[2] Diamond inclusion data for eclogitic garnet (DI-Ecl) from Davies et al. (2004).

Abbreviation: BLD, below limit of detection

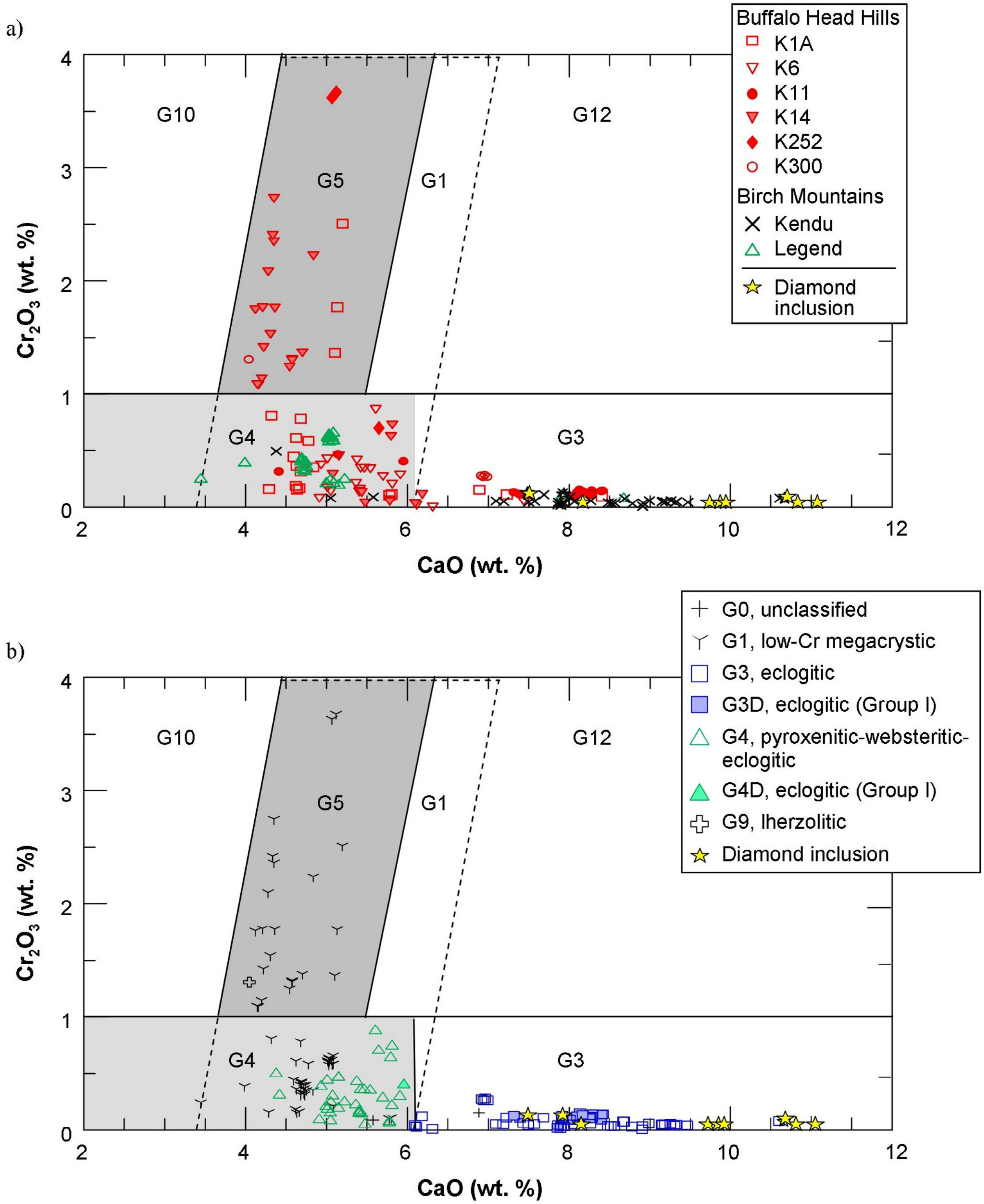
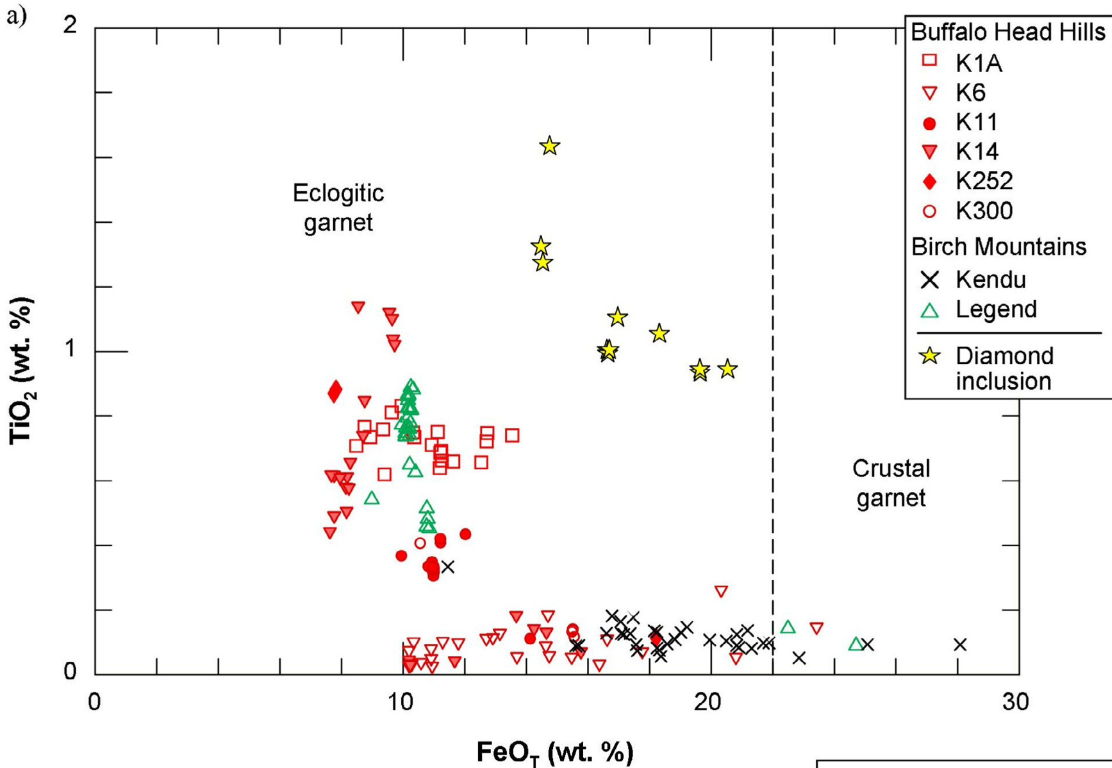


