MANTLE XENOLITHS FROM KIMBERLITE
NEAR KIRKLAND LAKE, ONTARIO

HENRY O.A. MEYER

Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47907, U.S.A.

MICHAEL A. WALDMAN

Waldman Consulting, 636 Cheyenne Drive, #14, Fort Collins, Colorado 80523, U.S.A.

BLAINE L. GARWOOD

Corenvironment, P.O. Box 111, Bear Lake, Michigan 49614, U.S.A.

ABSTRACT

Ultramafic mantle xenoliths, predominantly consisting of garnet lherzolite, occur in the C–14 kimberlite, approximately 25 km east-northeast of Kirkland Lake, Ontario. The xenoliths are coarse grained and show evidence of recrystallization and incipient metasomatism. Conditions of final equilibration of the xenoliths, based on a two-pyroxene geothermometer and Al-in-orthopyroxene geobarometer, range from 917°C and 35.8 kbar to 1221°C and 55.6 kbar. The xenoliths seem to have equilibrated at conditions close to a 40 mW/m² conductive geotherm, and most within the stability field of diamond. The xenoliths have probably been derived from a thick cratonic root-zone beneath this portion of Ontario.

Keywords: xenoliths, kimberlites, mantle, diamond, Kirkland Lake, Ontario.

SOMMAIRE

Nous décrivons des xénolithes ultramafiques, surtout de lherzolite à grenat, provenant du manteau et prélevés dans la kimberlite C-14, située à 25 km à l'est-nord-est de Kirkland Lake, en Ontario. Les xénolithes, à granulométrie grossière, montrent des signes de recristallisation et de métasomatose précoce. Les conditions d'équilibrage final des xénolithes, telles qu'indiquées par la géothermométrie des assemblages à deux pyroxènes et la géobarométrie d'après la teneur en Al de l'orthopyroxène, varie de 917°C, 35.8 kbar à 1221°C, 55.6 kbar. Les xénolithes semblent avoir atteint l'équilibre à des conditions voisines d'un profil géothermique selon un modèle de conduction de 40 mW/m², et dans le champ de stabilité du diamant, dans la plupart des cas. Les xénolithes auraient été dérivés de la racine cratonique profonde sous cette partie de l'Ontario.

(Traduit par la Rédaction)

Mots-clés: xénolithes, kimberlites, manteau, diamant, Kirkland Lake, Ontario.

INTRODUCTION

Diamond and kimberlite exploration northeast of Kirkland Lake, Ontario, has resulted in a number of discoveries of kimberlite. In at least one instance, a drill core in kimberlite has intersected a number of garnet-bearing ultramafic xenoliths of mantle origin. These xenoliths provide information on the hitherto unsampled region of the basal lithosphere in this part of the Superior Province of the Canadian Shield.

In spite of the discovery of kimberlites elsewhere in Canada, mantle xenoliths have been described in detail from only one kimberlite field (Mitchell 1977, 1978, 1987, Jago & Mitchell 1987, Kjarsgaard & Peterson 1992). The xenoliths described by Mitchell (1977) predominantly consist of garnet lherzolite and occur in the Elwin Bay kimberlite of Somerset Island, N.W.T. The paleogeotherm defined by the xenoliths is similar to those described for southern Africa (*e.g.*, Boyd & Nixon 1975) and Montana (Hearn & Boyd 1975). Mitchell (1978) suggested that the garnet lherzolite xenoliths in Somerset Island represent the upper limb of an apparently inflected geotherm and were formed as a consequence of deformation and metasomatism of

the upper mantle by a rising diapir or by thermal interactions between kimberlite and xenoliths. Xenoliths from the Ham kimberlite in Somerset Island also outline an inflected geotherm (Jago & Mitchell 1987), but Mitchell (1987) reassessed the data using different geothermobarometers than previously used and concluded that the geotherms are not inflected. Recently, Kjarsgaard & Peterson (1992) have re-examined the xenoliths in the kimberlites from Somerset Island and concluded that the apparent pressures and temperatures of equilibration of the xenoliths define a 44 mW/m^2 shield geotherm.

KIMBERLITE: OCCURRENCE AND NATURE

The occurrence of kimberlite in the Kirkland Lake area of northern Ontario has been known for over four decades (Satterly 1948, Lee & Lawrence 1968). The search for such rock was, in part, initiated by diamond finds in glacial outwash material in the region south of the Great Lakes (Hobbs 1899, Blue 1900, Flint 1957, Schwarcz 1965, Brown *et al.* 1967). Lee & Lawrence (1968) described an occurrence of kimberlite in the Upper Canada mine, Gauthier Township, 10 km east of Kirkland Lake, and Arima *et al.* (1986a) briefly noted the chemical and isotopic nature of the Nickila Lake kimberlite (B–30), Bisley Township (Fig. 1). Brummer *et al.* (1992a, b) summarized the history and results of kimberlite exploration in the Kirkland Lake area, and briefly described the Nickila Lake (B–30), C–14, A–1, AM–47, A–4, MA–20 and B–41 kimberlites.

