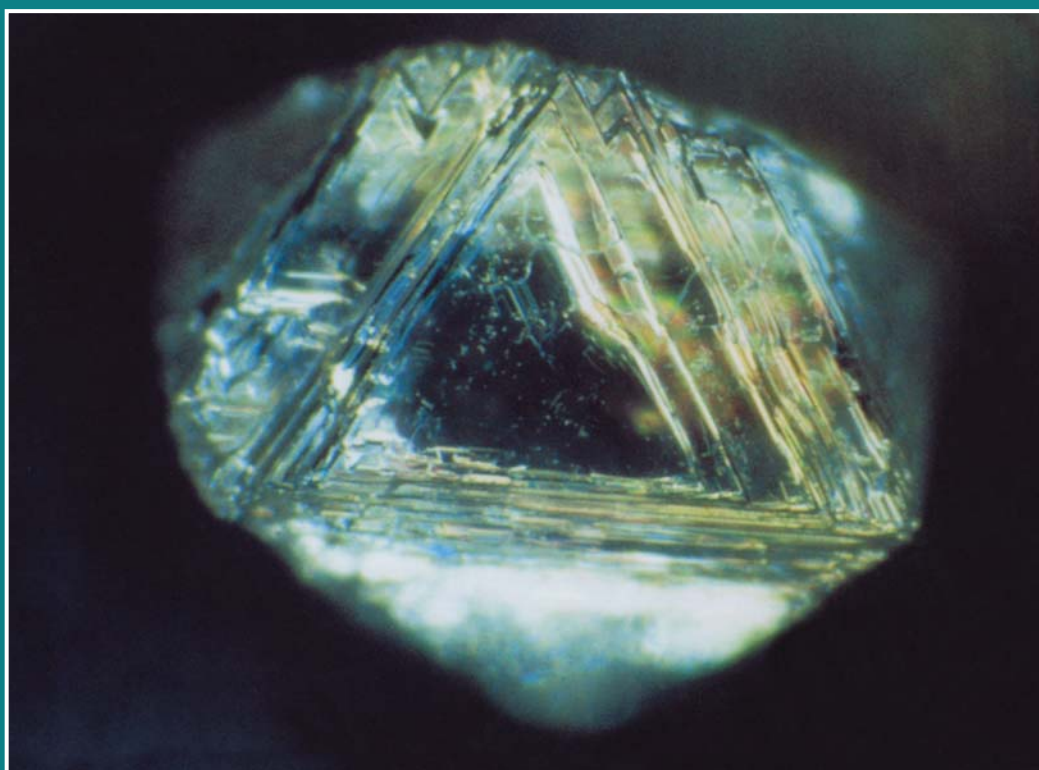




GEOLOGICAL SURVEY OF CANADA
BULLETIN 423

**DIAMOND EXPLORATION TECHNIQUES
EMPHASISING INDICATOR MINERAL
GEOCHEMISTRY AND CANADIAN EXAMPLES**

C.E. Fipke, J.J. Gurney, and R.O. Moore



1995



Natural Resources
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A 1.1 mm gem quality, flawless natural octahedral diamond from
the 1991 discovery core hole at Point Lake, N.W.T. Photograph by
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Critical reviewers

Tom McCandless

Bruce Kjarsgaard

Authors addresses

C.E. Fipke

*C.F. Mineral Research Ltd.
1677 Powick Road
Kelowna, B.C.
V1X 4L1
Canada*

J.J. Gurney

*Department of Geological Sciences
University of Cape Town
Rondebosch 7700
South Africa*

R.O. Moore

*BHP Diamonds Inc.
1697 Powick Road
Kelowna, B.C.
V1X 4L1
Canada*

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PREFACE

Not all kimberlites are diamond-bearing, consequently geologists need a tool, or tools, to help determine which are potentially diamondiferous. The authors of this volume review the use of various minerals and mineral assemblages (indicator minerals) as important aids in diamond exploration. These types of exploration tools can reduce the costs of exploration significantly by quickly identifying prospective areas. Large areas of the Canadian Shield and areas known to be underlain by rocks of the Shield are actively being explored for diamonds, with varying degrees of success. This volume will be of considerable help to Canadian diamond explorers.

Elkanah A. Babcock
Assistant Deputy Minister
Geological Survey of Canada

PRÉFACE

Les kimberlites ne sont pas toutes diamantifères. C'est pourquoi les géologues ont besoin d'un outil ou de plusieurs outils pour les aider à déterminer celles qui pourraient l'être. Les auteurs du présent volume passent en revue l'utilisation des divers minéraux et associations minérales (minéraux indicateurs) qui constituent des aides importantes à la prospection du diamant. Ces types d'outils d'exploration peuvent réduire considérablement les coûts d'exploration en permettant de déceler rapidement les zones prometteuses. La prospection du diamant entreprise dans de grandes régions du Bouclier canadien et dans des régions connues pour leur socle composé de roches du Bouclier donne un taux de succès variable. Le présent volume sera d'une aide considérable pour les prospecteurs canadiens du diamant.

Elkanah A. Babcock
Sous-ministre adjoint
Commission géologique du Canada

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DIAMOND EXPLORATION TECHNIQUES EMPHASISING INDICATOR MINERAL GEOCHEMISTRY AND CANADIAN EXAMPLES

Abstract

The vast Canadian Shield and adjacent areas underlain by cratonic rocks represent a highly prospective geological environment for diamonds. This has recently been demonstrated by the discovery of what appears to be a world-class diamondiferous kimberlite province in the Lac de Gras area of the Northwest Territories. The Lac de Gras discovery, together with others in Saskatchewan, Ontario and Quebec, resulted in a boom in diamond exploration activity in Canada on a massive scale.

A brief overview of the petrology of kimberlites and lamproites and the genesis of diamonds is presented before reviewing exploration techniques. Indicator mineral geochemistry was central to the exploration program which led to the discovery of the first kimberlite in the Northwest Territories, and in this report major emphasis is placed on the use of indicator minerals both as pathfinders to kimberlites and as a means of evaluating the diamond potential of exploration targets. Techniques involving the use of both major and trace element geochemistry are evaluated. The indicator mineral geochemistry results from a study of 18 localities investigated in a Geological Survey of Canada funded research project completed in 1989 are discussed. Since conventional indicator mineral techniques are not always applicable to lamproite exploration, alternative pathfinder minerals also have been reviewed.

Résumé

Le vaste Bouclier canadien et les régions adjacentes reposent sur des roches cratoniques qui représentent un milieu géologique très prometteur pour la découverte de gîtes diamantifères. La découverte de ce qui semble être une province de kimberlites diamantifères de classe mondiale dans la région du lac de Gras dans les Territoires du Nord-Ouest l'a récemment démontré. La découverte du gisement du lac de Gras, ainsi que d'autres gîtes en Saskatchewan, en Ontario et au Québec, a provoqué un regain d'activité à grande échelle dans le domaine de la prospection du diamant au Canada.

Un bref survol de la pétrologie des kimberlites et des lamproïtes et de la genèse des diamants est présenté, suivi d'une description des techniques d'exploration. La géochimie des minéraux indicateurs a été le point central du programme d'exploration qui a mené à la découverte de la première kimberlite dans les Territoires du Nord-Ouest; le présent rapport met donc l'accent sur l'utilisation des minéraux indicateurs autant comme traceurs des kimberlites que comme moyen d'évaluation du potentiel diamantifère des cibles d'exploration. Les techniques faisant intervenir la géochimie des éléments à la fois majeurs et traces sont évaluées. On y traite des données recueillies sur la géochimie des minéraux indicateurs au cours d'une étude de 18 localités analysées dans le cadre d'un projet de recherche financé par la Commission géologique du Canada et terminé en 1989. Étant donné qu'il n'est pas toujours possible d'appliquer les techniques classiques basées sur les minéraux indicateurs à l'exploration des lamproïtes, d'autres traceurs géochimiques sont également analysés.

INTRODUCTION

Preamble

Considering that diamondiferous diatremes are largely confined to the ancient stable cratons of the world (Clifford, 1970), the vast Canadian Shield and adjacent areas underlain by old stable craton represent a highly prospective geological environment for diamonds. Kimberlite minerals are present in the secondary environment over widespread areas in North America. Numerous reported diamond finds (e.g., in Canada, Alaska, the Great Lakes areas, California, and the Appalachian region) indicate high probability of economic pipes being found. In spite of this, very little serious exploration was undertaken by Canadian companies until recently.

On a global scale, less than 1% of kimberlite pipes are sufficiently diamondiferous to be economic. Fewer than 50 can be considered to be commercial, and of these, only around 15 are major producers (Jennings, 1990). Sophisticated technology can permit the differentiation of potentially mineable targets from the many subeconomic targets at an early stage of the evaluation process, thereby eliminating considerable expense.

To date, domestic and international diamond exploration expenditures by Canadian companies have not resulted in any profitable return on investment. However, the recent discovery of kimberlites and diamonds in the Northwest Territories has changed this

situation radically. In particular, the DiaMet/BHP discovery has been perceived by the local industry to be very important. It was initially announced that a total of 81 small diamonds up to 2 mm in size were recovered from a 59 kg core sample of kimberlite. Subsequently, several other kimberlites with grade estimates of up to 330 cts/100 tonnes have been announced by the DiaMet/BHP joint venture. Other operators have also reported similar encouraging results.

The world production of natural diamonds over the period 1983 to 1991 is summarized in Table 1. These figures reflect the success of the application of modern exploration techniques (such as geophysics and geochemistry). Apart from the relatively recent discovery of the Venetia kimberlite in South Africa, the most dramatic successes in the past 35 years have been in countries with previously minor roles as diamond producers, such as the former USSR, Botswana and Australia (Fig. 1; Table 1). The commissioning of producing mines around Mir and Udachnaya (Russia), Orapa, Letlhakane and Jwaneng (Botswana), and Argyle in Australia has resulted in these three countries now being responsible for 65% of the world's annual production of natural diamond. These enormous successes have promoted intense exploration interest in the areas concerned, as evidenced by the exploration expenditure for diamonds in Australia in 1984 (Fig. 2) (Atkinson, 1989).

Natural diamonds can be classified into three broad categories of quality: gem, near-gem, and industrial.

Table 1

World production figures for rough natural diamonds 1983-1991 (million carats)

Country	1983	1984	1985	1986	1987	1988	1989	1990	1991
Australia	6.2	5.7	7.06	29.2	30.0	35.0	37.0	36.0	36.0
Zaire	13.0	18.5	19.6	20.5	21.0	23.0	20.0	26.0	25.6
Botswana	10.7	12.9	12.6	13.0	13.0	15.0	15.2	17.4	16.5
USSR	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
South Africa	10.0	9.8	9.9	10.2	9.6	9.0	9.0	8.5	8.2
Namibia	0.96	0.93	0.91	1.0	1.0	0.9	0.9	0.8	1.2
South America	1.0	1.0	0.85	0.85	0.85	0.85	0.9	1.4	1.4
Ghana	0.8	0.33	0.6	0.55	0.44	0.3	0.2	0.7	0.7
CAR	0.3	0.3	0.5	0.6	0.6	0.45	0.6	0.4	0.4
Sierra Leone	0.3	0.42	0.4	0.4	0.36	0.3	0.6	0.4	0.4
Liberia	0.4	0.4	0.4	0.3	0.35	0.35	0.3	0.1	0.1
Tanzania	0.37	0.36	0.35	0.3	0.15	0.13	-	0.1	0.1
Angola	1.0	0.92	0.9	0.2	0.9	1.0	1.2	1.3	1.4
Guinea	-	-	-	-	-	-	0.2	0.2	0.2
Other countries	0.2	0.29	0.47	0.5	0.45	0.45	0.4	1.1	1.1
World totals	57.23	63.85	66.45	89.60	90.70	98.73	98.5	106.4	105.3

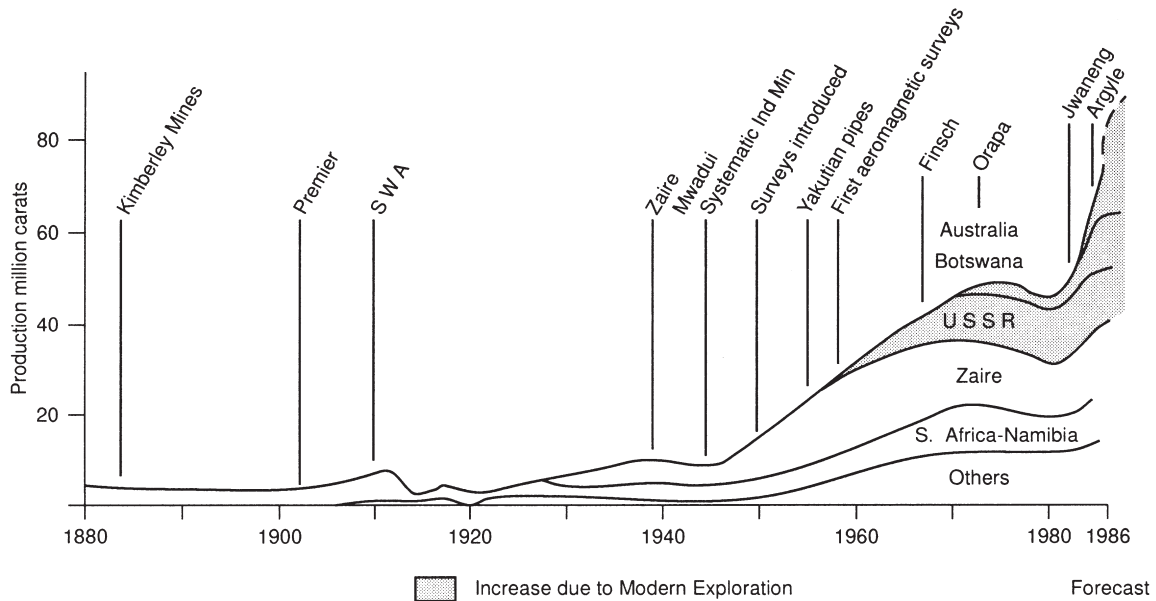


Figure 1. Growth in world diamond production (After Atkinson, 1989).

For this purpose, near-gems are defined as diamonds of poor quality, which can still be cut and polished to gems, but with a very poor yield. World production

averages about 40% gem plus near-gem diamonds with the remaining 60% being very low value industrial stones (Levinson et al., 1992).

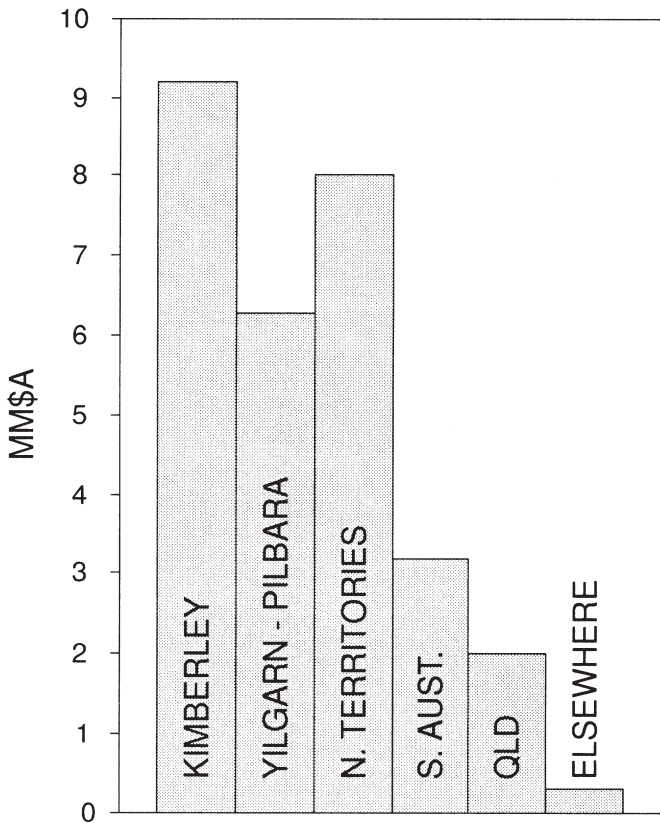


Figure 2. Estimated expenditure for diamond exploration in Australia for 1984 (after Atkinson, 1989).

The value of the world natural diamond production for 1990 exceeded US\$5.5 billion and a breakdown of the figures (Table 2), reveals that gem and near-gem quality stones account for US\$5.4 billion (or 98%) of this revenue. Figure 3 presents similar statistics for world diamond production in 1984.

Relative to other mineral and metal commodities, diamonds rank very high in value of world production. In 1984, diamonds were fifth after iron, gold, copper and zinc and ahead of nickel, uranium, platinum, lead and silver (Atkinson, 1989).

The international diamond market experienced a serious slump in the early 1980s, brought on by speculative investment which led to rapid price increases that could not be sustained. The ensuing dip in both prices and sales had not ended when production from Argyle in Western Australia started to enter the market. In contrast, record volumes of

Table 2

Value of the 1990 natural diamond production

Category	Weight	Value	US\$Mil
Gem	15%	78%	4290
Near-gem	40%	20%	1100
Industrial	45%	2%	110

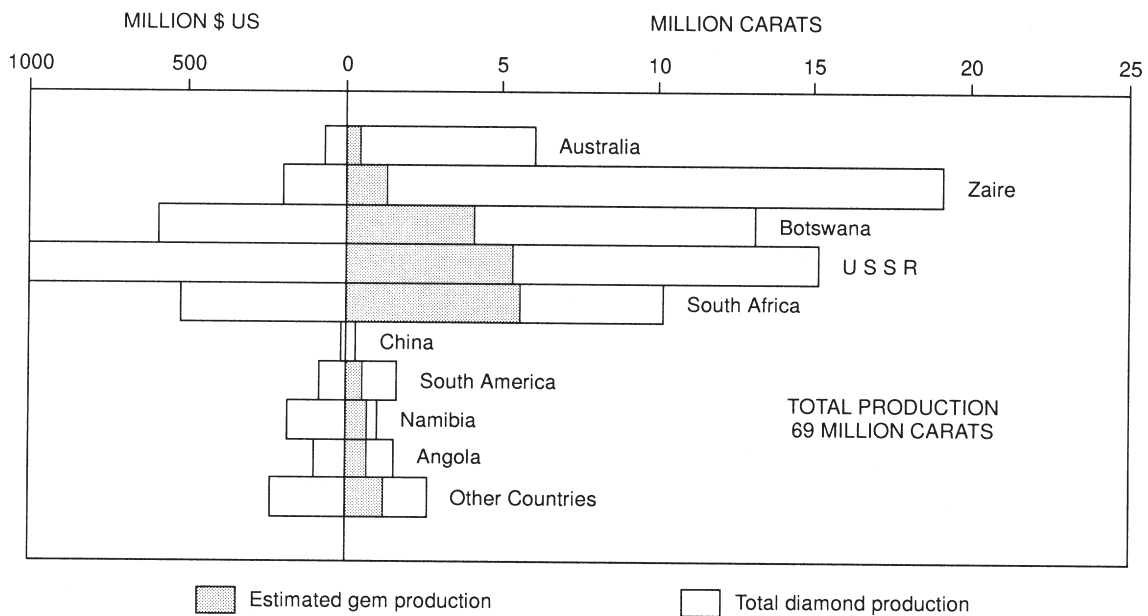


Figure 3. World diamond production for 1984, separated into gem and industrial categories (after Atkinson, 1989).

diamonds were traded recently at steady prices, even though Argyle added 50% to the previous levels of diamond production.

In 1992, in response to world-wide economic recession and the unstable situation in Angola, the diamond market again weakened. Producer confidence returned, however, in 1993 when record sales were made. In the same year, Venetia in South Africa came on stream and produced 5.9 million carats. Russia will develop another mine (Jubilee) in Siberia in the next few years and may develop one or more mines in the Arkhangelsk cluster on the Baltic Shield. The mining of marine diamonds in the South Atlantic Ocean commenced in earnest in 1991, and is set to expand, recovering over 400,000 carats in 1992. Any cessation of civil war in Angola could open up real possibilities for increased diamond production from that country. However, this is one diamond source where the product may not enter the market in an orderly fashion. Offsetting these potential increases in production will be the decline in production of Mir and its satellite kimberlites in Russia; the kimberlite mines in Kimberley, South Africa, and in the medium term, the alluvial beach deposits at Consolidated Diamond Mines in Namibia.

Alluvial deposits aside, kimberlite was the only economically viable source of diamonds until the discovery and commissioning of Argyle in the north of Western Australia. This has widened the scope for

locating a major diamond mine by demonstrating the viability of an additional diamond bearing rock-type, olivine lamproite. In addition, the regional geological setting of Argyle (Proterozoic Mobile Belt) has increased the areas of the earth that can be considered prospective for diamonds. It is now widely accepted that further discoveries in additional rock types are quite possible (Helmstaedt, 1992).

Large areas of the continental land mass within Canada were cratonised before 1.5 Ga (Levinson et al., 1992) and are therefore suitable candidates for regional diamond exploration programs. Potential targets include areas in the Northwest Territories, Alberta, Saskatchewan, Manitoba, and Ontario.

Although diamond deposits around the world have certain basic similarities, there are regional differences. These can be critical at all stages of an exploration project, from the initial phase of area selection to the final phase of planning a mine.

Distribution of kimberlites, lamproites and related rocks in North America

Kimberlites, and related rocks such as lamproites, alnoites and other varieties of lamprophyre have a wide distribution throughout North America (Fig. 4; Table 3). In the U.S.A. they occur in the western margin of the Appalachians, from New York to



Figure 4. Map illustrating the distribution of kimberlites and related rocks in North America. A full listing of the localities is presented in Table 3.

Tennessee; in the central region, including Kentucky, southern Illinois, Missouri, Kansas and Arkansas, and in the western states of Montana, Wyoming, Colorado, Utah, Arizona, and New Mexico. In Canada, they have been documented on Somerset Island, the Mackenzie Mountains, near Yellowknife in the Northwest Territories, in parts of Saskatchewan, Ontario, and Quebec, and in the Rocky Mountains in the region of the British Columbia-Alberta border.

Key references to the localities plotted on Figure 4 are listed in Table 3. The terminology used in a number of the older papers may not be in accordance with modern usage. In particular, lamprophyric rocks may be incorrectly classified as kimberlites.

Meyer and Kridelbaugh (1977), Watson (1967), Brummer (1978) and Dawson (1980) have presented accounts of some North American localities. A recent review is provided by Rock (1991).

The scope and aims of this study

In 1986 the Geological Survey of Canada funded a research project aimed at developing technology to assist and promote diamond exploration in Canada. To achieve this objective, 18 individual diatremes (including kimberlites, lamproites and lamprophyres) were selected for detailed study: 13 from Canada, two from the USA, two from South Africa, and one from Australia (Table 4). The two American localities were selected because they represent North American examples of a diamondiferous kimberlite (Sloan) and a diamondiferous lamproite (Prairie Creek). New Elands and Sover (South Africa) provided examples of diamondiferous kimberlites, while Argyle (Australia) is a richly diamondiferous lamproite.

Since the research to be undertaken covered a wide spectrum of geological disciplines, the policy adopted from the outset was to contract qualified experts in the various fields from both local and international sources and to collate their efforts into a detailed report (Geological Survey of Canada, 1989). This report is mainly a summary of certain aspects of that work including additional results.

A 32 kg bulk sample was collected from each locality, and six of the recently discovered diatremes in British Columbia (the Blackfoot, HP, Jack, Larry, Mark and Mike diatremes) were mapped for the first time. Detailed petrographic studies were undertaken on representative samples from all localities and the

results were used to select specific samples for whole-rock geochemical analysis. A combination of X-ray fluorescence and neutron activation techniques was used and analyses were undertaken by the Calgary laboratories of the GSC (XRF) and Activation Laboratories (NAA).

Heavy mineral concentrates were prepared from the remaining material (usually about 95% of the sample) by C.F. Mineral Research Limited. The mineralogy of each heavy mineral concentrate was documented and a representative number of the minerals present selected for quantitative SEM analysis. The nonmagnetic fraction of each concentrate was evaluated for micro-diamonds. Analytical procedures employed are documented in Geological Survey of Canada (1989).

The main emphasis of the study was to evaluate the use of indicator minerals to diamond exploration in North America. This approach, with various degrees of sophistication, has been in practice virtually since kimberlite was first recognized as a host for diamonds in South Africa over 100 years ago (Wagner, 1914). However, over the past two decades, the compositions of certain key indicator minerals, namely Cr-pyrop garnet, chromite, pyrope-almandine garnet and ilmenite, have been used in diamond exploration to permit an assessment of diamond potential (Sobolev, 1971; Gurney and Switzer, 1973; Sobolev et al., 1973; Sobolev, 1974; Lawless, 1974; Gurney, 1984; Gurney and Moore, 1991; Gurney et al., 1993).

The volcanic host rocks for diamonds merely represent the transporting agents for carrying diamonds from the upper mantle to the surface. The proven diamond source rocks are various types of peridotite (e.g., Dawson and Smith, 1975; McCallum and Egger, 1976; Pokhilenko et al., 1977; Shee et al., 1982) and certain high pressure eclogites (e.g., Rickwood et al., 1969; Sobolev, 1974; Reid et al., 1976; Robinson et al. 1984). The indicator mineral approach relies on the recognition of distinctive mineral suites which associate them with the source rocks for diamonds.

This bulletin provides a brief overview of the petrology of kimberlites and lamproites, the genesis of diamonds, exploration techniques, and an examination, in some detail, of the philosophy behind the use of indicator minerals in diamond exploration and the application of this technique to North American diatremes. Part 2 of Geological Survey of Canada (1989) summarizes the general geology of the eighteen localities investigated, and interested readers are referred to that publication for further details.

Table 3
Kimberlites and related rocks of North America

No.	Locality	Type	Reference
Canada			
1	Somerset Island, NWT	K	GSC Open File 2124, 1989
2a	Mountain Diatreme, NWT	K	GSC Open File 2124, 1989
2b	Point Lake, NWT	O	DiaMet/BHP Press Release (7 Nov. 91)
3	Saglek, Labrador	K?	Collerson (1976)
4	Aillik Bay, Labrador	La, K?	Hawkins (1976)
5	Castignon Lake, Quebec	C?	Dimroth (1970)
6	Chicoutimi, Quebec	La	Janse (1984)
7	Ille Bizard, Quebec	A	GSC Open File 2124, 1989
8	Bachelor Lake, Quebec	K, La?	Dawson (1967); Watson (1967)
9	Picton and Varty Lake, Ontario	K	Arima and Kerrich (1988)
10	Kirkland Lake, Ontario	K	GSC Open File 2124, 1989
11	Michaud Township, Ontario	K	Watson (1973)
12	Coral Rapids, Ontario	La, K?	Brown et al. (1967)
13	Hearst, Ontario	A, C	Nixon (1987); Janse et al. (1989)
14	Keith Township, Ontario	K	Watson (1973)
15	Wawa, Ontario	La	Mitchell and Janse (1982)
16	McKellar Harbour, Ontario	A	Platt and Mitchell (1982)
17a	Sturgeon Lake, Saskatchewan	K	GSC Open File 2124, 1989
17b	Fort à la Corne, Saskatchewan	K	Lehnert-Thiel et al. (1991)
18	Golden Cluster, British Columbia	K, L	GSC Open File 2124, 1989
19	Cranbrook Cluster, British Columbia	K, B	GSC Open File 2124, 1989
United States of America			
20	North-central Montana	K, L A, C	Hearn (1968); Mitchell and Hawkesworth (1984); Hearn and McGee (1984); Hearn (1989)
21	Iron Mountain, Wyoming	K	McCallum et al. (1975)
22	State Line, Colorado/Wyoming	K	GSC Open File 2124, 1989
23	Green Mountain, Colorado	K	Meyer and Kridelbaugh (1977)
24	Mule Ear, Moses Rock, Utah	K	McGetchin and Silver (1970); Stuart-Alexander et al. (1972)
25	Garnet Ridge, Arizona	M	Watson (1967b)
26	Buell Park, Arizona	M	Roden and Smith (1979); Smith (1979)
27	Green Knobs, New Mexico	M, K	Smith (1979)
28a	Riley County, Kansas	K	Brookins (1970a, b); Berendson et al. (1985)
28b	Woodson County, Kansas	L	Cullers et al. (1985); Coopersmith and Mitchell (1989)
29	Murfreesboro, Arkansas	L	GSC Open File 2124, 1989
30	South Eastern Missouri	La?	Mansker (1973)
31	W. Kentucky and S. Illinois	La?	Koenig (1956)
32	Elliot County, Kentucky	K	Boliver (1972), Hunt and Boliver (1972); Garrison and Taylor (1980); Schulze (1984)
33	Norris Kimberlite, Tennessee	K	Meyer (1975)
34	Mt. Horeb, Virginia	K?	Young and Bailey (1955); Sears and Bilbert (1973)
35	Masontown, Pennsylvania	K	Alibert and Albarede (1988); Hunter and Tylor (1984)
36	Dixonville, Pennsylvania	K	Hunter and Taylor (1984)
37	Syracuse, New York State	La?	Apfel et al. (1951)
38	Lake Ellen, Michigan	K	McGree and Hearn (1984)

Codes for rock types:

K = Kimberlites

B = Basaltic

L = Lamproite

C = Carbonatite

La = Lamprophyre

M = Minette

A = Alnoite

O = Olivine Melilitite

Table 4

The diatremes investigated in the Geological Survey of Canada research project

Diatreme	Geographic Locations	Rock type
Argyle	Kimberley Province, Australia	Lamproite
Batty	Somerset Island, NWT, Canada	Kimberlite
Blackfoot	Elkford, B.C., Canada	Lamprophyre
Cross	Elkford, B.C., Canada	Kimberlite
HP	Golden, B.C., Canada	Lamprophyre
Ile Bizard	Montreal, Quebec, Canada	Alnoite
Jack	Golden, B.C., Canada	Lamproite
Joff	Elkford, B.C., Canada	Kimberlite
Kirkland Lake	Bisley Township, Ontario, Canada	Kimberlite
Larry	Golden, B.C., Canada	Lamprophyre
Mark	Golden, B.C., Canada	Lamprophyre
Mike	Golden, B.C., Canada	Lamprophyre
Mountain	Mackenzie Mountains, NWT, Canada	Olivine Melilitite
New Elands	O.F.S., South Africa	Kimberlite
Prairie Creek	Pike County, Arkansas, USA	Lamproite
Sturgeon Lake	Prince Albert, Sask., Canada	Kimberlite
Sloan	Larimer County, Colorado, USA	Kimberlite
Sover	Cape Province, South Africa	Kimberlite

THE PETROLOGY OF KIMBERLITES

Mitchell (1986) provides an excellent review of the mineralogy, geochemistry and petrology of kimberlites. The brief overview which follows is intended to introduce the nonspecialist explorationist to the most important petrological characteristics of this complex variety of volcanic rock. Both this section of the manuscript and the corresponding section on lamproites were reviewed and considerably improved by contributions from B.H. Scott-Smith (pers. comm., 1994). Some of the common nomenclature used throughout this paper is defined in Table 5.

The nature of kimberlite

Kimberlites are a rare variety of potassic volcanic rocks, which are volumetrically insignificant on a global scale. They are petrographically and geochemically complex and consist of minerals, rock fragments and magmatic components which formed in diverse physical and chemical environments sampled at different points on their journey from the mantle to surface. The now widely accepted formal definition of kimberlite, proposed by Clement et al. (1984), is as follows:

Kimberlite is a volatile-rich, potassic, ultrabasic igneous rock which occurs as small volcanic pipes, dykes and sills. It has a distinctively inequigranular texture resulting from the presence of macrocrysts set in a finer grained matrix. This matrix contains, as prominent primary phenocrystal and/or groundmass constituents, olivine and several of the following minerals: phlogopite, carbonate (commonly calcite), serpentine, clinopyroxene (commonly diopside), monticellite, apatite, spinels, perovskite and ilmenite. The macrocrysts are anhedral, mantle-derived, ferromagnesian minerals which include olivine, phlogopite, picroilmenite, chromian spinel, magnesian garnet, clinopyroxene (commonly chromian diopside) and orthopyroxene (commonly enstatite). Olivine is extremely abundant relative to other macrocrysts, all of which are not necessarily present. The macrocrysts and relatively early-formed matrix minerals are commonly altered by deuteric processes mainly serpentinization and carbonatization. Kimberlite commonly contains inclusions of upper mantle-derived ultramafic rocks. Variable quantities of crustal xenoliths and xenocrysts may also be present. Kimberlite may contain diamond but only as a very rare constituent.

Table 5

Glossary of some technical nomenclature used in this paper

Rock Nomenclature	
Peridotite	A class of ultramafic rocks consisting predominantly of olivine, with or without other ferromagnesian minerals.
Lherzolite	A variety of peridotite consisting predominantly of olivine, orthopyroxene and clinopyroxene. Other minor phases may be present (e.g., garnet, spinel). It is by far the dominant rock type constituting the upper mantle. Very common as a xenolith in kimberlite.
Harzburgite	A variety of peridotite consisting predominantly of olivine and orthopyroxene. It is distinguished from lherzolite by the absence of clinopyroxene. It is considerably less common than lherzolite both in the upper mantle and as a xenolith in kimberlite.
Pyroxenite	An ultramafic rock consisting predominantly of clino- and orthopyroxene.
Eclogite	Typically a coarse grained bimineralic rock consisting of pyrope-almandine garnet and omphacitic clinopyroxene. Accessory minerals may include rutile, kyanite, coesite, sanidine, graphite and diamond.
Glimmerite	An ultrabasic rock consisting almost entirely of the micas phlogopite and/or biotite.
MARID suite	Distinctive group of nodules which are olivine free and consist of varying proportions of mica (phlogopite), amphibole (K-richterite), rutile, ilmenite and diopside (hence the acronym MARID).
Petrographic Terms	
Megacryst	a suite of discrete crystals commonly found in kimberlites. By definition >2 cm in longest dimension but can be up to 20 cm in size. The suite commonly consists of some or all of the following phases: olivine, ilmenite, garnet, clinopyroxene (cpx), orthopyroxene (opx), phlogopite and zircon.
Xenocryst	fragment of a crystal enclosed by a magma but not genetically related to it.
Xenolith	rock enclosed by a magma but not genetically related to it.
Phenocryst	relatively larger crystal set in the fine grained groundmass of a porphyritic rock. Phenocrysts form during the early crystallization history of the rock in which they are found.
Macrocryst	non-genetic term to include both phenocrysts and xenocrysts, usually in the size range 0.5-15 mm.
Tectonic Terms	
Lithospheric mantle	the rigid upper portion of the upper mantle that moves as a coherent mechanical unit with a velocity similar to the surface crustal plates.
Asthenospheric mantle	less rigid than lithospheric upper mantle and capable of internal convective motion by plastic flow. The lithosphere-asthenosphere boundary occurs at ~180 km below stable diamondiferous continental cratons.

Two distinct varieties of kimberlite (termed Group I and Group II) have been recognized in southern Africa, on the basis of isotopic criteria (Smith, 1983; Skinner, 1989), but to date, no Group II kimberlites have been identified elsewhere in the world.

Kimberlites are olivine-rich ultrabasic rocks, enriched in CO₂, TiO₂, K₂O and P₂O₅. They contain an

extremely high volatile component and are strongly enriched in incompatible trace elements such as Rb, Sr, Zr, Nb, Ba, Cs, Th, U, and Pb, and the light rare earth elements (Tables 6, 7).

Compared to most other volcanic rocks, kimberlites commonly have different near-surface modes of emplacement which result from the unusually high CO₂

Table 6
Representative compositions of kimberlites (from Mitchell, 1986)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO ₂	32.07	32.53	30.42	29.2	28.63	25.19	16.9	3.41	38.90	36.12	31.00	32.43	26.53	16.40
TiO ₂	0.83	1.38	2.95	4.70	1.07	1.89	0.93	12.23	1.67	1.45	1.33	3.88	1.84	1.94
Al ₂ O ₃	0.94	2.12	3.09	2.03	2.01	2.87	0.79	7.81	3.97	4.38	3.05	3.77	0.61	1.28
Cr ₂ O ₃	0.22	0.23	0.15	–	–	–	–	0.10	0.31	–	–	–	–	–
Fe ₂ O ₃	5.45	5.10	5.08	11.86*	4.02	3.72	7.04	19.66	3.57*	6.80	8.90*	4.18	6.68	3.49
FeO	3.22	3.78	6.28	–	5.38	6.72	3.47	12.12	–	2.68	–	9.49	6.50	5.45
MnO	0.16	0.15	0.18	0.85	0.14	0.22	0.24	0.43	0.15	0.22	0.15	0.19	0.22	0.19
MgO	38.45	31.35	25.14	31.11	34.02	29.69	16.6	11.93	19.92	22.82	23.99	26.63	32.78	17.24
CaO	5.67	7.59	9.72	7.47	11.92	13.59	26.4	17.15	7.06	8.33	11.43	8.04	9.58	24.81
Na ₂ O	0.05	0.05	0.08	0.13	0.20	0.01	–	0.26	0.28	0.29	0.05	0.26	0.06	0.99
K ₂ O	0.22	1.63	2.15	0.88	0.05	0.15	0.02	0.09	4.68	5.04	1.55	2.10	0.09	0.14
P ₂ O ₅	0.37	0.54	1.17	0.69	0.27	2.20	1.36	2.42	1.34	1.46	0.63	0.25	0.66	1.80
CO ₂	–	4.46	5.30	–	8.99	12.83	19.23	9.45	–	3.80	–	5.88	10.58	23.39
H ₂ O+	8.70	7.56	6.25	–	2.75	1.15	5.13	2.34	–	4.89	–	3.16	5.64	3.16
H ₂ O-	0.69	0.44	0.64	–	0.23	–	0.28	0.30	–	1.28	–	–	–	–
L.O.I.	3.09	–	–	9.94	–	–	–	–	11.39	–	16.33	–	–	–
	100.33	98.91	98.60	98.18	99.69	99.62	98.39	99.80	98.24	99.56	98.41	100.25	101.77	100.78

1, Shandong, China (Zhang and Liu, 1983); 2, Dike 202, Malibatso River, Lesotho (Gurney and Ebrathim, 1973); 3, Pipe 200, Lesotho (Gurney and Ebrahim, 1973); 4, base of macrocrystal-rich sill, Mayeng (Apter et al., 1984); 5, olivine-magnetite-perovskite cumulate, Benfontein (Dawson and Hawthorne, 1973); 6, composite sample of Benfontein sill (Dawson and Hawthorne, 1973); 7, magnetite-calcite-serpentine dike, Premier (Robinson, 1975); 8, magnetite perovskite cumulate, Benfontein (Dawson and Hawthorne, 1973); 9, Swartruggens Main dike (Skinner and Scott, 1979); 10, New Elands dike (Dawson, 1972); 11, Orroroo dike (Scott-Smith et al., 1984); 12-14, Holsteinsborg dikes, Greenland (Scott, 1979).