Figure 2. Conventional plot of Cr_2O_3 versus CaO in low-Cr garnet, with group-number classification from Grütter et al. (2004). Selected Buffalo Head Hills and Birch Mountains garnet xenocrysts are shown by a) body, and b) garnet classification. Eclogitic diamond-inclusion data from Davies et al. (2004) and Banas (2006; K14 and K252 kimberlites, n = 11).

a)



b)

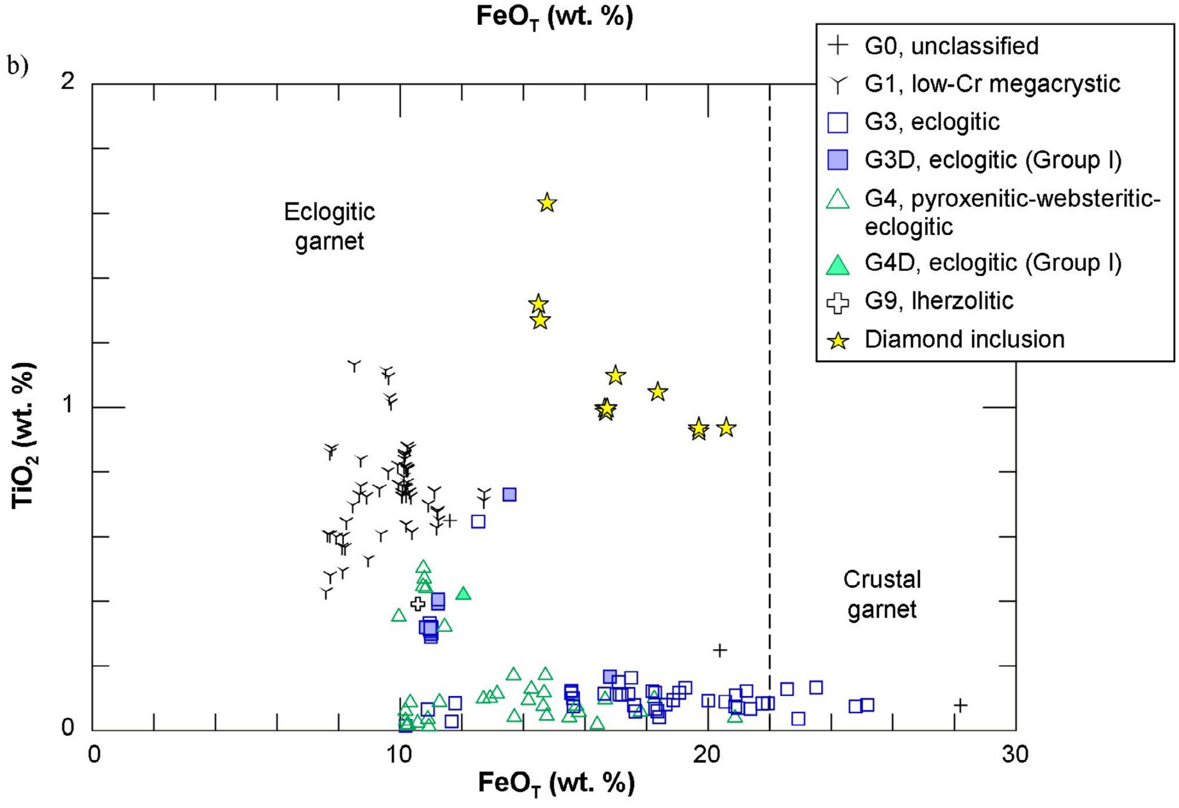


Figure 3. TiO_2 versus FeO_T in garnet, using the cut-off for eclogitic versus crustal garnet at 22 wt. % FeO_T from Schulze (1997). Selected Buffalo Head Hills and Birch Mountains garnet xenocrysts are shown by a) body, and b) garnet classification. Eclogitic diamond-inclusion data from Davies et al. (2004) and Banas (2006; K14 and K252 kimberlites, n = 11).