The kimberlite in the Upper Canada mine occurs as thin dikes cutting Archean metavolcanic rock. It is described as a micaceous kimberlite (Lee & Lawrence 1968, Watkinson & Chao 1973, Mitchell 1978), but is probably a mica-rich Group-I kimberlite (Mitchell 1986). Following the nomenclature of Clement (1979), and Clement & Skinner (1979), the kimberlite in the Nickila Lake, A–14 and A–1 diatremes predominantly
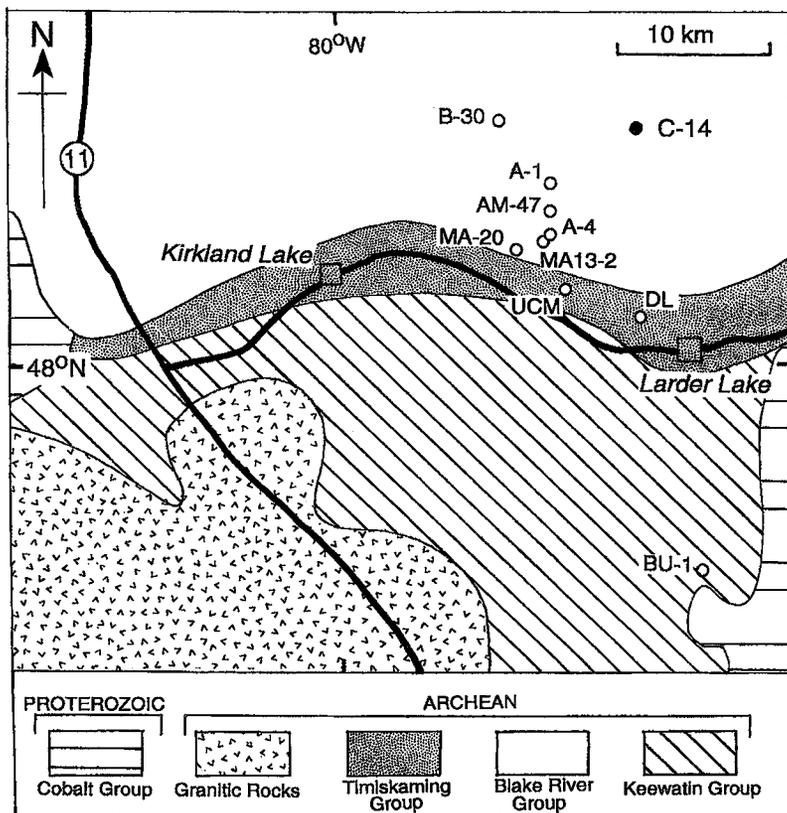
FIG. 1. General location map of kimberlites in the region of Kirkland Lake, Ontario (modified after Brummer *et al.* 1992a, b). The kimberlites were coded by others after the number assigned to the geophysical anomaly in a specific township. Thus C–14 is the fourteenth anomaly in Clifford Township.

consists of tuffisitic kimberlitic breccia, whereas AM–47 is predominantly hypabyssal kimberlite (Brummer *et al.* 1992b). Arima *et al.* (1986b) noted the occurrence of upper mantle xenoliths in the Nickila Lake kimberlite. Chemical and textural variations in mica from this same kimberlite and that in the Upper Canada mine were described by Arima *et al.* (1986b). Fragments of hypabyssal kimberlite (phlogopite-rich group-1 kimberlite) occur within the Nickila Lake kimberlite breccia. The kimberlite diatremes have intruded crustal rocks of the Archean Abitibi greenstone belt, Superior Province. Lee & Lawrence (1968) quoted a K–Ar isotopic age of 151 Ma for the kimberlite in the Upper Canada mine, and Arima *et al.* (1986a) determined an age of emplacement of 147 Ma for the Nickila Lake diatreme. Brummer *et al.* (1992b) reported ages between 147 and 158 Ma for seven kimberlites in the Kirkland Lake cluster.

Approximately 9 km east of the Nickila Lake kimberlite, a small (200 × 100 m) kimberlite, referred to as C–14, was discovered in Clifford Township as a result of a magnetic survey and subsequent drilling (Fig. 1). The kimberlite, examined in drill core, is a tuffisitic breccia, but at least three petrographic variants are recognized, each with a distinct mineralogy. Three xenoliths have acted as nuclei about which has crystallized earlier hypabyssal kimberlite. This material, together with the enclosed xenoliths, are autoliths in the intensely brecciated present host kimberlite.

Bulk chemical compositions of kimberlite are susceptible to error due to contamination by crustal and mantle xenoliths and megacrysts (Clement 1982, Mitchell 1986). A measure of the proportions of crustal or weathered material in a bulk composition of a kimberlite is provided by the "Contamination Index" of Clement (1982) [C.I. = $(SiO_2 + Al_2O_3 + Na_2O)/(MgO + 2K_2O)$]. A C.I. close to unity is considered to be representative of most uncontaminated kimberlites. The bulk composition of the least-contaminated sample (C.I. = 1.2) in the C–14 kimberlite is presented in Table 1, and compares favorably with the range of composition for kimberlites (Mitchell 1986). On the basis of the U/Pb isotopic system, Brummer *et al.* (1992b) reported an age of 156 Ma obtained from an average of six separate samples from the same intrusion.

ULTRAMAFIC XENOLITHS

Description

Several garnet-bearing ultramafic xenoliths were intersected in the drill core, but because of the small diameter of the core (~5 cm), the amount and size of the xenolithic material are limited. Nevertheless, some xenoliths are smaller than the core diameter, but from the general character of others, the maximum size for most xenoliths is probably less than 10 to 20 cm. A consequence of the small size of the xenoliths is that there is large uncertainty in the modal proportions of the constituent minerals. If lherzolite is defined as having ≥10% modal clinopyroxene (Streckeisen 1976), then all but one of the xenoliths would be classified as clinopyroxene-bearing harzburgite (± garnet). In contrast, if nomenclature is based only on the mineral assemblage, without recourse to modal percentages, then garnet lherzolite would account for 60% of the xenoliths, and lherzolites, 40%. The latter nomenclature is conventionally used in xenolith studies and will be utilized herein.