*Total Fe calculated as Fe₂O₃; L.O.I. loss on ignition

Table 7

Composition of "average kimberlite" compared with "average ultramafic rock" (from Middlemost, 1986; after Wedepohl and Muramati, 1979)

Element (ppm)	Average kimberlite (K)	Average ultramafic rock (U)	$\frac{K}{U}$
Al	18 900	14 300	1.3
Au	0.004	0.007	0.57
B	36	7	5.1
Ba	1 000	20	50
Be	≈ 1	≈ 0.4	≈ 2.5
C	16 200	100	162
Ca	70 400	27 200	2.6
Cd	0.07	0.06	1.2
Ce	200	1.93	104
Cl	300	110	2.7
Co	77	110	0.7
Cr	1 100	3 090	0.36
Cs	2.3	0.006	383
Cu	80	47	1.7
Er	1.45	0.40	3.6
Eu	3.0	0.16	18.8
F	1 900	97	19.6
Fe	71 600	64 830	1.1
Ga	≈ 10	2.5	≈ 4
Gd	8.0	0.74	10.8
Ge	≈ 0.5	1	≈ 0.5
Hf	7	0.6	11.7
Ho	0.55	0.16	3.4
K	10 400	390	26.7
La	150	0.92	163
Li	25	2	12.5
Lu	0.16	0.065	2.5
Mg	160 000	247 500	0.64
Mn	1 160	1 040	1.1
Mo	≈ 0.5	0.2	≈ 2.5
Na	2 030	2 230	0.91
Nb	110	1.3	84.6
Nd	85	1.44	59
Ni	1 050	1 450	0.72
P	3 880	220	17.6
Pd	0.053	0.01	5.3
Pr	22	0.32	68.8
Pt	0.19	0.06	3.2
Rb	65	1.2	54.1
S	2 000	≈ 4 000	0.5
Sc	15	15	1.0
Se	0.15	0.02	7.5
Si	147 000	203 300	0.72
Sm	13	0.40	32.5
Sn	15	0.52	28.8
Sr	740	22	33.6
Ta	9	≤ 0.1	≥ 90
Tb	1.0	0.12	8.3
Ti	11 800	780	15.1
Tm	0.23	0.067	3.4
V	120	50	2.4
Y	22	2.88	7.6
Yb	1.2	0.38	3.2
Zn	80	56	1.4
Zr	250	16	15.6

content of the erupting magmas. These differences required kimberlite-specific textural-genetic classifications to be established (Hawthorne 1975, Clement and Skinner 1985).

Kimberlites most commonly occur as carrot-shaped pipes, as dykes, or more rarely as sills (Fig. 5). Three zones have been recognized within kimberlite pipes: the crater, diatreme, and root zones. Kimberlite pipes vary in size, up to 216 hectares (Fig. 6a). The present surface area of kimberlite bodies not only reflects the nature of the eruption but also the degree of erosion within the kimberlite pipe.

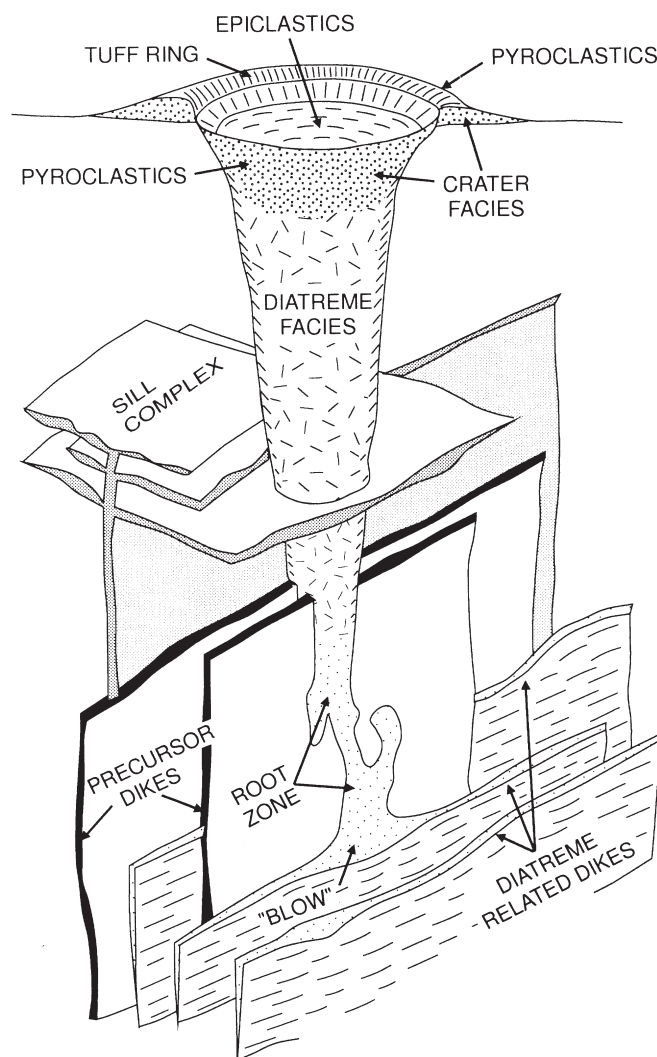


Figure 5. Model of an idealised kimberlite magmatic system, illustrating the relationship between crater, diatreme, and hypabyssal facies (not to scale). Hypabyssal facies include sills, dykes, root zone and "blow". Reproduced from Mitchell (1986).

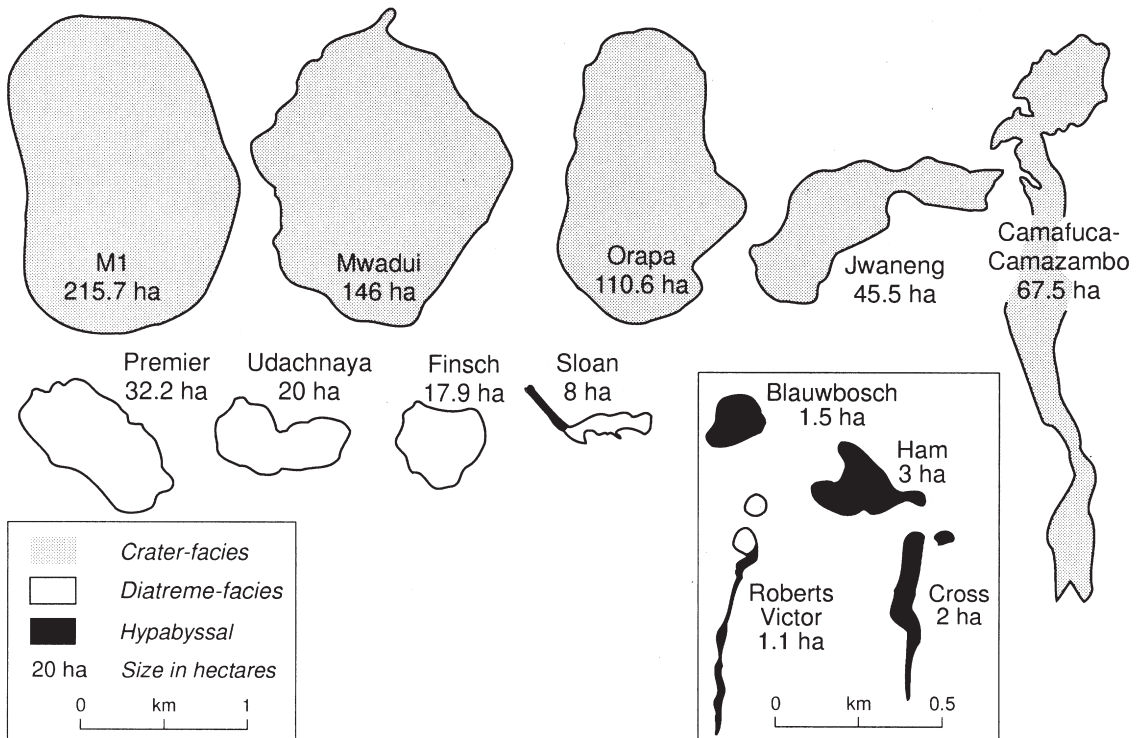


Figure 6a. Kimberlites: Plan views. Reproduced from Scott-Smith (1992).

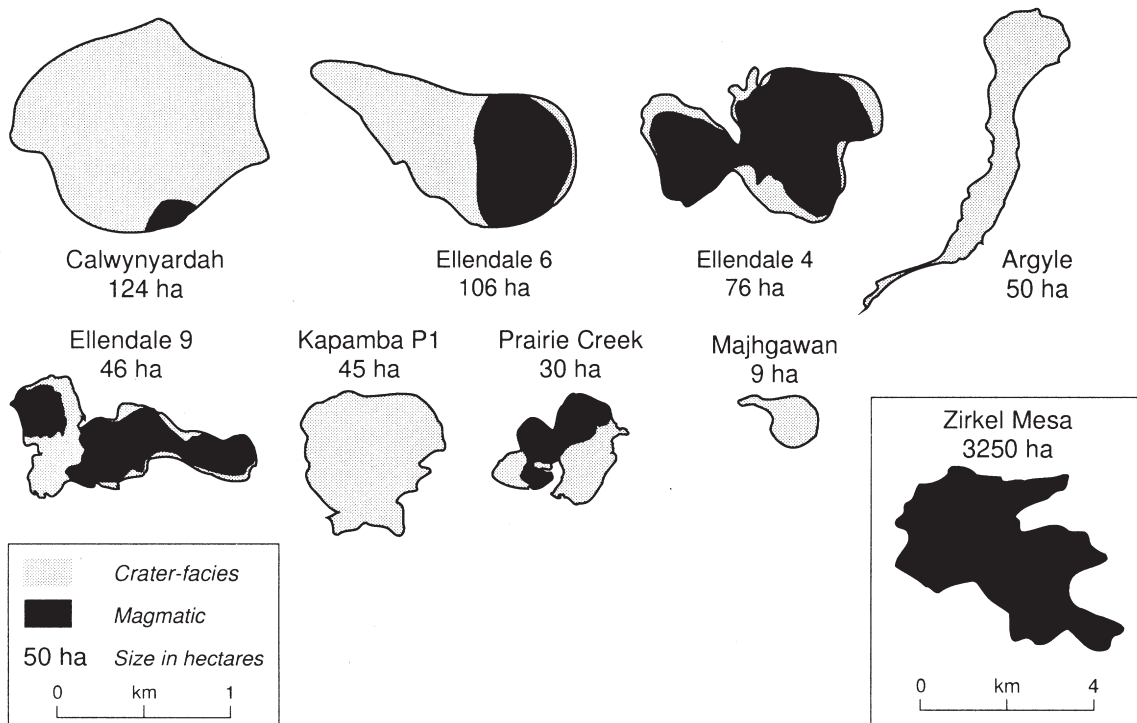


Figure 6b. Lamproites: Plan views. Reproduced from Scott-Smith (1992).

The root zones are infilled with rocks which have crystallized from magmatic kimberlite and have hypabyssal textures. These kimberlites are composed of relatively coarse-grained xenocrysts, which have been incorporated into the magma, and phenocrysts, both of which crystallized from the magma prior to emplacement. These xenocrysts and phenocrysts are set in a fine-grained groundmass which is composed predominantly of minerals that crystallized from the magma near the surface. Many of these rocks contain abundant primary carbonate and serpentine, testifying to their volatile-rich nature. Hypabyssal kimberlites also occur in dykes and sills. Hypabyssal kimberlites can be subdivided firstly into kimberlite and kimberlite breccia, based on their xenolith content (Clement and Skinner, 1985), and secondly, based on the modal abundances of the primary groundmass minerals (Skinner and Clement, 1979). Only minor quantities of hypabyssal kimberlites occur within known diatreme and crater zones.

The root zones are characteristically highly irregular in shape (Fig. 7). They are typically formed by several intrusive pulses of kimberlite magma with different

compositions, reflected by contrasting groundmass mineralogies. Many of these hypabyssal kimberlites formed during embryonic pipe development and may not have reached the surface (Clement, 1982; Clement and Reid, 1989).

The diatreme zone forms the main part of a kimberlite pipe (Fig. 5). In comparison to the root zone, it typically is comprised of fewer phases of intrusion. This zone typically has regular, steep contacts (Clement, 1982). The diatreme zones are mostly infilled with texturally unusual rocks which are the product of complex vapor-rich fluidised intrusive systems (Clement and Skinner, 1985) and degassing of the associated CO₂. These rocks have been termed tuffisitic kimberlites (Clement, 1982; Clement and Skinner, 1985), or tuffisitic kimberlite breccias if they contain abundant xenoliths. Pelletal lapilli are a characteristic constituent of these rocks, and the cementing matrix usually is composed of serpentine and microlitic clinopyroxene. The diatreme facies grades upward into crater-facies kimberlite and downward into hypabyssal-facies rocks.

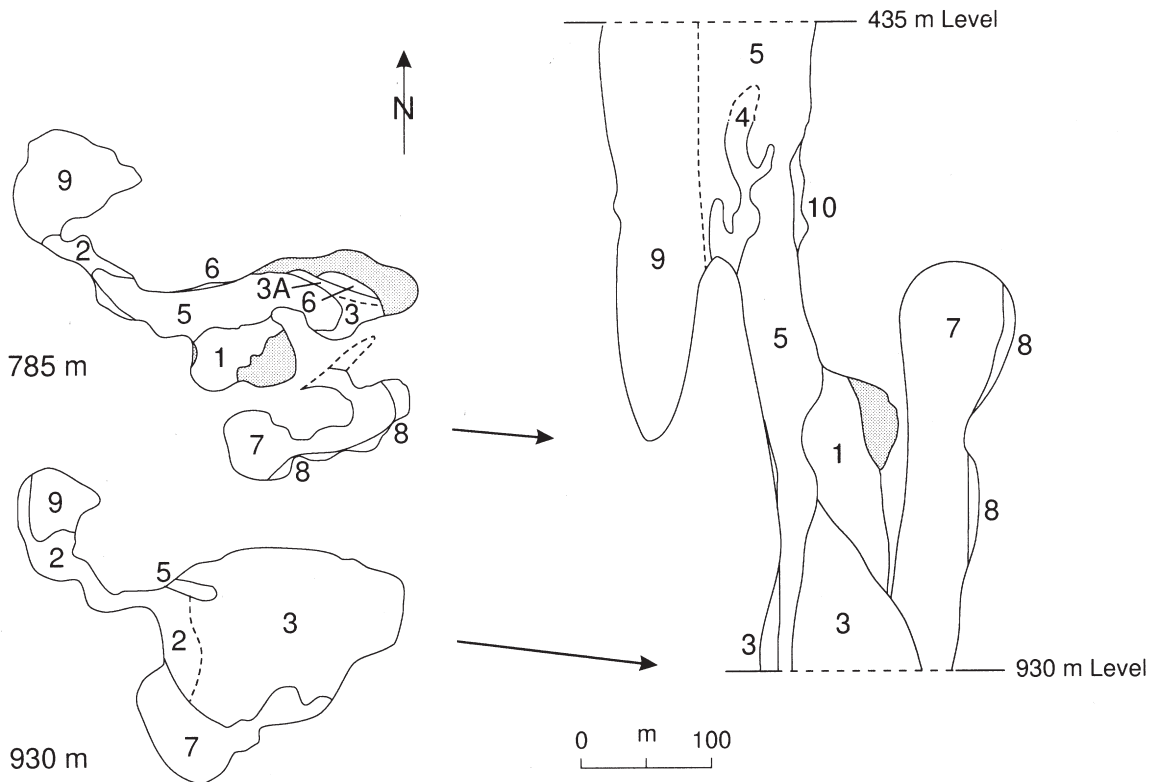


Figure 7. Vertical and horizontal cross-sections of the root zones of the Wesselton diatreme (Clement, 1982; Shee, 1984). Numbers signify petrographically distinct varieties of kimberlite (not in sequence of intrusion). Diagonal shading indicates contact breccias. Note the blind diatreme represented by units 7 and 8. Reproduced from Mitchell (1986).

The crater of a typical kimberlite pipe is the surface expression of an intrusion. Craters have shallower and more irregular contacts when compared to the diatreme below. The craters are infilled with primary pyroclastic material which may be reworked. Some craters may be long-lived and can contain crater lakes (e.g., Orapa in Botswana). The internal geology of craters can be very complex and each one will be unique.

Each of the zones within the kimberlite pipe (Fig. 5) has different diamond distribution characteristics. The diatreme zone typically has the simplest internal geology and therefore usually shows the least fluctuation in grade (Clement, 1982). In contrast, the root zones may have fairly complex internal geology with each phase having different diamond grades. The craters will typically be the most complex part of a kimberlite pipe, resulting from the interaction of primary pyroclastic processes and secondary re-sedimentation processes, both of which affect the diamond distribution.

The ultimate geometry of a kimberlite body depends on many factors, and deviations from any idealized model must be expected. The kimberlites at Mbuji-Mayi in Zaire (Meyer de Stadelhofen, 1963; Demaiffe et al., 1991) and Fort a la Corne in Saskatchewan (Lehnert-Theil et al., 1991) may be such exceptions.

Diamond grades of economically viable pipes range upward from 3 cts/100 tonnes to >200 cts/100 tonnes. Conversely, subeconomic pipes can have grades as high as 50 cts/100 tonnes. The reason for this extensive overlap is the wide range in average value of the diamonds. At some localities this is less than \$10/carats, whereas at others it can exceed \$300/carats. Letseng La Terae was a successful mine with a grade of approximately 3 cts/100 tonnes because it regularly produced large (>20 cts) diamonds of superb quality. This diatreme is in northern Lesotho. Fairly close by, in the eastern Orange Free State, the Monastery kimberlite is uneconomic although portions of the diatreme kimberlite run at about 50 cts/100 tonnes. The lowest grade kimberlite successfully worked at the present time is the Frank Smith deposit near Barkly West, South Africa, with a grade of 3 to 6 cts/100 tonnes.

Kimberlites commonly occur in clusters of 50 or fewer pipes, sometimes with only the larger or largest in the cluster being economically viable diamond deposits. The areal extent of the clusters varies widely, with a maximum separation of about 50 km. The ratio of mined to unmined kimberlites in some diamondiferous clusters is summarized in Table 8.

Table 8

Ratio of economic to non-economic kimberlites in some diamondiferous clusters (after Janse, 1985)

Kimberley	5 out of 15
Jagersfontein	1 out 9
Koffiefontein	1 out of 16
Finsch	1 out of 16
Orapa	2 out of 29
Jwaneng	1 out 7
Cullinan-Premier	1 out of 12
Mir	3 out of 6
Daldyn	2 out of 40
Alakit	1 out of 30
Venetia	3 out of 7

A wide range of foreign rock fragments commonly is incorporated into kimberlites. These include fragments of near-surface country rock, as well as rocks from the earth's upper mantle. The latter include five broad categories of rock types:

1. The peridotite-pyroxenite suite
2. Eclogites
3. Megacrysts
4. Metasomatised peridotites
5. Glimmerites and MARID-suite rocks

Further details on the definition and classification of these rock types are summarized in Table 5 and Figure 8. Lherzolite and harzburgite of the peridotite suite usually predominate, but megacryst minerals and eclogite xenoliths may be locally abundant. Fragmentation of crustal- and mantle-derived xenoliths during transportation in the kimberlite results in the addition of xenocrysts to the magma.

Kimberlites and lamproites show a wide range in age from Archean to Tertiary (Table 9). Numerous attempts have been made to identify some sort of periodicity in these ages (e.g., Pidgeon et al., 1989), but many would argue that no distinct pattern is present (e.g., Janse, 1985).

It has been noted that kimberlite intrusions can be repeated in the same locality at widely different ages, e.g., the Precambrian dykes at Wesselton and the Cretaceous Wesselton kimberlite. Also, there is a tendency for the age of intrusion to decrease when moving away from cratonic blocks; e.g., in South Africa, the Bushmanland kimberlites are younger than the Kimberley pipes. This is, however, a simplification of a complex picture.

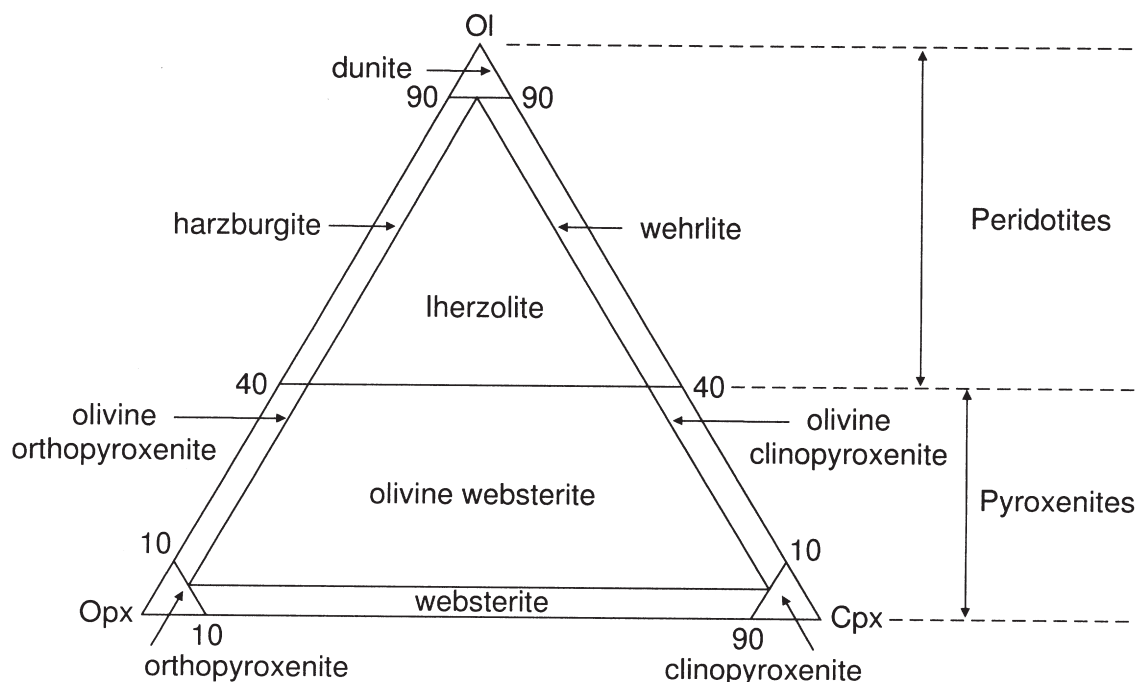


Figure 8. Classification of peridotites and pyroxenites as recommended by the International Union of Geological Sciences. Modal proportions are in volume percent. Reproduced from Dawson (1980).

Table 9

Summary of intrusion ages of kimberlites, lamproites and related rocks (modified after Janse, 1985)

Time Period	Age (Ma)	Localities
Recent	1	Leucite Hills (Wy), Eifel, Lake Bullenmerri (Australia)
Early Miocene	20	Ellendale, Australia
Oligocene	20–30	Mule Ear (Colorado Plateau)
Early Eocene	52–54	Nzega (Tanzania), Mwadui?, Bushmanland (S. Africa)
Late Cretaceous	65–80	Southern Cape South Africa, e.g., Sutherland
Middle Cretaceous	80–100	Kimberley, Jagersfontein, Monastery (S. Africa), Orapa (Botswana), Lesotho, Gross Bruckaros (Namibia), Arkansas, Coromandel (Brazil)
Early Cretaceous	115–135	Southern African Group II kimberlites, e.g., Finsch, Bellsbank, Roberts Victor etc., Angola, Batovi (Brazil), Zaire, Sierra Leone, Kansas, Kuoka (Siberia)
Late Jurassic	145–160	Klipfontein and Swartruggens (S. Africa), Guinea, New York, Kirkland Lake (Ontario), pre-Lena and Kuoyko-beyenchime (Siberia)
Early Jurassic	175–190	Liberia, Pennsylvania
Late Triassic	200	Dokolwayo (Swaziland)
Middle Triassic	215–235	Jwaneng (Botswana), Meimecha-Kotui (Siberia)
Early Permian	260–280	W. Kentucky, Illinois, Missouri
Late–Early Devonian	340–360	Stateline (Colorado–Wyoming), Alakit–Daldyn and Malo–Botuoba (Siberia)
Late Silurian	400–410	Somerset Island (NWT), Muna and Malo–Botuoda (Siberia)
Late Ordovician	440–450	Malo–Botuoba, Chomurdakh and Merchindem (all Siberia)
Cambrian	500–510	Colossus, River Range, Venetia, RSA Zimbabwe
Late Proterozoic	1000–1250	Argyle (Australia), India, Premier, Mali
Middle Proterozoic	1400–1700	Kuruman (S. Africa), Gabon, Liberia
Early Proterozoic	1900	Wesselton Dykes (S. Africa)

Knowledge of the expected age of target pipes can be very important when planning an exploration program for diamonds. Younger cover rocks and secondary sediments potentially suitable for sampling need to be identified.

Worldwide distribution of kimberlites

Kimberlite volcanism is restricted to a continental intra-plate setting and to date, no examples have been described from oceanic environments or young fold belts. Clifford (1966) recognized that areas of kimberlite magmatism are confined to regions of the continental crust underlain by old cratons (Fig. 9). These regions commonly consist of a core of very old (>2.4 b.y.) rocks surrounded by younger (>1 b.y.) metamorphic “mobile belts” that accreted to the cratons. Clifford (1966) and Dawson (1980) noted that economically important kimberlites are confined to on-craton settings, while those occurring within the younger accreted belts are not economic with respect to diamond content.

Kimberlites are widely distributed throughout the world. A comprehensive review of these occurrences is beyond the scope of this paper and the reader is

referred to Dawson (1980), Janse (1985), Mitchell (1986) and Gurney et al. (1991) for further details. Mitchell (1986) and Helmstaedt (1992) review the various tectonic settings in which kimberlites are found.

THE PETROLOGY OF LAMPROITES

The discovery of the diamond-bearing lamproites in northwestern Australia (Jaques et al., 1984) and the reclassification of some mineralogically anomalous kimberlites as lamproites, e.g., Prairie Creek, Arkansas (Scott-Smith and Skinner, 1984a), has invoked considerable interest in this group of rocks. Comprehensive reviews on lamproites include those of Bergman (1987), Mitchell (1989), and Mitchell and Bergman (1991).

The nature of lamproite

As with kimberlites, lamproites are a petrographically and geochemically complex clan of rocks. Scott-Smith and Skinner (1984a) proposed the following definition for lamproites:

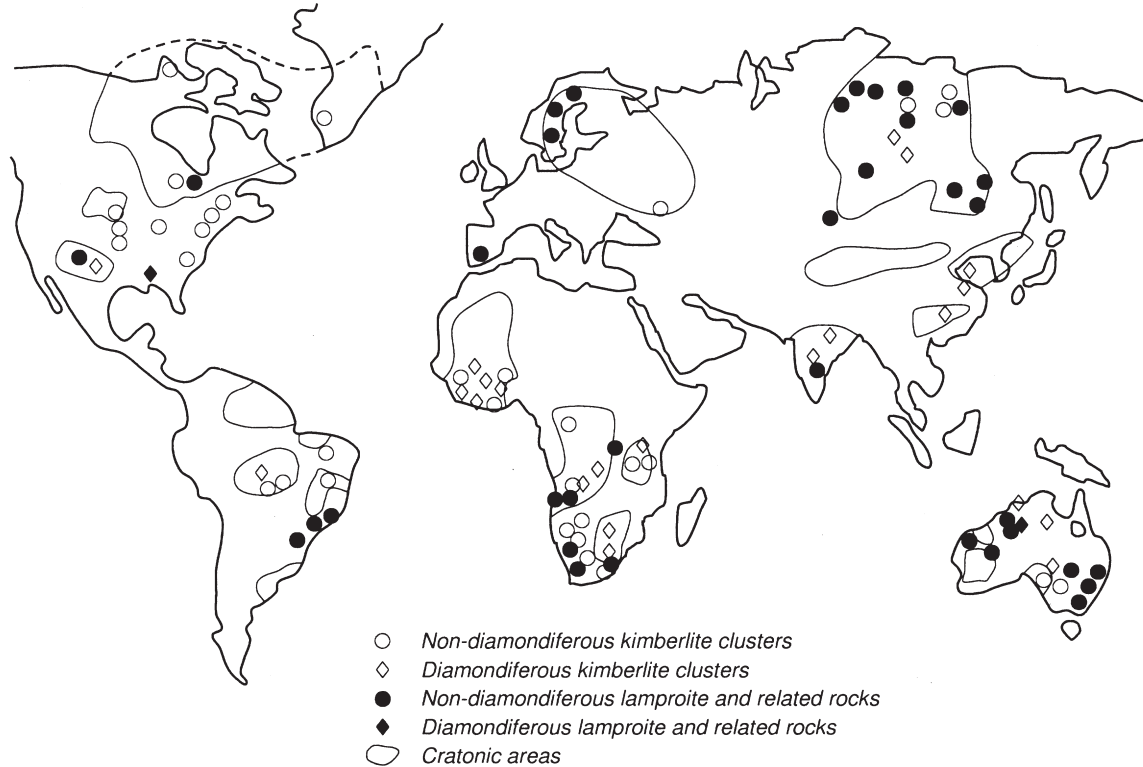


Figure 9. World distribution of kimberlites and lamproites in relation to Archean cratons. From Atkinson (1989); adapted from Janse (1984).

Lamproite is an ultrapotassic, magnesian igneous rock. It is characterised by high K_2O/Na_2O ratios, typically greater than five. Trace element compositions are extreme with high concentrations of Cr and Ni typical of ultrabasic rocks, as well as those more typical of highly fractionated or acid rocks, e.g., Rb, Sr, Zr, and Ba. Generally CO_2 appears to be absent.

Lamproites contain, as primary phenocrystal and/or groundmass constituents, variable amounts of leucite and/or glass, and usually one or more of the following minerals are prominent: phlogopite (typically titaniferous), clinopyroxene (typically diopside), amphibole (typically titaniferous potassic richterite), olivine and sanidine. Other primary minerals may include priderite, perovskite, apatite, wadeite, and spinel. Other minerals such as carbonate, chlorite and zeolite, if present, may not be primary.

Upper mantle-derived xenocrysts or xenoliths may or may not be present.

In a subsequent paper, Scott-Smith and Skinner (1984b) withdrew the condition that leucite is an essential constituent of lamproites.

The mineralogy of lamproites and kimberlites are compared and contrasted in Table 10. The presence of leucite, amphibole, sanidine, glass, priderite, wadeite and the absence of monticellite, primary carbonate and primary serpentine normally can be used to distinguish lamproites from kimberlites. Minerals such as nepheline, sodalite, hauyn, nosean, kalsilite, melilite, plagioclase, and melanite can be used to separate other rock types such as leucitites, katungites, kamafugites, nephelinites, melilitites, and alnoites from lamproites (Mitchell, 1989).

Lamproite terminology is complex. This results from the common use of locality-specific terminology by different authors attempting to accommodate the wide range of modally different rock types that are included in this clan. In addition to obscuring petrological relationships between lamproites, different names have been applied to petrographically similar rocks (e.g., madupite and jumillite), or to modal variants of a single petrographic type (e.g., wyomingite-cedricite-fitzroyite; Mitchell, 1989).

A revised lamproite terminology, similar to that used for kimberlites, was introduced by Scott-Smith and Skinner (1984a), and subsequently modified by

Table 10
Comparison of the mineralogy of lamproites and kimberlites

Lamproites	Kimberlites
Leucite*	Olivine
Glass*	Phlogopite
Phlogopite	Monticellite +
Clinopyroxene	Carbonate +
K-Richterite*	Serpentine
Olivine	Clinopyroxene
Perovskite	Orthopyroxene
Apatite	Apatite
K-feldspar*	Cr-spinel
Priderite*	Ilmenite
Wadeite*	Perovskite
Sr-barite*	Zircon
Cr-spinel	
Titanomagnetite	
Armalcolite	
Zircon	

*Phase unique to lamproites compared with kimberlites
+Phase unique to kimberlites compared with lamproites

Mitchell (1985) and Jaques et al. (1984). Lamproites are now classified on the basis of their modal mineralogy. To illustrate this, examples of the old lamproite terminology recast into the revised terminology are summarized in Table 11. To date, diamonds in commercial quantities have been recorded only from one olivine lamproite: Argyle (Atkinson et al., 1984). However, it provides 30% of the world's production by weight (6% by value).

Table 11
Nomenclature of lamproites (from Mitchell, 1989)

Historical Name	Revised Name
wyomingite	diopside leucite phlogopite lamproite
orendite	diopside sanidine phlogopite lamproite
madupite	diopside madupitic lamproite
jumillite	olivine diopside richterite madupitic lamproite
verite	hyalo-olivine diopside phlogopite lamproite
fortunite	enstatite phlogopite lamproite
cancarixite	diopside sanidine phlogopite lamproite
fitzoyite	leucite phlogopite lamproite
cedricite	leucite diopside lamproite
wolgidite	diopside leucite richterite madupitic lamproite
mamillite	leucite richterite lamproite
gaussbergite	hyalo-olivine leucite lamproite

In contrast to kimberlites, which can show vertical flaring over 2 km, lamproite bodies are much shallower. All known occurrences are less than 0.5 km deep. This difference is due to the lack of development of an extensive kimberlite-style diatreme and related root zone in lamproites. This feature partly reflects the relative paucity of CO₂ in erupting lamproite magmas when compared to kimberlites. As a result, lamproites appear to comprise only a crater with a small vent or feeder (Fig. 10). Many lamproites have champagne-glass shaped craters with shallow, irregular, pipe-wall contacts. Plan-view areas of lamproites range up to 124 hectares (Fig. 6b). The difference in pipe shapes between lamproites and kimberlites has important implications for diamond exploration (ore volume calculations and geophysical modelling).

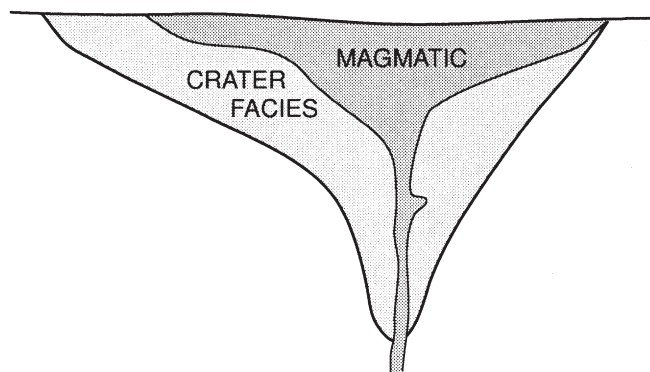


Figure 10. Schematic cross-section of a lamproite pipe illustrating the characteristic champagne glass shape. Note that the magmatic lamproite (hypabyssal facies) intrudes the crater facies pyroclastic material. After Scott-Smith and Skinner (1984b).

Lamproite craters are infilled with volcanoclastic rocks that are dominated by primary pyroclastic material, commonly lapilli tuffs. This material also may be resedimented. In many, but not all, bodies the pyroclastic material is intruded by later magmatic lamproite which usually forms a lava lake (Figs. 6b, 10). To date, economic quantities of diamonds have been found only in volcanoclastic lamproites. Lamproite eruptions and the resulting rocks are similar to those of other volcanoes, and standard terminology can be applied (e.g., Fisher and Schmincke, 1984). As expected, there are deviations from the model and some lamproites form steep-sided pipes (e.g., Argyle, Western Australia: Jaques et al., 1986; and Majhgawan: Halder and Ghosh, 1974) but they are infilled with crater-facies material and are not comparable to the diatreme-zone of kimberlites.

The major and trace element geochemistry of lamproites has been discussed in detail by Bergman (1987), and Mitchell and Bergman (1991), and comprehensive summaries for the West Kimberley province are provided by Jaques et al., (1984, 1986). Lamproites are ultrapotassic, peralkaline rocks which are enriched both in compatible and incompatible elements, especially Rb, Ba, Ti, Zr, and LREE. The averages and ranges in composition of some lamproite suites reported by Bergman (1987) are summarized in Tables 12 and 13. These averages are useful for highlighting the differences between kimberlites and lamproites. Noteworthy differences are that lamproites are distinctly and characteristically richer in SiO₂, Al₂O₃, K₂O, Rb, Ba, Sr, Zr and LREE and poorer in MgO, CaO, H₂O, CO₂, Ni, Co, and Cr compared with kimberlites (Jaques et al., 1984, 1986; Bergman, 1987; Mitchell, 1989; Mitchell and Bergman, 1991).

Worldwide distribution of lamproites

Bergman (1987) reviewed the global distribution of lamproites, and his location map is reproduced as Figure 11. Diamond-bearing lamproites are known from craton margins and adjacent mobile zones that have experienced relatively young and persistent faulting. The distribution of West Australian lamproites, for example, shows strong structural control by major fracture zones which apparently represent fundamental lines of weakness that provided a route through the crust (Atkinson et al., 1984). The diamondiferous Prairie Creek lamproite occurs a considerable distance from the craton in the Gulf Coastal Plains of south-central U.S.A.

Diamond-bearing lamproites have been reported from Australia, the USA and Africa. They appear to be much rarer than diamondiferous kimberlite, even allowing for the fact that they have not been targets for diamond exploration for very long.

OVERVIEW OF DIAMOND GENESIS

Volcanic sources of diamonds are very strongly associated with the old cores of the continental areas (Fig. 9). Kimberlites (~40) and lamproites (1) are the only rock types in which significant, economically viable diamond deposits, capable of sustained profitable mining, have been found so far. Other rock types have been reported to contain traces of diamond (e.g., lamprophyres, ophiolites, garnet granulites and tectonically emplaced ultramafics: Pearson et al., 1989; Shatsky et al., 1989; Helmstaedt and Gurney, 1994).

In both kimberlites and lamproites the diamonds may range in size from microcrystals (<50 μm) to macro-crystals (>1 cm). It is clear that the full diamond suite incorporates several overlapping populations with diverse origins, but these have yet to be precisely defined. Based on mineral inclusion studies, every diamond-bearing locality examined to date has at least two diamond populations represented, namely peridotitic and eclogitic. Further subdivisions may well be present but are not routinely identified.

Considerable literature on mineral inclusions in diamonds exists (e.g., Meyer, 1987). Twenty-two different mineral species have been identified as inclusions in diamonds, including diamond itself (Gurney, 1984). Seven species are common, the others are less abundant. Sulfide minerals are the most abundant inclusion found in diamonds and are associated with both eclogitic and peridotitic paragenesis. Magnesian olivine, orthopyroxene, Cr-pyrope garnet, and Cr-rich chromite are the other abundant primary inclusions of peridotitic paragenesis while, in addition to sulfide minerals, Cr-poor pyrope-almandine garnet and omphacitic clinopyroxene most commonly represent the eclogitic paragenesis.

Diamond-bearing xenoliths can be used to confirm diamond paragenesis determined from mineral

inclusions. Diamond-bearing eclogites are relatively common, with more than one hundred described in the literature (Gurney, 1989), and many others are known but not described. Diamond-bearing peridotite xenoliths are extremely rare but have been found at Aikhal and Udachnaya in the former USSR (Sobolev et al., 1969; Pokhilenko et al., 1977), in southern Africa (Dawson and Smith, 1975; Shee et al., 1982), the Colorado/Wyoming State Line district, U.S.A. (McCallum and Egger, 1976), and Argyle, Australia (Jaques et al., 1990). These xenoliths are not cognate to the host volcanic rock but have been sampled in the upper mantle and rapidly transported to the earth's surface.