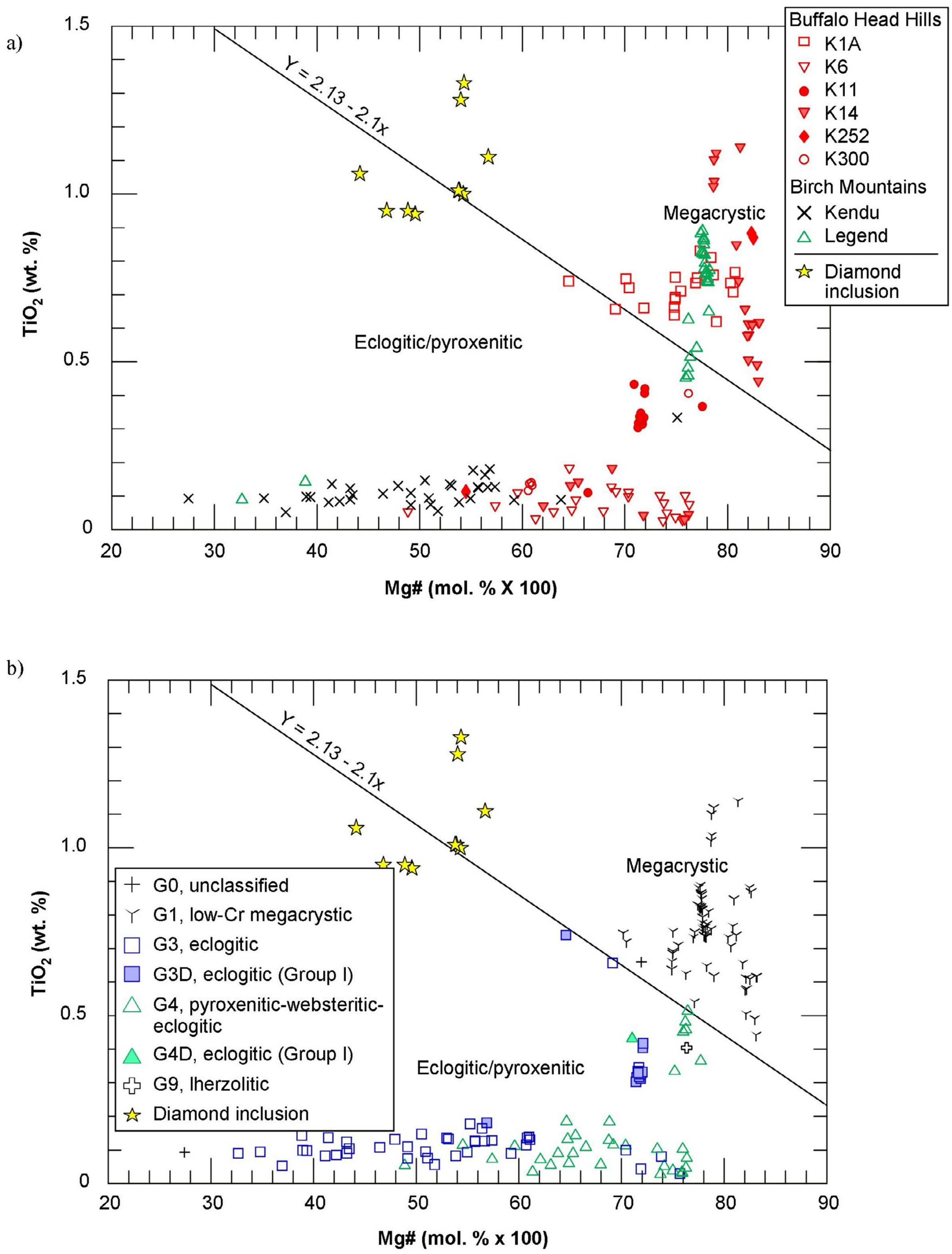


Figure 4. TiO_2 versus Mg# (Mg/[Mg+Fe]) in garnet, with the eclogitic/pyroxenitic versus megacrystic garnet fields from Grütter et al. (2004). Selected Buffalo Head Hills and Birch Mountains garnet xenocrysts are shown by a) body, and b) garnet classification. Eclogitic diamond-inclusion data from Davies et al. (2004) and Banas (2006; K14 and K252 kimberlites, n = 11).

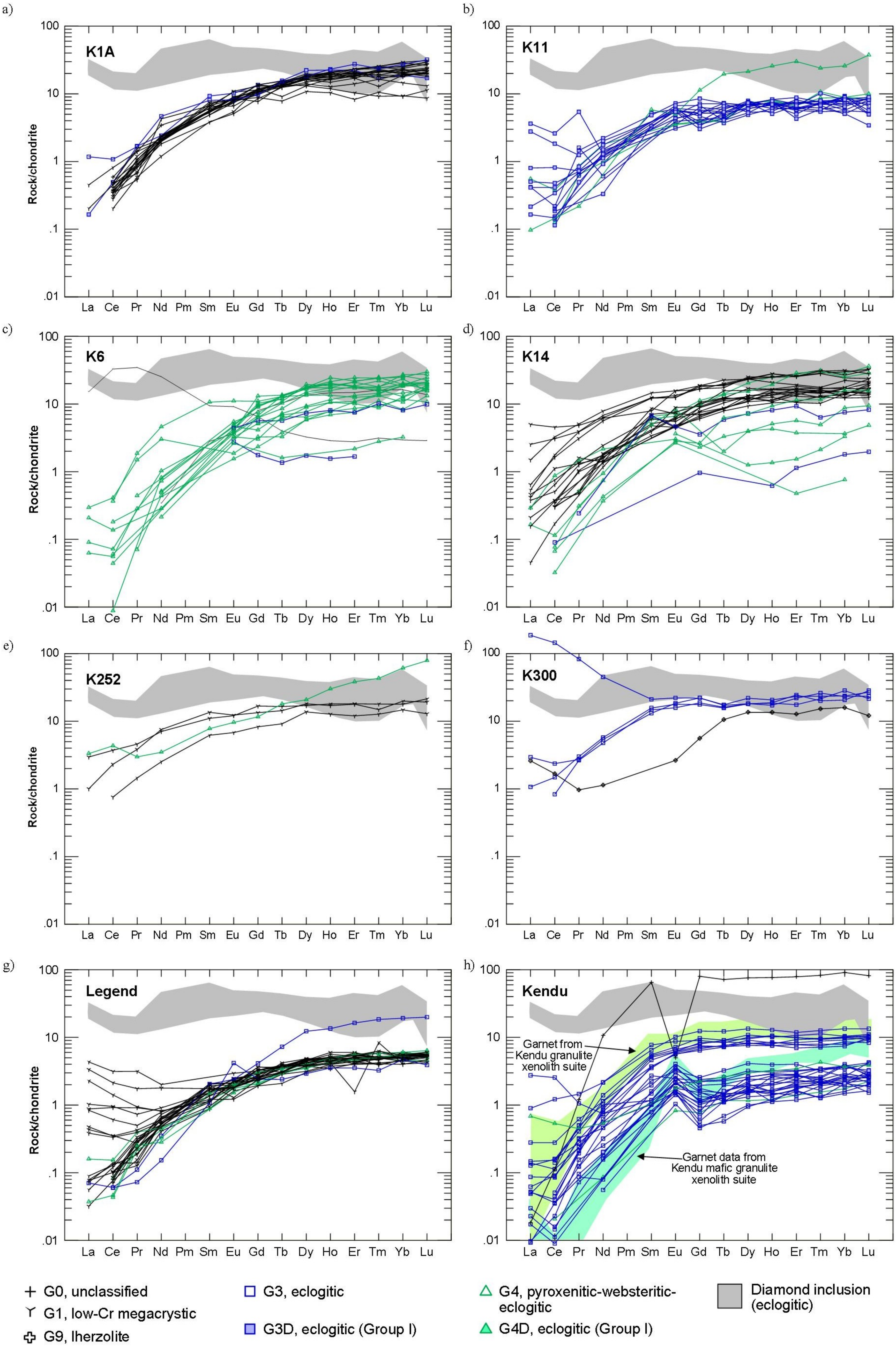


Figure 5. Rare-earth element plots for low-Cr garnet cores, normalized to the chondritic values of Sun and McDonough (1989). Shaded areas represent diamond-inclusion eclogitic garnet (*from* Davies et al., 2004). Kendu xenolith data from Eccles et al. (in press).

below the limit of detection) to higher HREE with Lu_N up to 22. A prominent feature of the G1 garnet REE is their overall fractionated pattern, which may be a feature that is characteristic of the growth patterns of megacrysts. The normal mid-ocean ridge basalt (N-MORB)–normalized spider diagram shows Ba and Sr depletion relative to Rb-Th and LREE-Zr, respectively (Figure 6a, d, g). The lack of a Ti anomaly helps to distinguish megacrystic (G1) garnet from other garnet species in this dataset.

5.4 Eclogitic Garnet

All of the bodies except K252 contain eclogitic (G3) garnet, which accounts for 28% of the total garnet in this study (Table 2). They are most dominant in the Kendu body, where they account for 88% of the garnet. They may also be dominant in the K300 body, but this observation is based on only five garnet analyses. On the molar Mg-Ca-Fe_T diagram (Figure 7), the majority of the G3 garnet plots in the field for Group B eclogitic garnet. There is a wide compositional array within the G3 group, particularly between the Buffalo Head Hills and Birch Mountains fields (Table 2; Figure 7). Eclogitic (G3) garnet from the Kendu and Legend bodies has significantly lower $Mg\#_{36–49}$ and higher $Ca\#_{38–45}$ and FeO (Kendu averages 19 wt. % FeO; n = 29) than any of the eclogitic (G3) garnet from the Buffalo Head Hills bodies ($Mg\#_{54–74}$ and higher $Ca\#_{21–35}$). Thus, eclogitic garnet from Kendu and Legend has lower pyrope and higher almandine and grossular end-member compositions ($Py_{27–34}Alm_{39–49}Gr_{21–22}$) compared to the Buffalo Head Hills bodies ($Py_{43–62}Alm_{22–32}Gr_{16–21}$).