The xenoliths are relatively coarse grained (≤ 6 mm). Two of the ten xenoliths display a porphyroclastic texture (Harte 1977), in which strained large grains of olivine have been in part recrystallized along grain boundaries, to small (0.05 – 0.5 mm) neoblasts of olivine. One xenolith is characterized by complete recrystallization of olivine to a granuloblastic texture of small equant crystals (0.3 mm), many having 120° angular relationships with neighboring grains (soap-bubble texture). The remaining xenoliths consist

TABLE 1. BULK COMPOSITION OF THE
C-14 KIMBERLITE

	C-14	Worldwide* Range
SiO_2 wt%	35.15	25.1 - 36.4
TiO_2	3.13	0.98 - 3.39
Al_2O_3	3.03	2.45 - 4.45
Cr_2O_3	0.28	0.11 - 0.25
Fe_2O_3	6.16	3.90 - 6.78
FeO	3.60	1.71 - 8.68
MnO	0.15	0.10 - 0.19
CaO	6.54	9.36 -21.4
MgO	27.64	17.0 - 28.6
NiO	0.14	
BaO	0.13	
Na_2O	0.32	0.12 - 0.48
K_2O	2.16	0.34 - 1.82
CO_2	1.77	4.58 - 16.2
H_2O+	6.96	3.70 - 10.2
Total	98.34	

			mean*
Co ppm	64		65
Nb	140		141
Rb	105		73
Sr	360		851
Zr	145		184
La	47		140
Y	<5		-
Th	5		17
Ta	20		11

* Worldwide ranges and means are taken from Mitchell (1986). The concentration of trace elements, including Ba, was determined using X-ray fluorescence, except for Co and Ni, where atomic absorption spectroscopy was used. The concentration of all other elements was determined using DC plasma - atomic emission spectroscopy.

TABLE 2. TEXTURE, MINERALOGY AND FINAL EQUILIBRATION CONDITIONS
SUMMARIZED FOR INDIVIDUAL XENOLITHS FROM C-14 KIMBERLITE

Sample * Number	Texture	Mineralogy								T(°C)		P(Kbar)	
		Primary				Secondary							
		Gt	Ol	Opx	Cpx	Phl.	Cpx	Sp		FB86	BKN	MC74	KB
155	P		x	x	x					1075	1133	48.8	48.3
167.2	P		x	x	x	x				885	957	40.0	41.9
168	C	x	x	x	x	x	x	x		1038	1140	51.7	54.1
198.2	G	x	x	x	x	x	x	x		1221	1297	55.6	60.9
199.7	C	x	x	x	x	x	x	x		1096	1210	54.7	59.0
308.5	C	x	x	x	x	x				995	1044	46.4	42.2
505	(C)	x	(x)	x			x	x					
506.2	(C)		(x)	x	x					1018		46.9	
506.7	(C)	x	(x)	x	x	x	x	x		969	1133	45.4	
506.8	(C)		(x)	x	x					917		39.8	

*Sample numbers represent relative position and depth (ft) in drill core.

P - porphyroclastic, C - coarse granular, G - granuloblastic.
Gt - garnet, Ol - olivine, Opx - orthopyroxene, Cpx - clinopyroxene, Phl - phlogopite,
Sp - spinel. Parantheses indicate olivines are completely altered to serpentine.

FB86, BKN, MC74, KB - see text.

of coarse granular lherzolite (± garnet), although three examples from the lowest portion of the drill core occur in which the olivine is completely serpentinized (Table 2). Unfortunately, the samples of the xenoliths in the drill core were not sufficiently large to provide enough material either for bulk chemical analyses or isotopic studies.

Mineral compositions

The constituent minerals of the xenoliths were analyzed using automated electron microprobes (MAC 400 and CAMECA SX50) at Purdue University. The analyses were performed with an accelerating voltage of 15 kV and a beam current of 20 nA. Well-analyzed minerals and synthetic glasses were used as standards. Data were reduced and corrected using Bence–Albee (MAC 400) and PAP (SX 50) procedures. Results of analyses of the same minerals using both microprobes were found to be similar and within the normal accuracy for microprobe data. Concentrations of major elements are accurate within ±2% of the element present, whereas concentrations of minor elements are less accurate, but are reproducible to ±0.08 wt%. Results of individual analyses listed in Table 3 are averages of a minimum of five analytical points per mineral grain.

For the determination of Ca in olivine, particular care was taken. At least five analyses were done for Ca on each of six different grains per xenolith. Throughout the period of time of the analyses, a specific standard olivine (SCKA 1), whose Ca content had been previously well determined as 0.0532 wt% Ca (G. Brey, pers. comm., 1992), was monitored. The average value for SCKA 1 (20 points) during the

monitoring process was 0.0544 wt% Ca with a standard deviation of 0.0044.

Olivine is predominant in all samples. Grains are generally 3–6 mm in major dimension, except in those xenoliths that display recrystallization. The olivine is forsteritic, varying between 91 and 92% Fo. TiO_2, Al_2O_3, Cr_2O_3 and CaO contents are all less than 0.05 wt% (Tables 3, 4). Orthopyroxene occurs in anhedral grains (< 2 mm) and is unaltered, even in those xenoliths in which the olivine has been completely replaced. Orthopyroxene also has a restricted compositional range between 92–93% En (Fig. 2). The concentrations of the minor oxides TiO_2, Al_2O_3, Cr_2O_3, CaO and Na_2O are all less than 1.00 wt%, of which Al_2O_3 is the highest, ranging between 0.5 and 0.9 wt% (Table 3). The highest Al_2O_3 content occurs in orthopyroxene in the granuloblastic xenolith, which also has the highest apparent temperature of final equilibration.