Peridotitic and eclogitic diamonds are unrelated populations. Yefimova and Sobolev (1977) have shown that in Siberian kimberlites, peridotitic diamonds overwhelmingly dominate eclogitic diamonds (>99%). However, this proportion may have been overstated, and eclogitic paragenesis is certainly more common than 1% of the total; a figure of 12% may be more accurate (Sobolev, pers. comm.). Numerous diamond-bearing eclogites have been found in Siberian kimberlites. Judging from the observations summarized by Meyer (1987), peridotitic diamonds appear to be most common worldwide, although not as dominant as they are in Siberia. Harris and Gurney (pers. comm.) show that in southern Africa, both

Table 12
Representative average compositions of lamproites (after Bergman, 1987)

	Leucite Hills USA (24)	Murcia-Almeira Spain (51)	West Kimberley Australia (98)	Average lamproite (worldwide) (309)
Volatile Free (wt%)				
SiO ₂	52.7±3.8	51.3±6.6	57.4±5.2	52.5±6.6
TiO ₂	2.4±0.3	5.1±1.5	1.5±0.2	3.0±1.7
Al ₂ O ₃	10.8±1.4	7.2±2.4	10.5±1.8	9.0±2.5
FeO*	5.1±1.4	7.1±1.1	5.3±1.1	6.8±2.2
MnO	0.9±.03	.09±.03	.08±.05	0.10±.05
MgO	8.4±2.3	11.7±7.5	10.5±4.7	12.3±6.6
CaO	6.7±3.8	6.0±8.0	4.9±2.4	6.1±4.4
Na ₂ O	1.3±0.5	0.5±0.3	2.0±1.0	1.4±1.0
K ₂ O	10.4±2.4	8.3±2.9	6.6±2.2	6.9±2.8
P ₂ O ₅	1.5±0.6	1.1±0.6	1.1±0.5	1.3±0.7
BaO	0.67±0.3	1.2±0.8	0.3±0.2	0.7±0.6
ZrO ₂	0.22±0.7	0.15±0.4	.08±.04	0.13±.07
Volatile Content (wt%)				
H ₂ O+	2.6±1.2	3.0±1.8	2.8±1.7	2.6±1.8
CO ₂	1.0±1.0	1.9±5.5	1.7±2.3	2.7±3.9

() = number of samples

*Total Fe calculated as FeO

Table 13

Average trace element abundances in kimberlites and lamproites (adapted from Mitchell, 1989)

Elements	1	2	Elements	1	2
Ag	0.134*	–	Nd	(85)	207
As	–	–	Ni	965	420
Au	(0.012)*	–	Os	1.34*	–
B	(36)*	–	P	(3880)	–
Ba	1100	5120	Pb	15.3	44
Be	1.6*	8	Pd	0.0081*	–
Bi	(0.024)*	–	Pr	(22)	–
Br	–	–	Pt	(0.19)*	–
Cd	(0.073)	–	Rb	73	272
Ce	(200)	400	Re	0.069*	–
Cl	202	–	Rh	0.0071*	–
Co	65	37	Ru	0.065*	–
Cr	893	580	S	1687	–
Cs	2.2*	1.7	Sb	–	–
Cu	93	52	Sc	14	17
Dy	–	6.3	Se	0.15*	–
Eu	(3.0)	4.8	Sm	(13)	24
Er	(1.45)	2.4	Sn	5.4*	–
F	2774	–	Sr	851	1530
Ga	5.7*	15	Ta	11	47
Gd	(8.0)	13	Tb	(1.0)	1.4
Ge	0.5*	–	Te	–	–
Hf	5.6	39	Th	17	46
Hg	(0.008)*	–	Ti	(11800)	–
Ho	(0.55)	1.1	Tl	(0.219)*	–
I	–	–	Tm	(0.23)	–
In	–	–	U	3.1	4.9
Ir	0.003*	–	V	100	123
La	(150)	240	W	–	–
Li	29	31	Y	22	27
Lu	(0.16)	0.23	Yb	(1.2)	1.7
Mn	(1160)	–	Zn	69	84
Mo	1.7*	–	Zr	184	922
Nb	141	95			

All values in ppm

*unreliable data or inadequate data base

1–worldwide kimberlites (Mitchell, 1986), values in parentheses after Muramatsu (1983); 2–worldwide lamproites from Bergman (1987)

modes of diamond paragenesis are found in widely varying proportions, and they conclude that there is a more significant eclogitic component on the Kalahari Craton (~25%) than is the case for the Siberian occurrences. Moreover, these authors suggest that eclogitic inclusions may be more common in larger sized diamonds, further emphasizing their economic significance.

In some of the more detailed studies of diamonds and their inclusions, it has been demonstrated several times that there may be more than one eclogitic and/or

peridotitic population present, and a minor websteritic association also has been identified (e.g., Moore and Gurney, 1989; Otter and Gurney, 1989; Gurney et al., 1991).

The majority of mineral inclusions in diamonds are small (~100 μm) and monomineralic, although bi- and polymineralic inclusions do occur. Multiphase inclusions are important because they allow the calculation of equilibration pressure and temperature of the host diamond by the application of the same mineral geothermometry widely used for upper mantle

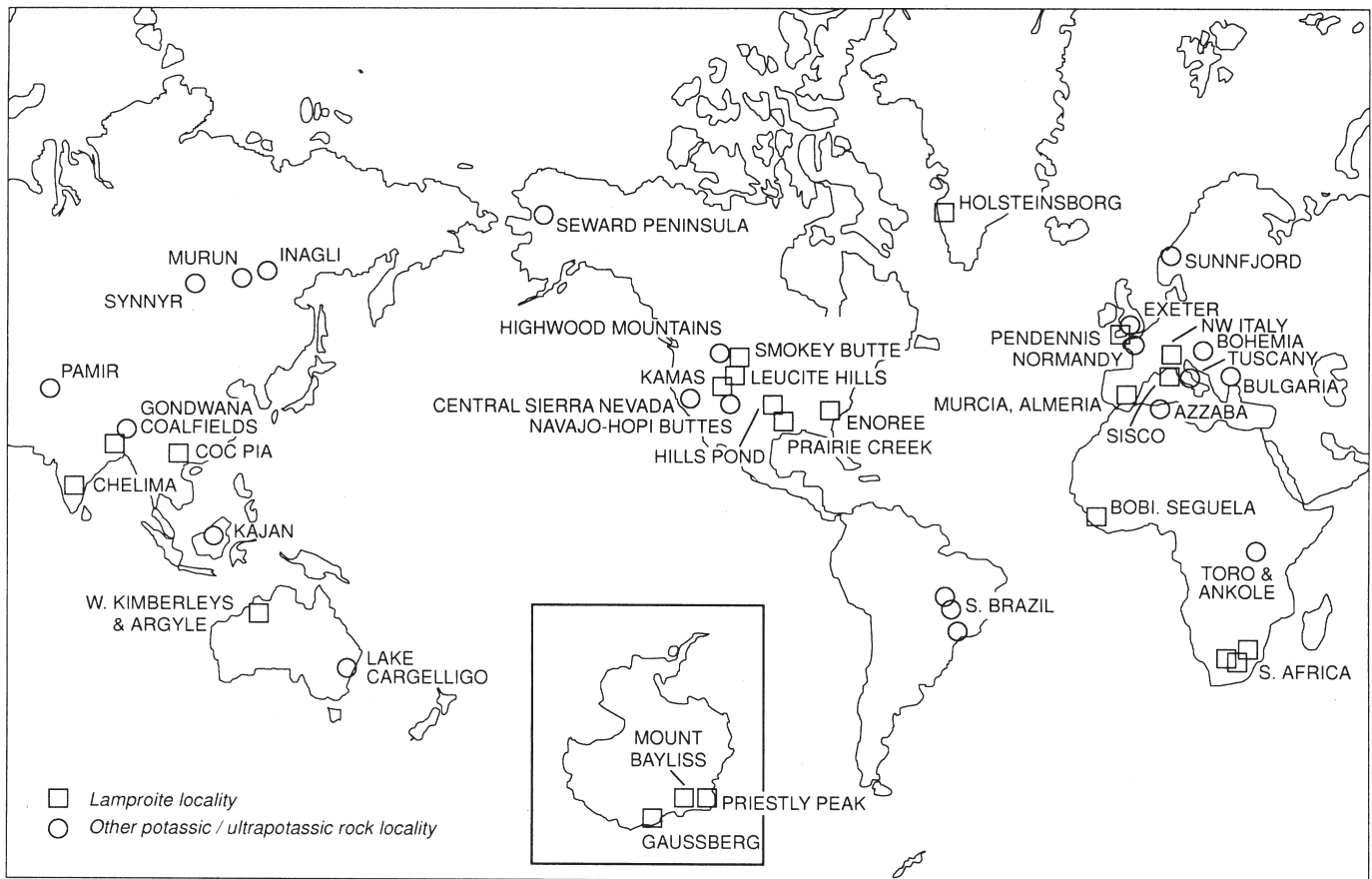


Figure 11. Map showing the locations of lamproite suites and some compositionally similar potassic-ultrapotassic rock suites. Reproduced from Bergman (1987).

xenoliths (e.g., Carswell and Gibb, 1984; Finnerty and Boyd, 1984). Estimated conditions of equilibration for co-existing peridotitic inclusions are between 900 and 1300°C, and 45 and 65 kbar (e.g., Meyer, 1987). These values lie within the region of diamond stability (Kennedy and Kennedy, 1976) and close to a ~40 mW/m² geotherm. This P/T range also spans the conditions estimated for diamond-bearing garnet lherzolite xenoliths described by Shee et al. (1982). It is not currently possible to determine unequivocal equilibration pressures for inclusions of the eclogite suite. Temperatures tend to be marginally hotter but still within the range calculated for the peridotitic suite (Gurney, 1989). Calculated equilibration temperatures for inclusions in diamonds suggest that the low geothermal gradients and deep root zones characteristic of ancient cratons today were established more than 3 b.y. ago (Boyd and Gurney, 1986).

At Monastery Mine in South Africa, eclogitic garnet inclusions from some diamonds show extensive pyroxene solid solution and appear to have a much deeper (>300 km) origin than is usual (Moore and Gurney, 1985, 1989). Similar garnets have been

identified in diamonds from Sao Luis, Brazil (Wilding et al., 1989) and Jagersfontein (Gurney et al., 1991). Such discoveries suggest a very deep origin for at least some diamonds and kimberlites.

The carbon isotope composition of diamonds has an important bearing on models for diamond genesis (Galimov and Kaminsky, 1982; Deines et al., 1984; Kirkley et al., 1991). The overall range in $\delta^{13}\text{C}$ is +5 per mil to -34.4 per mil (Fig. 12; Harris, 1987). Diamonds of peridotitic paragenesis are largely confined to $\delta^{13}\text{C}$ values between -2 per mil and -9 per mil (Sobolev et al., 1979; Deines et al., 1984, 1987). Eclogitic diamonds, on the other hand, have a wide range of carbon isotope compositions (-34 to +5 per mil $\delta^{13}\text{C}$).

Several studies have shown that the carbon isotopic composition of diamonds may be inhomogeneous and complex. Variations of $\delta^{13}\text{C}$ covering the range of the main peak in Figure 12 have been measured in a single, gem-quality small diamond from Mbuji Mayi in Zaire (Javoy et al., 1984). Large variations have also been recorded in coated stones (e.g., Swart et al., 1983;

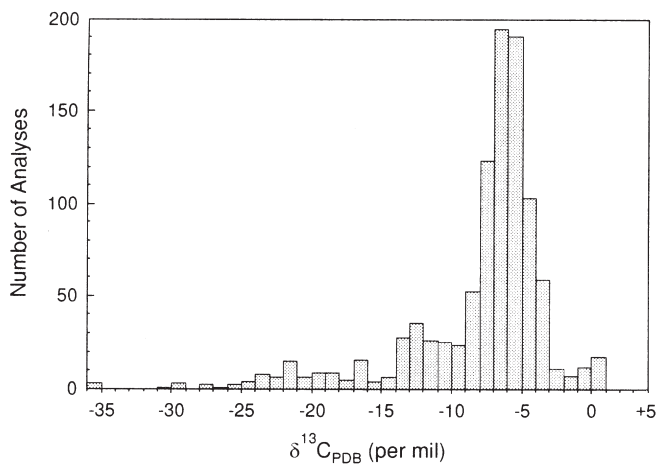


Figure 12. Histogram of the carbon isotopic compositions displayed by diamonds from worldwide sources. Peridotitic diamonds show a very restricted range in C-isotopic compositions which corresponds to the major abundance peak observed in this diagram (between -3 and -9 per mil). In contrast, eclogitic diamonds show C-isotopic compositions which range between +5 and -35 per mil. After Gurney (1989).

Boyd et al., 1986). However, while the central core of a coated stone may have any $\delta^{13}\text{C}$ value within the range for diamonds, the coats are always in the -2 to -9 per mil range (i.e., mantle derived carbon).

Fresh hypabyssal kimberlites have $\delta^{13}\text{C}$ ratios mainly within the range -5 to -7 per mil, and only rarely extend beyond the -2 to -9 per mil range recorded for peridotitic diamonds (Kirkley, 1987). Peridotitic diamonds and kimberlite therefore appear to have a carbon source which is probably derived from the homogenized convecting asthenosphere, whilst the source for some (possibly all) eclogitic diamonds is quite different. Eclogitic diamonds could be derived from an upper mantle that has retained a primary heterogeneity, or from crustal sources subducted into the mantle (e.g., Frank, 1969). The authors favor models involving recycled carbon (Helmstaedt and Gurney, 1984; Helmstaedt and Schulze, 1989).

Over the past decade, major advances have been made in determining the age of diamond formation. Using a composite of sulfide inclusions, Kramers (1979) first demonstrated that the inclusions (and by inference the host diamonds) were significantly older than the transporting kimberlites in the Finsch and Kimberley mines. Richardson et al. (1984) reported

Sm-Nd model-ages in excess of 3.2 Ga for peridotitic (harzburgitic) diamonds from Finsch and Bultfontein (South Africa) and subsequently also demonstrated an ancient origin for similar diamonds from Udachnaya in Siberia (Richardson, 1986a). Several other studies, using a variety of techniques, also have indicated very old ages for diamond (e.g., Takoaka and Ozima, 1978; Melton and Giardini, 1980; Evans and Qi, 1982; Ozima et al., 1983, 1984; and Kurz et al., 1986).

Another major finding of the Richardson et al. (1984) study was that it showed subcalcic Cr-pyrope garnet inclusions from Finsch and Kimberley to be enriched in light rare earth elements (LREE) in a manner not previously reported. This has been demonstrated to be true both for inclusions in diamonds from these two localities and for macrocrysts of subcalcic garnet from the host kimberlites (Shimizu and Richardson, 1987). The favored explanation invokes carbonate related metasomatism of pre-existing chemically depleted harzburgitic lithosphere and suggests that diamonds grew under subsolidus conditions (Shimizu and Richardson, 1987).

It has also been suggested that eclogitic diamonds are significantly younger than peridotitic diamonds. Richardson (1986b) reports Sm-Nd isochron ages from Premier of 1150 and 1580 m.y. for eclogitic garnet and clinopyroxene inclusions respectively, which are close to the Proterozoic emplacement ages of the diatremes (Kramers, 1979; Jaques et al., 1989). However, subsequent studies of eclogitic garnet and clinopyroxene inclusions in Orapa and Finsch diamonds yielded Sm-Nd isochron ages of 990 and 1580 m.y. respectively, compared with host kimberlite emplacement ages of ~100 m.y. (Richardson et al., 1990). Similar results for Finsch were obtained on eclogitic garnet inclusions recovered from a single diamond (Smith et al., 1991). This confirms the distinction between eclogitic and peridotitic diamonds, and establishes that both are xenocrysts which may have been stored in the continental mantle for extended periods of time before being sampled by the kimberlite/lamproite.

Frequently observed inclusions of diamond in diamond and the occurrence of coated stones, common at M'buji Mayi, Zaire and Koidu, Sierra Leone, show that more than one phase of diamond growth may take place within suites of diamonds from one locality (e.g., Boyd et al., 1986). Moreover, detailed studies of growth features in single diamonds by techniques such as cathodo-luminescence and infra-red spectroscopy reveal evidence of extremely complex histories for single crystals (Milledge et al., 1989).

Many diamonds are partially resorbed en route to the earth's surface from the upper mantle (Robinson, 1979; Robinson et al., 1989). Many attain a rounded dodecahedral morphology, implying a weight loss of the order of at least 45%. Under such oxidizing conditions it is considered probable that many microdiamonds would be completely resorbed and therefore disappear. Conversely, it has been proposed that at least some microdiamonds are a separate population (e.g., Haggerty, 1986), even though some recent work on microdiamonds suggests otherwise (Taylor, pers. comm.). Fibrous overgrowths (skins) on previously formed diamonds have been highlighted as having a young origin, as have Type Ib diamonds with single substitutional nitrogen in the diamond lattice.

In considering the origin of diamonds from an explorationist's point of view, it is worth noting that diamonds can be formed in meteoritic impact events. A consequence of this is that prospecting for macrodiamonds by searching for and recovering microdiamonds may yield false anomalies. A meteoritic origin for diamonds may extend to carbonado, a polymineralic aggregate of diamond microlites on which ablation surfaces have recently been identified (Milledge, pers. comm.).

Diamond genesis: summary of important points

In terms of exploration for diamonds, the important factors known about diamond genesis can be summarized as follows:

1. Macrodiamonds in economic deposits are derived from diamondiferous peridotite and eclogite source rock that formed in the lithospheric upper-mantle. They are accidental xenocrysts in the host kimberlite/lamproite.
2. Both peridotitic and eclogitic diamonds occur in every known diamond deposit world-wide.
3. Mineral inclusion abundances indicate that peridotitic diamonds are more abundant than eclogitic diamonds. However, relative xenolith abundances are reversed. This may be due to preferential disaggregation of diamondiferous peridotite, although this has not been proven.
4. Both modes of diamond paragenesis are usually significantly older than the volcanic host rock which transported the diamonds to the earth's surface.

5. Peridotitic diamonds have predominantly formed in chemically depleted peridotite near the base of the lithosphere (depth range 150-200 km), where they have been metasomatised in a Ti-poor, LREE, K and Rb enriched event.
6. Eclogitic diamonds are old, but show a range of ages all apparently younger than the oldest Archaean peridotitic diamonds (990-2700 m.y.).
7. Type Ib diamonds, fibrous coats of diamond on macrodiamonds, and possibly some microdiamonds are young and may be associated with the host magma.
8. If the above is true, the microdiamond content of a kimberlite or lamproite may not be closely related to the macrodiamonds in the same host diatreme.
9. Diamonds are likely to be found in regions of the earth with thick, cool lithospheric keels where old rocks are preserved. Consequently, continental cratons are prime targets for diamond exploration. Complex structural settings which will allow old keels to survive underneath younger rocks are not ruled out of contention. Detailed consideration should be given to the geotectonic evolution of the area under consideration (Helmstaedt and Gurney, 1991).
10. Transport to the surface from depths of diamond stability must be rapid and thus far has proven to involve highly volatile, ultrapotassic, ultrabasic volcanics. Exceptions to this have not been shown to be economically viable.
11. Some diamonds, particularly microdiamonds, in surficial deposits could have an impact-related meteoritic origin.

EXPLORATION TECHNIQUES

Kimberlite, historically the major primary source rock for diamonds, is extremely wide ranging in physical and chemical properties. The recognition of a second potentially economic primary source of diamonds in olivine lamproite expands this diversity considerably. The understanding that, at the very least, many of the macrodiamonds recovered from these so called "primary" host rocks actually formed in eclogite and peridotite within the upper mantle has destroyed the idea that kimberlite and diamonds are genetically related. A lamproite, such as at Argyle, which

produces approximately one third of the world diamond production (~35 million cts/year), is a major demonstration of this diversity of source.

A variety of exploration techniques should be integrated into a diamond exploration program. These may include aspects of petrology, mineralogy, geochemistry, geophysics, geobotany and remote sensing. The selection of the appropriate techniques for any prospecting program is governed by a large number of variables. Among these are the type of deposit sought, the physical and chemical properties of the country rocks, the geomorphologic and physiographic restraints of the terrain, the expected erosional levels of the targets, their anticipated ages of emplacement, the expected cover thickness and, of course, the funds available for the project.

A recent and comprehensive review of diamond exploration philosophy, practice and case histories is that of Atkinson (1989). For reference, reported costs of exploration techniques in Australia are summarized in Table 14.

After very briefly summarizing various techniques used in diamond exploration, the use of indicator minerals in the North American context is considered. Only indicator mineral techniques are dealt with at any length; discussion of other techniques is precursory, with appropriate references to more comprehensive reviews.

Table 14

Indicative cost of exploration techniques in Australia (A\$km⁻²) (from Atkinson, 1989)

	Regional reconnaissance	More detailed
Remote sensing (LANDSAT, SLAR, MSS, etc.)	0-20	-
Air photo	1	n.a.
Drainage	15	-
Aeromagnetics/Radiometrics	5-10	35
INPUT	-	100
Loaming	25-100	1000
Drilling	n.a.	very high

Variables: processing cost; scale; sample spacing.
Standards: flight line spacing overburden.

Remote sensing

A number of remote sensing techniques such as LANDSAT imaging, aerial photography and multispectral scanning may be applied to the search for

kimberlites. Due to its relatively coarse resolution (80 x 80 m), only large pipes (diameter >250 m) are likely to be detected by LANDSAT (Nixon, 1980). LANDSAT data usually are used in association with geophysical techniques in the structural analyses of kimberlite provinces (e.g., Woodzick and McCallum, 1984).

Aerial photography can be useful in diamond exploration. It is best utilized in close association with other exploration techniques rather than as a primary means of target detection. Specific applications include: regional structural and geomorphologic analysis, mapping, locating vegetation anomalies or outcropping pipes and/or dykes, and locating sample sites on streams (Atkinson, 1989). While aerial photographs have been of some practical use in identifying outcropping kimberlite pipes on Somerset Island, it is one of the author's (Fipke) experience that south of the Arctic islands both aerial photographs and Landsat imagery have had little success in North America as a primary means of detection.

Geophysical techniques

Ground and airborne magnetometer methods frequently have been effective in detecting kimberlite or lamproite pipes. Some examples known to the authors include Kirkland Lake, Ontario; Fort à la Corne, Saskatchewan; Lac de Gras, N.W.T.; Orapa and Jwaneng, Botswana; and Ellendale, Australia. In some areas it has had mixed success: at Prairie Creek, Arkansas for example, the barren peridotite phase shows up as a magnetic high, but the diamondiferous phases are undetected by magnetic methods. Many kimberlites and lamproites are undetectable by magnetic methods, including Sloan, Colorado and Argyle, Australia.

Pipes may show as magnetic highs or lows, or have no magnetic contrast with surrounding rock. Their magnetic response and contrast to the surrounding country rocks is partially dependent on the remanent magnetism of the pipe, determined by the prevailing magnetic field at the time of intrusion. The mineralogy of the pipe may also affect its magnetic susceptibility.

Some pipes can be detected by electrical methods (E.M., resistivity or VLF), for example, the Colorado State Line kimberlites (Carlson and Marsh 1989) and some kimberlites in the NWT, Canada. These methods are particularly successful where weathered, conductive, clay-altered upper portions of the pipe are developed and preserved. In these cases, particularly where the country rock is poorly conductive, suitable contrast may exist to facilitate detection. Conversely,

in areas of clay-altered host rocks these methods are less likely to be successful. Similarly, they have been found to be ineffective in areas with widespread lateritized sedimentary cover.

Kimberlite and lamproites commonly have a specific gravity less than that of the enclosing country rocks, and where this contrast is sufficient, ground-based gravity surveys may be an effective means of detection. At present, such methods are usually too time consuming and expensive to utilize as a routine regional reconnaissance tool but may be useful in following up heavy mineral anomalies where other methods are ineffective.

Geobotanical and geobiological methods

Soils developed over kimberlites commonly are enriched in trace elements such as niobium, phosphorus, nickel and chromium. Altered kimberlites usually have a high clay mineral content which promotes water retention. These features may give rise to vegetation anomalies over kimberlite bodies which in many cases are clearly visible. Examples known to the authors include the Bobbejaan and Star dyke systems, the Finsch Kimberlite, and dykes and pipes near Victoria West, all in South Africa. All clearly show up as vegetation anomalies on aerial photographs.

Alexander (1986) demonstrated that soil bacteria over kimberlite diatremes in Colorado showed a noticeable contrast with those over the country rock. This method also may have some potential; however its practical application in the exploration for kimberlites has not yet been demonstrated.

Bulk sample geochemistry

Whole-rock analyses of diatreme rocks are typically highly variable due to several features; most importantly, they usually contain significant volumes of xenolithic material and are characteristically highly altered. This makes classification via whole rock geochemistry complicated, if not impractical, and inaccurate when fresh matrix fragments free of xenolithic material cannot be obtained. This variability (and the difficulty of obtaining fresh samples) is exemplified by the whole rock samples from the diatremes analyzed and reported in Geological Survey of Canada (1989).

Due to the above considerations, no emphasis is placed on whole-rock geochemistry results in this

summary report. Because of the complex, variable and highly weathered nature of most alkaline rocks, diatremes usually can be confidently classified only after assessing a combination of petrographic, only mineralogical and, where practical, whole-rock geochemical data.

Kimberlites and lamproites are characterised by high concentrations of elements such as Mg, Ni, Cr, LREE, Ba, Sr, Rb, P, and Nb (Tables 6, 7, 12, 13). This signature can be used to assist in identifying weathered outcrops or drill cuttings and, theoretically, in regional stream and soil surveys to locate pipes. In practice, however, geochemistry of bulk samples is not particularly useful in exploration situations. Dispersion haloes for elements such as Ni, Cr, Mg and Nb in soils are generally limited to a few tens of meters from the source for both kimberlites and lamproites. In stream sampling, dispersion trains of anomalous values for these elements rarely extend more than a few hundred meters. Heavy mineral trains are generally far more extensive, and so the bulk geochemical method cannot compete with indicator mineral sampling both in terms of cost and effectiveness.

In searches for hidden ore bodies, geochemical analysis of drill cuttings for niobium can be useful in defining the overburden/kimberlite interface. This method has been used with great success in Botswana (Lee, 1993).

Indicator minerals

Sampling

The most widely used technique in basic diamond exploration is sampling for heavy minerals. This has been the practice for more than one hundred years, virtually since kimberlite was first recognized as a host for diamonds in South Africa. Resistant heavy minerals such as garnet, chromite, ilmenite, chrome diopside and, in special cases, olivine, are sought using a wide variety of sampling techniques which are tailored to suit local conditions. Sampling media may include stream sediments, eskers, basal tills, soils or deflation surfaces (loaming). Atkinson (1989) discusses in some detail sampling techniques (including sample size, sample spacing, etc.) and the relative size of indicator mineral dispersion haloes under various climatic conditions.

In certain areas, the surface morphology of indicator mineral grains (e.g., degree of abrasion, roundness, presence of kelyphite on garnets, etc.) can be used to estimate the distance from source. Grain size, as well as the number present, when normalized to

a constant sample weight, can also be useful (Jennings, 1990; Lee, 1993). Consistency in processing samples and careful consideration of all potential factors which could influence results (e.g., nature of sample site, local geomorphologic features, etc.) need to be taken into account in order to obtain useful and meaningful information (Afanasev et al., 1984).

If indicator minerals are coarse grained and plentiful, a primary concentration of samples may be carried out in the field using panning and/or jigging techniques. However, the more common practice is to dispatch samples to a laboratory for processing. Gregory and White (1989) describe modern laboratory processing methodology, which routinely makes use of a combination of gravity and heavy liquid concentrating techniques, followed by electromagnetic separations to produce a series of heavy mineral concentrate fractions. Alkali fusion and/or acid digestion procedures may be used to recover microdiamonds in some cases. The concentrates are assessed for the presence of indicator minerals and some minerals may be selected for microprobe analysis.

In any program, a detailed orientation survey is essential to determine the sampling procedures best suited to the area. Jennings (1990) documents the problems associated with tracking heavy mineral trains in glaciated terrains in Canada, where a suite of heavy minerals may be transferred from one till to many younger tills. In such conditions, a thorough knowledge of the glacial history of the region is required to successfully interpret and follow indicator mineral trains. Providing these problems can be successfully dealt with, there is no doubt that the heavy mineral method will continue to be very important for locating kimberlites in Canada's cold climate because indicator minerals are not rapidly altered by chemical attack. This is the case in Siberia, where groups such as the Amakhinsky team have made routine use of heavy mineral trails to locate kimberlites with great success (e.g., Afanasev et al., 1984).

In Australia much of the geologically favorable cratonic area consists of old, flat, low-lying land surfaces that are extensively lateritised. Very few minerals survive the acid conditions associated with the formation of these oxidized surface deposits. Kimberlite tracking by heavy minerals is hindered by lack of bedrock outcrop and destruction of virtually all indicator minerals except chromite, which also occurs in the bedrock (greenstone belt ultramafics and associated greywackes). Contrasting with this, indicator minerals survive the development of, and work their way through, over 100 m of the shallow

lake, surficial and aeolian deposits of the Kalahari Formation in Botswana (Lee, 1993). Similarly, since heavy mineral trails have been successfully followed in places such as Upper Peninsula, Michigan, USA and the NWT, Canada, sampling for indicator minerals clearly has potential in Canada. A review of local case histories and orientation studies taking cognisance of the regional parameters is essential.

The major element geochemistry of indicator minerals

Indicator minerals permit an assessment of the diamond potential of their source. This is routinely applied in exploration programs, based on the interpretation of the composition of indicator minerals. The criteria used vary widely and may be regionally dependent. Most of the screening mechanisms used to interpret the mineral compositions have been developed within exploration groups along independent lines, are considered to be classified information and have not been published.

In this study the indicator mineral distributions and compositions have been interpreted within the framework of a set of rules devised over the last 20 years by J.J. Gurney and modified for application to the project by R.O. Moore. The method was designed specifically for kimberlite occurrences in southern Africa, where it has been very successfully applied. It has been applied on other continents as well, including North America (e.g., Dummett et al., 1986; Carlson and Marsh, 1989). The authors of this report have successfully used the method at localities in Canada, such as the Northwest Territories for DiaMet/BHP; in Saskatchewan for Uranerz/Cameco, at Kirkland Lake; and for various diatremes near Golden, B.C.

It is stressed that this scheme is empirically derived and the localities constituting the orientation survey did not include lamproites. It has become apparent that the method is more difficult to apply to lamproites, not because the diamonds in lamproites are formed in different rocks or processes, but because fewer mantle macrocrysts are preserved on emplacement.

The model on which the evaluation method is based assumes that macrodiamonds are derived from peridotite and eclogite source rocks in the upper mantle which were sampled by the volcanic intrusive. The basis for this assumption is widely accepted and has already been discussed briefly. It is dealt with in considerably more detail by Gurney (1989), Gurney and Moore (1991a), and Kirkley et al. (1991).

Some diamonds contain mineral inclusions that can be clearly assigned to an eclogitic or peridotitic source, and a few are found in xenoliths of eclogite or, more rarely, peridotite. However, the unequivocal assignment of the paragenesis of most diamonds is not possible because they are recovered as single crystals that are devoid of any definitive inclusions. It is assumed that these diamonds have the same origins as the minority that can be defined. In support of this assumption, it is noted that on a worldwide basis more than 98% of the syngenetic inclusions reported from diamonds can be confidently assigned to the peridotitic and eclogitic paragenesis. No other major source has been identified. There is nothing that otherwise distinguishes the identifiable eclogitic or peridotitic diamonds from the balance of the diamond population at any particular source. Therefore, this vital assumption about the true source rocks for diamonds is considered justified (Gurney and Moore, 1991a).

The diamond grade of a particular diatreme will depend on factors such as:

- (a) how much diamond-bearing peridotite and eclogite are present,
- (b) what the diamond grade of the source rocks were, and
- (c) how well the diamonds were preserved during transportation to the surface.

The amount of diamond peridotite or diamond eclogite that has been sampled should be reflected in the amount of disaggregated mineral grains and/or xenoliths (disaggregated from those sources) present in the diatreme. If these can be identified, it should be possible to forecast whether diamonds could be present or not. Identification of garnets and chromites that have specific compositions has turned out to be a useful diamond indicator (e.g., Gurney, 1984, 1989). However, any forecasting of the diamond content of a rock that is in the mantle and cannot be directly sampled is impossible, so that variations in the grade of the source rock cannot be quantified in any rigorous way. The best available information is based on the diamond content of small xenoliths (e.g., Helmstaedt, 1992).

A fundamental requirement when using indicator minerals in prospecting is to be able to identify fragments of diamond-bearing rocks. This means discriminating between them and other rocks, including non-diamond bearing peridotites and eclogites, of which there are a large variety (Table 5; Fig. 8). Fortunately, diamond indicator minerals

usually can be identified by certain compositional parameters. This can be achieved in various ways. Cluster and multiple component discriminant analysis of compositions are widely used on databases of indicator mineral analyses. For instance, Dawson and Stephens (1975) classified kimberlite garnets into 12 groups by cluster analysis in an attempt to clarify source rocks for garnet macrocrysts. Danchin and Wyatt (1979) identified 52 groups within a much larger database, and Jago and Mitchell (1989) advocate a classification technique that combines cluster and discriminant analysis. However, the essential discriminating criteria come down to a few simple facts, and graphical methods are perfectly adequate, more illustrative and hence easier to understand and present.

The greater the abundance of macrocrysts from disaggregated, potentially diamondiferous source rocks in a diatreme, the better the grade of that diatreme may be. There are, however, exceptions to this general rule as must be expected considering the number of unknown factors involved, and the method is certainly not infallible.

Peridotitic paragenesis

In the peridotitic diamond paragenesis three sub-groupings of rocks are recognized as potentially diamondiferous sources: garnet harzburgite, chromite harzburgite and garnet lherzolite (definitions in Table 5). The harzburgites are depleted in calcium relative to the lherzolites, and this is reflected by the absence of diopside and the low content of calcium in their garnets. As with most classification schemes, there is overlap between categories. For instance, chromite and garnet can occur in the same harzburgite, and chromite can be present in a lherzolite. Other features are, however, incompatible; for example, a sub-calcic garnet cannot be in equilibrium with diopside and is therefore never found in a lherzolite. Because the calcium content of a calcium-saturated garnet is pressure dependent, care must be exercised in recognizing what constitutes a sub-calcic garnet.

Garnet

It has been suggested that the relative importance of peridotitic xenoliths with respect to diamonds is garnet harzburgite > chromite harzburgite > garnet lherzolite (Gurney, 1984). Garnet lherzolite is not a major component of a diamond inclusion suite at any locality yet described. This is fortunate, since garnet lherzolite is the most common mantle xenolith found in

kimberlite, and major element compositions cannot readily differentiate between a diamond-bearing and a barren garnet lherzolite (Gurney, 1985, for more detailed discussion). Therefore, garnets of lherzolitic composition have to be discriminated against in an exploration program or in evaluating the diamond potential of a diatreme. If additional information can be obtained about their source rocks, it can be demonstrated which of them formed in the diamond stability field. The newly developed Ni-thermometer of Griffin et al. (1989) may be of use in this regard (see subsequent section for further details), as may the presence of trace levels of K_2O in clinopyroxene, in some cases.

The component of diamonds derived from garnet harzburgite is assessed by considering both the number of sub-calcic garnets found in a diatreme and their degree of calcium depletion. These garnets are referred to as G10 garnets in this text and associated figures, whilst lherzolitic garnets are referred to as G9. The G10 field is indicated in Figure 13 (and all subsequent peridotitic garnet plots). Eighty-five percent of known Cr-pyrope diamond inclusion compositions plot on the Ca-poor side of the inclined line (as defined by Gurney, 1984). It has become the norm therefore to refer to this line as the 85% line. However, it was not defined on that basis. It was originally drawn to eliminate all garnets from known garnet lherzolites from the G10 calcium depleted side of the line. The calcium saturation level in a garnet from a garnet

lherzolite varies, with the lowest calcium values being found in the garnets from lherzolites with the highest equilibration pressures, such as the two diamond-bearing garnet lherzolites found by Shee et al. (1982) at the Finsch locality. A database of garnet compositions from southern African xenoliths was plotted on a CaO vs Cr_2O_3 graph and a line drawn to discriminate all lherzolites from the sub-calcic G10 field. The term "lherzolite line" was rejected, however, on the grounds that a "lherzolite line" depends on pressure and that no single line exists which fits that name. It was observed that 85% of the garnet inclusions in peridotitic diamonds analyzed at that time fell in the sub-calcic field and the non-genetic term "85% line" was first proposed.

In practice, very high pressure lherzolite garnets could plot with the sub-calcic G10 field. At lower pressures, lherzolite garnets plot well into the G9 field. In such circumstances, some harzburgitic garnets plot in the calcic G9 field. However, it has been empirically noted that peridotitic garnet suites from diamond-bearing kimberlites always have garnets that plot in the sub-calcic field. In poorly mineralized localities, such garnets will plot close to the line and be rare, whilst more abundant, more sub-calcic garnets are found in better mineralized occurrences. The 85% line could therefore equally well be called the diamond in line and is perhaps best thought of as such. All diamond-bearing kimberlites known to the authors contain garnets that plot in the sub-calcic field.

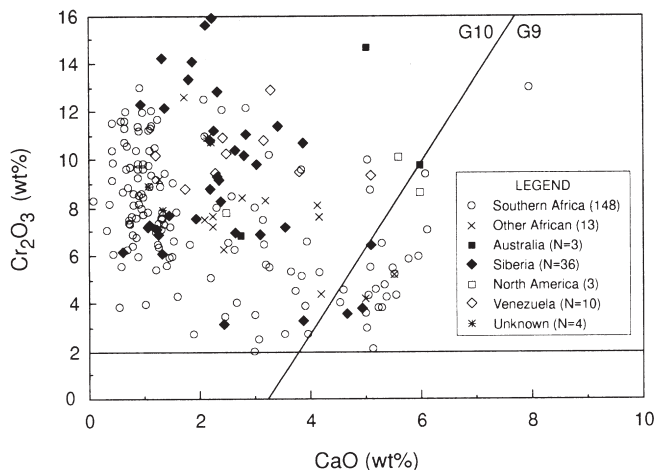


Figure 13. Cr_2O_3 -CaO plots for peridotitic garnet inclusions in diamonds from worldwide localities. Eighty-five percent of the garnets plot on the CaO-poor side of the inclined line which was defined by Gurney (1984). These subcalcic compositions are referred to as G10 garnets. The horizontal line drawn at 2 wt% Cr_2O_3 is used as an arbitrary division between eclogitic garnets below the line and peridotitic garnets above it.

The horizontal line drawn at 2 wt% Cr_2O_3 is to discriminate between peridotitic (Cr-rich) and Cr-poor garnets which are probably eclogitic or megacrystic. This is not strictly in accord with the original Dawson and Stephens (1975) classification but has been found to be readily applicable in prospecting.

Chromite

Chromite is used in a similar manner to garnet to provide an indication of the amount of diamonds in diatremes derived from disaggregated chromite harzburgite. The field of compositions shown in Figure 14 includes 98% of the known analyses. Chromites associated with diamonds have a high average chrome content (>60 wt% Cr_2O_3) together with moderate to high levels of magnesium (~12-16 wt% MgO). They are characterised by very low contents of titanium, usually less than 0.3 wt% TiO_2 , but which in rare cases exceed 0.6 wt% TiO_2 . The chrome content of macrocryst chromites is the most critical indicator of diamond potential from this source and is pressure dependent (Daniels, 1991).

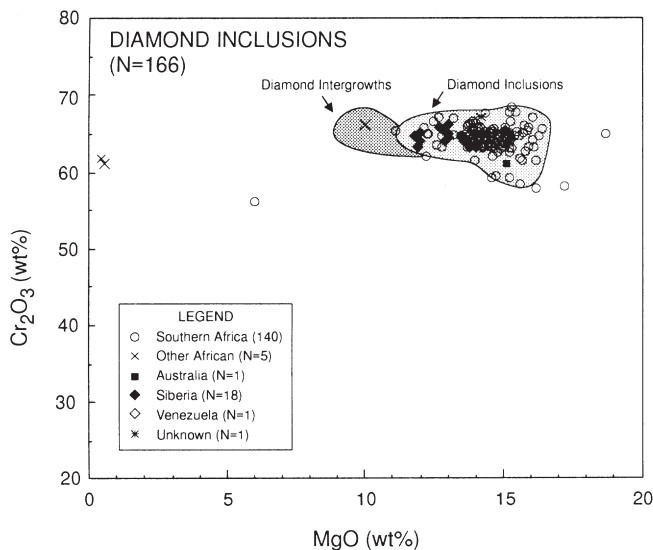


Figure 14. *MgO–Cr₂O₃ plots for chromite inclusions in diamonds from worldwide localities. Note the highly restricted, chrome-rich character of the inclusions. The preferred compositional field indicated includes >98% of the data points.*

Mantle-derived chromites show a wide variation in both major and minor element concentrations. Recent research has demonstrated that several sub-populations of chromite may be present in the xenocryst suite recovered from any one diatreme (Griffin and Ryan, 1992). These may represent:

- (a) macrocrysts derived from a wide range of source rocks (e.g., dunites, harzburgites, lherzolites, pyroxenites, etc.) which have been sampled from diverse regions of the upper mantle both within the diamond stability field and from shallower levels;
- (b) magmatic (phenocryst) chromites; and
- (c) xenocrysts which have reacted with the host volcanic rock.