Compositional variation of eclogitic garnet (G3) between bodies is also evident, as demonstrated for end-member compositions of Buffalo Head Hills bodies. Based on highest to lowest Mg# and from lowest to highest Ca#, K14 is anomalous with an average end-member composition of $Py_{62}Alm_{22}Gr_{16}$, followed by K1A and K11 ($Py_{56}Alm_{22–25}Gr_{16–21}$) and K6 and K300 ($Py_{43–49}Alm_{32}Gr_{17}$).

Eclogitic (G3) garnet is LREE depleted (La_N <2) with relatively flat HREE (Dy_N/Yb_N 0.6–1.3; e.g., Figure 5a, b, f, h). With 29 eclogitic G3 analyses, Kendu provides the best chance to discuss REE-trends for this low-Cr garnet type (Figure 5h). Two distinct G3 garnet patterns are evident in Kendu. Both patterns are LREE depleted, with one garnet trend characterized by a higher overall abundance of REE (La_N-Lu_N of about 116–312) and particularly HREE (5–21 Lu_N). A second trend of Kendu eclogitic (G3) garnet has a distinctive positive Eu/Eu* (where Eu* = [Sm + Gd] / 2) of up to 36 (Figure 5h). On the spider diagram, the G3 garnets are characterized by depletion of alkali-earth elements (e.g., Ba and Sr) and high-field-strength elements (e.g., Nb, Zr and Ti) relative to N-MORB, with Zr depletion being most pronounced in the Kendu G3 garnet (e.g., Figure 6a, b, f, h).

5.5 Pyroxenitic-Websteritic-Eclogitic Garnet

Pyroxenitic-websteritic-eclogitic (G4) garnets occur in the K6, K11, K14, K252, Kendu and Legend bodies, accounting for 22% of the total garnet in this dataset (Table 2). The G3 and G4 garnet groups can be differentiated, albeit with some overlap, on the molar Mg-Ca-Fe_T diagram in Figure 7, where the majority of the G3 and G4 garnet data plot in the Group B and A eclogite fields, respectively (Figure 7). In this classification, which is based on Shervais et al. (1988) and Taylor and Neal (1989), the Group A field comprises garnets derived from an ultramafic, predominantly pyroxenitic source.

Pyroxenitic-websteritic-eclogitic (G4) garnets are most abundant in the K6 body, where they account for 82% of the total garnet. The G4 garnets are also prominent in the K14 body (27%). When G4 garnet (n = 1) from the K252 body is not included, the pyroxenitic-websteritic-eclogitic (G4) garnet has a narrow compositional range of $Mg\#_{67–76}$—regardless of body or field—with similar average end-member compositions, $Py_{57–66}Alm_{20–28}Gr_{10–13}$ (Table 3; Figure 7).

Rare-earth element patterns of the pyroxenitic-websteritic-eclogitic (G4) garnet from the K6 body have depleted La_N, Pm_N and Sm_N that are below the limit of detection, and gently sloping HREE (Dy_N/Yb_N

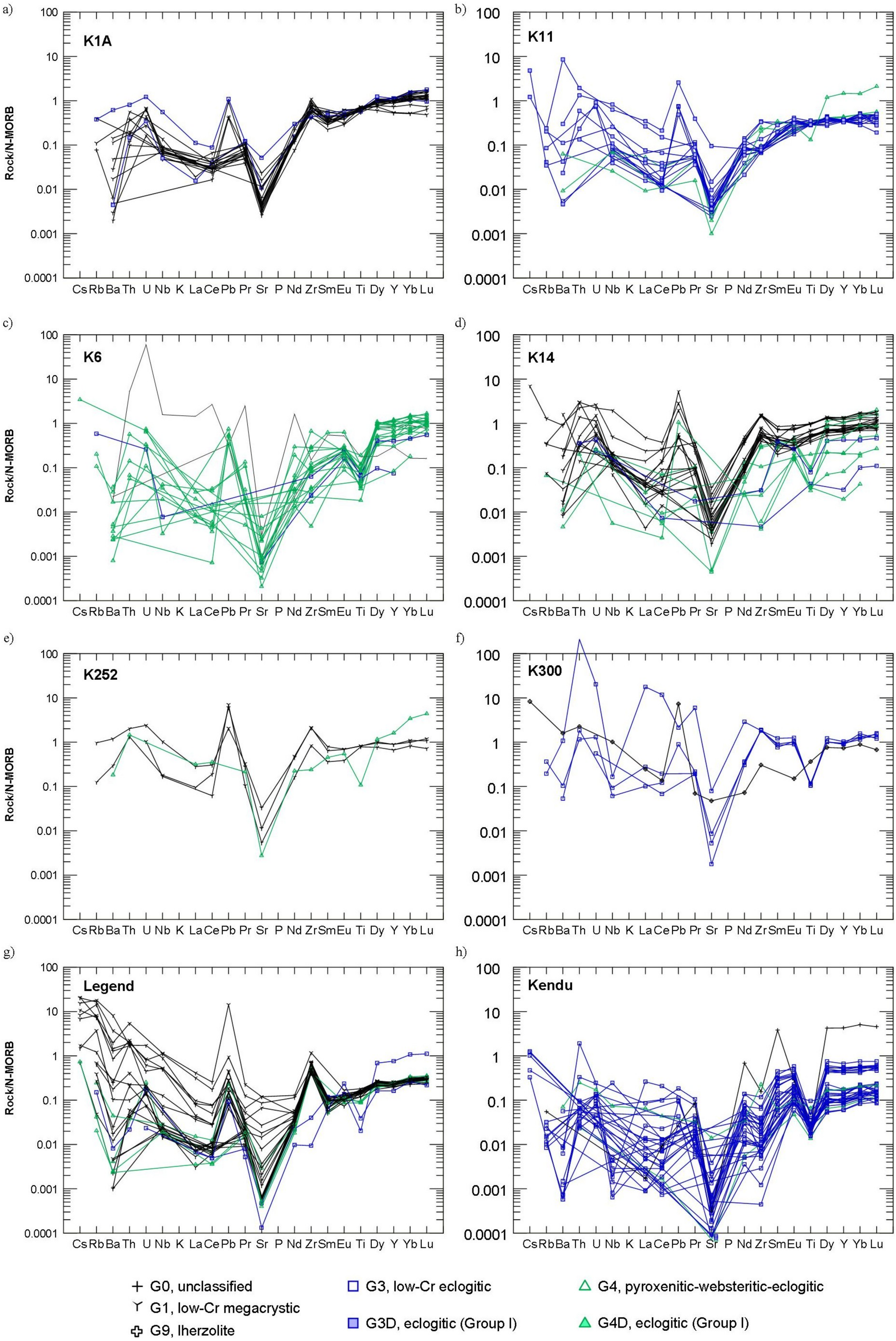
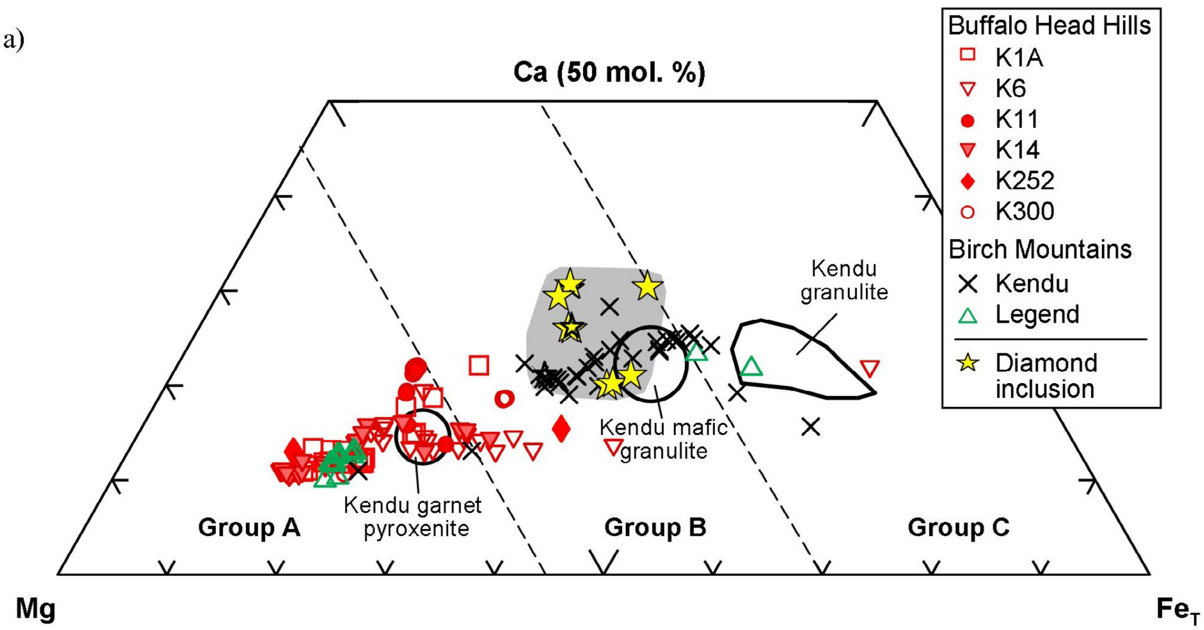