Emerald green clinopyroxene occurs as irregular grains, < 2 mm across, and is characterized by varying degrees of a "wormy" or "spongy" alteration that proceeds from the margins inward to the core. It is diopsidic, with minor solid-solution toward jadeite. The proportions of Ca:Mg:Fe are constant and average 53:43:4 (Fig. 2). Chromium contents vary between 0.8 and 2.3 wt% Cr_2O_3, whereas Al_2O_3 ranges between 1.73 and 2.52 wt%, and Na_2O contents, between 1.50 and 2.51 wt% (Table 3). The altered "spongy" rim to the pyroxene is slightly enriched in Ca relative to the core, and on average contains more Ti and Cr, and less Al and Na than the core (Table 3). Similar textural and chemical features of alteration have been noted in diopside in xenoliths from other worldwide localities (*e.g.*, Ehrenberg 1982, Hops *et al.*

TABLE 3. AVERAGE COMPOSITION OF PRIMARY MINERALS IN XENOLITHS

| | 168 | | | | | 198.2 | | | | | 199.7 | | | | |
| | | | Cpx | | | | | Cpx | | | | | Cpx | | |
	Ol	Opx	Core	Rim	Garnet	Ol	Opx	Core	Rim	Garnet	Ol	Opx	Core	Rim	Garnet
SiO$_2$ wt%	41.1	57.9	54.8	54.3	41.5	41.3	57.7	54.3	53.3	42.2	41.1	57.6	55.6	52.7	41.3
TiO	0.02	0.09	0.21	0.18	0.02	0.04	0.23	0.52	0.44	0.88	0.04	0.07	0.16	0.81	0.30
Al$_2$O$_3$	0.02	0.54	2.21	0.98	19.1	0.00	0.95	2.52	0.88	18.3	0.02	0.58	2.16	1.36	17.3
Cr$_2$O$_3$	0.02	0.32	2.03	2.34	5.39	0.05	0.45	1.95	2.21	5.67	0.07	0.36	2.34	2.41	7.23
FeO	8.64	5.11	2.65	2.33	7.50	7.63	4.61	2.82	2.55	6.68	8.39	4.92	2.56	2.58	7.47
MgO	49.6	34.5	16.2	17.1	19.1	50.4	34.6	17.8	18.6	20.4	49.9	34.7	16.1	16.5	18.5
CaO	0.03	0.50	18.6	20.2	5.83	0.05	0.79	17.3	19.7	5.32	0.03	0.46	17.7	21.2	5.97
MnO	0.06	0.06	0.11	0.06	0.44	0.11	0.12	0.10	0.06	0.32	0.14	0.12	0.11	0.14	0.34
NiO	0.34	0.11	0.03	0.11	0.02	0.30	0.08	0.06	0.00	0.01	0.30	0.11	0.04	0.06	0.00
Na$_2$O	0.00	0.24	2.24	1.41	0.00	0.00	0.23	2.05	1.32	0.07	0.00	0.00	2.51	0.99	0.00
K$_2$O	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.03	0.01	0.01	0.00	0.00	0.31	0.00	0.00
Totals	99.8	99.3	99.1	99.0	99.1	99.8	99.8	99.4	99.0	99.8	100.0	99.0	94.6	98.7	98.4

| | 308.5 | | | | | 155 | | | | 167.2 | | | |
| | | | Cpx | | | | | Cpx | | | | Cpx | |
	Ol	Opx	Core	Rim	Garnet	Ol	Opx	Core	Rim	Ol	Opx	Core	Rim
SiO$_2$ wt%	40.9	57.6	54.5	54.6	41.9	40.0	56.6	54.1	53.5	39.5	57.0	54.3	54.5
TiO	0.00	0.02	0.00	0.27	0.09	0.00	0.11	0.28	0.30	0.00	0.09	0.58	0.25
Al$_2$O$_3$	0.00	0.65	1.73	1.51	19.7	0.05	0.80	2.51	1.02	0.00	0.57	0.61	2.41
Cr$_2$O$_3$	0.00	0.23	1.20	1.45	4.92	0.00	0.38	2.07	2.51	0.02	0.30	1.50	2.48
FeO	8.86	5.18	2.52	2.66	7.90	8.43	5.41	2.66	2.53	9.21	5.62	4.23	2.30
MgO	49.4	34.6	17.3	16.9	19.3	50.3	35.9	16.4	17.3	51.0	36.3	19.6	15.7
CaO	0.03	0.50	20.4	20.9	5.68	0.03	0.61	18.3	21.0	0.02	0.28	18.5	19.5
MnO	0.16	0.11	0.07	0.09	0.41	0.11	0.11	0.12	0.13	0.13	0.13	0.14	0.09
NiO	0.22	0.08	0.07	0.05	0.00	0.34	0.12	0.03	0.05	0.35	0.11	0.07	0.03
Na$_2$O	0.00	0.18	1.50	1.19	0.00	0.00	0.14	2.35	1.07	0.00	0.09	0.82	2.45
K$_2$O	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.03	0.00	0.00	0.00	0.01	0.00
Totals	99.6	99.2	99.3	99.8	99.8	99.3	100.0	98.8	99.3	100.2	100.5	100.4	99.7

| | 506.7 | | | | 506.2 | | | 506.8 | | | 505 | |
| | | Cpx | | | | Cpx | | | Cpx | | | |
	Opx	Core	Rim	Garnet	Opx	Core	Rim	Opx	Core	Rim	Opx	Garnet
SiO$_2$ wt%	57.8	55.4	54.5	42.1	58.0	55.2	54.2	57.5	53.9	52.9	58.5	41.5
TiO	0.07	0.15	0.36	0.27	0.07	0.13	0.38	0.09	0.27	0.60	0.05	0.26
Al$_2$O$_3$	0.61	2.24	1.37	22.4	0.70	2.14	1.28	0.72	2.28	1.28	0.92	17.9
Cr$_2$O$_3$	0.07	0.82	0.96	2.38	0.31	1.84	2.21	0.30	1.64	1.83	0.49	7.08
FeO	5.27	2.63	2.66	7.78	4.58	2.26	2.37	5.26	2.55	2.56	4.31	6.03
MgO	35.3	16.7	17.0	20.1	34.7	16.6	17.1	35.1	16.5	17.4	34.4	20.4
CaO	0.43	20.0	21.8	4.84	0.52	19.3	20.9	0.38	20.3	22.1	0.80	5.48
MnO	0.12	0.07	0.12	0.44	0.12	0.09	0.11	0.13	0.10	0.09	0.16	0.29
NiO	0.00	0.05	0.00	0.00	0.05	0.05	0.05	0.08	0.04	0.03	0.01	0.03
Na$_2$O	0.00	1.52	0.42	0.00	0.33	1.96	1.20	0.00	1.96	0.99	0.00	0.08
K$_2$O	0.00	0.02	0.03	0.02	0.01	0.02	0.01	0.00	0.02	0.02	0.00	0.00
Totals	99.6	99.7	99.2	100.4	99.4	99.6	99.7	99.6	99.5	99.7	99.6	99.0

All Iron reported as FeO.