It is important that an attempt is made to recognize as accurately as possible which of the above chromite types are present in the dataset under consideration, before proceeding with an assessment of diamond potential. Further details on potential methodologies to achieve this are provided in a subsequent section (see section, Trace element techniques).

For exploration purposes, three compositional types of chromites are recognized as important (Fipke, 1991). These include chromites of diamond inclusion and intergrowth compositions, or DI chromites, and high-content chrome-titanium, or Cr-Ti, chromites. The former group plot within the field of high MgO and high Cr₂O₃ compositions characteristic of

chromites included or intergrown with diamond (Fig. 15). DI chromites generally contain <0.6 TiO₂ wt% whilst Cr-Ti chromites contain >0.8 wt% TiO₂ and plot within the high Cr-Ti field characteristic of lamproites and kimberlites.

The remaining chromites present in the CF Mineral database of 1348 kimberlite and lamproite chromite analyses generally contain relatively low Cr and high Al, and/or Fe. These Al/Fe chromites plot within the overlap or mixed field of Figures 16a-c, along with chromites from alkali basalt, alnoite, and other igneous rocks of relatively shallow derivation.

The ranges in major element concentrations of these three types of chromites, based on the aforementioned database and including a further 216 compositions of chromites intergrown with or as inclusions within diamonds, is summarized in Table 15a.

Figures 15g-k illustrate that out of a database of 1006 chromite compositions from rock types other than kimberlites and lamproites, nine grains (i.e., <1%) plot in the Cr₂O₃-MgO compositional field characteristic of chromites from inclusions and intergrowths. These include four chromites from ophiolites (Cyprus and Australia), four from alpine and layered ultramafics, and one from a basic volcanic (Guinea). A comparison of the Cr₂O₃-TiO₂ characteristics of chromites from lamproites and diamondiferous kimberlites with the chromites from non-kimberlite and non-lamproite sources is illustrated in Figure 16. One hundred and ninety out of 756 lamproite chromites (25%) plot within the field unique to kimberlites and lamproites. No chromites from sources other than kimberlite or lamproite have been identified to plot within this unique field (Figs. 16a, b). However, in geologically rare instances, such as at Lashaine in Tanzania where basic and carbonatitic volcanic magmas are considered to have intruded kimberlite (Nielson 1989), all types of diamond indicator minerals may occur as wall rock contaminants in volcanics of shallow derivation. Nevertheless, the detection of high Cr-Ti chromites (similar to those in Fig. 16) in regional stream sediment sampling programs will be useful for identifying the presence of a kimberlite or lamproite source, even if abundant chromites from other sources are present.

The physical characteristics of chromites can be distinctive (Fipke, 1991). Chromites from diamondiferous lamproites occur as rounded to spherical and disc-shaped forms (Plate 1), exhibiting regular, polycentric stepped development and resorption sculpturing of octahedral cleavage faces (Plate 5). Modified octahedrons that exhibit grey resorption frosting are also present to a minor extent (Plate 1).

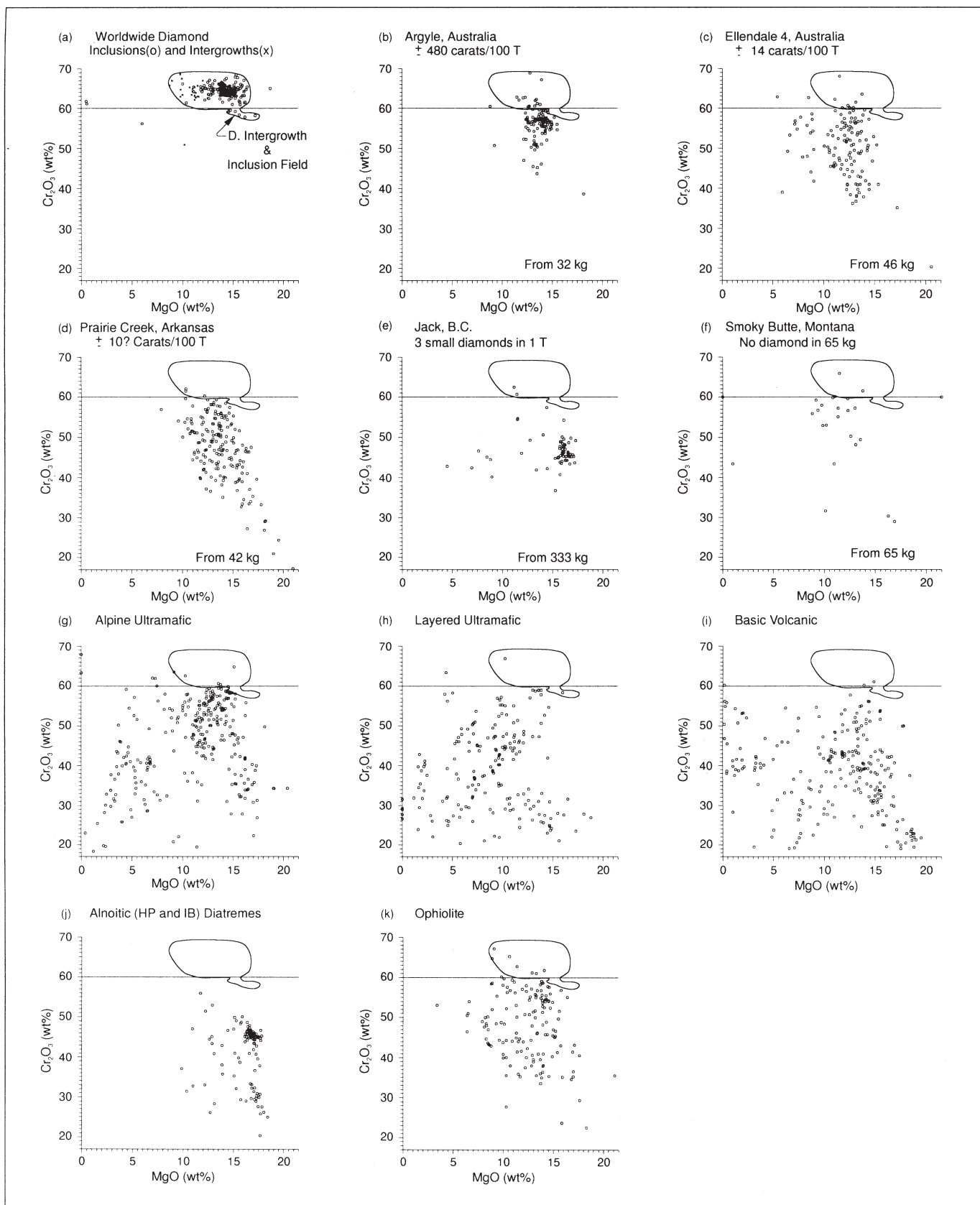


Figure 15(a-k). Cr_2O_3 -MgO plots for chromites from lamproite sources.

Table 15a

Typical compositional ranges of chromites

	DI chromites	Cr-Ti chromites	Al/Fe chromites
Cr ₂ O ₃	57.8–69.0	36.3–63.66	17.2–60.8
MgO	8.7–18.7	6.4–16.8	0–21.0
TiO ₂	< 0.6	0.8–8.7	< 5.3
Al ₂ O ₃	1.9–14.0	0.57–16.8	3.8–50.0
FeO*	9.3–20.0	13.7–30.2	8.7–50.0
MnO	< 1.0	< 1.6	< 1.9

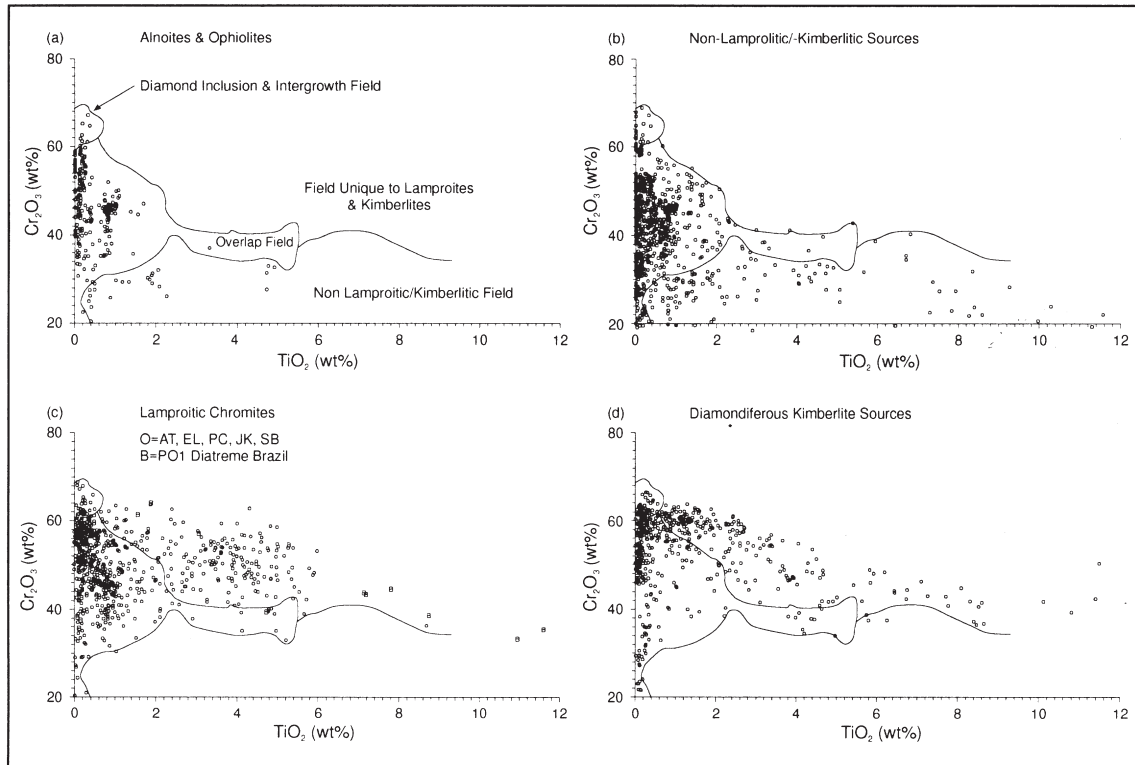


Figure 16(a-d). Comparison of Cr₂O₃-TiO₂ plots of chromites from lamproites and kimberlites with chromites from non-diatreme sources. Data from 1006 analyses.

Less commonly, chromites of both morphological types exhibit brilliant, unresorbed, unaltered, black metallic surficial lustre as do other insulated or broken surfaces (Plate 1). In some cases, broken surfaces exhibit a brown translucence along thin edges. Recognition of diatreme chromites on the basis of their physical attributes is a useful supplementary aid to the geochemical classifications discussed previously.

Eclogitic paragenesis

Studies of eclogite xenoliths entrained in kimberlite have distinguished two distinct varieties: Group I

eclogites are texturally and chemically homogeneous and usually contain measurable enrichments of sodium in garnet, and potassium in clinopyroxene (McCandless and Gurney, 1989); Group II eclogites, on the other hand, do not show these enrichments. Diamonds are found only in association with Group I eclogites, and the most diagnostic chemical parameter for the recognition of diamond potential, based on empirical evidence, is the presence of trace enrichments of sodium in the garnets. This is commonly accompanied by moderate to high levels of TiO₂ (Danchin and Wyatt, 1979). Figure 17 is a plot of TiO₂-Na₂O for eclogitic garnet in diamond inclusions, with examples from around the world.

Figures 17 and 18 illustrate that garnet inclusions in eclogitic diamonds show a range in sodium concentrations from 0.06 to 0.7 wt% Na₂O. A noteworthy feature illustrated in Figure 17 is that the garnet inclusions recovered from Argyle and Ellendale eclogitic diamonds have significantly higher sodium contents compared to other known inclusions.

Sodium content equal to or greater than 0.07 wt% Na₂O is considered to indicate equilibration at pressures high enough to be compatible with the presence of diamond (Gurney, 1984). It is important to note that megacryst garnets also show enrichment in sodium and titanium and overlap with eclogitic garnets in many other respects. However, usually they can be discriminated from each other by the use of a combination of geochemical parameters such as their TiO₂, CaO, MgO and FeO content.

The eclogitic host rocks vary widely in diamond content. Huge disparities in diamond content have been noted even within different portions of the same xenolith (e.g., Hatton and Gurney, 1979). Robinson et al. (1984) estimate the average diamond content of diamond-bearing eclogite to be at least 0.1%. Based on this figure, they calculated that the entire diamond content of the Orapa kimberlite (~0.2 ppm) can be obtained by the incorporation of as little as one part of diamond-eclogite per 5000 parts of kimberlite. Similar calculations have been presented by Helmstaedt (1992).

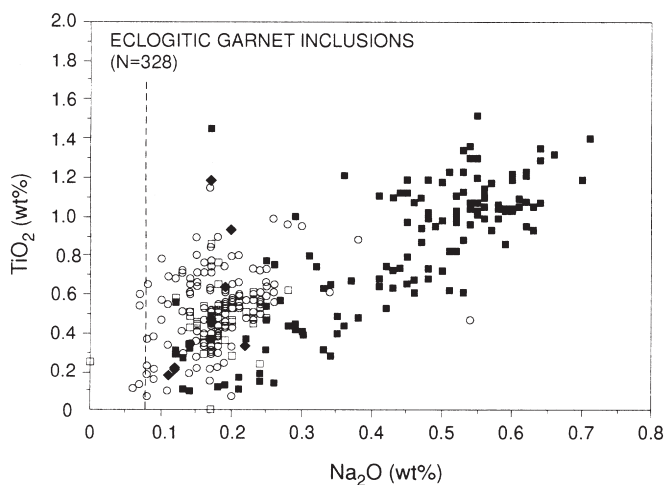


Figure 17. TiO₂-Na₂O plots for garnet inclusions in eclogitic diamonds from worldwide localities. For exploration evaluations, garnets with Na₂O > 0.07 wt% are considered significant. Inclusion data plotted includes: southern Africa-149; Australia-134; Siberia-9; North America-36. Symbols as for Figures 13 and 14.

Overall assessment of diamond grade

The contribution to the overall diamond population from peridotite and eclogite paragenesis is forecast by establishing the abundance of the garnets and chromites derived from the disaggregation of the mantle host-rock. These diamond sources are additive, and a significant contribution from any one of them could be sufficient to provide an economic grade in a diatreme. Both peridotitic and eclogitic diamond components are always present in diamondiferous diatremes. Either can predominate. It is necessary to establish both the compositions of the indicator minerals and their relative abundances if anything more than the simple presence of diamonds is to be assessed.

Diamond preservation

Having sampled a diamondiferous rock or rocks in the mantle, the magma must carry the mantle sample to the surface. Conditions within the magma en route upwards must at some stage be outside the diamond stability field, and providing the kinetics of the reactions are sufficiently rapid, diamond may be converted to graphite, or more frequently to CO₂ (Eggler, 1989). The rate will be controlled in part by the oxygen fugacity of the magma. The effect of this resorption on the diamond content of an intrusion can be large (Robinson et al., 1989). In the model developed for southern Africa, it appears that ilmenite compositions may give some measure of these redox conditions (Gurney and Moore, 1991). Ilmenite suites with low Fe³⁺/Fe²⁺ ratios are associated with better diamond preservation than those with higher ratios. In ilmenites from kimberlites, highly oxidizing conditions are associated with low MgO. High Cr³⁺ can be found in either association. Droop (1987) has reviewed techniques for computing Fe³⁺/Fe²⁺ ratios from electron microprobe data.

In this study we rate the overall diamond compositional characteristics of the ilmenites from each locality investigated and forecast a diamond preservation potential (DPP). This figure represents an estimate of the percentage of the original diamond population sampled by the kimberlite which will survive the intrusion event. This empirical prediction is based on a comparison with other localities world-wide in the database of Gurney and Moore and does not have a quantitative theoretical basis. Of course, the preservation index can only be applied meaningfully to diamondiferous pipes.

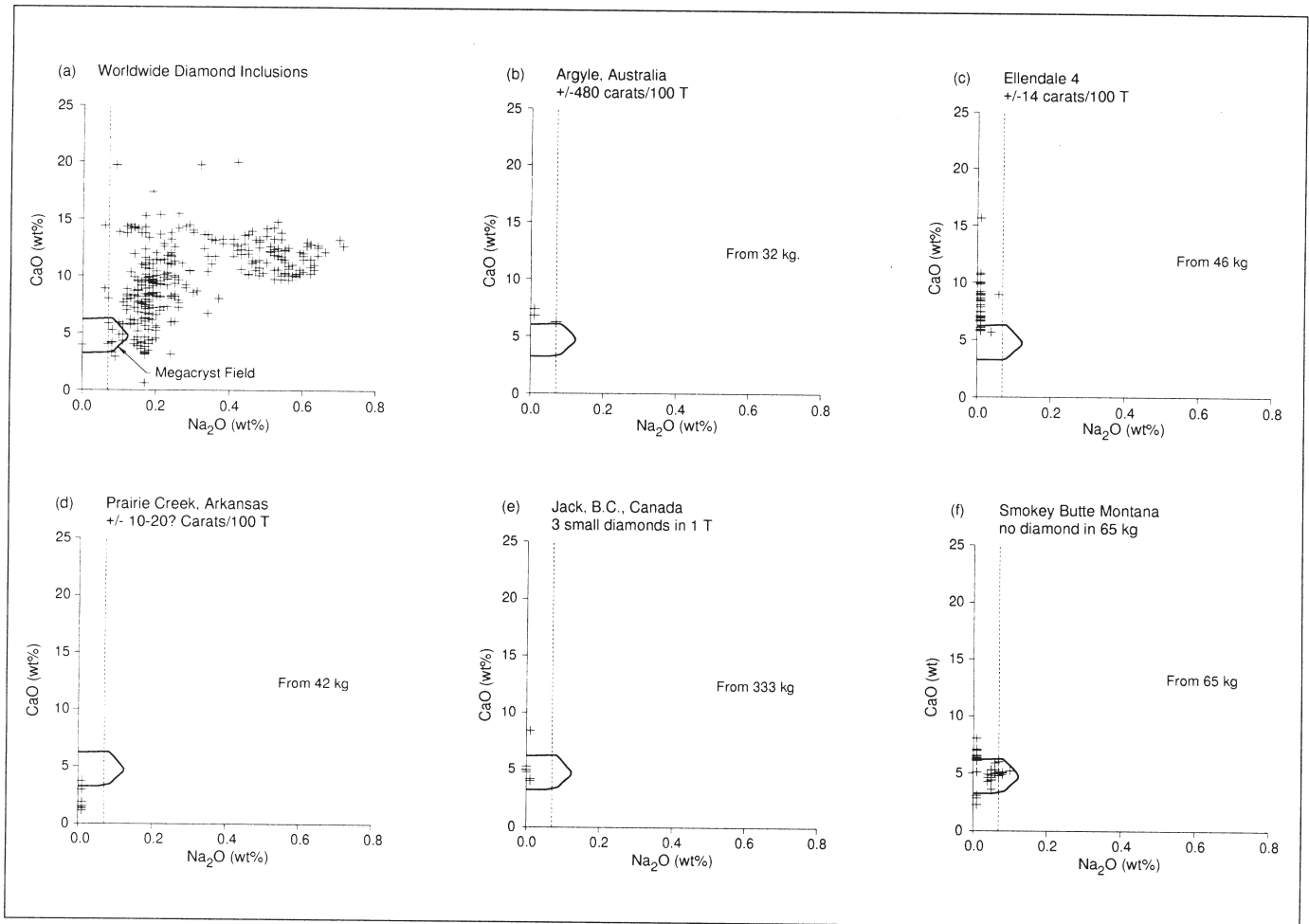


Figure 18(a-f). CaO-Na₂O plots for Cr-poor garnets from lamproites and inclusions in diamonds.

Reliability of the technique

A final question is how much reliance to place on diamond potential forecasts based on the geochemistry of indicator minerals. The method is not infallible. The kimberlites in the Kuruman area, South Africa, and results from Bulljah (an ultramafic lamprophyre) and Argyle in Australia are examples where the method does not work. However, the system is a major aid to exploration programs as well as the evaluating of the diamond potential of known kimberlites. In Botswana, where it was applied to several tens of kimberlites discovered under the Kalahari desert in the early 1980s, the heavy mineral analyses correctly identified all the barren kimberlites, as well as all the diamond-bearing kimberlites, and identified the best ore-bearing body (GO25) immediately after the first batch of heavy minerals from that source were analyzed. In this environment of hidden ore bodies, it was an unqualified success (Lee, 1993).

In a 1975 stream sampling program in Venezuela, the presence of G10 garnets from a nearby diamond source was noted in the Guaniamo region, where the primary source of some of the alluvial diamonds has now been found (Nixon et al., 1989). In Swaziland an earlier program used similar analyses to demonstrate the proximity of a then unknown primary source (the Dokolwayo kimberlite) to the Hlane alluvial diamonds. Accurate forecasts about the presence or absence of diamonds also have been made for Brazilian kimberlites and for numerous localities in southern Africa (both barren and diamond-bearing), and these data now constitute the database mentioned earlier. The indicator mineral method has been successfully applied in the Banankoro region in Guinea, west Africa. In the USA, it was used to assess the Georges Creek dyke in the Colorado/Wyoming State Line District (Carlson and Marsh, 1989), provided acceptable forecasts for the nearby Schaffer and Sloan 2/5 diatremes and predicted the absence of diamonds

at Iron Mountain. The assessment of heavy minerals in the kimberlites of Upper Peninsula, Michigan, again is in general accord with the known facts of the area (McGee and Hearn, 1984).

A more recent spectacular success of the use of the geochemistry of indicator minerals has been the discovery of diamondiferous kimberlites in the Northwest Territories. The first discovery, that of Point Lake by the DiaMet/BHP joint venture, was the culmination of over ten years of tracing indicator mineral trains eastwards, after early reports on their mineral chemistry had shown them to be extremely favorable for diamond potential. In 1978, a joint venture was formed between C.F. Mineral Research Ltd, Superior Oil, and Falconbridge Minerals to explore for various commodities in Western Canada, including diamonds. During July 1981, at the encouragement of Hugo Dummett of Superior Oil, C. Fipke and S. Blusson collected several samples in an area near Blackwater Lake on the Mackenzie River. These samples were found to include mantle minerals which had compositions similar to diamond inclusion compositions, which encouraged further exploration for their source. This search spanned ten years, co-ordinated throughout that period by C. Fipke, with various partners after Superior Oil and Falconbridge abandoned their participation in the exploration program. In 1984 DiaMet was formed, and funded the project between 1985 and 1990. In a report by Minerale Dienste, authored by John J. Gurney and Rory O. Moore, to DiaMet in May of 1990, highly diamondiferous kimberlite was predicted to be the source of minerals in samples submitted for study (Plate 2). Assessing samples submitted from the "GLDT claims", an unspecified area in DiaMet's NWT land holdings, a report that included the figures reproduced here as Figures 19 to 22 was compiled. The data indicated a very high potential for peridotitic diamonds from chromite harzburgite and garnet harzburgite sources (Figs. 19, 20), Group I eclogite sources (Fig. 21), and ilmenite compositions (Fig. 22) consistent with high potential for diamond preservation. In concluding that report, the authors predicted the following about the overall diamond potential of the area: "The indicator mineral compositions from the GLDT claims leave no doubt that a very positive potential for the presence of both peridotitic and eclogitic diamonds exists in the area. In both parageneses large numbers of grains show exceptionally favourable compositional characteristics which are consistent with high diamond grades. The GLDT dataset represents the best for diamond potential that we have seen anywhere in the world and we have no doubt that highly diamondiferous kimberlite is the source of the heavy minerals." Point

Lake discovery was identified by drilling in 1991, and a bulk sampling program in 1992 provided a grade estimate of 68 cts/100 tonnes. Subsequently, several other kimberlites within the main claim block with grade estimates of up to 330 cts/100 tonnes have been announced by the DiaMet/BHP joint venture. Plate 2 shows a suite of typical indicator minerals recovered from the DiaMet/BHP claim and classified by CF Mineral Research Laboratory.

Similar forecasting is now routinely applied in the DiaMet/BHP diamond exploration program in the NWT of Canada, with 39 diamondiferous kimberlites confirmed to date.

The authors have found heavy mineral indicators to be a valuable and universally applicable aid to assessing the potential of a possible diamond source. The fact that the diamonds are being traced by association with fragments of the mantle rocks from which they have been originally released by disaggregation is such a fundamental association that, whatever geological vehicle has been used to convey them to the surface, the relationship may hold. Where it does not, further geochemical detective work may reveal an explanation. The diamonds may not have been preserved en route to the surface; the lithosphere may not have been thick enough, or the geothermal gradient low enough to permit formation and/or storage of diamonds. The apparently necessary metasomatic activity that may have a particularly important role in the formation of peridotitic diamonds may never have occurred, and/or a suitable carbon source may therefore not have been available. Subsequent younger metasomatism may have altered the redox state of the lithospheric mantle leading to partial or even complete diamond resorption. Clues to these facts may be available, some of them in the major and trace element content of other mantle minerals that occur in the diatreme under investigation. Given the wide range of uncertainties, a balanced view has to be permissive of exceptions to the empirical rules, since these are certain to occur.

Helmstaedt and Gurney (1994) have shown the evaluation of the geotectonic evolution of a prospective area to be a critical step in any diamond exploration program. They have introduced the concept of "mantle root friendly" and "mantle root destructive" processes and have recognized cratonic areas where these parameters can be assessed by either geophysical or geochemical means, sometimes both. It is clear from this study that it is not sufficient to identify a suitable cratonic area en bloc as suitable prospecting terrain. Cratons, having been accreted in a series of ancient events, may have important sub-domains within them

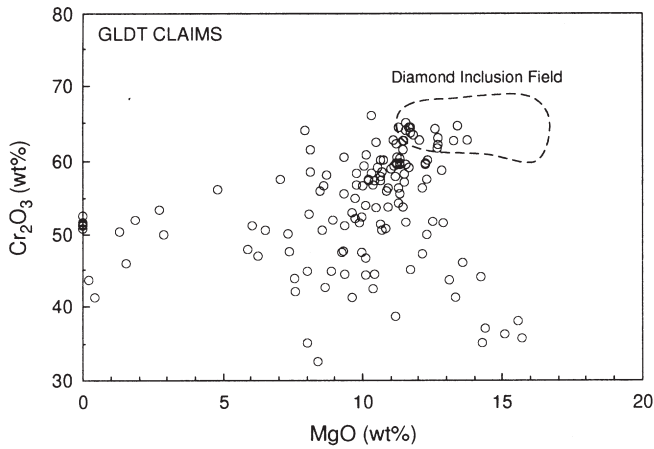


Figure 19. Chromites composition plot. Reproduced from Minerale Dienste "GLDT" report on claims in DiaMet's property block, N.W.T., 1990. (see text)

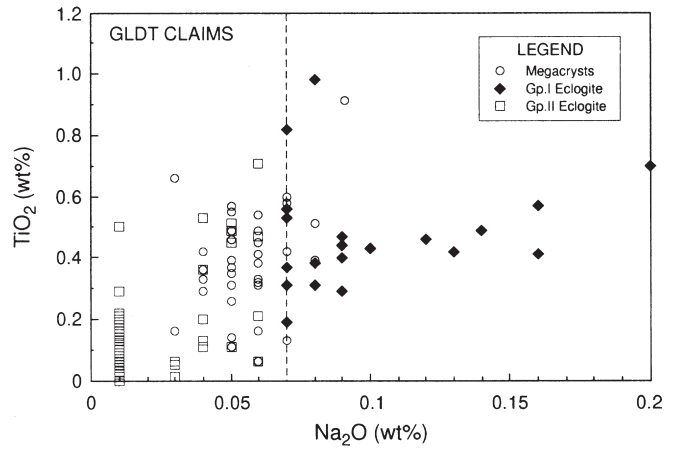


Figure 21. Low-Cr garnet composition plot. Reproduced from Minerale Dienste "GLDT" report on claims in DiaMet's property block, N.W.T., 1990. (see text)

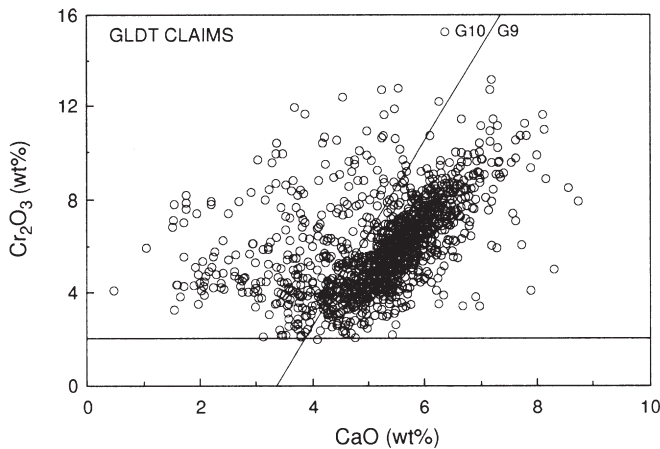


Figure 20. Peridotitic garnet composition plot. Reproduced from Minerale Dienste "GLDT" report on claims in DiaMet's property block, N.W.T., 1990. (see text)

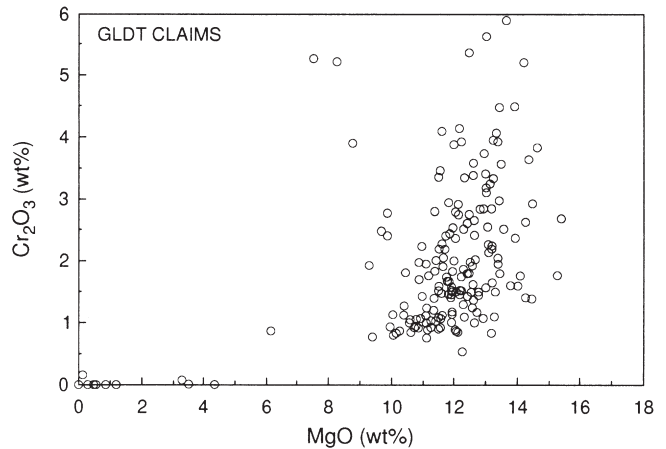


Figure 22. Ilmenite composition plot. Reproduced from Minerale Dienste "GLDT" report on claims in DiaMet's property block, N.W.T., 1990. (see text)

that need to be recognized. The mineral compositions identified as being important for diamond exploration are essentially the chemical fingerprints of deep, cool lithospheric mantle roots.

However, G10 garnets can be produced in environments other than deep, cool keels of continents (Boyd and Nixon, 1989). They can occur also in continental keels that are too hot and thin to contain diamonds (Shee et al., 1989). Clues to these exceptions can be obtained from the calcium and aluminium contents of orthopyroxenes, the Ca/(Ca+Mg) ratios of clinopyroxenes, or by the application of the Ni-thermometer of Griffin et al. (1989) to selected peridotitic garnets.

In general, the target with the best sub-calcic garnets, the highest chrome chromites, the biggest population of high sodium eclogitic garnets and the most magnesian ilmenites should be accorded highest priority in an exploration program. Equally it is so unlikely that any mantle derived rock will retain abundant diamonds and absolutely no trace of the original diamond host rocks, that to pursue any target that is forecast to be barren is to pursue the least potential target. However, Argyle is an exception which demonstrates that even these low rank potential targets may warrant pursuit.

Trace element techniques

The Ni-thermometer

A relatively new technique for assessing the diamond potential of diatremes from the composition of Cr-pyrope garnets has been proposed by Griffin (Griffin et al., 1989, 1991) who demonstrated that under upper mantle conditions, the partitioning of Ni between garnet and olivine is strongly temperature-dependent. From this relationship the "Ni-thermometer" was calibrated, enabling the estimation of equilibration temperatures from the Ni content of single Cr-pyrope garnet grains. Assuming a steady state geotherm of 40 mW/m² and based on xenolith and diamond inclusion data, Griffin et al. (1989) proposed that garnets associated with diamond should yield Ni-temperatures in the range 950 to 1250°C.

When the Ni-thermometer is applied to garnet concentrates from kimberlites and lamproites, Griffin et al. (1991) demonstrated that in areas where a "cratonic" geotherm is applicable, diamond-rich kimberlites and lamproites contain high proportions of garnets with Ni-temperatures (T_{Ni}) in the "diamond window" (i.e., 950-1250°C), while diamond-poor diatremes contain a high proportion of garnets with $T_{Ni} < 950^\circ\text{C}$. These lower temperatures reflect the shallower regions of the mantle that have been sampled, where graphite rather than diamond is the stable form of carbon. Griffin et al. (1991) report that many of these low grade or barren pipes also contain abundant high-temperature garnets ($T_{Ni} > 1250^\circ\text{C}$). They interpret the presence of these garnets to be a negative factor for diamond potential because reaction with high temperature magmas either destroys the diamonds or prevents their formation.

The Ni-thermometer represents a potentially useful new tool both for research and diamond exploration. The equilibration temperatures derived by this method however have been demonstrated to need revision (Canil, 1994), and as yet there is no record to prove or disprove its general applicability.

Two fundamental problems with the technique are that it ignores the vagaries of the kimberlite sampling processes in the mantle and also fails to consider the parageneses of the garnets. Furthermore, the "diamond window", initially selected with hindsight provided by available information on the Kaapvaal Craton, is not universally applicable: for instance it appears to shift to lower values for Siberian diamond-bearing areas and to higher temperatures for the Limpopo mobile belt. Therefore, the conductive geotherm for the area under consideration needs to be

defined. Even when it is, various garnets with no necessary link to diamond genesis are certain to fall within the selected window. These may include garnets from coarse lherzolites, metasomatised lherzolites, high-T deformed peridotites, Matsoku-type websterites, wehrlites, pyroxenites, megacrysts, rare eclogitic garnets, and, of course, a few G10s from harzburgites. The overwhelming majority of these rocks have no relation to diamonds, and it is unreasonable to expect the garnets derived from them to convey any meaningful message about diamond content.

Unlike the previously described discriminants using the "85% line", this method fails to draw a consistent boundary between "diamondiferous" and "non-diamondiferous" sources. Rather the T_{Ni} distributions obtained from concentrate garnets provide an indication of the temperature range of the upper mantle which has been sampled by the diatreme. This can be useful in an area where the geothermal gradient is close to 40 mW/m² (e.g., southern Africa) because it gives an indication as to whether the diamond stability field has been sampled. However, paragenetic considerations and geothermal gradient variations, together with uncertainty regarding the calibration of the original geothermometer (Canil, 1994), mitigate against its utility as an independently reliable diamond exploration aid. Furthermore, the high precision Ni analyses require a proton microprobe. Since this is a highly sophisticated instrument, such analyses are not cheap. Considering that electron microprobe data may also be required in order to normalize the trace element analyses, this technique can become extremely expensive to use on a routine basis in exploration. This situation may change, however, and use of an ICP instrument should be considered.

As a supplementary aid the Ni-thermometer can provide valuable information. Selected grains can be analyzed for trace elements in order to verify that they equilibrated within the diamond stability field. Since garnet solubility in orthopyroxene is pressure dependent, orthopyroxene can be used to refine geothermal gradients in prospective areas where the Ni-thermometer is to be applied.

Chromite discriminants

Chromite is a particularly useful indicator mineral in areas where chemical weathering is prevalent because it is resistant to such processes. For example, it is commonly the only indicator mineral to survive the extensive laterite developed over much of Australia, and in such terrains it may be the only useful

pathfinder to a potential orebody. Some overlap occurs between the compositions of certain groupings of kimberlite spinels from other rock types, including greenstone terrains, ophiolite sequences, layered ultramafic and mafic igneous complexes, and associated harzburgitic and dunitic bodies. There is also a small amount of overlap between the compositions of Cr-rich chromites of diamond inclusion composition and chromites from non-diamondiferous sources. These problems are very relevant in Australia where chromites from komatiites and greenstone sequences abound.

A very brief outline of recent new techniques is provided here. For further details, the reader is referred to Griffin et al. (1991, 1992).

(a) The CART Statistical Classification System: CART (classification and regression trees) is a relatively new multivariate statistical technique which can be applied to the classification of indicator mineral compositions. In essence, the technique uses a preselected dataset to construct a classification tree which, once constructed, allows unknown samples (chromite analyses) to be classified in terms of simple variables. Specifically, this technique facilitates the discrimination of spinels derived from regional sources (no diamond potential) and diatreme sources (potentially diamondiferous) with a high degree of probability.

The technique is particularly applicable to the regional reconnaissance (target location) phase of diamond exploration, and its application is necessary only if the regional rocks have liberated spinels into the secondary environment, which could be confused with diatreme chromites.

(b) Zr-Nb Discriminant: Griffin et al. (1991) noted that chromites from kimberlites and lamproites commonly contain levels of Zr and/or Nb which are significantly greater than the minimum detection limit of the proton microprobe (i.e., >6 ppm). The proportion of grains showing these enrichments in a given diatreme may range from 10% to 90% and generally is highest in Group 2 kimberlites and lamproites. Analysis of the surface of rough grains is especially effective in using this criterion to recognize grains that have resided in alkaline ultramafic magmas. These elements are virtually always below detection limits in chromites from greenstone terrains and ophiolites (Griffin et al., op cit.).

The use of these discriminants is applicable only to the regional reconnaissance phase of a diamond

exploration program. Since not all diatreme chromites show enrichments in these two trace elements, results should be interpreted with caution.

(c) Zn-Ni Geothermometry: By applying the Ni-thermometer to garnet, Griffin et al. (1992) calculated the equilibration temperature for over 70 chromite-chrome pyrope pairs from xenoliths and concentrates from kimberlites in South Africa, Siberia and the USA. This calculation is based on the assumption that both minerals equilibrated with olivine. Results demonstrate that the Zn content of chromite shows a strong negative correlation with temperature, while Ni in chromites shows a weaker positive correlation with temperature. The Zn-T correlation is thought to reflect the temperature-dependent partitioning of Zn between olivine and spinel. Chromites with <700 ppm Zn and >600 ppm Ni are reported as being most likely formed within the diamond stability field.

Use of the Zn and Ni contents of macrocryst chromites to predict whether they crystallized within the diamond stability field may be a useful exploration aid. However, the method has similar shortcomings to the application of the Ni-thermometer for garnet. Specifically, it assumes that chromite was in equilibrium with olivine and garnet. Thus the original host paragenetic assemblage is critical. Variable geothermal gradients introduce further uncertainty. Finally, the empirical correlation between T and Zn_{chr} incorporates any error in the calibration of the original Ni-thermometer, as well as errors inherent in the zinc thermometer itself.

(d) Chromite Populations: Several populations of chromite may be present within any one kimberlite or lamproite pipe. However, the recognition of these populations is complicated by considerable overlap in compositions.