Figure 6. Spider plots for low-Cr garnet cores, normalized against normal mid-ocean ridge basalt (N-MORB; Sun and McDonough. 1989).

a)



b)

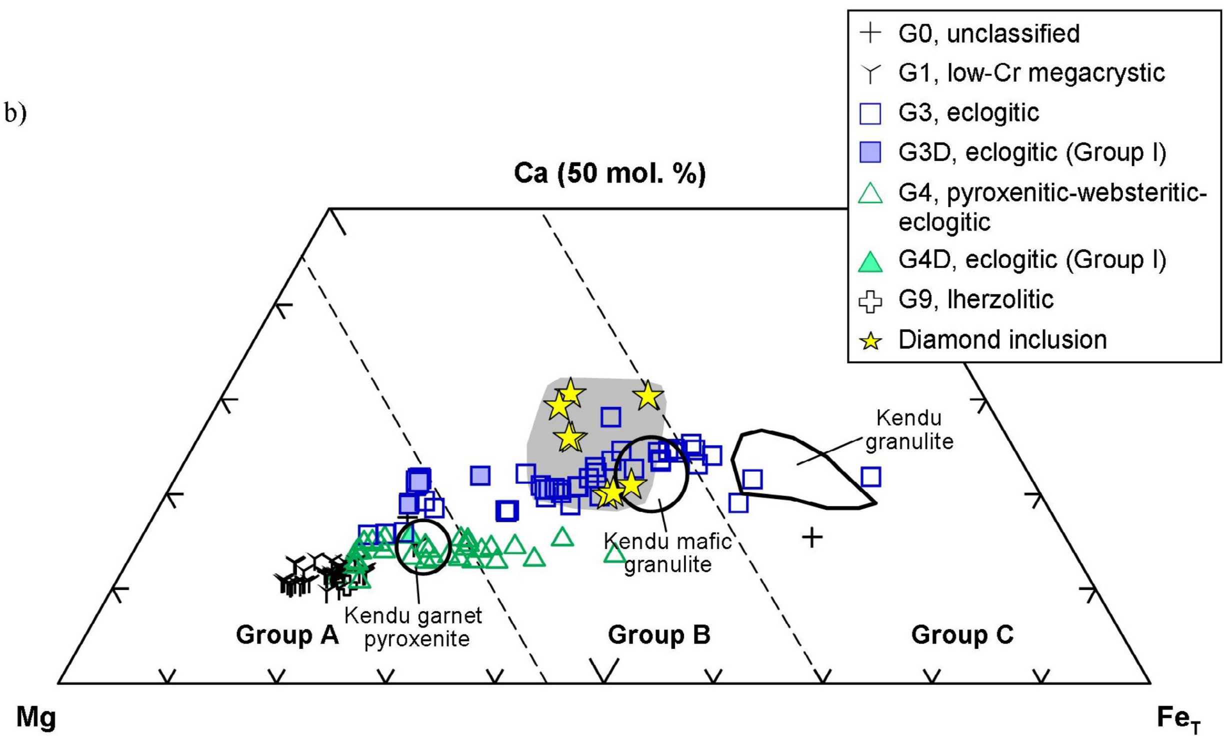


Figure 7. Molar Mg-Ca-Fe$_T$ in garnet cores, with Group A, B and C eclogite fields from Shervais et al. (1988). Selected Buffalo Head Hills and Birch Mountains garnet xenocrysts are shown by a) kimberlite body, and b) garnet classification. Light-shaded polygon represents eclogitic diamond-inclusion data from Davies et al. (2004) and Banas et al. (2006; K14 and K252 kimberlites, n = 11). The labelled polygons represent garnet-core data from garnet pyroxenite, mafic granulite and granulite xenoliths from the Kendu body ('Garnet pyroxenite (Group A eclogite), mafic granulite and granulite xenoliths from northeastern Alberta: evidence of ~1.5 Ga upper mantle and lower crust in western Laurentia', Eccles et al., in press).

0.5–1.1), with Lu_N up to 52 (Figure 5c). The G4 garnets have Sr and Ti N-MORB depletion relative to Pb-Nd and MREE-HREE, respectively.