1989); those authors have suggested that the alteration of the diopside margins may represent an attempt to chemically re-equilibrate in response to rapid decompression.

Pale pink to pale purple garnet, less than 3 mm in size, is invariably surrounded by a kelyphitic rim of varying thickness. The garnet is Mg-rich (pyrope) (Fig. 2, Table 3), with TiO$_2$ contents between 0.02 and 0.88 wt%. Na$_2$O contents are below the limit of detection (0.01 wt%). Chromium ranges from 2.38 to 7.23 wt% Cr$_2$O$_3$, and calcium, between 4.8 and 6.0 wt% CaO (Fig. 3). Included in Figure 3 for comparison are data for a number of garnet macrocrysts from the kimberlite. Most of the garnet compositions, including those of the macrocrystic garnet, fall within the field defined as G–9 (Dawson & Stephens 1975)

TABLE 4. CONCENTRATION OF CALCIUM IN OLIVINE

Sample Number	Nos. of Points	Ca El.%	Std-dev.	CaO Wt%
155	20	0.0212	0.0058	0.0296
167.2	24	0.0129	0.0073	0.0180
168	15	0.0186	0.0042	0.0260
198.2	24	0.0371	0.0052	0.0520
199.7	25	0.0229	0.0047	0.0321
308.5	25	0.0197	0.0047	0.0276

and have Cr_2O_3 contents between 2.2 and 10.5 wt%, CaO from 1.98 to 7.57 wt%, and TiO_2 less than 0.70 wt%.

Associated with the garnet and developed between the kelyphitic rim and the neighboring minerals (mostly olivine) are narrow small irregular plates of phlogopite, tiny grains of chromite, some enclosed in phlogopite, and occasional Al-rich diopside (Table 5). The spinel associated with the kelyphitic rim is Al-rich and Ti-poor; in contrast, the spinel included in phlogopite is richer in Cr and Ti (Table 5). The mica, Al-rich pyroxene and spinel represent the result of incipient modal metasomatism. Similar features have been
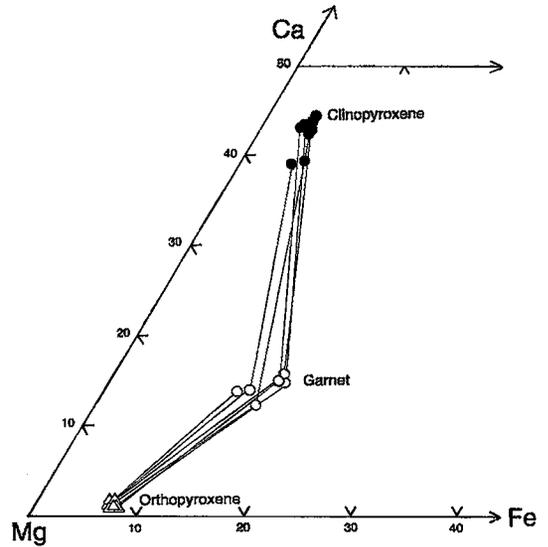
FIG. 2. Compositions of coexisting orthopyroxene, clinopyroxene and garnet from ten xenoliths in C–14 kimberlite, plotted in terms of the major elements Ca–Mg–Fe.
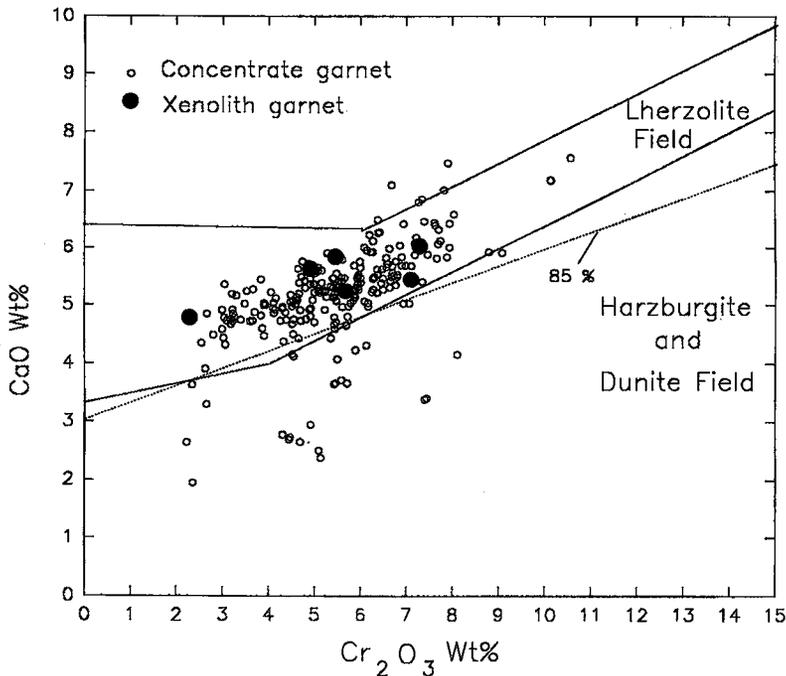
FIG. 3. CaO *versus* Cr_2O_3 relationships for garnet from xenoliths and kimberlite, C–14 diatreme, Ontario. Fields outlined for garnet from lherzolite and harzburgite–dunite from Sobolev (1974). The dotted line represents the boundary below which plot 85% of ultramafic-suite garnet inclusions in diamond (after Gurney 1984).