Griffin et al. (1992) demonstrated that sub-populations within diatreme chromite xenocrysts are a real and recognizable feature. In their classification scheme, the major and trace element compositions of chromites from lamproites, Group I and Group II (South African) kimberlite, diamond inclusion and garnet harzburgite and lherzolite sources have been plotted onto many trace and major element binary diagrams. The contoured results of Griffin et al. (1992) demonstrate that most chromite compositions from Group I chromite harzburgite sources plot in P1 field areas, most chromites from Group II kimberlites in P2 field areas, and most chromites from lamproites in P3

and P4 field areas (Table 15b). The recognition of these populations is important for two reasons:

(i) if possible, it is essential to identify xenocryst chromites which are relevant to the diamond potential of the diatreme (P1 chromites) and base assessments only on these. Incorrect assessments could easily be made for Group 2 kimberlites where P2 chromites (which are magmatic in origin and have nothing directly to do with diamond potential) are particularly abundant. Similarly, the P3 (magmatic) and P4 (low pressure macrocrysts) chromites in lamproites are not relevant to diamond potential.

(ii) the recognition of major chromite populations in samples potentially allows the identification of the source before it is found; e.g., the presence of abundant P3 and P4 population chromites in stream or loam samples would indicate the target to be a lamproite. If early signs such as this are correctly identified, exploration strategy could be refined to maximize the chances of success.

Unfortunately, the application of the Griffin et al. (1992) classification criteria to new data sets appears to have some practical problems. Specifically, many chromite compositions do not classify uniquely into one particular category, a problem noted in the results of an attempted classification for some chromites investigated in this study (Fipke, 1991).

INDICATOR MINERALS FROM LOCALITIES INVESTIGATED

Analytical results of indicator minerals have been assessed and interpreted with respect to diamond potential using the techniques discussed earlier. A full listing of minerals recovered is summarized in Table 16. To facilitate comparison between localities, the results for each of the four mineral species considered to be important diamond indicators (Cr-pyrope garnet, chromite, Cr-poor garnet and ilmenite) are discussed under separate headings. These separate forecasts are then reviewed as a unified assessment by locality, and the forecasts compared with known facts about each.

The indicator minerals recovered and analyzed from all diatremes investigated, together with compositions of diamond inclusion minerals from worldwide sources, also have been classified by methods adapted from those reported by Dawson and Stephens (1975) and Stephens and Dawson (1977). A summary of the abundances of indicator minerals and a breakdown of the various sub-categories of garnet and clinopyroxene

Table 15b
Characteristics of chromite populations identified by Griffin et al. (1992)

	P1	P2	P3	P4	XENOS	D.I.
Host rock	Gp. 1&2 kimberlites	Gp 2 kimberlites	Lamproites	Lamproites	Xenoliths	Diamonds
Paragenesis	Gp. 1&2 kimberlites	Magmatic	Magmatic	Lo-P macrocrysts	Harz + Lherz	Harzburgitic
Cr ₂ O ₃	55-65 wt%	53-60 wt%	38-55 wt%	42-55 wt%	50-65 wt%	> 60 wt%
TiO ₂	< 1	2-4 wt%	mostly < 1%	< 1 wt%	mostly < 1 wt%	mostly < 0.5 wt%
Al ₂ O ₃	5-11 wt%	bimodal: 7-9&2-4%	10-18 wt%	15-22 wt%	4-20 wt%	4-10 wt%
Fe ₂ O ₃	low	higher than P1	low to moderate	low to moderate	low	low
MgO	12-15 wt%	9-12 wt%	11-14 wt%	12-15 wt%	10-14 wt%	12-17 wt%
Ga	usually < 20 ppm	bimodal: av. > P1	50-70 ppm	20-40 ppm	mostly 10-60 ppm	10-40 ppm
Zn	500-700 ppm	500-700 ppm	200-600 ppm	800-1600 ppm	400-2000 ppm	200-700 ppm
Ni	600-1000 ppm	1000-1200 ppm	1000-1700 ppm	400-600 ppm	mostly 200-1000 ppm	500-1000 ppm

Table 16

Summary of indicator minerals recovered and analysed from the diatremes investigated

Locality	Chromite	Cr-pyrope garnet	Cr-poor garnet	Ilmenite	Cr-rich cpx	Cr-poor cpx
Argyle	113	3	55	21	4	18
Batty	41	45	26	18	18	6
Blackfoot	180	0	0	3	62	21
Cross	140	73	13	2	21	0
Hp	85	0	0	0	47	8
Ile Bizard	44	0	36	25	38	61
Jack	76	47	63	82	7	31
Joff	82	0	12	1	25	6
Kirkland Lake	128	138	7	82	65	19
Larry	190	0	11	0	0	2
Mark	66	0	24	0	0	1
Mike	114	0	0	0	1	0
Mountain	32	2	11	19	2	11
New Elands	119	127	18	6	42	1
Prairie Creek	198	18	79	41	130	52
Sturgeon Lake	48	69	36	40	19	0
Sloan	66	111	61	36	43	1
Sover	98	40	13	3	41	188

Notes: Peridotitic garnets defined as having 2 wt% Cr₂O₃; Cr-poor garnets <2 wt% Cr₂O₃; Cr-rich cpx 0.5 wt% Cr₂O₃; Cr-poor cpx <0.5 wt% Cr₂O₃.

cpx = clinopyroxene

recovered from these samples is compared with the figures for worldwide diamond inclusions in Table 17. Readers requiring a fuller consideration of the application of the Stephens and Dawson (1977) statistical classification are referred to Geological Survey of Canada (1989).

Cr-pyrope garnet

Cr-pyrope garnets were recovered from eleven of the localities investigated, but were not recovered from the Blackfoot, HP, Ile Bizard, Joff, Larry, Mark, Mike and Mountain diatremes. Additional data on the Jack sandy breccia (JKM) and Prairie Creek breccias (PC) derived from the Superior Oil database yielded further information on peridotitic garnets. The Superior data were obtained through processing rock samples in excess of 200 kg in size (Table 17).

In all cases, the G10 garnets recovered were round to broken grains that showed a wide range in color, from pale pinkish-purple through reddish-purple to deep-purple. It was not possible to distinguish these grains on the basis of color from other purple-colored G9 garnets present in the concentrates. Although pink, orange and red G10 garnets have been encountered in

kimberlites tested at the C.F.M. laboratory, bluish to greyish and lavender purple G10s are generally the dominant color. The characteristics of individual suites are plotted in Figure 23.

Peridotitic garnets (denoted "PG" in Table 17) are pyropes with >2 wt% Cr₂O₃ (2% is an arbitrary cutoff value that has proved to be a reasonably accurate and practical discriminant). Cr-poor garnets (denoted "EG" in Table 17) include all garnets with <2 wt% Cr₂O₃ and <25 wt% FeO. Both eclogitic and megacryst garnets are represented in this group. Regional garnets (denoted "RG" in Table 17) represent Mn-rich garnets and garnets with >25 wt% FeO. Such garnets are assumed to be derived from regional and deep crustal sources. In the Dawson and Stephens (1975) classification system, peridotitic garnets are represented in Groups G1, G2, G9, G10, G11 and G12 (Table 17).

Each of the two South African kimberlites, New Elands and Sover, yielded suites of Cr-pyrope with compositional characteristics highly favorable for diamond potential (Figs. 23a, b). In both cases a high proportion of the analyzed grains fall within the G10 2-D compositional field, and large numbers of these grains show extremely subcalcic compositions

Table 17

Indicator minerals recovered from diatreme rock samples compared with diamond inclusion minerals from worldwide sources¹

ID	DIA. Macro and Micro	Rock type	Orig. wt/kg Norm.	Zircon amt.	Tourmaline amt.	Chromite %Cr ₂ O ₃		Ilmenite		GARNETS								
						>60	60	PL	IL	CFM MODIFICATION OF DAWSON CLASS-								
										G1	G2	G3	G4	G5	G6	G7	G8	
										P&M	P&E	E&R			E	P	E	
AT	Vab	L	32	ab	mod	+13 21	+100 159	+8 13	+13 21	0 0	2 3	2 3	0 0	8 13	0 0	0 0	0 0	
EL4	mod	L	46	ab	Vab	8 9	+69 76	+3 3	+44 48	0 0	0 0	34 37	1 1	25 27	0 0	0 0	0 0	
JKM	tr	L	180	ab	ab	2 1	12 3	48 13	11 3	6 2	3 1	0 0	0 0	0 0	0 0	0 0	0 0	
JK2	tr	L	90	mod	mod	0 0	+21 12	2 1	13 7	1 1	0 0	1 1	0 0	3 2	0 0	0 0	0 0	
JK3	nil	L	63	min	min	0 0	+41 32	0 0	8 6	0 0	0 0	0 0	0 0	2 2	0 0	0 0	0 0	
PC64	min	L	21	ab	min	1 2	+116 272	5 12	4 9	0 0	0 0	1 2	0 0	40 94	0 0	0 0	0 0	
PC65	mod	L	21	ab	mod	2 5	+79 189	15 36	0 0	0 0	0 0	1 2	0 0	20 48	0 0	0 0	0 0	
SB	nil	L	65	tr	nil	3 2	20 16	+75 58	7 5	30 23	6 5	6 5	0 0	16 12	0 0	0 0	0 0	
SF1	nil	L	22	min	nil	0 0	32 73	4 9	1 2	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	
LRO	nil	PL	31.4	min	nil	0 0	+91 145	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	
LRD	nil	PL	45.9	tr	nil	0 0	+99 108	0 0	0 0	0 0	0 0	0 0	0 0	1 1	0 0	0 0	0 0	
MR	nil	PL	34	min	tr	0 0	+66 97	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	
MK	tr	PL	30.1	min	tr	0 0	+114 189	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	
PO1	nil	PL	16.7	min	min	1 3	16 48	40 120	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	
BT	tr	K	73.7	min	nil	2 1	39 26	+17 12	1 1	13 9	0 0	0 0	0 0	3 2	0 0	0 0	0 0	
CC	nil	K	62.5	tr	nil	1 1	+139 111	1 1	1 1	10 8	0 0	0 0	0 0	0 0	0 0	0 0	0 0	
JF	nil	K	64.3	min	tr	0 0	+82 64	0 0	1 1	0 0	0 0	1 1	0 0	0 0	0 0	0 0	0 0	
KL1	tr	K	23.2	min	nil	0 0	32 69	+28 60	0 0	1 2	0 0	5 11	0 0	0 0	0 0	0 0	0 0	
KL5	tr	K	4.7	tr	nil	3 32	+92 979	+54 574	0 0	1 11	2 21	1 11	0 0	1 11	0 0	0 0	0 0	
NE	ab	K	20.8	min	nil	40 96	+79 190	1 2	5 12	2 5	0 0	7 17	0 0	0 0	0 0	0 0	0 0	
SK	tr	K	36	min	min	1 1	47 65	+40 56	0 0	28 39	6 8	16 22	1 1	0 0	1 1	0 0	0 0	
SL	mod	K	44.2	min	nil	1 1	+65 74	+36 41	0 0	9 10	2 2	41 46	0 0	0 0	1 1	0 0	0 0	
SV	ab	K	9.5	tr	nil	+70 368	28 147	2 11	1 5	14 74	0 0	50 263	0 0	0 0	0 0	0 0	0 0	
BF	nil	AL	70.5	min	nil	0 0	+180 128	0 0	3 2	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	
HP	nil	AL	60.2	tr	nil	0 0	+85 71	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	
IB	nil	AL	65.2	tr	nil	0 0	44 34	+25 19	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	
MD	nil	OM	100	mod	nil	0 0	32 16	10 5	9 5	0 0	1 1	0 0	0 0	0 0	0 0	0 0	0 0	
DIAMOND INCLUSIONS:																		
South Africa						132	6	3	0	3	1	75	62	4	7	2	0	0
North America						1	0	2	2	0	0	28	5	3	0	0	0	0
Australia						1	0	0	1	1	0	6	93	0	34	0	0	0
USSR						8	0	1	0	3	0	6	4	0	0	0	0	0

¹Values normalized to 50 kg are shown under each result. Diamond Inclusion Compositions provided by Gurney and Moore, 1990.

Vab: very abundant, ab: abundant, mod: moderate, min: minor, tr: trace, L: lamproite, PL: possibly lamproite?, K: Kimberlite, AL: alkaline lamprophyre, OM: olivine melilitite, M: megacryst, E: eclogitic, P: peridotitic, R: regional, V: volcanic, C: clinopyroxene, +: additional unanalysed present, IL: Ilmenite, PL: picroilmenite.

Table 17 (cont'd.)

IFICATIONS				CLINOPYROXENES															
				MOORE CLASS			DAWSON										MOORE		CFM
							CP1	CP2	CP3	CP4	CP5	CP6	CP8	CP9	CP10	CE	CP	CV	
G9	G10	G11	G12	E	P	R	P&E			E	P		E						
0	0	1	0	3	3	49	1	2	0	0	0	0	0	0	0	0	18	4	2
0	0	2	0	5	5	78	2	3	0	0	0	0	0	0	0	0	29	6	3
16	8	6	0	54	+28	23	0	0	0	0	35	1	0	0	0	0	0	+37	+1
18	9	7	0	59	31	25	0	0	0	0	38	1	0	0	0	0	0	41	1
4	1	20	0	3	34	0	0	0	0	0	0	0	0	0	0	0	?	?	?
1	0	6	0	1	9	0	0	0	0	0	0	0	0	0	0	0	?	?	?
2	4	5	0	3	10	39	0	0	0	0	0	0	0	0	0	0	2	0	3
1	2	3	0	2	6	22	0	0	0	0	0	0	0	0	0	0	1	0	2
0	0	1	0	3	1	13	0	3	0	0	1	0	0	0	0	0	19	5	9
0	0	1	0	2	1	10	0	2	0	0	1	0	0	0	0	0	15	4	7
3	0	0	0	3	3	51	0	6	0	0	26	3	0	0	0	0	+1	+32	+6
7	0	0	0	7	7	120	0	14	0	0	61	7	0	0	0	0	2	75	14
0	0	0	1	6	1	23	1	7	1	0	36	1	0	0	0	0	+15	+37	+39
0	0	0	2	14	2	55	2	17	2	0	86	2	0	0	0	0	36	89	93
21	1	35	0	50	76	13	0	1	0	0	5	7	0	0	0	0	8	19	2
16	1	27	0	39	59	10	0	1	0	0	4	5	0	0	0	0	6	15	2
10	0	0	0	0	10	0	0	0	0	0	2	0	0	0	0	0	0	2	5
23	0	0	0	0	23	0	0	0	0	0	5	0	0	0	0	0	0	5	11
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	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	9	0	0	0	0	0	0	0	0	0	0	1	0	1
0	0	0	0	1	0	10	0	0	0	0	0	0	0	0	0	0	1	0	1
0	0	0	0	1	0	23	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	1	0	34	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0
0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	6	0	0
28	0	17	0	15	43	12	0	3	1	0	8	4	0	0	0	0	+5	+17	+1
19	0	12	0	10	29	8	0	2	1	0	5	3	0	0	0	0	3	12	1
43	3	30	0	16	+71	0	0	1	2	0	17	1	0	0	0	0	0	+7	+14
34	2	24	0	13	57	0	0	1	2	0	14	1	0	0	0	0	0	6	11
1	0	0	0	3	0	5	0	6	2	0	15	0	0	0	0	0	2	9	+20
1	0	0	0	2	0	4	0	5	2	0	12	0	0	0	0	0	2	7	16
14	7	17	0	5	+39	0	0	2	0	0	7	22	0	0	0	0	1	34	0
30	15	37	0	11	84	0	0	4	0	0	15	47	0	0	0	0	2	73	0
32	12	47	0	2	+98	0	0	8	1	1	16	3	0	0	0	0	13	29	1
340	128	500	0	21	0	0	0	85	11	11	170	32	0	0	0	0	138	309	11
26	77	30	3	1	+127	0	0	1	0	0	12	26	0	0	0	0	+1	+42	0
63	185	72	7	2	305	0	0	2	0	0	29	63	0	0	0	0	2	101	0
28	1	24	0	36	+68	0	0	0	0	0	16	1	0	0	0	0	0	+18	+1
39	1	33	0	50	94	0	0	0	0	0	22	1	0	0	0	0	0	25	1
22	11	80	0	57	+107	4	0	7	0	0	32	2	0	0	0	0	0	+42	0
25	12	90	0	64	121	5	0	8	0	0	36	2	0	0	0	0	0	48	0
26	33	4	0	87	+40	1	0	0	0	0	6	34	0	0	0	0	0	41	+1
137	174	21	0	458	211	5	0	0	0	0	32	179	0	0	0	0	0	216	5
0	0	0	0	0	0	0	0	3	9	0	52	2	0	0	0	0	1	8	+75
0	0	0	0	0	0	0	0	2	6	0	37	1	0	0	0	0	1	6	53
0	0	0	0	0	0	0	0	1	3	0	34	2	0	0	0	0	3	4	+49
0	0	0	0	0	0	0	0	1	2	0	28	2	0	0	0	0	2	3	41
36	0	0	0	0	36	0	0	11	7	8	11	1	0	0	0	0	+25	+28	+45
28	0	0	0	0	28	0	0	8	5	6	8	1	0	0	0	0	19	21	35
1	0	0	0	0	2	5	6	3	0	0	0	0	0	0	0	0	9	2	2
1	0	0	0	0	1	3	3	2	0	0	0	0	0	0	0	0	5	1	1
5	97	8	1	149	114	0	0	5	0	0	5	4	48	10	6	0	132	17	0
0	3	1	0	36	4	0	0	0	0	0	2	0	15	3	1	0	21	4	0
0	2	0	0	133	3	0	0	0	0	0	2	0	16	4	6	0	43	3	0
0	26	4	0	13	30	0	0	2	0	0	6	2	3	1	0	0	4	10	0

AT: Argyle Tuff, Aust.; EL4: Ellendale 4, Aust.; Jk: Jack, B.C., Can.; PC: Prairie Creek, Ark.; SB: Smoky Butte, Mont.; SF: Fortuna, Spain; LR: Larry, B.C., Can.; MR: Mark, B.C., Can.; Mk: Mike, B.C., Can.; PO: Presidente Olegario, Brazil; BT: Batty, N.W.T., Can.; CC: Crossing Creek, B.C., Can.; Jf: Joff, B.C., Can.; KL: Kirkland Lake, Ont., Can.; NE: New Elands, South Africa; SK: Sturgeon Lake, Sask., Can.; SV: Sover, South Africa; BF: Blackfoot, B.C., Can.; HP: HP, B.C., Can.; IB: Ile Bizard, Que., Can.; MD: Mountains Diatreme, N.W.T., Can. CE = Eclogitic clinopyroxenes. CP = Peridotitic clinopyroxenes. CV = Clinopyroxenes from regional volcanic sources.

(<2.5 wt% CaO) in combination with moderate to high chrome content ($\text{Cr}_2\text{O}_3 > 6 \text{ wt}\%$). These features are indicative of a very high potential for diamonds from a garnet harzburgite source for both localities, speculatively in the 60-100 cts/100 tonne range.

The Cr-pyrope recovered from the Sloan and Kirkland Lake kimberlites indicate a low diamond potential (~1-10 cts/100 tonnes) from a garnet harzburgite source (Figs. 23c, d). The compositional characteristics of the two Kirkland Lake garnet populations (KL-1 and KL-5) are slightly different, but both are consistent with low diamond grades. The three datapoints clustered well within the G10 field represent the most favorable compositions for diamond potential, but their proximity on the plot indicates that they may represent fragments of the same grain from KL1.

The compositional characteristics of the Cr-pyrope garnets from the Prairie Creek, Batty, Crossing Creek, Jack and Sturgeon Lake diatremes are indicative of very minor to trace amounts of diamond from garnet harzburgite source rocks (Figs. 23e-i). The Prairie Creek and Batty suites are unusual in that they both have one G10 garnet which is considerably more subcalcic and Cr-rich than the rest of the garnets. The significance of these grains is difficult to assess but, taken at face value, they are interpreted to reflect a minor diamond content. At most locations, where only one or two G10 garnets are present, they are typically only marginally subcalcic and plot close to the 85% line, such as is seen for the Crossing Creek, Jack and Sturgeon Lake diatremes (Figs. 23g-i). These localities may have only microdiamonds or a very low macrodiamond content (<1 ct/100 tonnes) from a garnet harzburgite source.

No diamond potential from a garnet harzburgite source is predicted for the Argyle (Fig. 23j) and Mountain diatremes, but in both cases too few Cr-pyrope grains were recovered to permit a reliable forecast.

Chromite

Chromites were recovered from all eighteen diatremes investigated (Table 16), and these are used to assess the diamond potential of chromite harzburgite source rocks at each locality. The characteristics of individual suites are plotted on a series of Cr_2O_3 vs MgO plots in Figure 24.

Only the two South African localities, Sover and New Elands, have chromites consistent with good

diamond potential from a chromite harzburgite source. Both suites of chromites have a very high average chrome content, and a significant proportion of grains plot within the field of compositions associated with diamond (Figs. 24a, b). The overall characteristics of the Sover chromites are better than those of New Elands.

The Argyle chromites show compositional characteristics consistent with a moderate to low diamond potential from a chromite harzburgite source (Fig. 24c). While the average chrome content of the suite is high (~58 wt% Cr_2O_3), the majority of grains have lower Cr_2O_3 contents than those associated with diamond.

Figures 24d-f show that the Batty, Sloan and Jack diatremes all have two chromites which plot in, or very close to, the field of compositions associated with diamond. This suggests the potential for a low diamond contribution from this source or at best grades of <1 ct/100 tonnes from a chromite harzburgite source for these pipes. The Batty chromites show a higher average and more restricted range in chrome than the Jack and Sloan suites.

The composition of chromites recovered from the remaining twelve localities: Prairie Creek, Kirkland Lake, Crossing Creek, Sturgeon Lake, Mike, Larry, Mark, Joff, Ile Bizard, Mountain Diatreme, Blackfoot, and HP, all indicate negligible potential for diamond from a chromite harzburgite source (Fig. 24).

Discriminant classification and trace element studies

A set of chromites representing the DI, Cr-Ti and Al/Fe from Argyle, Ellendale 4, Jack, Prairie Creek and Smoky Butte was submitted to CSIRO in Sydney, Australia for analysis to assess the practicality of the trace element techniques recently proposed by Griffin et al. (1991, 1992). Trace element and Zn-thermometer temperature results are listed with major element compositions in Table 18.

The compositions of most of the DI, Cr-Ti and Al/Fe chromites from the lamproites investigated in this study (Table 18) plot in the P1 field areas typical of Group I kimberlite chromites derived from chromite harzburgite. Such findings are not unexpected because it is known that lamproite, as well as Group I and Group II kimberlite magmas, can intrude chromite harzburgite sources of diamond (Gurney and Moore, 1989). However, in most cases the chromite

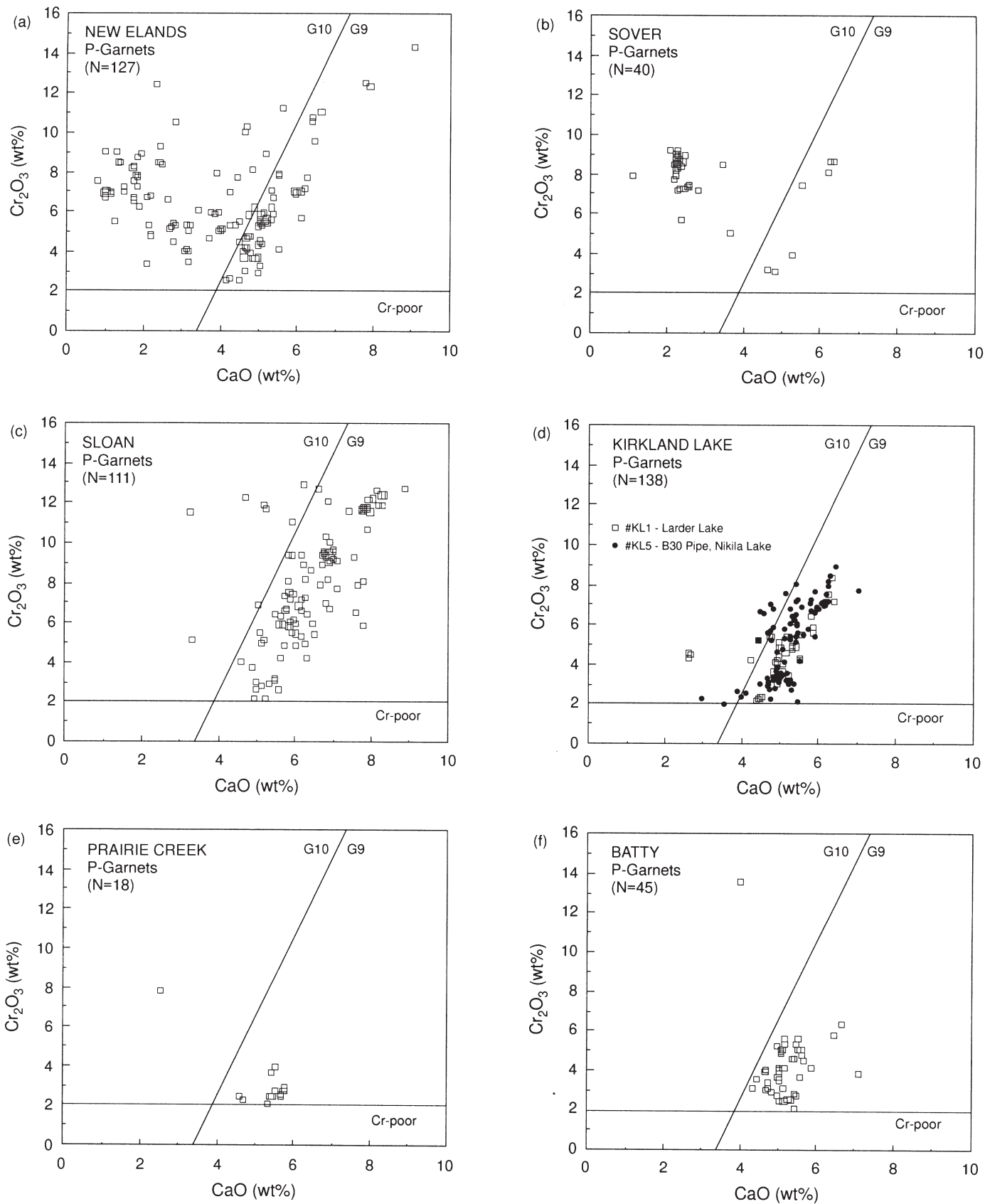


Figure 23(a-f). Peridotitic garnet compositions for the localities investigated.

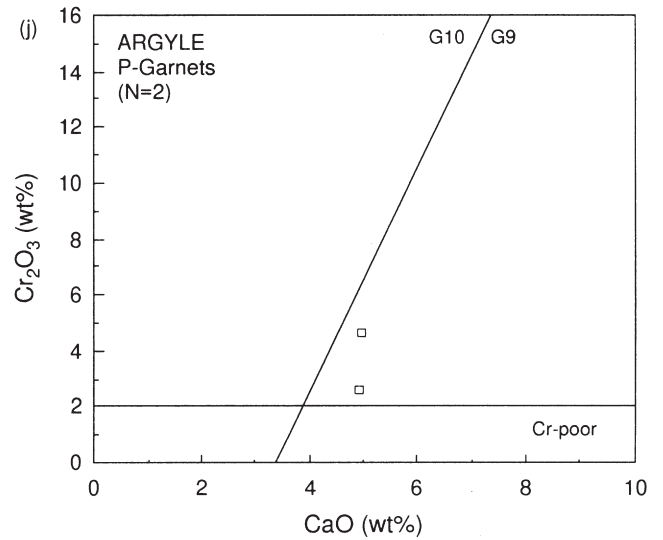
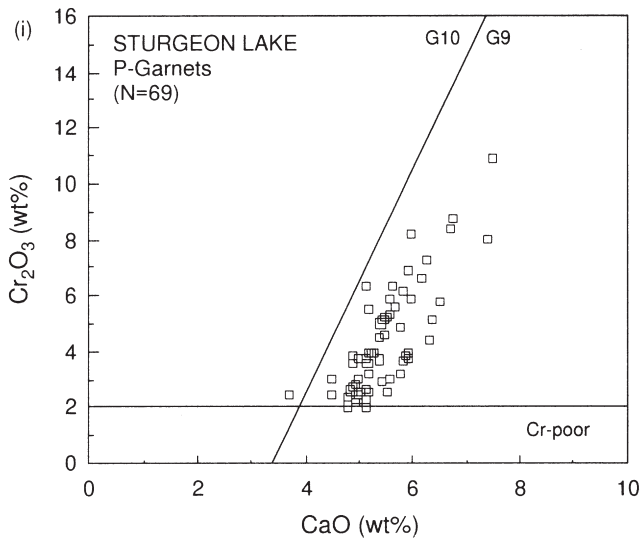
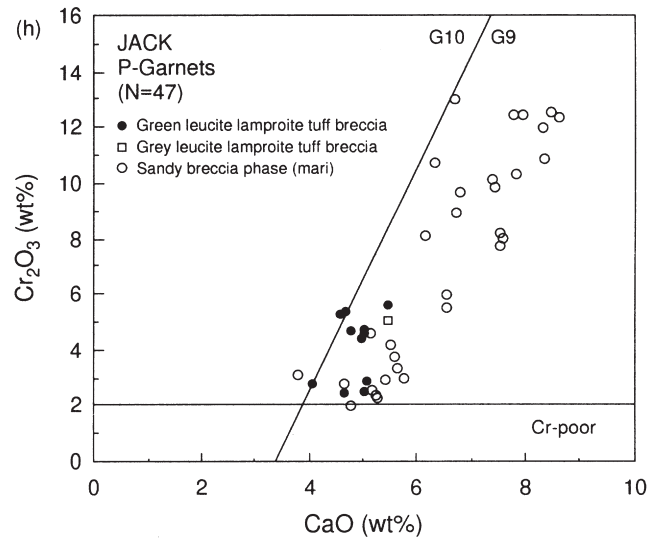
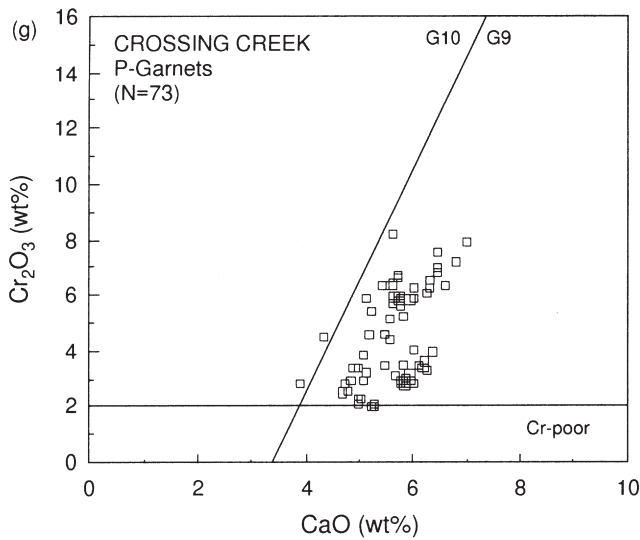


Figure 23(g-j). (cont'd.)

compositions shown in Table 18 failed to plot in a single defined field, but cross over into two or more of the P1, P3 and P4 field areas in the different binary discriminant diagrams of Griffin et al. (1992) (e.g., $\text{TiO}_2\text{-Ni}$, $\text{Cr}_2\text{O}_3\text{-Ni}$, MgO-Ni , Zn-Ni , Ga-Ni , etc.). A few Cr-Ti chromites from Argyle plot in the P2 field, characteristic of Group II kimberlites rather than lamproite. These ambiguities reflect, in part, the practical difficulties of applying this classification technique to new areas.

Seventy-five per cent of the Cr-Ti chromites submitted for study fall within the 950-1250°C diamond window (Table 18). However, many of these (noting the ambiguity of classification mentioned earlier) classify as P2 chromites, thought to be of magmatic origin (Griffin et al., 1992). In addition,

52% of the high-Al/Fe chromites (mainly of shallow crustal origin) which plot within the mixed fields of Figures 16 (a-d) also plot within the 950-1250°C diamond window. However, since magmatic and crustal chromites do not reveal anything about the mantle, its temperature, or whether it has diamonds, these have to be recognized and separated out before looking at the temperature distribution of the rest of the chromite suite.

Assuming a geothermal gradient similar to that prevailing below the Kalahari Craton in southern Africa ($\sim 40 \text{ mWm}^{-2}$), fifteen of the seventeen DI composition chromites (88%) in Table 18 fall within the temperature window of 950-1250°C, defined by Griffin et al. (1991) to be favorable for the presence of diamond. Two chromites from Ellendale 4 give

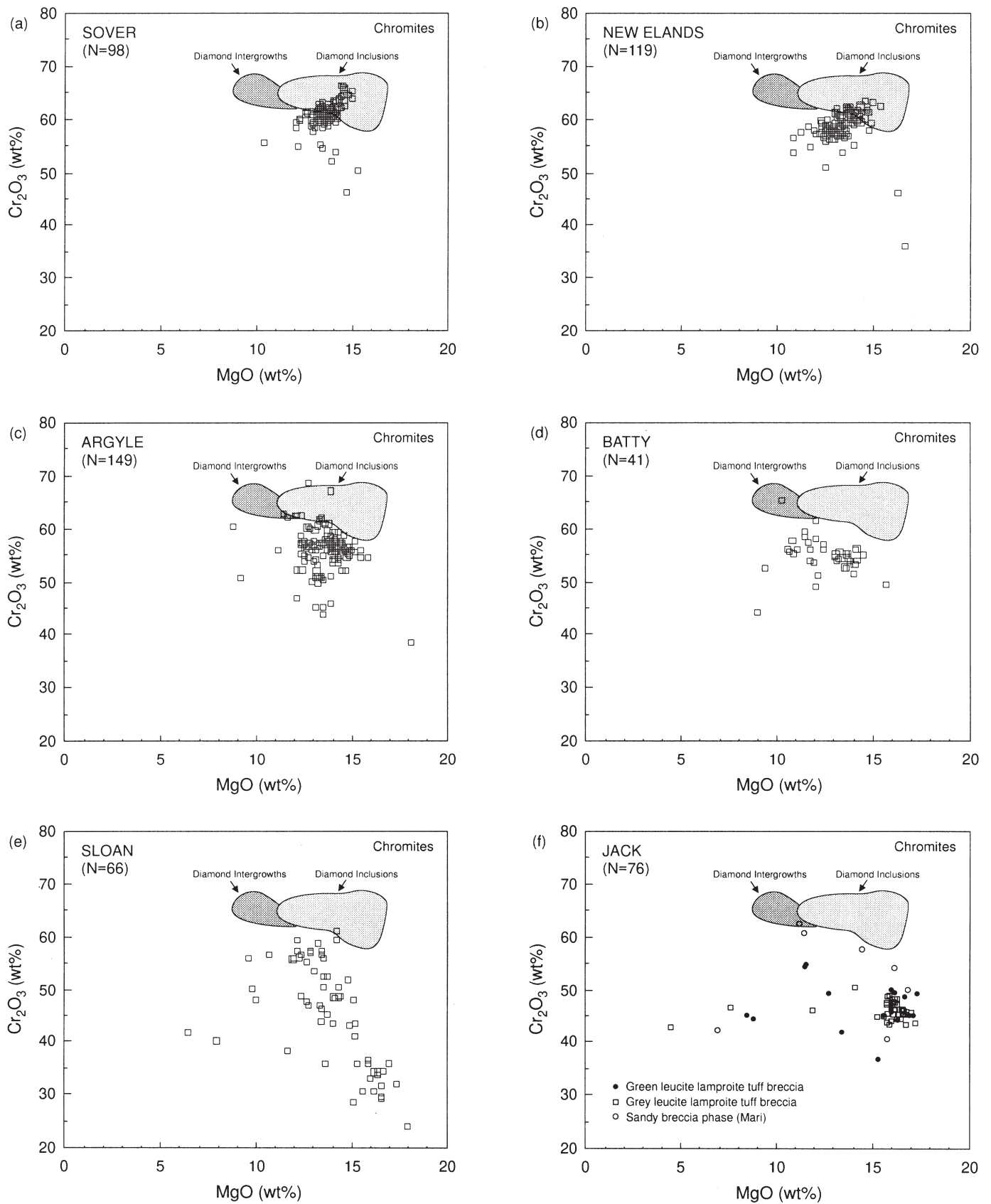


Figure 24(a-f). Chromite compositions for the localities investigated.

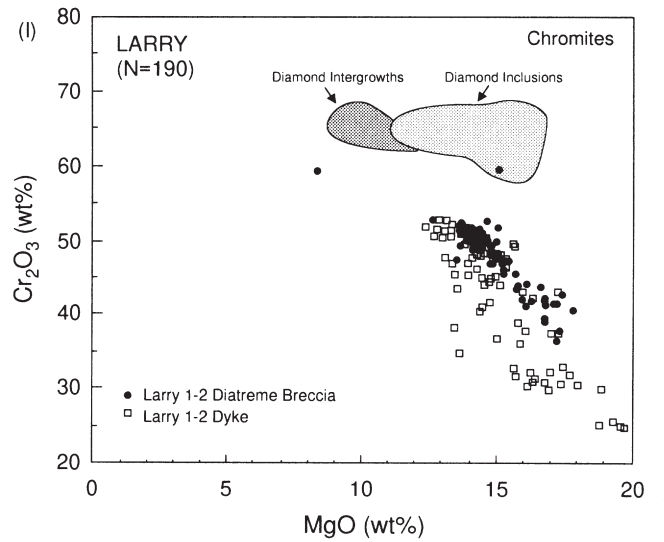
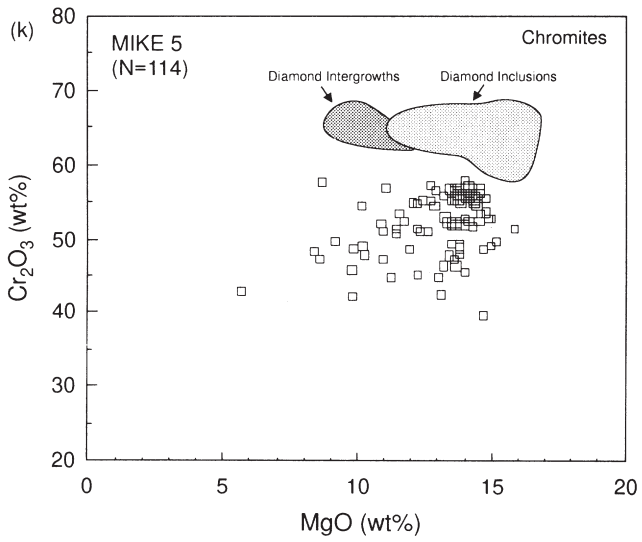
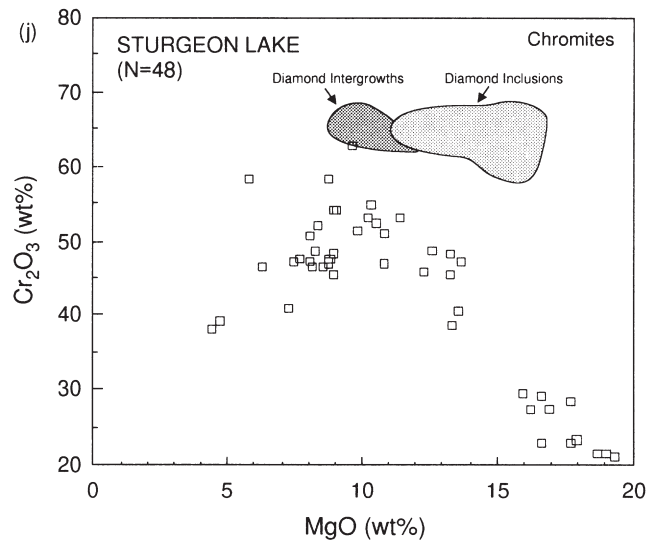
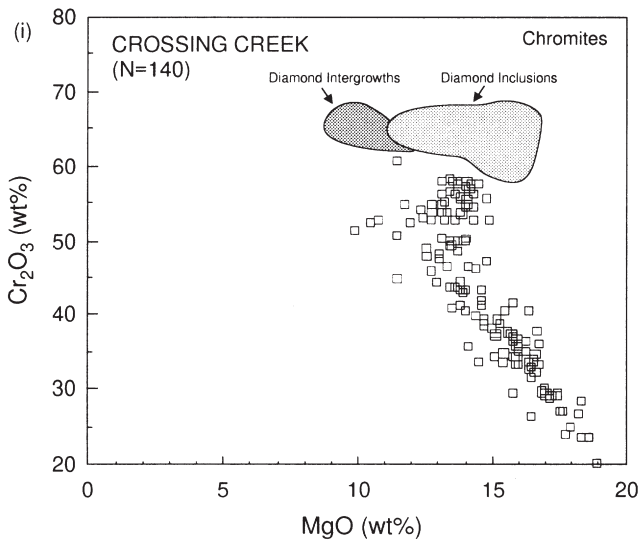
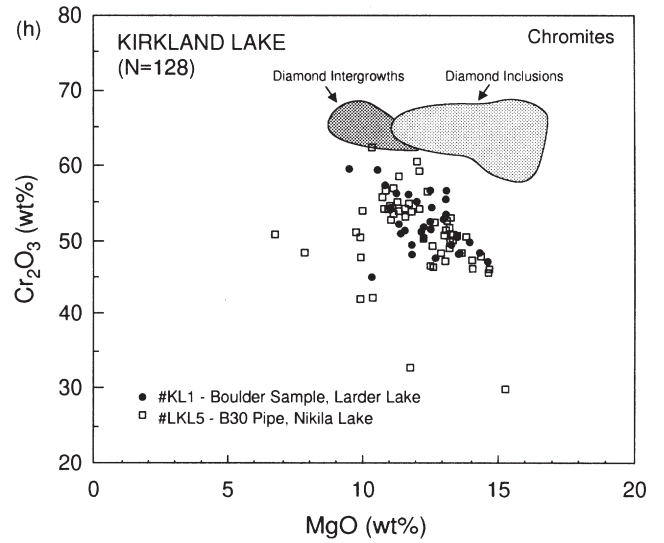
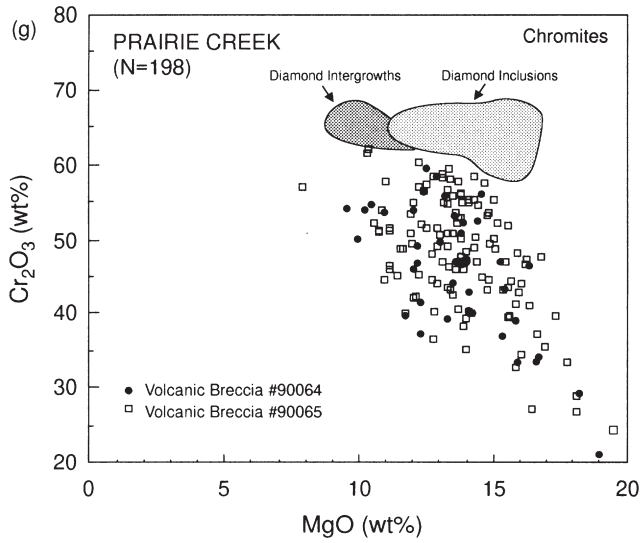


Figure 24(g-l). (cont'd.)