5.6 'D'-Designated (Diamond-Facies) Eclogitic Garnet

The 'D' designation, or diamond facies, in the G3D and G4D categories of Grütter et al. (2004) constitutes a replacement for the term 'Group I eclogitic', which originally referred to a coarse-grained eclogite texture (MacGregor and Carter, 1970) but now also has a compositional connotation (i.e., Na_20 >0.7 wt. %; McCandless and Gurney, 1989). Thus, eclogitic (G3) and pyroxenitic-websteritic-eclogitic (G4) garnets with Na_20 >0.7 wt. % are referred to as diamond-facies eclogitic G3D and G4D garnet, based on these elevated Na compositions in eclogitic diamond inclusions.

A high proportion of the K11 low-Cr garnet (74%) is classified as G3D (n = 13) and G4D (n = 1). The G3D garnet from K11 has end-member compositions of $Py_{55–58}Alm_{22–23}Gr_{18–21}$ (Table 3). The single G4D garnet from K11 ($Py_{59}Alm_{24}Gr_{14}$) is the only G4D garnet in this dataset. Variable LREE (La_N of 0.1–2.3) and flat to gently sloping HREE ((Dy_N/Yb_N 0.9–1.3) characterize the REE profiles of G3D garnet (Figure 5b). The spider diagram shows a fairly flat profile relative to N-MORB, except for pronounced positive Pb and negative Sr anomalies. In addition, there is no apparent Zr or Ti anomaly, which also distinguishes G3D garnet from all other garnet profiles in this dataset.

Other 'D' classified garnet includes single eclogitic G3D garnets in both K1A and Kendu; however, the G3Ds constitute a low portion relative to other garnet types in these bodies.

6 Discussion and Conclusions

6.1 Comparison between Low-Cr Garnet Results and Previous Xenolith Data

With the exception of the eclogitic diamond-inclusion data from Davies et al. (2004) and Banas et al. (2006), which are discussed in the following section, there are few eclogite xenolith studies from the northern Alberta kimberlite province to draw upon for comparisons with the data presented herein. Eccles et al. (in press) are documenting representative garnet pyroxenite, mafic granulite and granulite xenoliths from the Kendu body in the Birch Mountains field. Of the Kendu data, the eclogitic (G3) garnet from this study corresponds well with the mafic granulite suite of xenoliths in both major-element (Figure 7) and trace-element chemistry, particularly the positive Eu/Eu* (Figure 5h). Mafic granulite has a tight cluster of calculated P-T conditions that average 18.8 kbar and 730ºC, based on the intersections of clinopyroxene-garnet-plagioclase-quartz reactions (Eccles et al., in press).

A second correlation, albeit less convincing, can be drawn between Fe- and REE-rich G3 garnet from Kendu body and the Kendu granulite suite of xenoliths described by Eccles et al. (in press; Figures 5, 7). The granulite P-T estimates range from 13.3 to 15.5 kbar and from 750º to 830ºC, with an average of 14 kbar and 800ºC (Eccles et al., in press).

6.2 Comparison between Low-Cr Garnet Results and Previous Diamond-Inclusion Data

Unlike some peridotitic minerals, it is not possible to calculate the equilibrium pressure and/or temperature from single grains of eclogitic garnet. Sobolev and Lavrent'ev (1971) and McCandless and Gurney (1989) suggested that diamond-facies eclogitic (formerly Group I eclogitic) inclusions in diamond commonly have Na_2O >0.7 wt. %. The Na content of eclogitic garnet, therefore, is currently the best indicator of equilibration depth and association with diamond. It should be noted, however, that high-Na garnet is also observed in some graphite-bearing eclogite xenoliths (Grütter and Quadling, 1999) and, conversely, that garnet in diamond-bearing eclogite may have relatively low Na content (<0.07 wt. %; Cookenboo et al., 1998). In addition, several authors have shown that high Na_2O in garnet inclusions in diamond is accompanied by high TiO_2 (e.g., Danchin and Wyatt, 1979; Schulze, 1997).

In this study, the diamondiferous K11 body (Table 1) has the highest number of G3D and G4D garnets (n = 14 of 19) with Na_2O contents between 0.07 and 0.09 wt. %. Single G3D garnet grains from diamond-poor or barren K1A and Kendu have 0.14 and 0.11 wt. % Na_2O, respectively. Figure 8 shows that, except for a single G3D garnet from K1A, all of the G3D and G4D data plot just inside the high Na_2O-TiO_2 diamond-facies eclogitic field of Schulze (1997). The Buffalo Head Hills K11 body has the strongest geochemical association with diamond-facies eclogitic garnet and diamond in this dataset.

Figures 2–8 include the eclogitic diamond-inclusion data from the Buffalo Head Hills kimberlite field, as reported by Davies et al. (2004) and Banas et al. (2006). Eclogitic garnet inclusions in diamond from northern Alberta are characterized by high Na_2O (averaging 0.29 wt. %, n = 9, and up to 0.48 wt. %; Figure 8), moderately high TiO_2 such that they straddle the macrocrystic-eclogitic line (Figure 4), and high overall REE abundance (17–22; Figure 5). Exception for the Mg-Ca-Fe_T diagram (Figure 5), garnet analyzed in this report bears little resemblance to the diamond-inclusion data. On Figure 5, the association between the diamond-inclusion field and the Kendu eclogitic G3 garnet does not support diamond potential because we have shown that these compositions are more likely related to garnet associated with mafic granulite xenoliths from the Kendu body, which are not consistent with the pressure and temperature associated with diamond formation.

Thus, we reason that

1) except for the K11 body, garnet derived from diamondiferous eclogite was simply not present in the sample material available to this study;
2) for the bodies sampled in this study, the predominant protolith for diamonds in northern Alberta is peridotitic; and/or
3) the low-Cr garnet xenocrysts in this study have been subjected to a complex history of melt depletion with subsequent enrichment (supported by the depleted LREE, downwards convex REE and MREE enrichment), compared to diamond-inclusion eclogitic garnets, which are preserved.

6.3 Benefit to Future Diamond Exploration in Alberta

The release of these data and interpretations will help diamond explorers evaluate low-Cr garnet xenocrysts recovered and analyzed in surficial heavy-mineral surveys. The results of our study show that there is no unequivocal link between the low-Cr garnet xenocrysts cited here and the Buffalo Head Hills diamond-inclusion data of Davies et al. (2004) and Banas et al. (2006). At least two noteworthy links, however, are discussed. First, there is an association between a predominance of G3D garnet xenocrysts and the diamondiferous K11 body in the Buffalo Head Hills. Secondly, the majority of the G3 garnet xenocrysts from the barren Kendu body are likely related to a shallow mafic granulite layer. Thus, one benefit of this study is that future regional indicator-mineral surveys can use these data to differentiate between low-Cr garnet types. These results agree with previous eclogitic garnet literature that explorers should concentrate on low-Cr garnet with higher Na_2O (i.e., G3D/G4D garnet) and Mg#. This study also provides a locale and comprehensive set of data for future target evaluation and studies.