TABLE 5. AVERAGE COMPOSITIONS OF SECONDARY MINERALS IN XENOLITHS

	168			198.2			199.7		
	Cpx	Mica	Spinel*	Cpx	Mica	Spinel	Cpx	Mica	Spinel
SiO_2 wt%	50.9	41.6	0.25	52.8	38.7	0.71	54.5	39.3	0.24
TiO_2	0.23	0.98	0.23	0.75	4.34	3.33	0.23	3.20	4.57
Al_2O_3	6.52	12.9	42.2	4.21	14.7	20.6	3.21	13.3	11.3
Cr_2O_3	0.75	1.06	23.3	1.05	2.43	40.4	0.94	1.86	46.4
FeO	3.52	3.40	13.7	4.64	3.89	16.4	5.95	5.14	24.1
MgO	16.5	24.4	19.1	20.0	20.7	16.6	22.4	20.9	13.2
CaO	20.0	0.00	0.04	14.6	0.00	0.18	11.8	0.00	0.02
MnO	0.27	0.08	0.36	0.30	0.00	0.32	0.42	0.07	0.42
NiO	0.02	0.24	0.12	0.05	0.07	0.00	0.00	0.15	0.00
Na_2O	0.68	0.03	0.00	0.41	0.26	0.00	0.23	0.04	0.00
K_2O	0.01	10.5	0.00	0.01	9.30	0.02	0.02	9.29	0.09
Totals	99.4	95.2	99.3	98.9	94.5	98.4	99.7	93.3	100.4

	506.7			167.2	308.5	505
	Cpx	Mica	Spinel*	Mica	Mica	Spinel*
SiO_2 wt%	47.1	37.6	0.29	40.6	41.6	0.50
TiO_2	0.86	2.89	0.18	2.12	0.24	0.55
Al_2O_3	11.8	17.1	54.2	13.2	12.4	39.8
Cr_2O_3	0.90	2.20	12.5	1.13	0.57	26.2
FeO*	4.29	4.61	13.2	4.27	3.32	11.7
MgO	13.6	20.2	20.1	23.1	24.6	19.1
CaO	19.6	0.00	0.14	0.0	0.00	0.13
MnO	0.17	0.25	0.31	0.04	0.04	0.19
NiO	0.00	0.09	0.00	0.18	0.29	0.11
Na_2O	1.06	0.57	0.00	0.07	0.00	0.21
K_2O	0.01	9.44	0.01	10.3	10.0	0.00
Totals	99.5	94.9	101.0	95.1	93.0	98.5

Total Fe reported as FeO.
*Spinel associated with kelyphite. In samples 198.2 and 199.7 the spinel occurs as inclusions in phlogopite.

recognized in the Somerset Island xenoliths (Mitchell 1977) and worldwide (e.g., Boyd & Nixon 1975, Dawson 1987, Erlank et al. 1987).

The compositions of the major minerals in the xenoliths are all generally comparable with those in lherzolite (± garnet) xenoliths from kimberlites in Canada (Mitchell 1978, 1987) and the United States, e.g., Montana (Hearn & Boyd 1975), Colorado–Wyoming (McCallum et al. 1975, Eggler et al. 1987) and Kentucky (Schulze 1984). Equivalent minerals also occur in xenoliths from southern Africa (see Nixon 1987, for detailed references).

Temperatures and pressures of equilibration

Temperatures and pressures of final equilibration have been estimated for the xenoliths on the basis of mineral composition. For comparison, two different pairs of geothermometer – barometer have been used (Table 2); the results are shown in Figures 4a and 4b. One pair consists of the two-pyroxene thermometer as modified by Finnerty & Boyd (1987) [FB86], with pressure estimated from the Al content of the ortho-pyroxene coexisting with garnet (MacGregor 1974) [MC74] (Fig. 4a). The second pair chosen is a combi-

nation of the Brey & Köhler (1990) geothermometer [T_{BKN}], based on coexisting pyroxenes, and pressure determined from the Ca content of olivine (Table 4) in the presence of clinopyroxene (Köhler & Brey 1990) [P_{KB}] (Fig. 4b). Unfortunately, because of the complete serpentinization of olivine, pressure could not be determined in three xenoliths.

Both pairs of geothermobarometers result in a similar relative sequence of pressures and temperatures for the individual xenoliths. However, temperatures calculated using T_{BKN} versus P_{KB} are consistently higher than those determined from the FB86–MC74 pair. This is illustrated in Figure 4b, in which the xenoliths plot above the reference 40 mW/m² conductive geotherm of Pollack & Chapman (1977) and are closer to a 44 mW/m² geotherm. In contrast, use of FB86 versus MC74 results in temperatures and pressures of equilibration for the xenoliths close to the reference geotherm (Fig. 4a). The xenolith having a granulo-blastic texture falls off the general trend at a higher temperature than the others. Irrespective of which geothermobarometer is used, the majority of the xenoliths seem to have equilibrated within the stability field of diamond. Temperatures and pressures were also determined for five xenoliths using T_{BKN} versus
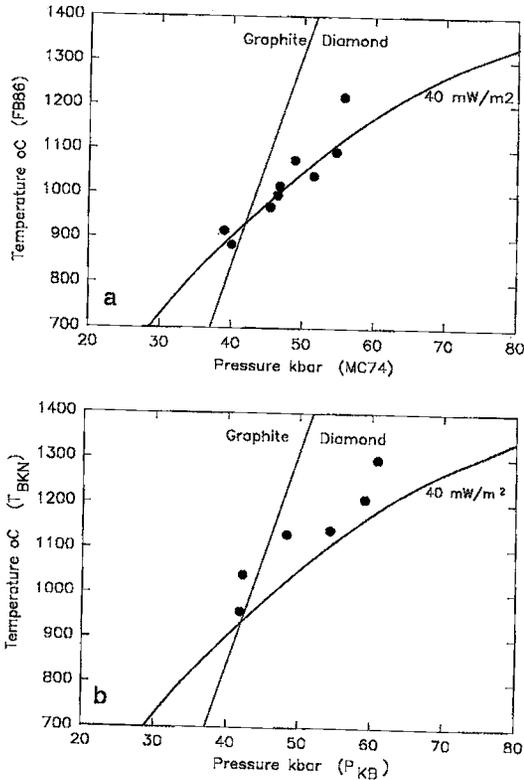
FIG. 4. Estimates of temperature and pressure of equilibration for xenoliths from the C–14 kimberlite, Ontario. a) T determined from Finnerty & Boyd (1987) [FB86], and P derived from MacGregor (1974) [MC74]. b) T estimated from Brey & Köhler (1990) [T_{BKN}] and pressure calculated using Köhler & Brey (1990) [P_{KB}]. Diamond–graphite equilibrium curve after Kennedy & Kennedy (1976), and 40 mW/m² conductive geotherm from Pollack & Chapman (1977).