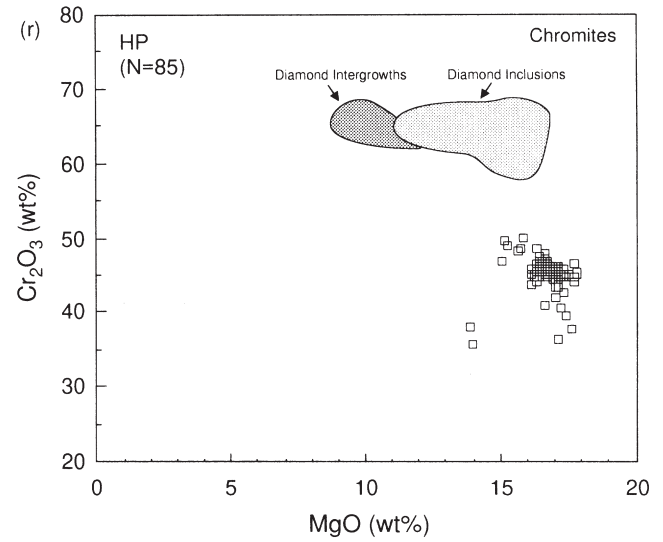
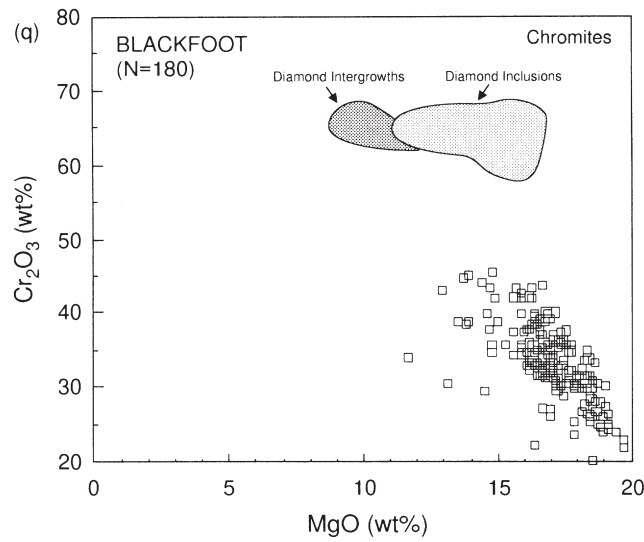
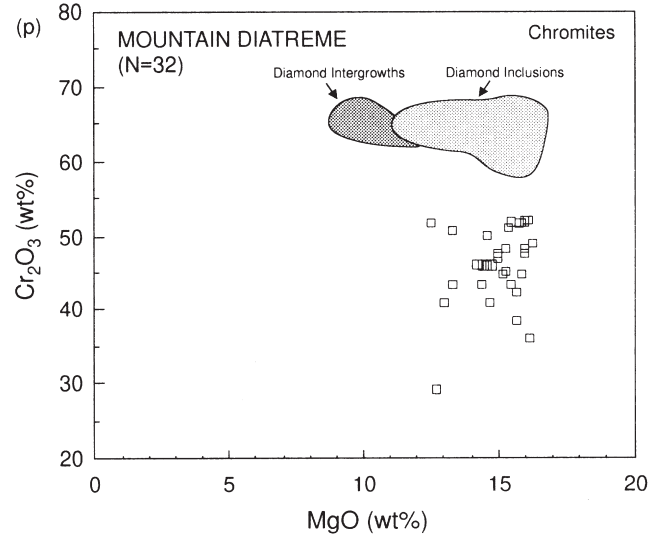
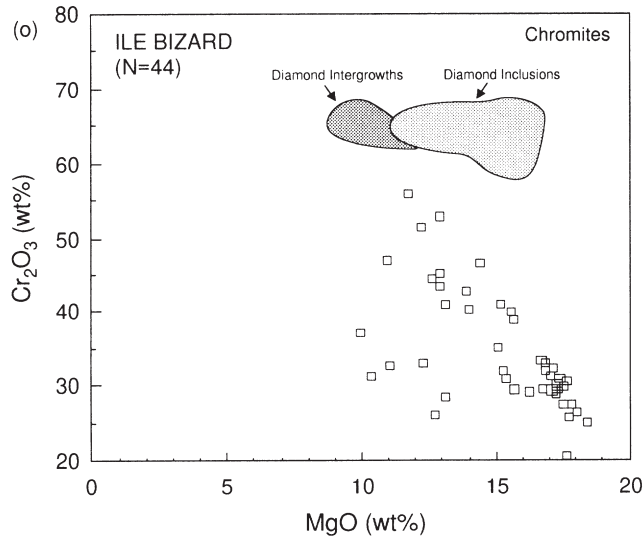
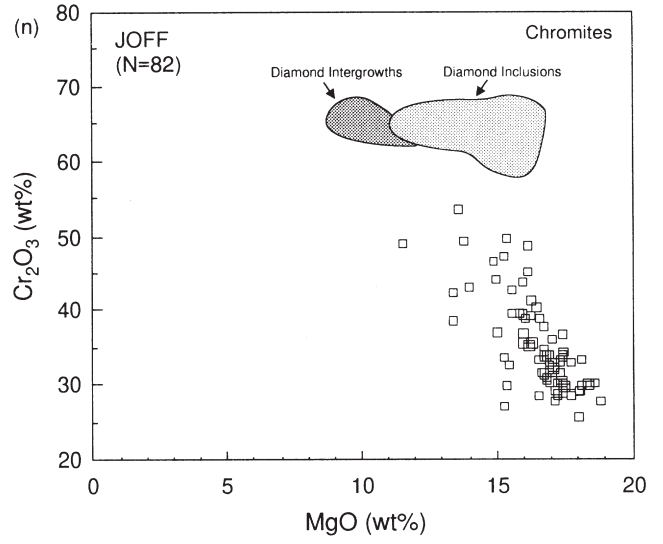
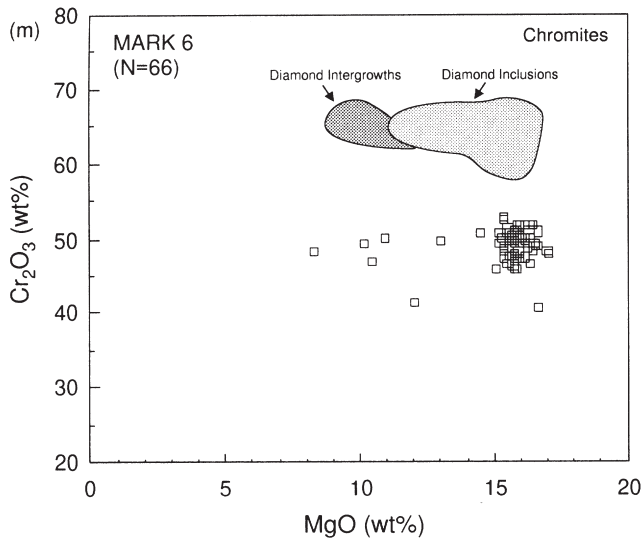


Figure 24(m-r). (cont'd.)

Table 18

Compositions of DI, Cr-Ti and Al-Fe chromites from lamproites

ID	Grain	Min	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CSIRO Proton Probe Analysis					
									Ni ppm	Zn ppm	Ga ppm	Zr ppm	Nb ppm	T(Zn) °C
AT	410c	DI CR	nd	7.30	62.19	17.39	0.26	11.39	632	540	42.10	nd	nd	1070*
AT	042c	DI CR	0.15	9.80	60.15	15.33	0.25	12.44	565	568	33.10	nd	nd	1051*
AT	046c	DI CR	0.18	7.09	61.26	17.94	0.30	11.31	622	515	47.70	nd	nd	1088*
AT	512c	DI CR	0.37	10.67	58.42	15.31	0.27	13.46	612	730	10.10	nd	nd	964*
AT	052c	DI CR	nd	2.95	69.25	13.84	0.30	12.72	490	506	8.33	5.99	nd	1095*
AT	054c	DI CR	0.22	10.15	59.74	15.02	0.30	13.64	763	560	36.60	nd	nd	1056*
AT	724c	DI CR	nd	8.31	61.42	15.72	0.24	11.84	574	583	24.80	nd	nd	1035*
EL4	075c	DI CR	0.25	9.69	60.81	15.50	0.23	11.74	531	844	39.10	6.10	nd	919
EL4	083c	DI CR	0.32	4.50	60.77	22.04	0.37	10.31	549	435	30.40	17.40	4.83	1158*
EL4	084c	DI CR	0.14	5.57	63.83	16.18	0.35	12.03	645	477	14.30	nd	nd	1119*
EL4	087c	DI CR	0.36	9.22	60.46	15.99	0.35	12.09	557	804	37.30	nd	4.59	934
EL4	102c	DI CR	0.25	7.51	61.42	16.51	0.34	13.12	698	547	16.90	nd	nd	1065*
EL4	102c	DI CR ¹							736	574	20.10	nd	nd	1065*
EL4	026c	DI CR	0.87	5.12	60.78	19.65	0.36	10.91	753	465	82.80	nd	5.61	1130*
EL4	028c	DI CR	nd	1.82	66.77	17.09	0.25	11.18	923	409	nd	nd	nd	1185*
PC64	522c	DI CR	0.56	7.83	59.63	17.09	0.28	13.85	774	514	68.60	16.10	7.81	1089*
SB01	048c	DI CR	nd	9.69	60.48	13.02	0.21	14.63	800	548	17.60	nd	nd	1064*
SB1	315c	DI CR	0.56	2.53	63.20	19.09	0.37	11.52	566	603	12.60	6.71	nd	1029*
AT	071c	TI CR	0.55	14.13	52.21	18.39	nd	13.28	1050	739	64.40	nd	nd	960*
AT	711c	TI CR	2.45	9.84	54.98	16.39	0.23	14.37	1190	789	29.50	nd	nd	939
AT	712c	TI CR	nd	13.69	57.10	13.41	0.30	13.69	840	1120	65.40	27.40	11.50	449
AT	721c	TI CR	2.17	10.57	56.00	15.30	0.00	14.95	1000	492	27.60	8.38	nd	1107*
EL4	811c	TI CR	4.16	5.79	53.01	23.56	0.43	11.55	1280	466	50.10	51.30	5.14	1128*
EL4	813c	TI CR	0.67	17.19	43.58	22.86	0.28	13.10	1230	379	47.00	4.37	4.61	1219*
EL4	813r	TI CR ¹							816	566	16.90	372.00	16.20	1052*
EL4	086c	TI CR	5.38	2.78	53.17	22.42	0.45	13.92	845	556	15.70	127.00	18.00	1059*
EL4	106c	TI CR	2.51	4.05	61.05	19.44	0.35	8.81	887	691	46.10	34.90	nd	982*
EL4	106r	TI CR ¹							874	544	45.80	28.70	nd	1067*
EL4	109c	TI CR	4.36	3.10	57.40	19.48	0.36	11.97	790	524	16.30	235.00	22.30	1082*
EL4	109c	TI CR ¹							866	520	25.20	252.00	24.10	1085*
JK2	161c	TI CR	1.03	7.31	54.21	24.27	0.24	10.41	767	756	40.00	8.24	4.85	953*
JK2	111c	TI CR	2.80	9.45	43.91	33.10	0.34	7.66	1290	846	43.90	nd	5.44	918
PC64	526c	TI CR	1.17	5.99	58.32	20.17	0.22	11.93	658	337	50.80	nd	3.80	1277
PC65	354c	TI CR	3.16	4.17	59.75	16.46	0.26	13.73	876	505	29.70	63.00	nd	1096*
PC65	355c	TI CR	4.32	12.37	40.79	24.57	nd	14.60	1660	345	69.30	26.60	4.14	1266
PC65	355c	TI CR ¹							1530	301	60.90	21.60	nd	1338
PC65	357c	TI CR	3.76	7.37	51.61	20.69	0.27	13.65	916	638	26.70	90.70	nd	1009*
PC65	480c	TI CR	4.86	6.93	50.03	21.13	0.28	14.43	769	498	28.80	213.00	23.70	1102*
PC65	485c	TI CR	4.36	8.88	48.90	20.21	0.36	14.81	1020	447	28.20	129.00	32.20	1146*
PC65	485c	TI CR ¹							1110	466	34.70	112.00	23.50	1129*

¹Additional proton probe analysis of different spot of same chromite grain.

*Zn temperature within 950–1250°C diamond window.

c=core analysis, r=rim analysis

MnO by University of Cape Town, South Africa

Table 18 (cont'd.)

ID	Grain	Min	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CSIRO Proton Probe Analysis					
									Ni ppm	Zn ppm	Ga ppm	Zr ppm	Nb ppm	T(Zn) °C
PC65	486c	TI CR	nd	35.85	30.30	15.80	nd	14.09	1220	2950	71.40	nd	nd	633
PC65	486c	TI CR ¹							932	645	37.20	107.00	11.20	1005*
PC65	486c	TI CR ¹							1310	3020	63.50	nd	nd	629
PC65	486c	TI CR ¹							2050	3090	69.30	nd	nd	625
PC65	486c	TI CR ¹							1400	2950	71.40	nd	nd	633
PC65	487c	TI CR	1.93	4.11	60.39	16.12	0.35	13.50	610	499	21.20	111.00	11.20	1101*
SB01	111c	TI CR	6.44	7.13	46.53	23.71	0.31	13.42	1630	360	43.50	nd	nd	1245*
SB01	018c	TI CR	1.06	7.26	54.69	25.62	0.44	9.06	663	1740	29.80	49.00	5.79	735
SB01	038c	TI CR	4.63	8.23	49.26	22.83	0.24	12.95	1390	400	47.20	nd	nd	1196*
SB1	312c	TI CR	1.61	4.26	57.09	23.34	0.30	11.01	998	680	56.00	8.79	6.74	988*
SB1	810c	TI CR	2.82	3.45	57.96	21.18	0.33	11.99	933	638	56.20	6.41	nd	1009*
SB1	816c	TI CR	1.24	5.14	57.95	21.74	0.30	11.59	767	667	36.60	4.74	nd	994*
AT	411c	AL CR	0.17	10.65	58.36	15.60	0.23	13.29	728	592	29.20	nd	nd	1036*
AT	047c	AL CR	nd	11.85	59.80	13.02	0.27	14.16	691	555	15.40	4.35	4.64	1060*
AT	511c	AL CR	0.15	10.72	58.69	15.85	0.30	13.32	714	596	28.30	nd	nd	1033*
AT	513c	AL CR	0.15	20.05	46.67	18.87	nd	12.89	790	582	36.90	4.42	nd	1042*
AT	055c	AL CR	nd	12.66	57.02	15.02	0.24	13.82	836	594	14.90	nd	nd	1035*
AT	057c	AL CR	0.22	13.40	55.78	15.64	0.22	13.37	720	667	31.80	nd	nd	994*
AT	722c	AL CR	0.41	15.27	50.98	18.90	nd	12.84	791	550	67.50	nd	nd	1063*
AT	078c	AL CR	nd	14.34	54.36	15.62	0.23	13.85	765	739	45.70	nd	nd	960*
AT	079c	AL CR	nd	22.78	43.44	18.71	nd	12.91	969	686	43.00	nd	nd	984*
EL4	073c	AL CR	0.13	19.40	50.47	14.18	0.23	13.60	604	993	30.40	nd	nd	872
EL4	073c	AL CR	nd	47.16	20.92	9.35	nd	19.08	2020	1990	17.50	nd	nd	707
EL4	815c	AL CR	0.47	13.26	53.55	21.64	0.36	7.62	981	1230	51.50	48.60	nd	815
EL4	1010c	AL CR	0.65	16.86	49.22	18.44	0.37	12.77	812	700	62.80	4.65	nd	977*
EL4	105c	AL CR	0.43	12.23	51.23	21.37	0.29	12.86	1070	404	48.70	4.04	6.79	1191*
JK2	163c	AL CR	0.97	17.83	45.59	17.39	nd	15.13	1120	434	42.10	nd	nd	1158*
JK2	164c	AL CR	0.19	30.50	36.77	15.08	0.00	15.27	755	1470	48.20	nd	6.89	772
JK2	102c	AL CR	0.77	19.24	45.49	16.21	nd	15.36	1220	317	40.20	nd	5.97	1310
PC64	062c	AL CR	0.19	17.77	43.24	24.65	0.33	12.10	689	766	15.00	12.00	nd	949
PC64	523c	AL CR	0.45	9.17	49.61	26.06	0.28	11.86	1190	395	69.90	nd	nd	1201*
PC64	524c	AL CR	0.18	11.26	57.43	15.96	0.35	12.16	585	728	44.30	4.49	nd	965*
PC65	352c	AL CR	0.26	24.55	43.06	16.32	0.22	13.29	731	1040	32.80	nd	nd	859
PC65	478c	AL CR	nd	24.08	44.13	15.60	nd	13.61	598	1270	32.00	nd	nd	808
PC65	481c	AL CR	0.11	13.88	53.76	20.48	0.32	9.96	268	1100	29.20	nd	nd	845
SB01	113c	AL CR	0.72	26.68	29.67	30.02	0.25	10.26	1390	2760	71.90	nd	nd	645
SB01	016c	AL CR	0.64	22.42	40.34	23.44	nd	12.00	943	2530	45.80	nd	nd	660
SB1	314c	AL CR	nd	39.24	27.51	12.97	nd	16.87	1470	1500	40.90	nd	nd	768
SB1	039c	AL CR	1.03	29.04	29.07	21.56	0.24	16.30	1680	320	86.60	nd	nd	1304

Zn-temperatures of 919 and 934°C and, although these fall short of the “diamond window”, they are within the expected margin of error associated with the technique. However, the geothermal gradient in the region of the Ellendale diatremes is higher than that of the Kalahari Craton (Jaques et al., 1986). Conventional geothermometry techniques applied to a variety of mantle-derived mineral assemblages (if such material is available from diatremes) would better define regional geotherms and improve the utility of the method for new prospective areas.

The analysis of more than one 30 µm spot in the core region of individual chromite grains yielded similar trace element results in six instances (Table 18). Only in one case did a rim analysis yield substantially higher Zr and Nb along with lower Ni and Ga, relative to the core analysis of the same grain (Table 18, grains EL-813 and PC65-486). The high Zr and Nb on the rim of grain EL-813 could be attributable to magmatic reaction or metasomatism. The high Zr and Nb, as well as low Ni and Ga core of grain PC65-486, also may be attributable to metasomatism on a fracture or, less likely, to Zr-Nb mineral inclusions within the 30 µm beam area analyzed. The cores of Cr-Ti chromites are, in most cases, enriched in Zr-Nb (Table 18), whilst these elements are in most cases not detected in the DI and Al/Fe chromites analyzed.

Cr-poor garnet

In this study, Cr-poor garnets are arbitrarily defined as having less than 2 wt% Cr₂O₃. This will include garnet macrocrysts from several types of paragenesis, including some peridotites, Group I and II eclogites, megacrysts and “regional” garnets derived from high-grade crustal metamorphic rocks. Plots of TiO₂ versus Na₂O for the suites recovered from the localities investigated are presented in Figure 25.

Garnets showing significant trace enrichments of sodium (>0.07 wt% Na₂O) were recovered at five of fifteen localities where Cr-poor garnets were present (Figs. 25a-e). These include Crossing Creek (8 out of 13), New Elands (9 out of 18), Sloan (11 out of 61), Sover (12 out of 13) and Sturgeon Lake (11 out of 36).

At Crossing Creek, none of the eight high-Na₂O garnets is thought to be derived from eclogitic source rocks. Rather, their geochemical characteristics suggest that they represent a suite of high-pressure megacrysts. Such megacrysts are in no way related to the formation of diamonds. They are, however, useful in that their

presence in a pipe can be used to establish whether or not the kimberlite has sampled a lithospheric mantle keel of sufficient thickness to contain diamonds.

The New Elands low-Cr garnet suite indicates potential for the presence of some eclogitic diamonds, but a low eclogitic diamond component is forecast.

At Sloan, only 11 of the 61 Cr-poor garnets analyzed showed significant sodium enrichments (Fig. 25c). Of these grains, just over half are interpreted to be derived from potentially diamondiferous Group I eclogite, while the remaining high-sodium grains classify as megacrysts. A low potential for eclogitic diamonds is indicated.

Of the low-Cr garnets analyzed at Sover, the majority have significant sodium concentrations (Fig. 25d). Many of these fall into an overlap class between Group I eclogitic garnets and high-pressure megacrysts. This makes any semi-quantitative forecasting based on this limited dataset impractical, although a clear potential for a significant component of eclogitic diamond exists. Further analyses on additional low-Cr garnets from Sover at CF Minerals confirm that Group I eclogitic garnets are well represented, and overall a high potential for eclogitic diamonds is indicated (Fipke, pers. comm. 1994).

At Sturgeon Lake, 11 of the 36 Cr-poor garnets analyzed showed significant trace enrichments in sodium (Fig. 25e). Four are interpreted to represent Group I eclogite and seven as high-pressure megacrysts. This result implies low potential for the presence of eclogitic diamonds.

In terms of potential for eclogitic diamonds, the results for all remaining localities were negative (Figs. 25f-o). Some of the garnets from these localities are iron-rich garnets from crustal granulites, which have been documented in the Argyle area (Jaques, pers. comm. 1989).

Ilmenite

As previously discussed, ilmenite analyses have been used to forecast a diamond preservation potential (DPP) factor for specific localities. This factor represents an estimate of the percentage of the original diamond population sampled by the kimberlite which will survive the intrusion event. Plots of Cr₂O₃ versus MgO for the ilmenites recovered from each locality are plotted in Figure 26.

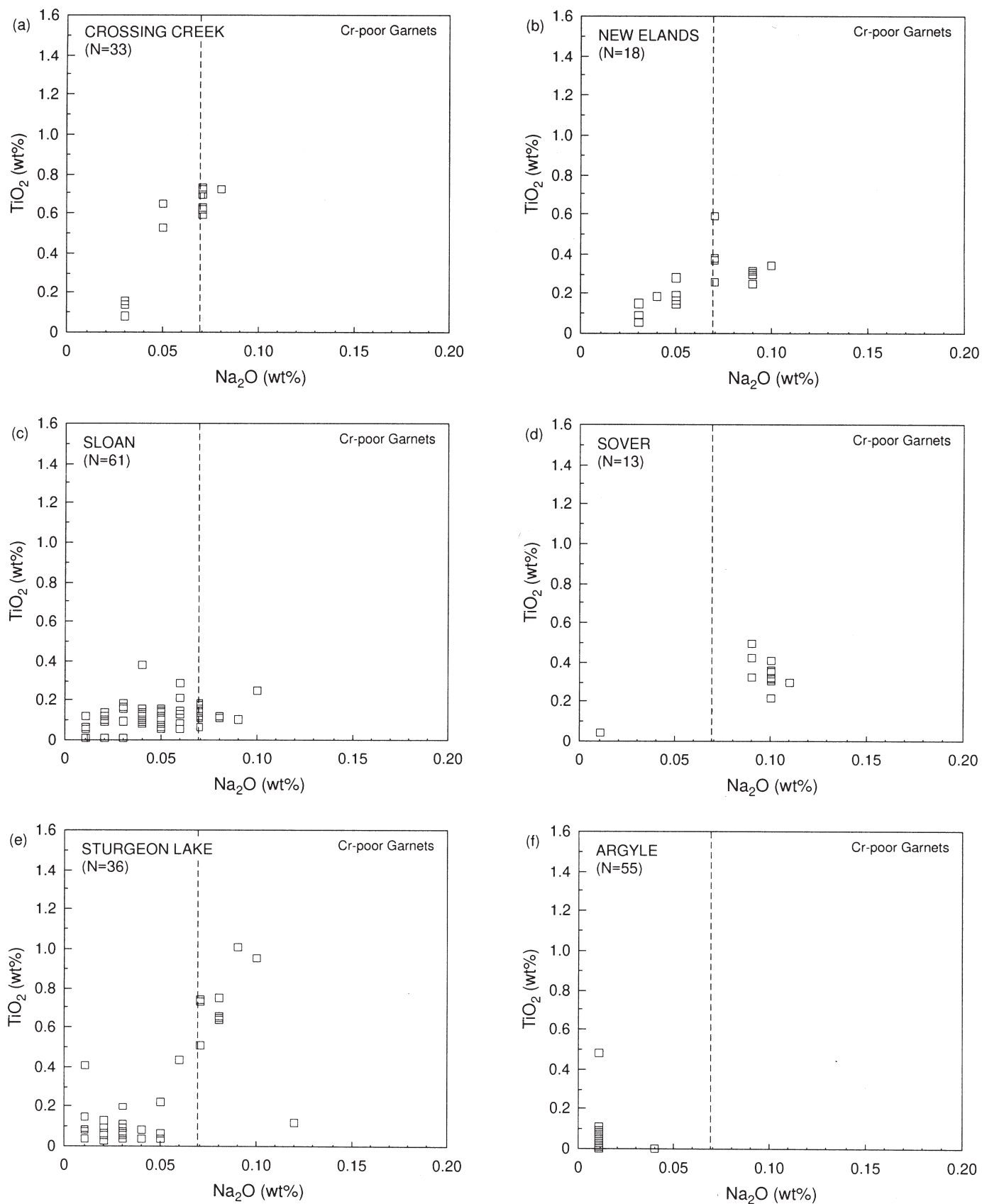


Figure 25(a-f). Cr-poor garnet compositions for the localities investigated.

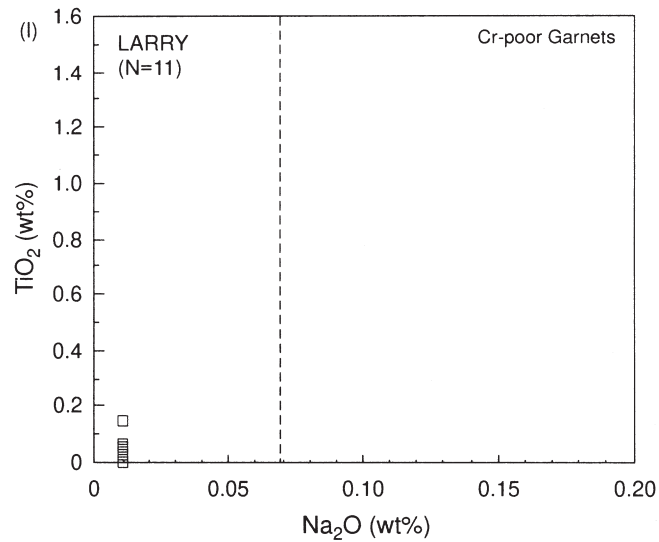
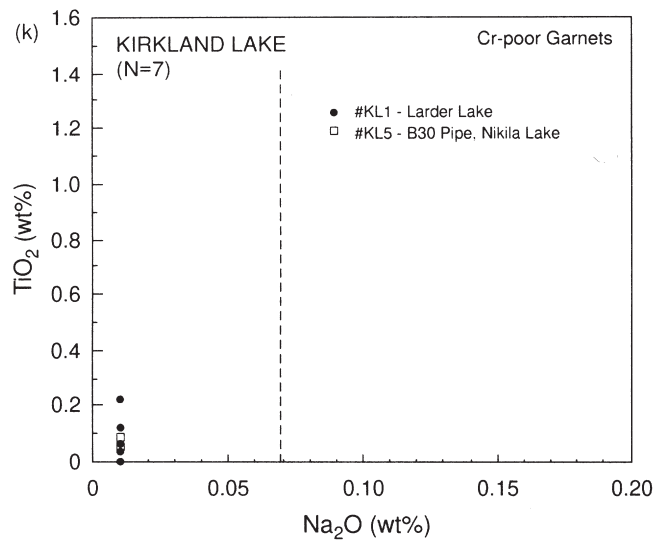
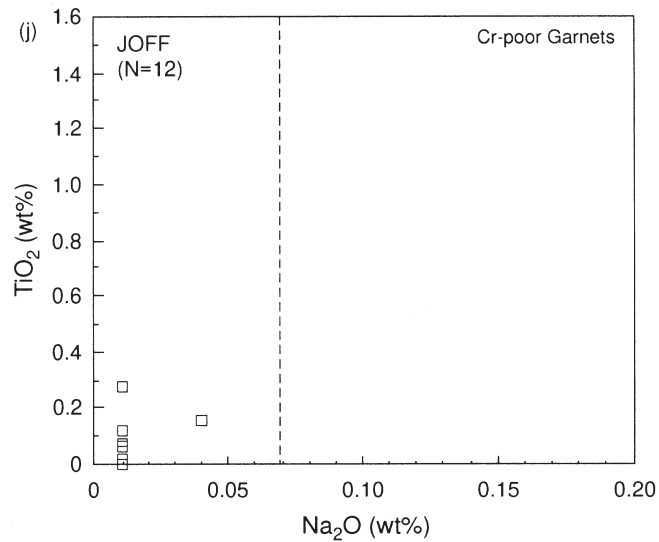
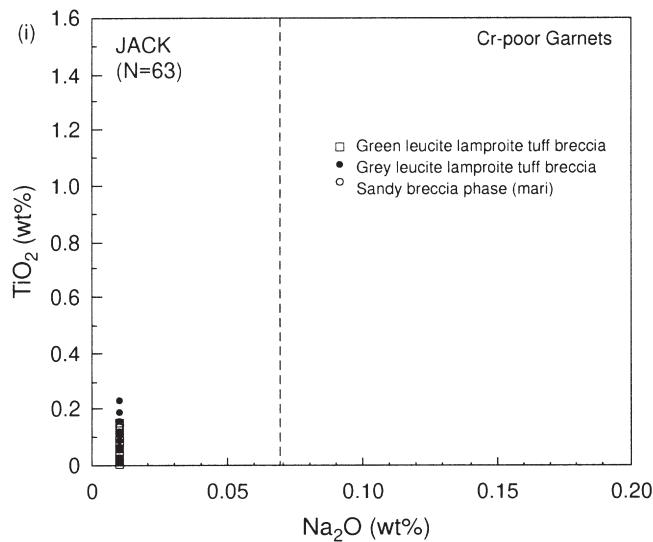
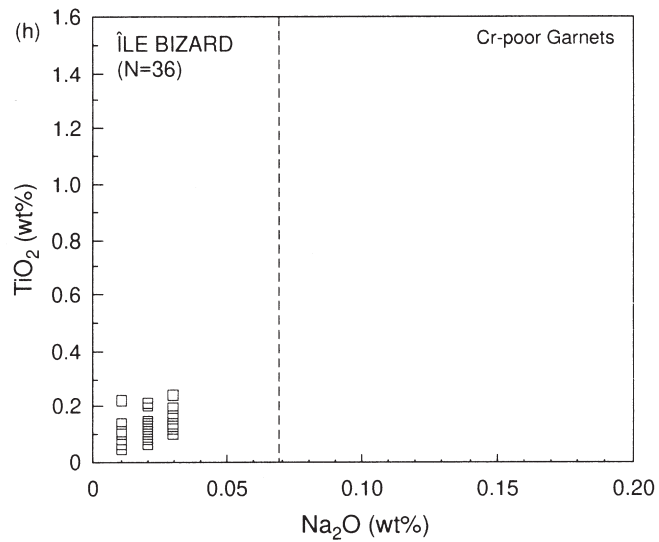
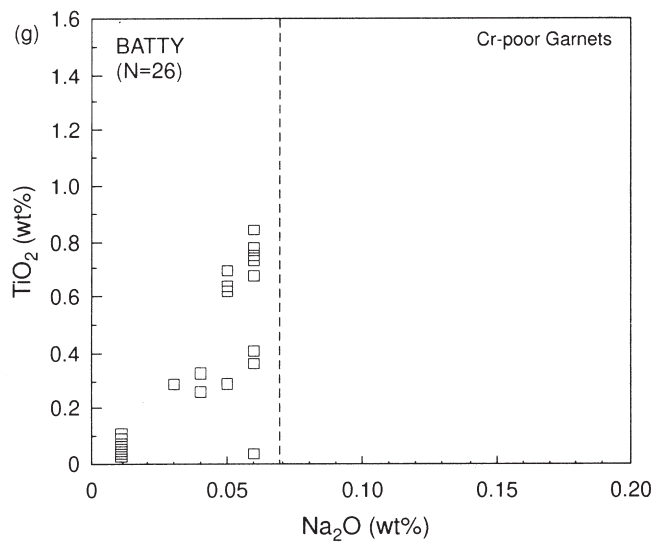


Figure 25(g-l). (cont'd.)

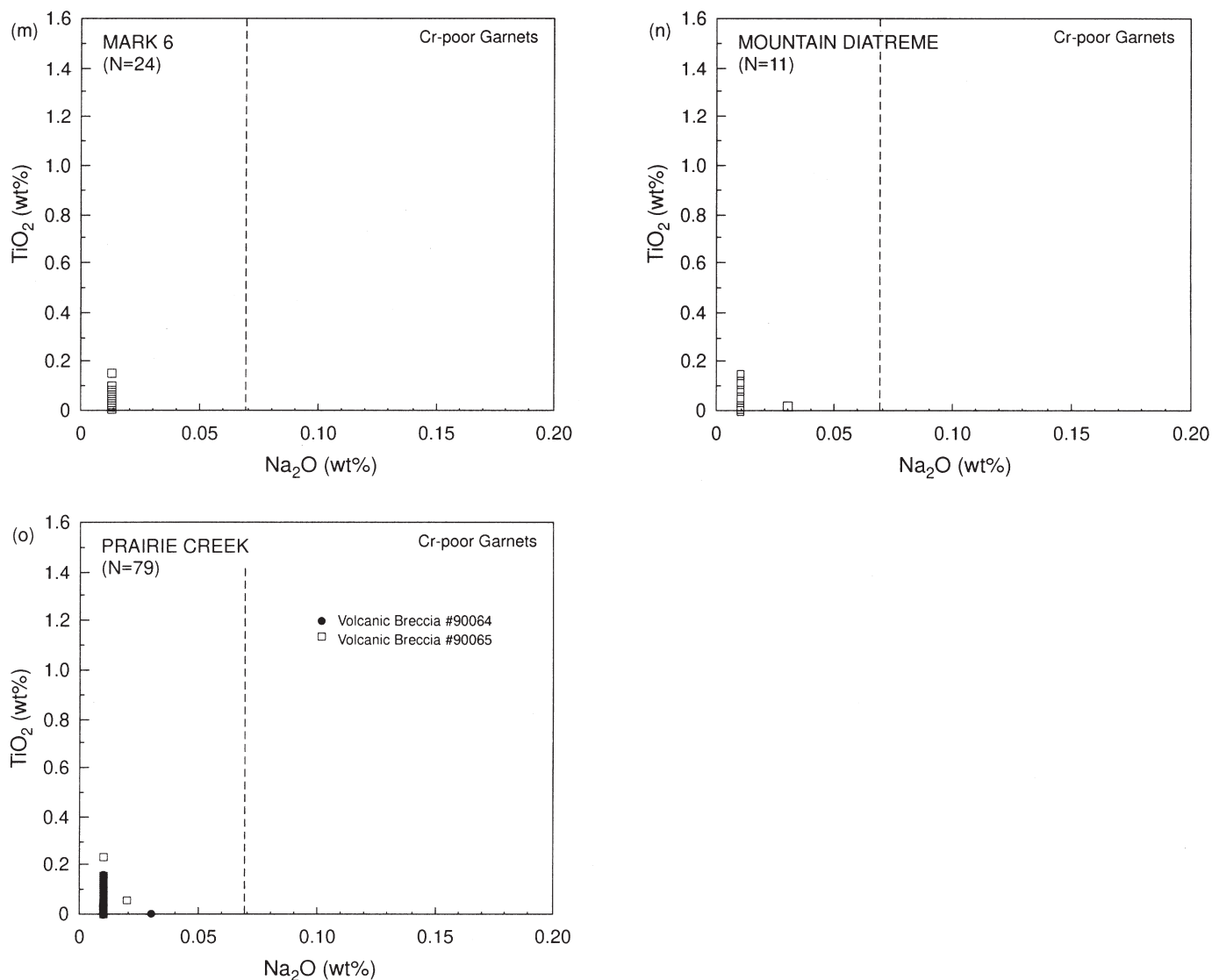


Figure 25(m-o). (cont'd.)

Argyle, Batty, Jack, Prairie Creek, Sloan, and Sturgeon Lake (Figs. 26a-f) are all forecast to have a high DPP. The ilmenites from these localities show compositions generally consistent with reducing conditions, which in turn implies that diamond content will not be greatly affected by resorption processes. More than one ilmenite population is evident in the Jack, Prairie Creek, Sloan, and Sturgeon Lake suites. The ilmenites with very low magnesium contents (generally <4 wt%) are more than likely derived from country rock fragments and consequently have no bearing on the diamond preservation potential of the pipe.