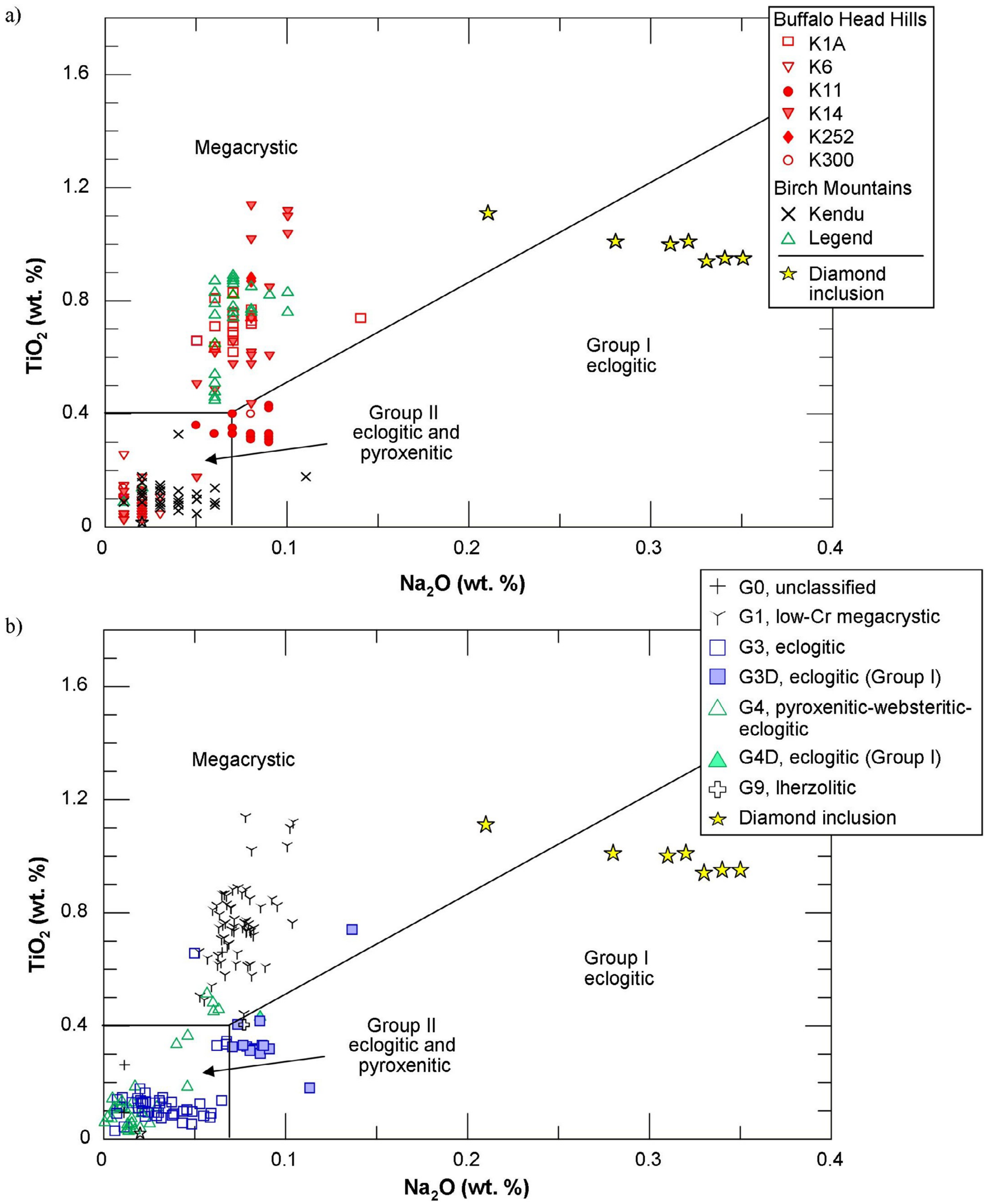


Figure 8. TiO_2 versus Na_2O in garnet, with megacrystic and eclogitic Group I and II fields from Schulze (1997). Selected Buffalo Head Hills and Birch Mountains garnet xenocrysts are shown by a) body, and b) garnet classification. Eclogitic diamond-inclusion data from Davies et al. (2004) and Banas (2006; K14 and K252 kimberlites, n = 11). Three diamond-inclusion garnets from Davies et al. (2004) with Na_2O of between 1.53 and 1.57 wt. % are not shown at this scale.

7 References

Aravanis, T. (1999): Legend property assessment report, Birch Mountains area, Alberta; Alberta Energy and Utilities Board, EUB/AGS Mineral Assessment Report 20000003, URL <http://www.ags.gov.ab.ca/publications/abstracts/MIN_20000003.html> [September 2009].

Armstrong, J.T. (1988): Comparison of Monte Carlo, ZAF and $\phi(\rho Z)$ procedures; *in* Microbeam analysis–1988, D.E. Newbury (ed.), San Francisco Press, San Francisco, California, p. 239–246.

Atkinson, E. and Pryde, R. (2006): Seismic investigation of selected kimberlite pipes in the Buffalo Head Hills kimberlite field, north-central Alberta; Alberta Energy and Utilities Board, EUB/AGS Special Report 79, URL <http://www.ags.gov.ab.ca/publications/abstracts/SPE_079.html> [September 2009].

Aulbach, S., Griffin, W.L., O'Reilly, S.Y. and McCandless, T.E. (2004): Genesis and evolution of the lithospheric mantle beneath the Buffalo Head Terrane, Alberta (Canada); Lithos, v. 77, p. 413–451.

Banas, A., Stachel, T., Muehlenbachs, K. and McCandless, T.E. (2006): Diamonds from the Buffalo Head Hills, Alberta: formation in a non-conventional setting; Lithos, v. 93, p. 199–213.

Boyer, L.P. (2005): Kimberlite volcanic facies and eruption in the Buffalo Head Hills, Alberta; M.Sc. thesis, Mineral Deposit Research Unit, University of British Columbia, 156 p.

Carlson, S.M., Hillier, W.D., Hood, C.T., Pryde, R.P. and Skelton, D.N. (1999): The Buffalo Hills kimberlites: a newly-discovered diamondiferous kimberlite province in north-central Alberta, Canada; *in* Proceedings of the Seventh International Kimberlite Conference, J.B. Dawson Volume, 1998, J.J. Gurney, J.L. Gurney, M.D. Pascoe and S.H. Richardson (ed.), Red Roof Design, Cape Town, South Africa, p. 109–116.

Cas, R.A.F., Porritt, L., Pittari, A. and Hayman, P. (2008): A new approach to kimberlite facies terminology using a revised general approach to nomenclature for all volcanic rocks: descriptive to genetic; Journal of Volcanology and Geothermal Research, v. 174, p. 226–240.