P_{BKN} (Brey & Köhler 1990) and resulted in the estimated conditions of equilibration for the xenoliths lying closer to the 40 mW/m² geotherm than the 44 mW/m². Use of T_{BKN} and P_{BKN} requires knowledge of the compositions of four phases (garnet + olivine + orthopyroxene + clinopyroxene). Consequently, because garnet and olivine are absent in some xenoliths, T_{BKN} and P_{BKN} could not be determined for all samples.

DISCUSSION

Besides Somerset Island (Mitchell 1987, Jago & Mitchell 1987, Kjarsgaard & Peterson 1992), data on xenoliths also are available for kimberlites and allied

rocks in the United States, for example, the Williams diatreme, Montana (Hearn & Boyd 1975), State Line kimberlites (Eggler: see Finnerty & Boyd 1987), The Thumb minette, New Mexico (Ehrenberg 1978, 1982) and Hamilton Branch kimberlite, Kentucky (Schulze: see Finnerty & Boyd 1987) (see also Eggler *et al.* 1987 for other localities). Temperatures and pressures of equilibration for xenoliths from the above localities are shown in Figure 5, together with data for xenoliths from the C–14 kimberlite near Kirkland Lake.

Comparison of the temperature – pressure distribution for xenoliths from the localities mentioned above in North America suggests differences and similarities. For example, the general distribution of T–P determinations for Somerset Island, Northwest Territories, and The Thumb, New Mexico, are somewhat similar; whereas the Somerset Island data lie along the graphite–diamond equilibrium curve (Kennedy & Kennedy 1976), data for The Thumb define a lower-pressure trend lying entirely within the stability field of graphite (Fig. 5). Xenoliths from the Williams diatreme, Montana, overall have higher T–P of equilibration than those from other localities, and are, on average, about 100°C higher than the closest data for xenoliths from the Hamilton Branch kimberlite, Kentucky. Xenoliths from the C–14 kimberlite near Kirkland Lake have a T–P distribution somewhat between those from Hamilton Branch and the State Line (Colorado–Wyoming) kimberlites.
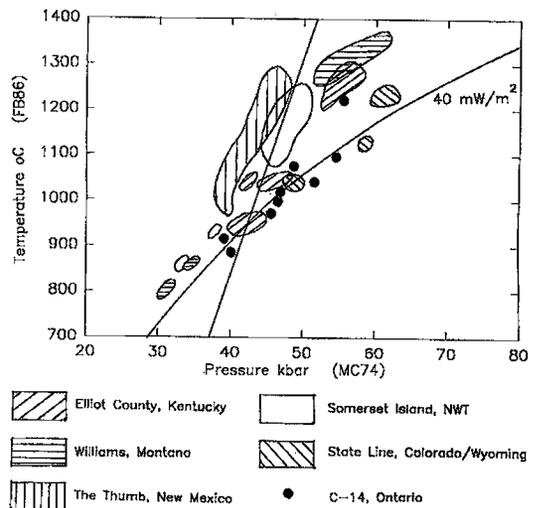
FIG. 5. Temperatures and pressures of equilibration for selected suites of xenoliths from localities in North America (see text for references).

However, comparisons of conditions of equilibration of the xenoliths need to be treated with caution; other factors, such as the age of intrusion of the host kimberlite, must be considered. It is also important that comparisons only be done on xenolith suites for which estimates of temperatures and pressures of equilibration have been determined using the same geothermometer – barometer pair. For example, in contrast to the reconstruction of the xenolith suite from Somerset Island, which lies along the graphite–diamond boundary (Fig. 5), Mitchell (1987) concluded that the same suite equilibrated in the stability field of graphite as a consequence of his adoption of the geothermometer of Wells (1977) and the geobarometer of Wood (1974). Although the original formation of the ultramafic rocks from which the xenoliths were derived is probably Archean or Proterozoic in age, subsequent thermal and metasomatic events, including effects of entrainment in the host kimberlitic magma, have probably modified both the original chemistry and fabric. Furthermore, thermal events, such as the heat source that provided the impetus for kimberlite eruption, also may have locally perturbed an otherwise possibly stable cratonic geotherm. Nevertheless, it has been noted (*e.g.*, Finnerty & Boyd 1987) that most low-temperature xenoliths associated with cratonic regions have equilibrated close to the 40 mW/m² geotherm, if the FB86–MC74 combination is utilized, irrespective of age of eruption. As noted earlier, xenoliths from the C–14 kimberlite in Ontario follow this worldwide trend.

Xenoliths and diamond

Diamond has been found in several ultramafic xenoliths from southern Africa (Dawson & Smith 1975, Shee *et al.* 1982), Siberia (Sobolev *et al.* 1969a, Pokhilenko *et al.* 1977), the State Line region of Colorado and Wyoming (McCallum & Eggler 1976) and Australia (Jaques *et al.* 1990). In spite of these discoveries, the occurrences of diamond-bearing ultramafic xenoliths are relatively rare, and most are harzburgitic, although exceptional dunitic xenoliths contain diamond in Siberia (Pokhilenko *et al.* 1977).