Kirkland Lake and Ile Bizard are forecast to have moderate to low DPP. The ilmenites recovered from

the two Kirkland Lake samples investigated are compositionally different (Fig. 26g). The suite from sample KL1 shows a trend of increasing chrome with magnesium content and, as such, is indicative of favorable conditions for diamond preservation. On the other hand, the suite from sample KL5 is less attractive in that the ilmenites have higher inferred Fe³⁺ content and lower magnesium content (~4.5 wt% MgO). In addition, chrome content increases at the low MgO end of the trend. These features are thought to accompany increased Fe³⁺.

The ilmenites from Ile Bizard (Fig. 26h) show a range in MgO content from ~6.5 to 11 wt%, but all have very low concentrations of Cr₂O₃. A low DPP is forecast.

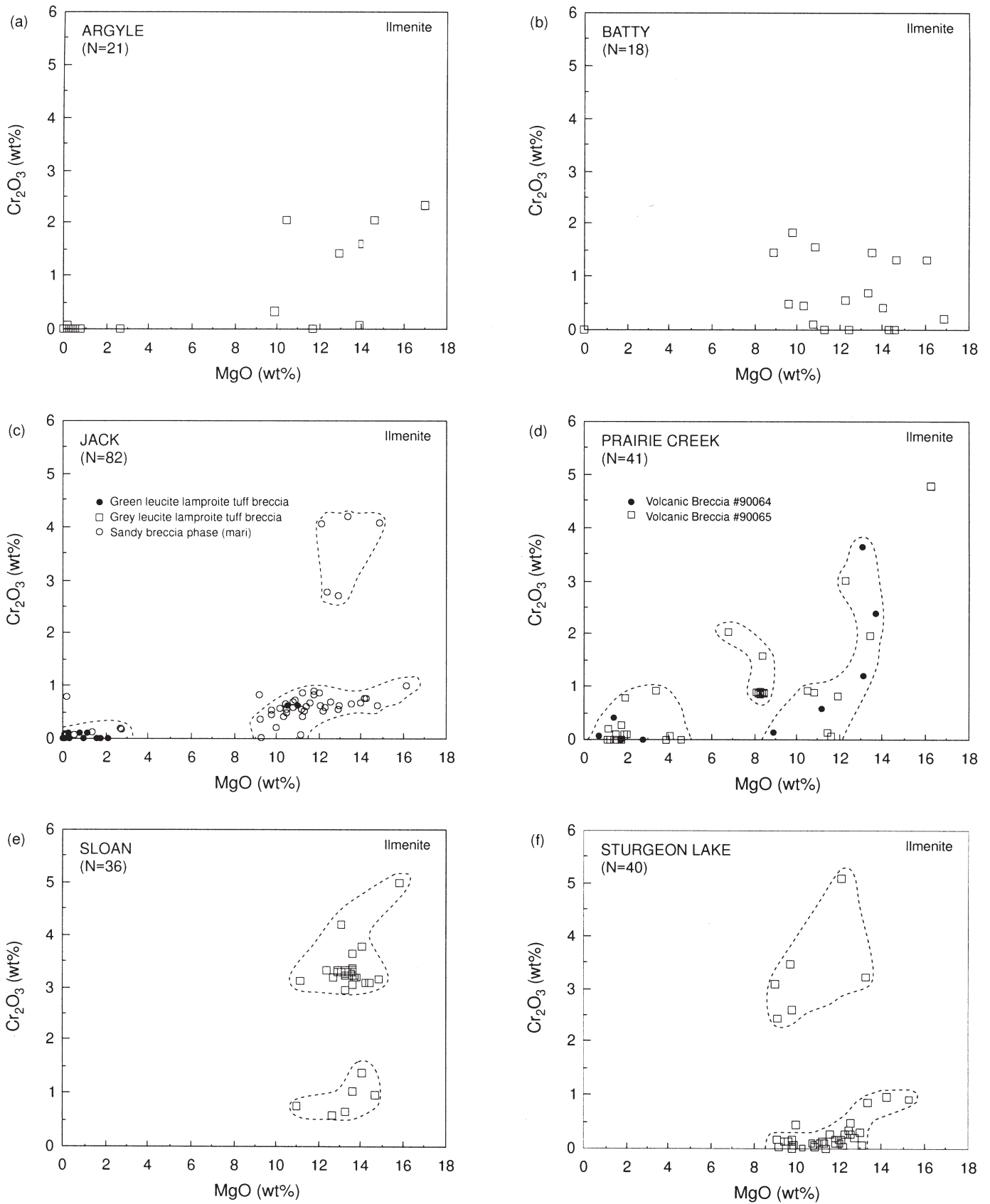


Figure 26(a-f). Ilmenite compositions for the localities investigated.

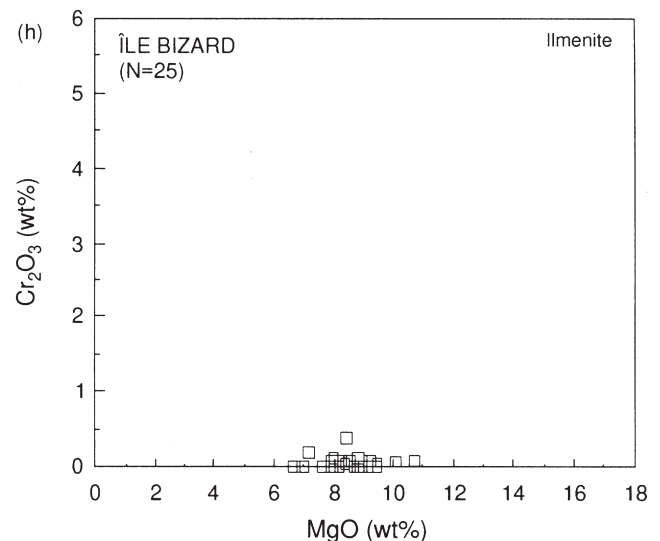
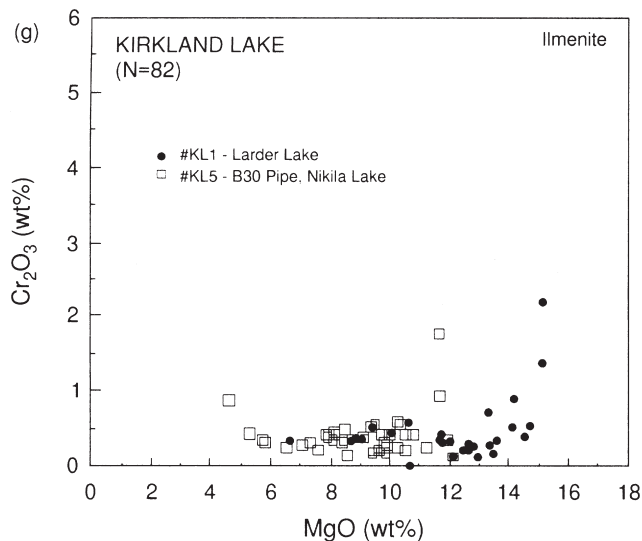


Figure 26(g-h). (cont'd.)

Blackfoot, Crossing Creek, Joff, Mountain Diatreme, New Elands and Sover have too few data for a meaningful assessment of the diamond preservation potential to be made for these localities.

Overall diamond forecasts and grade comparisons

Results are reviewed in Table 19. The following comments should be considered in conjunction with that table.

The forecast for Argyle, a high-grade lamproite dominated by diamonds of eclogitic paragenetic origin (Jaques et al., 1989), is far too low compared to actual results. Only a minor component of diamonds from a chromite-harzburgite source is predicted; both garnet harzburgite and eclogitic (based on low-Cr garnet compositions) forecasts are zero, which is clearly incorrect. A similar but not as dramatic situation exists for Prairie Creek. Grades of between 10 and 20 cts/100 tonnes have been determined for certain phases within this diatreme, although the overall grade is significantly lower than this. No detailed study of mineral inclusions in diamonds from Prairie Creek has yet been undertaken and so, whilst it is known that both parageneses are represented, the relative importance of each paragenesis is not. Irrespective of those details, the forecast is clearly too low in that it predicts no component of eclogitic diamonds and only a very minor component of diamonds from a garnet harzburgite source. The rarity of silicate indicator minerals in lamproites is now emerging as a characteristic feature of the rock type. While a suitable explanation for this oddity has not yet emerged, two

potential causes can be proposed. Certain mineral species, such as garnet, may be assimilated by the lamproite magma, and/or garnet is altered to secondary minerals in retrograde reactions. These and other possibilities are discussed further in the later discussion about lamproite exploration. They should be borne in mind when considering the results for all lamproites reported here.

The Batty, Blackfoot, Cross, HP, Ile Bizard, Jack, Joff, Kirkland Lake, Larry, Mark, Mike, Mountain, and Sturgeon Lake diatremes are all either barren of diamond or have had only trace amounts of diamond recovered, indicating very low grade. Where sufficient data are available, none of these diatremes are forecast to have a significant component of diamonds from any of the potential source rocks considered.

Sloan has a grade of 8-20 cts/100 tonnes (Shaver, 1988), and a recent study found eclogitic diamonds to predominate over peridotitic diamonds, roughly in the ratio 3:1 (Otter and Gurney, 1989). The forecast grade shows good agreement with the actual grade, since a low grade from each of the eclogitic and garnet harzburgite sources is predicted, with a very minor contribution from chromite harzburgite. As discussed previously, these components are additive to the total grade. The high forecast DPP suggests that these diamonds have been relatively well preserved. The forecast does not accurately reflect the paragenetic proportions, however, since surprisingly few Group I eclogite garnet macrocrysts were identified. However, this lack of resolution is not surprising considering the limited sample sizes and the inherent error in the forecasts.

Table 19

The diamond potential of the localities investigated, based on the heavy mineral geochemistry

Locality	Rock type	Gar-Harz diamonds	Chr-Harz diamonds	Eclogite diamonds	Gross diamonds	Diamond preserve	Net diamonds	Actual diamonds
Argyle	Lamproite	Nil	Low	Nil	V. Low	V. Good	V. Low	V. High/20
Batty	Kimberlite	V. Low	V. Low	Nil	V. Low	Good	V. Low	Nil 0/0
Blackfoot	Lamprophyre	Nil	Nil	Nil	Nil	Nil	Nil	Nil 0/0
Cross	Kimberlite	V. Low	Nil	Nil	Almost Nil	No Data	Almost Nil	Nil 0/0
HP	Lamprophyre	Nil	Nil	Nil	Nil	No Data	Nil	Nil 0/0
Ile Bizard	Alnoite	Nil	Nil	Nil	Nil	Nil	Nil	Nil 0/0
Jack	Lamproite	V. Low	Nil	Nil	Almost Nil	V. Good	Almost Nil	Almost Nil 1/1
Joff	Kimberlite	Nil	Nil	Nil	Nil	No Data	Nil	Nil 0/0
Kirkland Lake Sample KL5	Kimberlite	Low	Nil	Nil	V. Low	Good	Low	Low
Kirkland Lake Sample KL1	Kimberlite	Low	Nil	Nil	V. Low	Poor	Almost Nil	Unknown
Larry	Lamprophyre	Nil	Nil	Nil	Almost Nil	No Data	Almost Nil	Nil 0/0
Mark	Lamprophyre	Nil	Nil	Nil	Nil	No Data	Nil	Nil 1/0
Mike	Lamprophyre	Nil	Nil	Nil	Nil	No Data	Nil	Nil 0/0
Mountain	Alk. Basalt	Nil	Nil	Nil	Nil	Nil	Nil	Nil 0/0
New Elands	Kimberlite (Gp II)	V. High	High	Low	V. High	No Data	V. High	Mod sev./1
Prairie Creek	Lamproite	V. Low	Nil	Nil	Almost	No Data	Almost Nil	Low/Mod 0/0
Sturgeon Lake	Kimberlite	V. Low	Nil	V. Low	V. Low	Good	V. Low	Unknown 0/0
Sloan	Kimberlite	Low	V. Low	Low	Low	V. Good	Low	Low/Mod sev./2
Sover	Kimberlite (Gp II)	High	V. High	V. High	V. High	No Data	V. High	High sev./1

Forecast Diamond Grade Categories: Nil = Barren; Almost Nil = Microdiamonds only; V. Low = 0-1 ct/100 t; Low = 1-10 cts/100 t; Moderate = 10-40 cts/100 t; High = 40-100 cts/100 t; V. High = > 100 cts/100 t.

Categories for Diamond Preservation: Nil = 100% resorbed; Poor = 70-99% resorbed; Good = 30-70% resorbed; V. Good = 10-30% resorbed; Excellent = 0-10% resorbed.

New Elands kimberlite has a diamond grade in the region of 20 to 30 cts/100 tonnes. No paragenetic data are available, although at nearby Roberts Victor, a petrographically similar Group II kimberlite of the same age, 85% of the inclusions in diamond are peridotitic. The forecast predicts a very high component of peridotitic diamonds from both garnet and chromite harzburgite sources. No ilmenite data are available, consequently a DPP factor was not calculated. Unless highly oxidizing conditions in the upper mantle or kimberlite magma has caused significant resorption of diamond, the forecast grade clearly overestimates the actual grade for New Elands.

Sover is a profitable mine even though it is a dyke which seldom exceeds 60 cm in width. Because of wall rock contamination, true grades of pure kimberlite are hard to establish and are reported to be very variable. An average of >40 cts/100 tonnes is almost certain, and high localized values >100 cts/100 tones are apparently encountered from time to time. Visual inspection of inclusions in diamonds suggests that the paragenetic split is approximately 1:1 with respect to eclogitic and peridotitic parageneses. The forecast therefore correlates well with the known characteristics of this kimberlite, predicting a high component of diamonds from both peridotitic and eclogitic sources. Once again, insufficient data were available to compute a DPP due to a scarcity of ilmenites in the concentrate, a common characteristic of Group II kimberlites such as Sover and New Elands.

Discussion

Most of the North American occurrences emerge with a low forecast. This may be substantially correct, but caution must be applied where that occurrence is a lamproite because Argyle is greatly under-rated by the geochemical appraisal method. Therefore, in this report the predictions for the Jack, Larry, Mark and Mike diatremes might be low. However, the forecasts are in good accord with what is actually known about those localities with respect to microdiamond recoveries.

Multivariate statistical approach

In addition to the simple graphical discriminant diagrams utilized for the assessments, a multivariate statistical approach was developed and tested. The potential advantage of such a technique is that the covariance of a number of compositional variables can be simultaneously assessed, which could lead to the

recognition of features or trends not evident with a two-dimensional approach.

In simple terms, the technique involves expressing the dataset of compositions of inclusions in diamonds used in this study in terms of two multi-element equations (factors) by subjecting them to a factor analysis. The indicator mineral compositions are then expressed in terms of these factors and graphically assessed for similarities with inclusion compositions. Geological Survey of Canada (1989) contains further details.

Applying the expressions to the peridotitic garnet and chromite datasets for the localities investigated yields results which are in full agreement with the more simple "key elements" geochemical approach (Figs. 27, 28). However, the statistical method will not be successful in discriminating potential eclogitic diamond sources, because the critical (but very subtle) enrichments in Na₂O are effectively swamped by the numerous major element components constituting the factors.

The authors are of the opinion that the statistical approach offers no significant advantage over the graphical method. On the contrary, two major disadvantages with this method are: (a) the high degree of computation and data manipulation required, and (b) trends observed on factor plots are not readily understood in terms of geological processes.

EXPLORATION FOR LAMPROITES

While the indicator mineral geochemistry technique developed by Gurney and Moore has been very successful in locating and evaluating kimberlites all over the world, available evidence to date suggests it is not as successful when applied to lamproites (e.g., Fipke, 1991; Smith et al., 1991). This is so despite the fact that mineral inclusion studies (e.g., Hall and Smith, 1985; Jaques et al., 1989) have unequivocally demonstrated that the diamonds occurring in lamproites are derived from the same peridotitic and eclogitic source rocks which supply diamonds to kimberlites. The fundamental principles on which the technique is based should therefore be equally valid for lamproites. The primary reason for the reduced success of the technique is that indicator mineral abundances can be orders of magnitude lower in lamproites compared to kimberlites. In fact, in some cases, the silicate minerals associated with the dominant source of diamonds in the diatreme (e.g., eclogitic garnet and clinopyroxene at Argyle) are as scarce as the diamonds themselves.

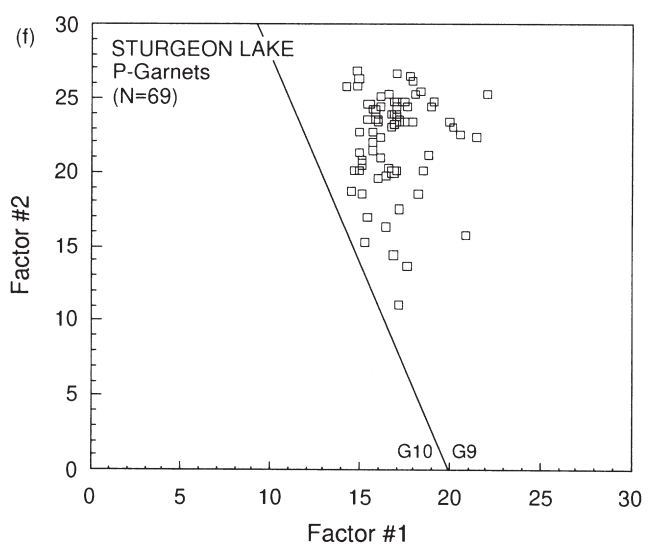
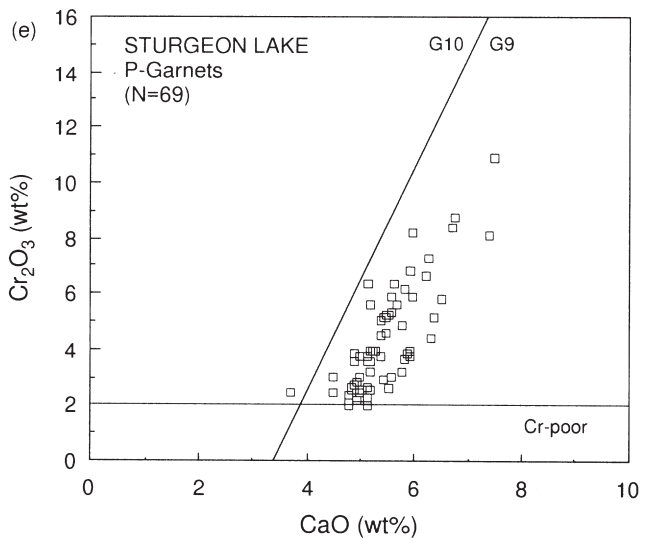
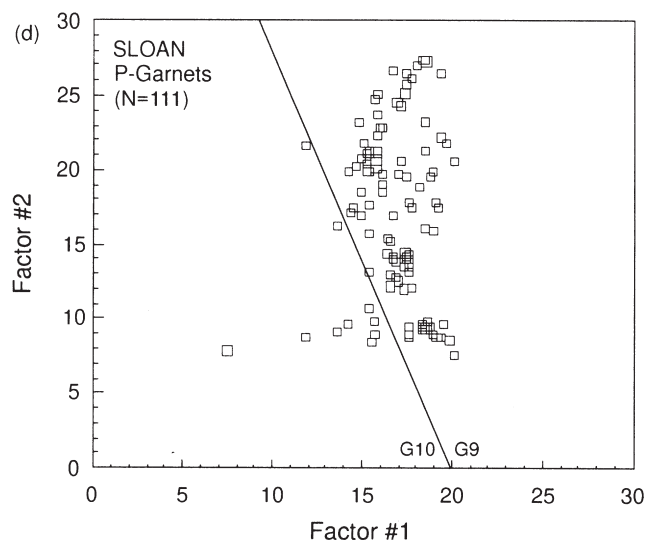
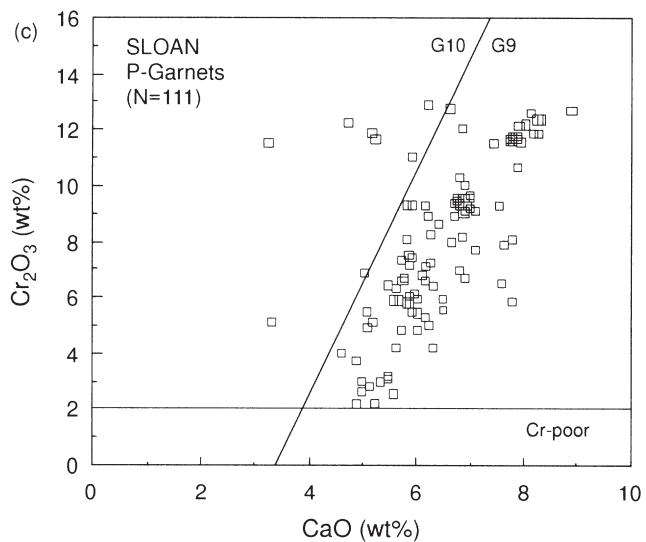
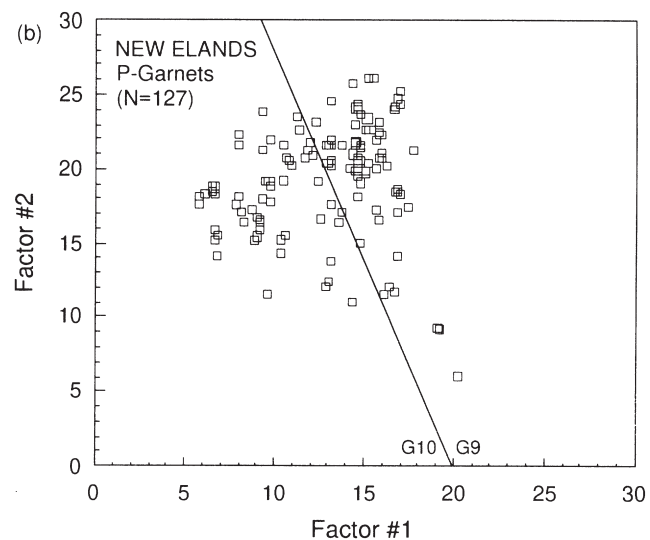
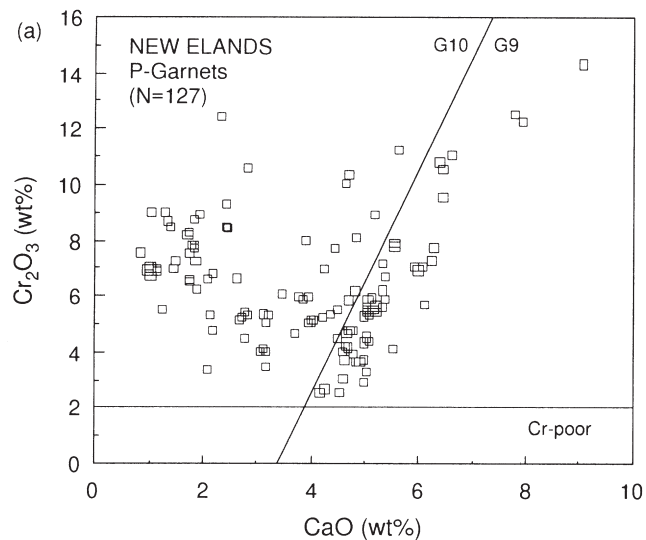


Figure 27(a-f). Comparison of selected peridotitic garnet factor plots against major element equivalents.

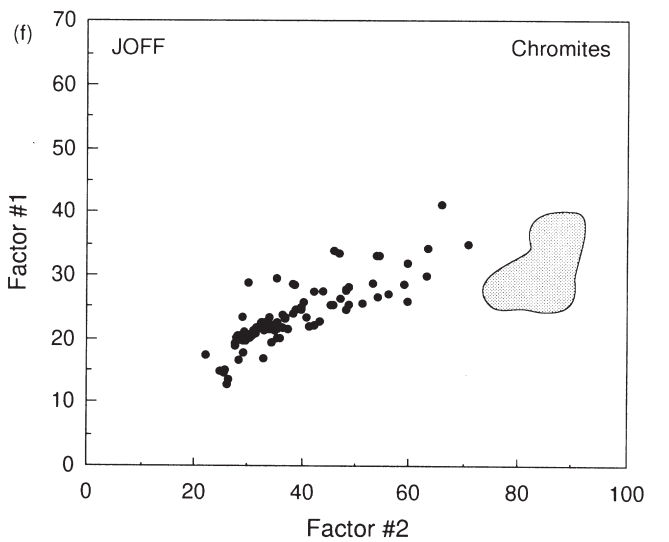
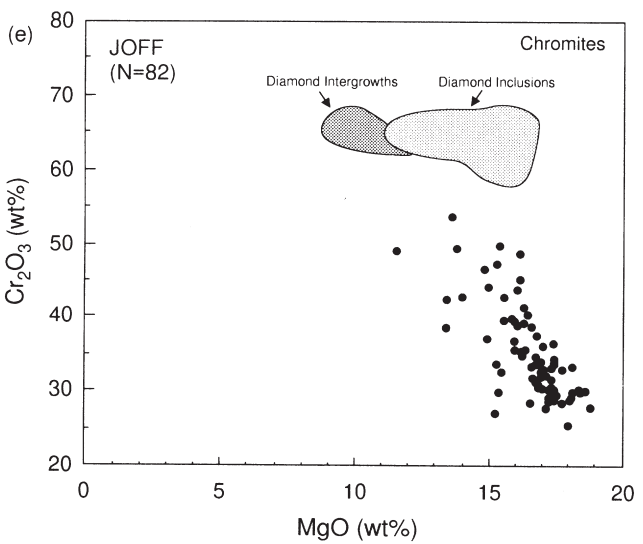
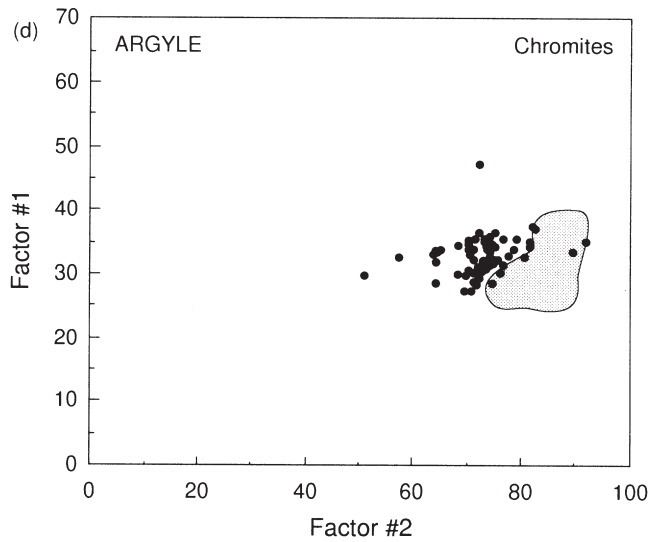
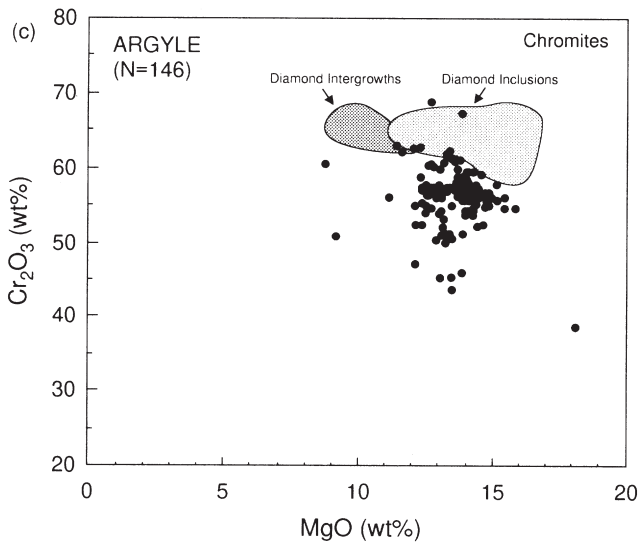
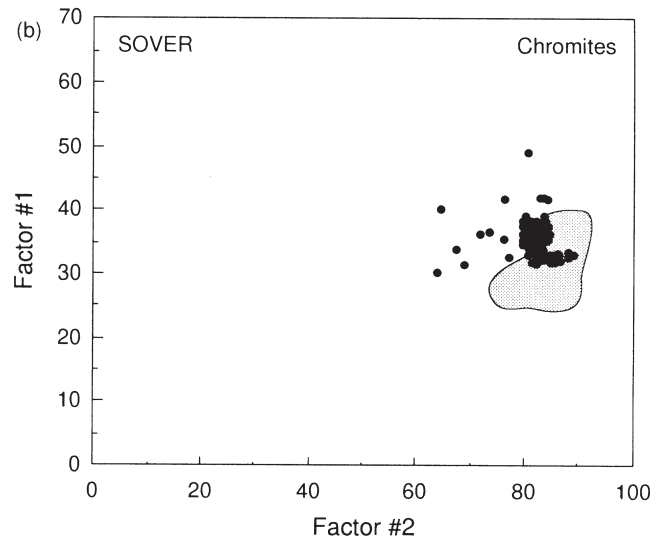
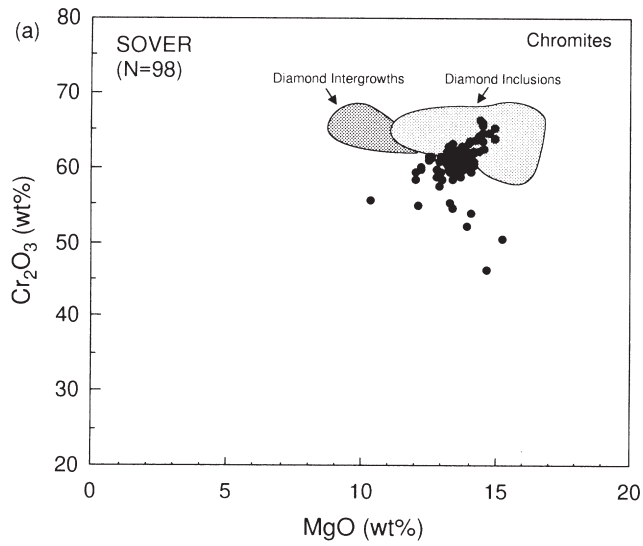


Figure 28(a-f). Comparison of selected chromite factor plots against major element equivalents.

This problem is particularly clear in the results reported earlier for indicator forecasts at Argyle. As previously mentioned, two potential causes for the rarity of silicate minerals at Argyle and in lamproites in general could be: (a) that certain mineral species, such as garnet, are assimilated by the lamproite magma, and/or (b) that mantle macrocrysts are replaced by secondary minerals in retrograde reactions. Evidence in support of (b) has been documented by Jaques et al. (1990), who describe the replacement of garnet in diamond-bearing peridotites by an assemblage of aluminous spinel and pyroxenes at Argyle. Argyle could be a special case in another respect. It would appear that the lamproite was intruded into unconsolidated, presumably wet sediments. This could have contributed to the alteration of the mantle xenocrysts.

Argyle and other lamproites, such as at Jack, could easily be overlooked in regional sampling surveys for heavy minerals if based on conventional indicator minerals. This reinforces the need to evaluate alternative pathfinder minerals for use in exploration programs aimed at locating lamproites. C.F. Mineral Research has documented the physical and chemical characteristics of several varieties of abrasion-resistant heavy minerals recovered from the ten lamproite localities investigated, and some of the results are summarized in this section. Notable features relevant to the lamproite results include:

- only three eclogitic (E) and three peridotitic (P) garnets were recovered from 32 kg of the most diamondiferous sandy tuff phase at Argyle (AT)
- only two E and three P garnets were recovered from 42 kg of the most diamondiferous phase from Prairie Creek (PC)
- similar low counts for these minerals were obtained for the Jack (JK) diatreme
- the Ellendale 4 (EL4) diamondiferous lamproite has an abundance of conventional kimberlite indicator minerals
- the most abundant abrasion-resistant heavy minerals present in the diamondiferous lamproites (AT, EL4, PC, JK) are chromites, G5 garnets (relatively Fe-rich), zircons and tourmalines.

Alternative pathfinder minerals

Some of the minerals discussed here (e.g., ilmenite) have been discussed previously in terms of the Gurney and Moore classifications. That information is not repeated here; rather some additional information

which may be particularly pertinent to lamproite exploration, compiled by Fipke and based largely on work undertaken by C.F. Mineral, is briefly discussed. Readers are referred to Geological Survey of Canada Open File Report 2124 (1989) and Fipke (1991) for further information on these topics.

Microdiamonds

The Argyle lamproite was discovered by collecting 40 kg bulk samples of alluvium and concentrated for micro- and macrodiamonds. Three such samples collected at 5 km intervals along Smoke Creek (now mined for alluvial diamonds), downstream from Argyle, contained 2, 4, and 5 diamonds respectively (Jaques et al., 1986).

Many companies exploring for diamonds in Australia have utilized flotation, fusion, and mechanical methods of concentrating microdiamonds in exploration samples. It is reported that such diamonds are present over widespread areas and, in many cases, may represent dispersed low-grade sedimentary or meta-sedimentary deposits of no economic significance rather than a lamproite or kimberlite target. It has been suggested that some of this regional distribution may be related to meteoritic impacts, as tektites are. Hence microdiamond recoveries may not always be pathfinders to terrestrial macrodiamond deposits.

Most diamond mines grade an order of magnitude less than Argyle. Consequently, impractically large exploration samples would be needed to have a fair chance at diamond detection. For instance, at the Point Lake kimberlite, N.W.T., Canada, which grades at approximately 68 cts/100 tonnes, five 12 kg samples of -2.8 mm till collected down-ice, within 200 m of the kimberlite, contained abundant indicator minerals but not a single micro- or macrodiamond. Four small microdiamonds were recovered from a 550 kg till sample collected 200 m down-ice, but sampling on this scale is seldom practical. Large scale sampling and recovery of diamonds may be warranted in the follow-up stages of exploration. However, in general exploration, using indicator minerals has proved a more reliable and cost effective technique than prospecting for diamonds itself.

Ilmenite

The utility of ilmenite compositions in assessing mantle redox conditions has been discussed previously and is not repeated here.

Ilmenite is not commonly found in association with diamond, but isolated cases of ilmenite inclusions in diamond have been reported in the literature. The majority of these inclusions (those from Argyle, South America, and Monastery Mine) are virtually pure end-member ilmenite (Table 20). Picroilmenite is reported as an inclusion in diamonds from Zaire, the Mir kimberlite in Yakutia, and from Finsch, South Africa (Table 20). With the exception of the example from Finsch, which is a true inclusion (J.J. Gurney, pers. comm., 1992), the foregoing picroilmenite "inclusions" may be intergrowths with diamond (S.E. Haggerty, pers. comm., 1991). Meyer (1987) classifies the Fe-rich ilmenites as belonging to eclogitic diamond paragenesis and the picroilmenites with peridotitic diamond paragenesis. Ilmenite is a rare accessory mineral in mantle-derived peridotite (Cox et al., 1973; Harte and Gurney, 1975) and has also been described in diamond-bearing examples (Pokhilenko et al., 1977). Furthermore, ilmenite is a common member of the megacryst suite of high pressure minerals whose relation to diamond source rock, if any, is unclear.

Trace to minor amounts of both high-Mn ilmenite and high-Cr picroilmenite were detected in all diamondiferous and non-diamondiferous lamproites studied. Owing to their flying-saucer-shaped or broken morphology, such ilmenites can be distinguished from regionally developed crystalline forms. However, the low quantities of these species of ilmenite in lamproite suggest that, on their own, both species would be unreliable heavy mineral sediment indicators. High-Mn ilmenite is typical of lamproite and shallow derived diatremes. It can be generated by secondary weathering processes associated with groundwater circulation; these ilmenites are commonly zoned and should not be used to provide information on mantle redox conditions or diamond resorption. Such secondary alteration is usually well developed in ilmenites from older diatremes such as Premier Mine (Wyatt, 1979).

Zircon

Meyer and Svizero (1973) reported that the first documented zircon inclusion in diamond appeared slightly elongate and very pale brown in color. Further examples have since been reported from Zaire (Ntanda et al., 1982); Monastery Mine, South Africa (Moore and Gurney, 1989); and Sloan, U.S.A. (Otter and Gurney, 1989). In all cases the inclusions are essentially pure $ZrSiO_4$ with only traces of impurities detected. Picroilmenite, phlogopite, chromite, chrome diopside and diamond have been reported as inclusions in kimberlite zircons (Botkunov et al., 1980; Kresten et al., 1975; Raber and Haggerty, 1979) which suggests that they are occasionally accessory minerals to rocks

of peridotitic paragenesis. Zircon occurs in MARID rocks and metasomatised peridotite (e.g., Bayly et al., 1979; Kinny and Dawson, 1992). Zircon also is a commonly documented member of the kimberlite megacryst suite, particularly well represented at the Monastery Mine where it has been found in association with ilmenite, olivine, phlogopite and clinopyroxene (Moore, 1986). These megacryst zircons are characterised by unusually low uranium (<10 ppm) and thorium contents and have been used to define the age of some host intrusions (Davis et al., 1976). Megacryst zircons are generally honey-colored, sometimes colorless, and may grow to several centimeters in size. They have been reported only in Group I kimberlites, not Group II kimberlites or lamproites (in common with other minerals of the megacryst suite).

In lamproites and kimberlites tiny (<0.5mm), typically round to spherical, purple to brown-colored, non-fluorescent zircons and pink to honey colored, orange fluorescent (to UV light) zircons were recovered in all 23 diatremes tested (Table 17). In some cases these zircons contain concentric overgrowths of dark purple or pink zircon on round, light-coloured cores. These zircons typically contain glassy to frosted textures that are similar to E and P garnets in that they are uniformly frosted in the hollows as well as the outer edges. Conversely, clastic zircon xenocrysts are typically frosted or abraded on outer edges but unaltered in hollows. Round to sub-rounded clastic zircons are commonly clear or white in color but can also be pink or purple, in which case they may not be easily distinguishable from the round "diatreme" zircons present in the same concentrate.

Parrish and Reichenbach (*in* Fipke et al., 1989) indicate that unabraded diatreme zircons from eleven North American diatremes (BT, BF, CC, HP, JK, JF, MR, MK, MD, PC and SL) yielded 49 to 559 ppm U and generally older (1,046 to 2,685 my) $Pb^{207/206}$ isotope ages relative to euhedral to subhedral zircons from the same diatremes. The generally high U and Th values and old ages of the "diatreme" zircons suggest that they are derived from cratonic basement formations intruded by diatreme magmas (Fipke et al., 1989). Similar round to well rounded varieties of zircons of a variety of colors have been recovered from 1.4 and 1.7 b.y. old plutonic rocks in Grand County, Colorado (Schroeder, 1984).