Cookenboo, H.O., Kopylova, M.G. and Daoud, D.K. (1998): A chemically and texturally distinct layer of diamondiferous eclogite beneath the central Slave craton, northern Canada; 7th International Kimberlite Conference, Extended Abstracts, p. 164–165.

Danchin, R.V. and Wyatt, B.A. (1979): Statistical cluster analysis of garnets from kimberlites and their xenoliths; 2nd Kimberlite Symposium, Extended Abstracts, p. 22–27.

Davies, R.M., Griffin, W.L., O' Reilly, S.Y. and McCandless, T.E. (2004): Inclusions in diamonds from the K14 and K10 kimberlites, Buffalo Head Hills, Alberta, Canada: diamond growth in a plume?; Lithos, v. 77, p. 99–111.

Dawson, J.B. and Stephens, W.E. (1975): Statistical classification of garnets from kimberlite and associated xenoliths; Journal of Geology, v. 83, p. 589–607.

Eccles, D.R. and Simonetti, A. (2008): A study of peridotitic garnet xenocryst compositions from selected ultramafic bodies in the northern Alberta kimberlite province: implications for mantle stratigraphy and garnet classification; Energy Resources Conservation Board, ERCB/AGS Earth Sciences Report 2008-01, 26 p, URL <http://www.ags.gov.ab.ca/publications/abstracts/ESR_2008_01.html> [September 2009].

Eccles, D.R., Simonetti, S.S. and Cox, R. (in press): Garnet pyroxenite and granulite xenoliths from northeastern Alberta: evidence of ~1.5 Ga lower crust/mantle in western Laurentia; Precambrian Research.

Eccles, D.R. Creaser, R.A. Heaman, L.M. and Ward, J. (2008): Rb-Sr and U-Pb geochronology and setting of the Buffalo Head Hills kimberlite field, northern Alberta; Canadian Journal of Earth Sciences, v. 45, no. 5, p. 513–529.

Eccles, D.R., Heaman, L.M., Luth, R.W. and Creaser, R.A. (2004): Petrogenesis of the Late Cretaceous northern Alberta kimberlite province; Lithos, v. 77, no. 1, p. 435–459.

Grütter, H.S. and Quadling, K.E. (1999): Can sodium in garnet be used to monitor eclogitic diamond potential? *in* Proceedings of the 7th International Kimberlite Conference, J.B. Dawson Volume, J.J. Gurney, J.L. Gurney, M.D. Pascoe and S.H. Richardson (ed.), Red Roof Design, Cape Town, South Africa, p. 314–320

Grütter, H.S., Gurney, J.J., Menzies, A.H. and Winter, F. (2004): An updated classification scheme for mantle-derived garnet, for use by diamond explorers; Lithos, v. 77, p. 841–857.

Gurney, J.J. (1984): A correlation between garnets and diamonds; *in* Kimberlite occurrence and origins: a basis for conceptual models in exploration, J.E. Glover and P.G. Harris (ed.), Geology Department and University Extension, University of Western Australia, Publication 8, p. 143–166.

Hamilton, W.N., Langenberg, W.C., Price, M.C. and Chao, D.K. (1999): Geological map of Alberta; Alberta Energy and Utilities Board, EUB/AGS Map 236, scale 1:1 000 000.

Hood, C.T.S. and McCandless, T.E. (2004): Systematic variations in xenocryst mineral composition at the province scale, Buffalo Hills kimberlites, Alberta, Canada; Lithos, v. 77, p. 733–747.

Jarosewich, E. (2002): Smithsonian microbeam standards; Journal of Research of the National Institute of Standards and Technology, v. 107, p. 681–685.

MacGregor, I.D. and Carter, J.L. (1970): The chemistry of clinopyroxenes and garnets of eclogite and peridotite xenoliths from the Roberts Victor mine, South Africa; Physics of the Earth and Planetary Interiors, v. 3, p. 391–397.

McCandless, T.E. and Gurney, J.J. (1989): Sodium in garnet and potassium in clinopyroxene: criteria for classifying mantle eclogites; *in* Kimberlites and related rocks, J. Ross (ed.), Geological Society of Australia, Special Publication No. 14, v. 2, p. 827–832.

Ross, G.M., Broome, J. and Miles, W. (1994): Potential fields and basement structure—Western Canada Sedimentary Basin; *in* Geological Atlas of the Western Canadian Sedimentary Basin, G.D. Mossop and I. Shetsen (comp.), Canadian Society of Petroleum Geologists and Alberta Research Council, Special Report 4, p. 41–48.

Schmidberger, S.S., Simonetti, A., Heaman, L.M., Creaser, R.A. and Whiteford, S. (2007): Lu-Hf, in situ Sr and Pb isotope and trace element systematics for mantle eclogites from the Diavik diamond mine: evidence for Paleoproterozoic subduction beneath the Slave craton, Canada; Earth and Planetary Science Letters, v. 254, p. 55–68.

Schulze, D.J. (1987): Megacrysts from alkaline volcanic rocks; *in* Mantle xenoliths, P.H. Nixon (ed.), John Wiley & Sons Ltd., New York, p. 433-452.

Schulze, D.J. (1997): The significance of eclogite and Cr-poor megacryst garnets in diamond exploration; Exploration and Mining Geology, v. 6, p. 349–366.

Shervais, J.S., Taylor, L.A., Lugmair, G.W., Clayton, R.N., Mayeda, T.K. and Korotev, R.L. (1988): Early Proterozoic oceanic crust and the evolution of the sub-continental mantle: eclogites are related rocks from southern Africa; Geological Society of America Bulletin, v. 100, p. 411–423.

Skelton, D., Clements, B., McCandless, T.E., Hood, C., Aulbach, S., Davies, R. and Boyer, L.P. (2003): The Buffalo Head Hills kimberlite province, Alberta; *in* Slave Province and northern Alberta field trip guidebook, B.A. Kjarsgaard (ed.), Geological Survey of Canada, Miscellaneous Publication G-293, p. 11–19.

Sobolev, N.V. and Lavrent'ev, Y.G. (1971): Isomorphic sodium admixture in garnets formed at high pressures; Contributions to Mineralogy and Petrology, v. 31, p. 1–12.

Sun, S.-S. and McDonough, W.F. (1989): Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes; *in* Magmatism in the ocean basins, A.D. Saunders and M.J. Norry (ed.), Geological Society, London, Special Publication 42, p. 313–345.

Taylor, L.A. and Neal, C.R. (1989): Eclogites with oceanic crustal and mantle signatures from the Bellsbank kimberlite, South Africa, part I: mineralogy, petrography and whole rock chemistry; Journal of Geology, v. 97, no. 5, p. 551–567.

Wood, B.D., Scott Smith, B.H. and de Gasparis, S. (1998): The Mountain Lake kimberlitic pipes of northwest Alberta: exploration, geology and emplacement model; *in* 7th International Kimberlite Conference, Extended Abstracts, p. 960–962.