Early isotopic evidence (Kramers 1979) and suggestions (Meyer 1979) that diamond is a xenocryst in kimberlite were proven correct by the radiometric age determinations of syngenetic ultramafic garnet inclusions in diamond (Richardson *et al.* 1984). The unusual chemical composition of these garnet inclusions, first noted by Meyer (1968), was also noted in rare garnet xenocrysts in kimberlite (Nixon & Hornung 1968, Sobolev *et al.* 1969b, 1973, Gurney & Switzer 1973). Garnet, as well as magnesian ilmenite, chromite, and chromian diopside, have long been used as indicator minerals in kimberlite exploration, for example, in the discovery of the diamond-

bearing Orapa kimberlite, Botswana, by geologists of the DeBeers company prior to 1967, and earlier in the discovery of the Mir and Udachnaya kimberlites, Siberia (Sobolev 1959). Since the early 1970s, on the basis of chemistry of garnet inclusions and work by Sobolev (1971, 1974) and coworkers, the calcium–chromium relationship of kimberlitic garnets has been used to assist in kimberlite and diamond prospecting (*e.g.*, Gurney 1984).

Currently, the general consensus is that diamond formed in ultramafic and eclogitic rocks in the pre-existing mantle, which were subsequently disrupted, possibly by events that eventually produced kimberlitic magma. Fragments of these disrupted rocks are the xenoliths that occur in kimberlite. The disruption and disintegration of the mantle rocks may have been a consequence of incorporation into a raising thermal diapir associated with kimberlitic magmatism. This disintegration also resulted in the incorporation of mineral constituents, including diamond, as xenocrysts into the ascending kimberlite. If the suggestion is correct that diamond and xenoliths in general are related, then the question arises as to what information can be provided from xenoliths concerning diamond and, more specifically, the prospects of diamond occurring in a particular xenolith-bearing kimberlite.

Evidence to date has demonstrated that kimberlites whose suite of xenoliths provides values of P–T of equilibration generally within the stability field of graphite are for the most part barren or uneconomic in terms of diamond content (*e.g.* Louwrensia and Hanaus kimberlites, Namibia: Mitchell 1984; East Griqualand kimberlites: Boyd & Nixon, in Finnerty & Boyd 1987; Belmonte kimberlite, Brazil: Boyd & Nixon, in Meyer & Svisero 1987). The absence of diamond and the low physical conditions of equilibration for the xenoliths in the African examples have been interpreted as due to thinner lithosphere occurring close to the margin of the craton than in the central cratonic region (MacGregor 1975, Boyd & Gurney 1986).

In the case of the North American localities of xenoliths, and using the southern African model, The Thumb minette, New Mexico (Ehrenberg 1982) should be devoid of diamond; none has yet been recorded. In contrast, all other localities, including the Somerset Island array of xenoliths, which are closest to the diamond–graphite equilibrium boundary, have diamond potential. Nevertheless, diamond has not been recorded either from the Williams diatreme, Montana (Hearn & Boyd 1975) or from the Kentucky kimberlite, in spite of periodic exploration since the turn of the century in the case of the latter location. Although diamond does occur in the State Line kimberlites, the grade is generally too low, other than in the George Creek kimberlite, to sustain economic production. Equally well, the presence of diamond in subeconomic quantities is known in the kimberlites of

Somerset Island (Brummer 1978). Diamond does occur in the C–14 kimberlite, Ontario, and its occurrence is the subject of further prospection; currently, the indications are that it is subeconomic.

Thus, at present, P–T arrays of conditions of equilibration based on xenoliths in kimberlite can be used to indicate the likely absence of diamond in a particular kimberlite, but cannot be used to unequivocally indicate the presence of diamond in economic quantities. In cases where the P–T array indicated by xenoliths suggests the absence of diamond, it is possible that diamond was once present in the kimberlitic magma that sampled and carried the xenoliths to the surface. However, temperature and redox conditions in the magma may have been sufficient to cause resorption of diamond. Information on such redox conditions can be estimated, in part, from spinel and ilmenite occurring in the kimberlite. Nevertheless, kimberlites generally occur in clusters, and variation in diamond content from pipe to pipe is the norm. Obviously, the sampling of all kimberlites in a cluster for xenoliths may produce a more significant result.

Mantle structure

The xenoliths described herein from the C–14 kimberlite in Ontario are similar in type, mineral chemistry, texture and possible metasomatic effects to xenoliths from kimberlites worldwide, including those from other North American localities. It would thus appear that the petrology of the cratonic root-zones sampled by kimberlites from the Proterozoic to late Cenozoic is broadly similar.

Based on the interpretation of xenolith data, MacGregor (1975) and Boyd & Gurney (1986) have suggested a thick cool root-zone up to 220 km thick beneath the Kaapvaal craton. At the margins of the craton, this thickness decreases and, correspondingly, the lithosphere – asthenosphere boundary lies closer to the Earth's surface toward the southern Atlantic and Indian oceans. Extension of this model to other cratonic areas, especially those with diamond-bearing kimberlites, has been suggested, but insufficient evidence, compared to the abundant data for southern Africa, has precluded significant discussion. High-resolution seismic tomography is a relatively new method of imaging the Earth's interior. Anderson *et al.* (1992) suggested the presence of a high-velocity zone or stable craton beneath the area of interest in Ontario, to depths greater than 220 km. Similar results of tomography are apparent beneath the Kaapvaal craton.

Finnerty & Boyd (1987) considered the xenolith data from the few localities in North America to indicate a similar upward shelving of the lithosphere – asthenosphere toward the Arctic (Somerset Island) – in the north and New Mexico (The Thumb) in the south, comparable to that which occurs in the Kaapvaal craton in southern Africa. Based on the overall pattern of P–T conditions of equilibration for the xenoliths from the C–14 kimberlite, we suggest that the locality has a non-marginal position within the North American craton.

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