Clifford (1966) first indicated that, on a worldwide basis, economically important kimberlites typically intrude >2.4 b.y. cratons. Recent unpublished ion probe dates on round, pink and purple zircons from the AT, EL4, JK and PC diamondiferous lamproites (Dr. P. Kinney from A.N.U., Australia) indicate the

Table 20
Diamond inclusion compositions. Data from literature sources

ID	Grain	Min	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	NiO	Nb ₂ O ₃	ZrO ₂	References
Ilmenites Intergrowths/Inclusions																
Argyle	163	IL	0.03	51.83	0.01	0.01	46.63	0.68	0.47	0.04	0.01	0.01	0.01	0.01	0.05	Jaques et al., 1986
Brazil	1	IL	0.22	50.10	0.15	0.03	48.00	0.74	0.16	0.01	0.00	0.00	0.00	-	-	Meyer et al., 1973
Kim. S. Am.	5	IL	0.12	51.90	0.21	0.00	47.60	0.64	0.14	0.03	0.00	0.00	0.00	-	-	Meyer et al., 1976
Monastery	22	IL	-	39.49	2.53	0.18	51.83	0.23	3.15	-	-	-	-	-	-	Moore, 1989 (41KC)
Finsch	1	PIL	0.04	52.10	0.78	0.01	33.80	0.26	11.80	0.04	0.03	0.01	0.03	-	-	Tsai, 1978
Mir	2	PIL	0.01	52.90	0.47	0.44	36.50	0.27	9.10	-	-	-	-	-	-	Sobolev et al., 1976a
Zaire	3	PIL	0.16	52.50	0.48	2.54	29.50	0.29	13.00	0.04	0.17	0.00	0.05	-	-	Ntanda et al., 1982
Rutile Intergrowths with Diamond																
Mir	2	RUT	0.00	95.10	0.46	0.07	1.47	0.00	0.02	0.00	-	-	-	-	-	Sobolev, 1977
Mir	3	RUT	0.00	97.40	0.53	0.07	1.20	0.00	0.02	0.00	-	-	-	-	-	Sobolev, 1977
Mir	4	RUT	0.06	95.60	0.51	0.13	1.46	0.00	0.06	0.00	-	-	-	-	-	Sobolev, 1977
Mir	9	RUT	0.04	95.00	0.53	0.09	1.46	0.00	0.00	0.00	-	-	-	-	-	Sobolev, 1977
Rutile Diamond Inclusions																
Argyle	84	RUT	0.05	97.85	nd	0.05	0.82	nd	nd	0.04	nd	nd	nd	0.26	0.90	Jaques et al., 1986
Argyle	150	RUT	0.05	98.53	nd	nd	0.04	nd	nd	0.03	nd	nd	nd	1.77	0.04	Jaques et al., 1986
Ellendale 9	919	RUT	-	99.00	-	0.65	0.35	-	0.00	-	-	-	-	-	-	Hall and Smith, 1984
Ellendale 9	8	RUT	0.06	99.16	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.13	0.15	Jaques et al., 1986
Brazil	2	RUT	0.06	99.80	0.03	0.16	0.19	-	0.02	0.01	-	-	-	-	-	Meyer, 1973
Brazil	4	RUT	0.09	99.60	0.27	0.11	0.24	0.01	0.06	0.01	-	-	-	-	-	Meyer, 1975
Sloan	1	RUT	nd	97.80	0.06	0.08	0.25	nd	nd	0.10	-	-	-	-	-	Otter, 1989
Sloan	2	RUT	nd	96.00	0.35	nd	0.32	nd	nd	0.05	-	-	-	-	-	Otter, 1989
Sloan	3	RUT	nd	97.00	0.50	0.10	0.37	nd	nd	0.10	-	-	-	-	-	Otter, 1989
Sloan	4	RUT	nd	97.00	0.50	0.10	1.00	nd	0.10	0.06	-	-	-	-	-	Otter, 1989
Sloan	5	RUT	nd	96.90	0.67	nd	0.58	nd	nd	0.09	-	-	-	-	-	Otter, 1989
Sloan	6	RUT	nd	98.70	0.30	0.08	0.19	nd	nd	0.06	-	-	-	-	-	Otter, 1989
Sloan	7	RUT	nd	95.90	2.45	0.08	0.29	nd	nd	nd	-	-	-	-	-	Otter, 1989
Sloan	8	RUT	nd	97.40	0.45	nd	0.30	nd	nd	0.08	-	-	-	-	-	Otter, 1989
Sloan	9	RUT	nd	98.10	0.45	0.08	0.24	nd	nd	0.08	-	-	-	-	-	Otter, 1989
Sloan	10	RUT	nd	95.90	0.41	0.05	0.31	nd	nd	0.10	-	-	-	-	-	Otter, 1989
Sloan	11	RUT	nd	98.40	0.20	0.08	nd	nd	nd	0.05	-	-	-	-	-	Otter, 1989
Sloan	12	RUT	nd	98.80	0.48	0.06	0.45	nd	nd	0.06	-	-	-	-	-	Otter, 1989
Unknown	3	RUT	0.24	96.70	1.35	0.34	1.03	0.05	0.01	0.26	-	-	-	-	-	Prinz et al., 1975
Unknown	4	RUT	0.08	90.00	1.91	0.17	6.48	0.11	0.07	-	-	-	-	-	-	Prinz et al., 1975
Unknown	1	RUT	0.20	95.00	2.30	0.04	0.27	0.10	-	0.10	-	-	-	-	-	Ntanda et al., 1982
Corundum																
Monastery	1	COR	nd	3.05	96.42	nd	nd	nd	0.09	nd	0.02	nd	-	-	-	Moore, 1986
Sloan	52	COR	nd	1.14	98.00	nd	nd	nd	0.04	0.03	-	-	-	-	-	Otter, 1989
Sloan	114	COR	nd	2.01	96.20	nd	nd	nd	0.05	0.04	-	-	-	-	-	Otter, 1989
Unknown	6	RUB	0.29	0.09	97.40	1.30	0.22	0.02	0.13	0.02	0.04	0.00	0.01	-	-	Otter, 1989
Kyanite																
Argyle	1318	KYA	36.84	nd	63.16	nd	nd	nd	nd	nd	nd	nd	-	-	-	Hall and Smith, 1985
Finsch	4	KYA	36.40	0.11	62.80	nd	0.16	-	0.00	-	-	-	-	-	-	Gurney et al., 1979
Premier	2	KYA	37.00	0.10	62.87	0.05	0.34	-	0.17	0.04	nd	-	-	-	-	Gurney et al., 1986
Sloan	1	KYA	37.20	0.12	61.60	nd	0.35	nd	0.08	nd	nd	nd	-	-	-	Otter, 1989
Zaire	5	KYA	36.70	-	61.10	2.40	0.40	-	-	-	-	-	-	-	-	Ntanda et al., 1982
Zaire	6	KYA	36.80	-	62.40	0.10	0.30	-	-	-	-	-	-	-	-	Ntanda et al., 1982
Zaire	1	KYA	37.00	-	62.00	0.03	0.90	-	-	-	-	-	-	-	-	Ntanda et al., 1982
Zaire	2	KYA	37.30	0.03	62.00	0.12	0.27	0.00	0.03	0.00	0.00	0.00	0.00	-	-	Ntanda et al., 1982
Unknown	3	KYA	36.60	0.10	62.10	0.03	0.30	-	0.04	-	-	-	-	-	-	Prinz et al., 1975

presence of several groupings of zircon ages, but >2.4 b.y. zircons are present in each of these lamproites. There are no >2.4 b.y. clastic units outcropping in the region of any of the aforementioned pipes. The source of these old zircons could be from >2.4 b.y. cratonic rocks, or they could represent second or third generation zircons which have been recycled into younger sedimentary rocks.

A practical method of distinguishing round, potentially thermally altered clastic zircons from cratonic zircons is needed before any conclusions of economic significance can be made from zircon distribution. However, the presence of zircons yielding Archean ages in any diatreme is of interest in that it may indicate the existence of ancient lithosphere, and hence a source rock for diamonds.

Orthopyroxene

Orthopyroxene is a relatively common mineral inclusion in diamonds where it occurs as high magnesian enstatite associated with peridotite paragenesis. Figure 29a demonstrates that, with the exception of a few websteritic inclusions related to eclogitic diamonds from Orapa and Monastery (e.g., Moore et al., 1989), orthopyroxene inclusions have a restricted range of composition. Only two orthopyroxenes from lamproites are reported: in diamonds from Ellendale 4. and one from Argyle (Jaques et al., 1986), and these are compositionally indistinguishable from other orthopyroxene inclusions. A set of 196 orthopyroxene compositions from non-diamond bearing rocks throughout the world, including barren lamproites and kimberlites, is plotted in Figure 29a for comparison. There is no overlap with the field for orthopyroxene compositions from rocks other than kimberlite or lamproite. However, a few orthopyroxenes from barren kimberlites (e.g., Elliot County, Kentucky) plot within the range of compositions for orthopyroxene inclusions. Characteristically, the enstatite associated with diamond is higher in MgO and lower in FeO, Al₂O₃, CaO, and Na₂O compared to other orthopyroxenes. The low CaO and Al₂O₃ contents correlate with low equilibration temperatures and high pressures, compatible with diamond stability.

Orthopyroxene was found to be quite abundant in Ellendale 4 but minor to absent in the other lamproites investigated. A total of 141 grains were analyzed from Ellendale 4, five from the Jack and three from Argyle. These were 0.3-0.8 mm in size, subhedral, translucent and ranging from colorless to brownish, and dark greenish to grey. Literature sources produced another six analyses from Ellendale diamondiferous lamproites

and one from Argyle, which are all plotted with analyses of orthopyroxenes from diamondiferous kimberlites on Figure 29b.

Sixty-five orthopyroxenes from diamondiferous kimberlite, as well as three from Ellendale 4 and a single orthopyroxene analysis from Argyle, Ellendale 11, and from another West Kimberley diamondiferous lamproite, plot within the diamond inclusion field of orthopyroxene inclusions in diamond.

The relatively fragile and unstable minerals such as orthopyroxene, olivine and clinopyroxene would not be expected to survive significant alluvial transport and would, consequently, not be very useful as pathfinder minerals in prospecting for diamondiferous diatremes in some environments. Indeed, the presence of these minerals in heavy mineral samples from tropical and subtropical environments generally implies that the sample was collected 2 km to 3 km from source (Fipke, pers. comm.).

Some cases, however, have been reported where even these fragile minerals are relatively persistent. In Canada, Fipke (pers. comm.) reports Cr-diopsides to be present in alluvium for distances of up to 50 km downstream from the Blackfoot diatreme in S.E. British Columbia. In the cold climate of the NWT, Canada, indicator minerals appear to be transported in continental glaciers and preserved over distances of 600 km westward from the Lac de Gras area. Similarly, in Alberta a lamproite exploration program has detected small quantities of olivine and orthopyroxene which overlap with diamond inclusion compositions, and elevated K₂O clinopyroxenes, in streams containing anomalous amounts of chromites and other indicators (Fipke, 1991). Similar results have been reported from Siberia; Afanasev et al. (1984) report that olivines appear to have been transported up to 100 km downstream from the Upper Muna kimberlite field. They note that, whilst larger olivine grains (>1 mm) are considerably abraded during transportation, smaller grains are relatively well preserved.

Apart from the cold weathering conditions in parts of Canada and Siberia, McCandless (1990) offers the following additional explanation: "The presence of fine-grained material in gravel can significantly hinder the wear of the xenocryst minerals even when much larger clasts comprise 50% of the sediment. Presumably the fine-grained component cushions the xenocryst minerals from contact with other clasts by increasing the overall viscosity of the sediment charge." This could be a major factor in glacial deposits.

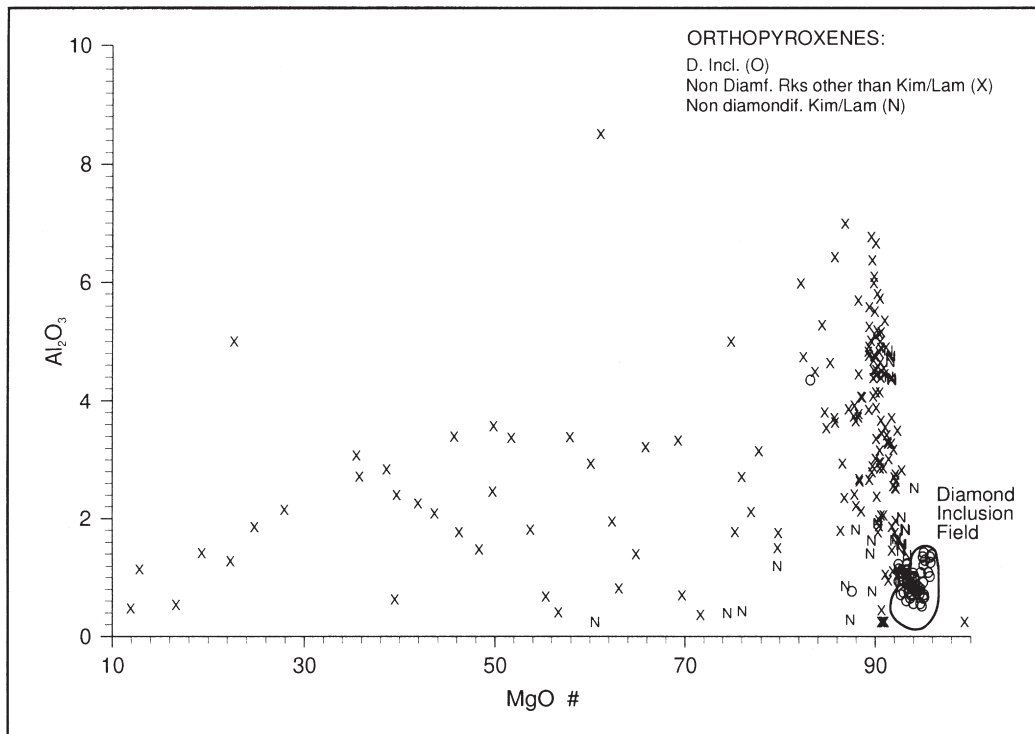


Figure 29a. Comparison of compositions of orthopyroxene from inclusions in diamond with other orthopyroxenes (data from literature sources).

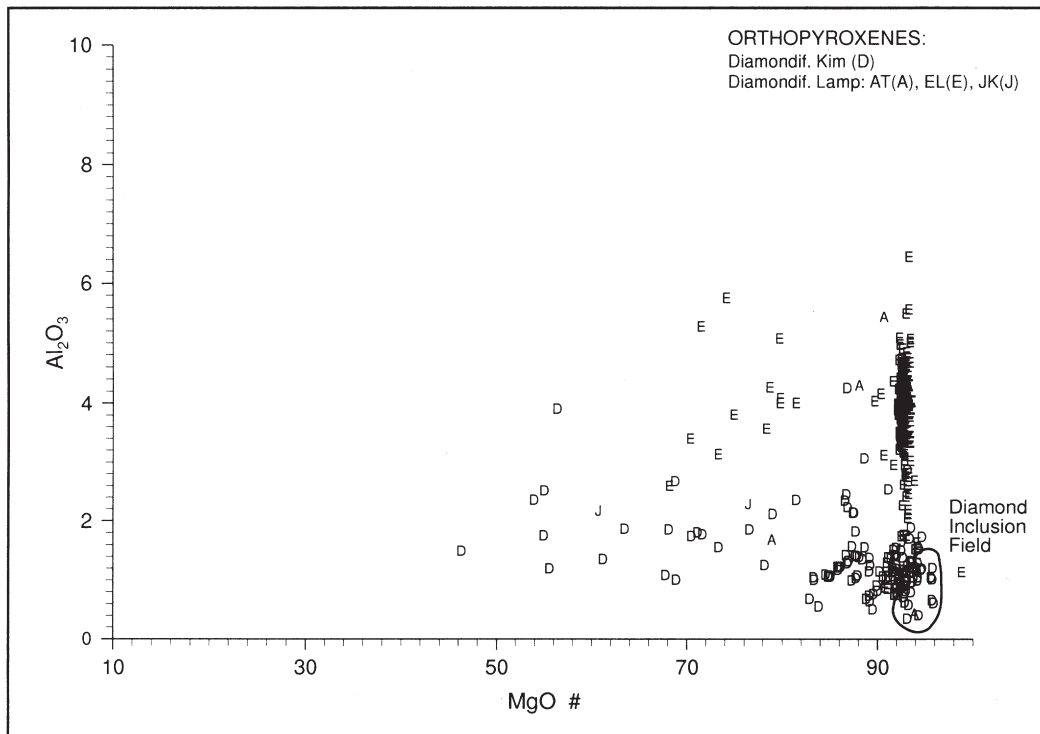


Figure 29b. Comparison of compositions of orthopyroxene from inclusions in diamond with orthopyroxenes from kimberlite sources.

Based on the above, Fipke reports that orthopyroxene of diamond inclusion composition is insufficiently abundant to constitute a routine indicator mineral for locating and assessing the diamond potential of targets, but when it is found it may yield useful information.

Clinopyroxene

Gurney and Moore (1989) indicated that in certain circumstances it may be useful to evaluate the potassium content of clinopyroxene. McCandless and Gurney (1989) have demonstrated that the clinopyroxenes in eclogite associated with diamonds commonly show trace enrichments in K_2O (>0.07 wt%). Potassium is not compatible in the clinopyroxene structure, but trace amounts may be accommodated under the high pressure conditions necessary for diamond formation (e.g., Erlank and Kushiro, 1970).

Studies of eclogitic rocks (e.g., Switzer and Melson, 1969) have shown that potassium-bearing clinopyroxenes are unstable at low pressures. Decompression melting, with consequent loss of K_2O to the fluid phase generated, leads to rapid loss of K_2O . Extreme care, therefore, has to be exercised in the sense that only fresh portions of mineral grains without any cloudiness, cracking, exsolution or fluid inclusions should be selected for K_2O analysis. Single grains commonly show more than one of these features, leading to the inhomogeneous distribution of potassium.

In order to further explore the potential of clinopyroxene as an alternative pathfinder, the compositions of both eclogitic and peridotitic clinopyroxene inclusions in diamonds from around the world and those of the clinopyroxenes recovered from the diatremes studied have been classified into groups based on both the discriminant and range methods of Stephens and Dawson (1977) (Table 17). In addition, these compositions have been classified on the basis of simple discriminants into Cr-poor (CE) and Cr-rich (CP) kimberlite clinopyroxenes and a group representing clinopyroxenes derived from regional volcanic sources (CV) which have >3.3 wt% Al_2O_3 and >19.6 wt% CaO. A considerable number of pyroxenes did not classify within the classification ranges of Stephens and Dawson, indicating that these ranges need adjusting to fit a larger database.

While Table 17 illustrates that CP8, CP9, and CP10 eclogitic clinopyroxenes are the most abundant types found as inclusions in diamond from both kimberlites

and lamproites, none of these types has been recovered from any of the project samples. Furthermore, these eclogitic clinopyroxenes (jadeitic diopsides) have never been reported in matrix kimberlite or lamproite.

The diamondiferous Argyle, Prairie Creek, Ellendale 4, and Jack lamproites, as well as the non-diamondiferous Smoky Butte lamproite, contain pyroxenes that fit the CP1, CP2, CP5, and CP6 groups of Stephens and Dawson (1977). Diamond inclusions fall into three of these groups: CP2, CP5, and CP6. One CP5 has been recovered from an Ellendale diamond (Jaques et al., 1986), and three clinopyroxenes which do not classify within the Stephens and Dawson (1977) ranges have been identified in diamonds from the Ellendale and Prairie Creek lamproites (Table 17).

CP1, CP2, CP5, and CP6 clinopyroxenes were identified not only in diamondiferous lamproites but also in the investigated lamprophyric diatremes that are assumed to be barren of diamond (Table 17). Therefore, it appears that no direct correlation between clinopyroxene compositional groups and diamond content can be made.

It is concluded that where bright green Cr-diopside (CP) is a useful visual pathfinder mineral for the location of kimberlite and/or lamproite diatremes, an abundance of elevated K_2O CE or CP clinopyroxenes provides further encouragement for diamond potential.

Olivine

Olivine is well represented as an inclusion in diamond from both kimberlites and lamproites; characteristically highly magnesian-rich forsterite ($Fe_{0.2-96.6}$), with significant amounts of nickel (0.2-0.49 wt% NiO). Jaques et al. (1989) analyzed a total of nine olivines from Argyle and Ellendale 4, and compositions fall within the range reported for diamond inclusion olivines from worldwide sources.

The composition of 145 olivines from non-diamondiferous rocks including kimberlites, lamproites and other "regional" varieties, has been compared with the composition of diamond inclusions on all possible combinations of inter-element plots. A considerable overlap in compositions exists. Only on the Fo (Mg) versus Cr_2O_3 plot (Fig. 30a) is some discrimination between the datasets possible.

Olivine was not an abundant constituent of any of the heavy mineral concentrates derived from lamproites studied for this report. This is not

surprising since olivine readily alters to serpentine and talc. Nevertheless, some olivines were recovered and analyzed from the lamproites considered in this project, and these analyses, along with olivine analyses from worldwide diamondiferous lamproites and kimberlites, give a wide range of compositions which partially overlaps the field of diamond inclusion compositions (Fig. 30b). For example, the following proportions of olivines plot within the diamond inclusion compositional field for these localities: Argyle: 8 out of 20; Ellendale 4: 10 out of 23; Jack: 1 out of 13; Prairie Creek: 2 out of 5. Furthermore, 36 out of 193 olivine compositions from diamondiferous kimberlite plot within the diamond inclusion olivine compositional field (Fig. 30b), whilst none of the 5 olivine compositions from the barren Smoky Butte lamproite plot within this field.

Despite some problems of compositional overlap, Fipke reports that olivine can be utilized as a diamond indicator mineral in the glacial areas of Canada where fine grained glacial sediments protect them from abrasion and where cold temperatures inhibit secondary alteration.

Kyanite

A small number of kyanite inclusions have been reported in diamonds from both kimberlites and lamproites (Table 20). In addition to its relatively rare occurrence in Group I and II varieties of eclogite, kyanite has been documented to occur in several diamond-bearing eclogite xenoliths from southern Africa and from the former USSR (e.g., Dawson, 1980).

With one exception, the kyanite inclusions in diamonds have very low concentrations of trace element impurities. The documented exception is of kyanite recovered from a Zairian diamond with a relatively high chrome content (2.4 wt% Cr₂O₃, Table 20). Sobolev (1977) reports the occurrence of high-Cr kyanite and corundum in the Zagadochnaya kimberlite. However, since kyanite with 2.2-4.35 wt% Cr₂O₃ also has been documented to occur in basic metamorphic rocks in N.W. Spain (Ibarguchi et al., 1991), high-Cr kyanite cannot be regarded as unique to kimberlite. In addition, Zagadochnaya is barren of diamonds; consequently, high-chrome kyanite holds little promise as a diamond indicator.

Three small (0.3-1.1 mm) grains of white, subrounded to subhedral kyanite and a single (1.1 mm)

bluish-white, subhedral broken kyanite were detected in concentrates from the Argyle and Ellendale 4 lamproite respectively. All of these had very pure compositions similar to the bulk of the kyanite inclusions (Table 20). The majority of kyanites from regional metamorphic rocks also show very pure compositions (Deer et al., 1963). Apart from eleven similar kyanite grains recovered from the weakly diamondiferous Batty (BT) and Kirkland Lake (KL) kimberlites, no other examples were detected in the diatremes studied (Table 17).

This evidence suggests that kyanite is unsuitable for use as an indicator mineral in exploration for lamproites (and kimberlites).

Corundum

At least four occurrences of corundum inclusions in diamond are reported in the literature (Table 20). Corundum-bearing eclogite xenoliths (including both Group I and II varieties) have been described from diamondiferous kimberlites in Siberia (e.g., Aikhal and Mir) and South Africa (e.g., Frank Smith, Roberts Victor, New Elands, Bellsbank, Bobbejaan, Jagersfontein and Koffiefontein). Sobolev (1977) reports a light blue sapphire variety of corundum in an eclogite xenolith from Mir which hosts two 1.5 carat diamonds. Corundum may be present in several other varieties of non-diamondiferous rocks such as ultramafic and calc-alkaline lamprophyres and alkaline basaltic diatremes.

The only significant minor element impurity detected in the three corundum inclusions from Sloan and Monastery was titanium, which occurs at levels of 1.1 to 3.1 wt% TiO₂ (Table 20). A ruby corundum inclusion reported by Meyer and Gubelin (1981) is low in titanium (0.09 wt% TiO₂) but contains 1.3 wt% Cr₂O₃.

Minor amounts of subhedral, subrounded and/or broken corundum grains, ranging in size between 0.3 and 0.7 mm, were recovered in the heaviest non-magnetic concentrates of all of the lamproites tested. These grains are typically translucent to clear white, but light brown and pink varieties were also present. Light blue sapphire, as well as milky white pseudo-octahedral corundum, was detected in the Jack (Phase 2) lamproite. The paragenesis of these corundums is uncertain, and there does not appear to be any way to link them to diamond potential because corundum inclusions in diamonds are very rare and the compositional range poorly defined.

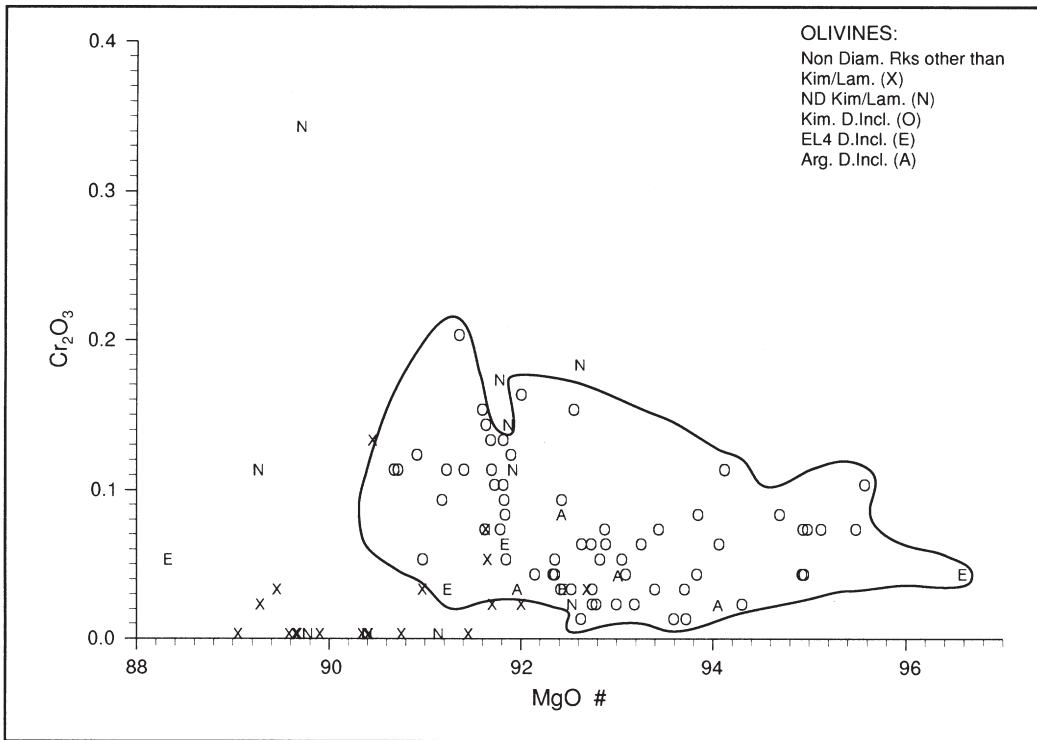


Figure 30a. Comparison of compositions of olivine from inclusions in diamond with other olivines (data from literature sources).

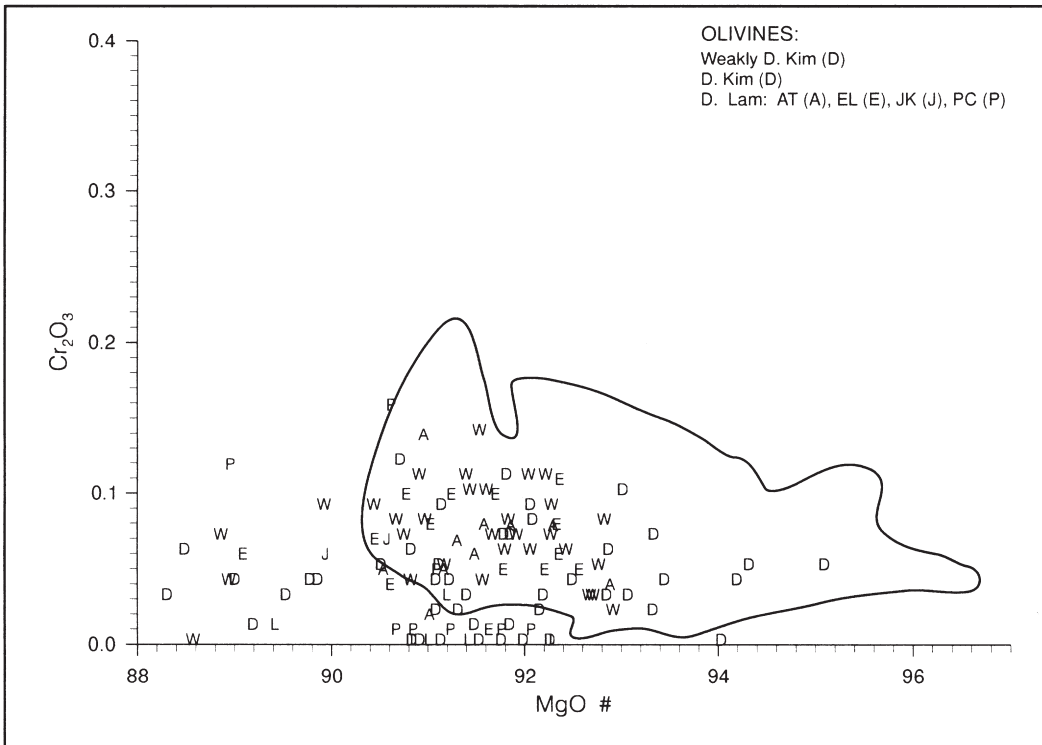


Figure 30b. Composition of olivine from diamondiferous kimberlite and diamondiferous lamproite sources.

Rutile and related minerals

The compositions of rutiles intergrown with diamonds from Mir, as well as those included in diamonds from the Argyle and Ellendale lamproites, and various worldwide kimberlites are summarized in Table 20. They generally show relatively pure end-member compositions, but minor amounts of Al_2O_3 , Cr_2O_3 and FeO may be present. Kimberlite rutiles commonly show significant concentrations of niobium, but Nb_2O_5 analyses are available only for the three inclusions from Argyle and Ellendale, where levels of 0.13 to 1.77 wt% are reported.

Nb-bearing rutile was recovered as a minor to abundant accessory mineral in all the lamproite samples evaluated where it occurs as spherical or rounded, brown to grey or black, translucent to opaque grains. Rutile and Nb-bearing rutile have also been documented as relatively common accessory minerals in kimberlites from all over the world (e.g., Fipke, 1991; Haggerty, 1991). They occur in MARID rocks, is a ubiquitous minor phase in eclogites, and commonly is found in metasomatised peridotites and polymict peridotites. In the samples from the Jack diatreme, Nb-rutile, together with dolomite and possible silicates, form rounded "autoliths," which are easily mistaken for altered disc-shaped ilmenites. Locally, the Nb-rutile contains tiny blebs of an unidentified mineral that analyzes 49-56 wt% Nb_2O_5 , 17-27 wt% TiO_2 , 13-17 wt% FeO, and 7-8 wt% WO_3 ; as well as tiny blebs of an unidentified Zr-Ti-Fe silicate (Plates 3, 4). The latter unidentified Zr-Ti-Fe silicate, with compositions ranging between 25-53 wt% ZrO_2 , 13-32 wt% TiO_2 , 0.6-22 wt% FeO and 13-26 wt% SiO_2 , is also present in the Argyle lamproite (A.L. Jaques, unpublished data). Up to 29 wt% Nb_2O_5 and 1-6 wt% WO_3 have been detected in rutiles from Jack. Haggerty (1991) reports rutile from Orapa with up to 20.9 wt% Nb_2O_5 and 1.7 to 4.1 wt% Cr_2O_3 .

In addition to rutile formed in the upper mantle (kimberlite, lamproite and eclogite), it is typically found in pegmatites and contact metamorphic rocks, such as meta-limestones and meta-argillites.

With the exception of a single grain of Nb-rutile from Ile Bizard, rutile was undetected in all the other four bulk samples of barren alkaline lamprophyre (Table 17 - PO23, BF, HP and MD). Although rutile is not sufficiently abundant to be of routine use in diamond exploration, where Nb-rutile is found in association with other indicators it may provide further encouragement for diamond potential (Fipke, 1991).

Magnetite

Garanin and Kudryavtseva (1990) established that the black coloration of bort from three kimberlites in Siberia is caused by numerous hematite and magnetite inclusions. They contend that such inclusions are formed during the end stage of diamond crystallization, which includes Ti-chromite, pentlandite, apatite, calcite and phlogopite. In contrast, Sobolev (1985) assigns magnetite to a diamond-bearing (Group I) eclogite paragenesis.

Whilst Jaques et al. (1986) report hematite to be present in Argyle and Ellendale diamonds, no magnetite inclusions have been recovered from lamproite diamonds to date. Meyer (1987) documents inclusions of magnetite in diamond from the Sloan and Mir kimberlites and several other areas. Moore and Gurney (1989) report nine magnetite and six hematite inclusions in diamond from the Monastery kimberlite, while Otter and Gurney (1989) identified a possible syngenetic magnetite inclusion in a diamond from Sloan. Published analyses by latter authors indicate the magnetite inclusions to be typically pure end-member compositions, but in a few cases minor impurities were detected (up to 0.48 wt% TiO_2 , 1.31 wt% Al_2O_3 , 0.05 wt% Cr_2O_3 , 0.18 wt% MnO and 3.73 wt% MgO).

Small quantities of magnetite (i.e., <0.1 g/kg of bulk sample) were present in all of the lamproites (AT, EL4, JK, PC and SB) tested, occurring typically as <0.5 mm black grains of highly variable morphology (rounded to broken, anhedral and/or euhedral, octahedral forms). Compositions are variable, but end-member compositions similar to the magnetites included in diamond predominate. However, similar pure forms of magnetite are very common in crustal rocks, and no practical method of recognizing magnetites from diatreme sources has yet been developed. Therefore, this is not yet a useful mineral in diamond exploration.

Tourmaline

Minor to abundant quantities of spherical, light translucent, brown to opaque brown, dravitic tourmalines were recovered from all diamondiferous lamproite tested (AT, EL4, PC, JK), but were not recovered from the Smoky Butte (SB) barren lamproite. Minor amounts of round tourmalines have also been recovered from the Sturgeon Lake (SK) and Joff (JF) kimberlites, as well as a potential lamprophyre diatreme located near Presidente

Olegario, Brazil (PO1), which is located upstream from an alluvial diamond-mining area (Table 17). Tourmalines were not identified in other diatremes tested. The tourmalines, where present, are characteristically unzoned, exhibit glassy to frosted textures typical of kimberlite P and E garnets, and generally lack abraded surface textures (Plate 6).

Fifty-four out of 57 (95%) of the diatreme tourmalines analyzed show the restricted compositional ranges summarized in Figure 31. Core and rim analysis of many of the grains undertaken by Robert King of the University of Saskatchewan did not indicate any major element chemical zonation.

Eighty-two examples from a database of 462 worldwide tourmaline compositions supplied by D.J. Henry, D.B. Clarke and R. King also fall within the restricted compositional ranges of the diatreme tourmalines. Most of the regional tourmalines that classify with the diatreme tourmalines originate from mineral deposits (e.g., the Sullivan Pb-Zn Mine in B.C., Canada), or granitoids and associated pegmatites and aplites.

Trace element analyses of typical diatreme tourmaline undertaken by CSIRO in Sydney, Australia, give ranges of 20-115 ppm Ga and 0-200 ppm Sr (Table 21). Variable concentrations of Cr, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Mo, Ba, Pb, Th, and U were also detected (Table 21). Replicate analyses completed on two different 30 μm spots in the core region of five individual grains generally yielded consistent results, but some significant discrepancies were noted (e.g., Grain PC 04108, Table 21). In such cases, variations could be due to the presence of microscopic inclusions. The tourmalines from lamproite/lamprophyre diatremes (AT, EL4, PC, JK and PO) give a frequency distribution range of 80-640 ppm Zn. In contrast, Zn values range between 670 and 4800 ppm in the tourmalines from the Sturgeon Lake kimberlite in Saskatchewan (Table 21).

Initially, the round tourmalines were regarded as round xenocrystic grains derived from wallrock sandstone units sampled by the lamproite or kimberlite during intrusion. However, the thousands of tourmaline grains recovered from the diatremes investigated to date are always very similar in physical appearance, i.e., rounded, light to dark brown in color and unzoned. Moreover, most tourmaline grains analyzed yield consistent major element compositional ranges which are significantly different to regional tourmalines. If the round tourmalines originate from

sandstone lithologies and considering the global distribution of the diatremes investigated, one could reasonably expect some variation in color, zonation and composition. This is not the case in those studied to date.

Eighty-two analyses of tourmaline cores from predominantly igneous rock sources yield major element compositions equivalent to the diatreme tourmalines. However, if the diatreme tourmalines are xenocrysts from either igneous or metamorphic source rocks, it would be anticipated that they would exhibit some vestige of the elongate, idiomorphic, zoned form characteristic of both metamorphic and igneous tourmalines. For instance, the Batty pipe of Somerset Island, Canada, contains substantial amounts of elongate euhedral sillimanite assimilated from an unexposed metamorphic unit intruded by the kimberlite.

An alternative model, which could possibly account for the textural and compositional features of the tourmalines present in diamondiferous diatremes, has been proposed by Fipke (1991). The model would also explain the occurrence of jadeitic diopside (Group CP8) as a relatively common inclusion in diamond while it is absent in the rock matrix of kimberlite and lamproite. This model envisages an olivine-rich magma intruding a Group I and/or Group II eclogite unit at approximately 150 km depth and, on transport to relatively shallow 30-50 km levels, assimilating and rounding the jadeitic diopside and kyanite components of the eclogite. Differentiation, in response to the crystallization of olivine and other phenocrystal phases from the magma, would concentrate boron and weak acid gases. These would be available with olivine and assimilated Al_2O_3 and SiO_2 components of the magma for reaction adjacent to the crust interface with (now rounded) jadeitic diopside to form round, unzoned dravitic tourmaline pseudomorphs. Boron is present in amounts of 9-115 ppm in matrix kimberlite and 8-175 ppm in matrix lamproite (Fipke et al., 1989).

If such a model is responsible for rounded tourmaline pseudomorph development, then tourmalines with elevated K_2O - TiO_2 within the Group I clinopyroxene compositional field outlined in Figure 31 would have a higher probability of being derived from Group I diamond-bearing eclogite. In fact 100% of the tourmalines analyzed from Argyle, 55% from Ellendale 4, 50% from Prairie Creek, 50% from the Jack lamproite, and 17% from the Sturgeon Lake kimberlite plot within this field in Figure 31. Although only 59 tourmalines have been analyzed, the number of

Table 21

Core compositions of round tourmalines extracted from lamproite and kimberlite

ID	Grain	Microprobe Analysis by University of Saskatchewan and K ₂ O* by University of Cape Town											
		SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	B ₂ O ₃	F	CL
AT	04101	35.82	0.95	33.44	7.36	0.02	5.82	0.80	1.79	0.06*	10.6	0.1	0.0
AT	04102	34.99	1.04	33.22	9.57	0.00	4.26	0.62	1.86	0.05*	10.5	0.2	0.0
AT	04103	34.87	0.90	33.93	7.68	0.02	5.44	0.70	1.83	0.04*	10.5	0.1	0.0
AT	04104	34.90	0.70	33.74	9.54	0.10	4.08	0.41	1.92	0.04*	10.4	0.3	0.0
AT	04105	35.43	0.24	34.56	10.17	0.05	3.06	0.15	1.61	0.04*	10.5	0.3	0.1
AT	04105												Duplicate
AT	04106	35.03	0.99	33.03	8.12	0.02	4.76	0.59	1.75	0.04*	10.4	0.3	0.0
EL4	17801	34.18	0.49	32.43	12.32	0.11	1.99	0.14	1.69	0.03*	9.9	0.0	0.0
EL4	17801												Duplicate
EL4	17804	36.24	0.07	32.44	6.58	0.00	6.85	0.38	1.58	0.01*	10.5	0.0	0.0
EL4	17802	35.85	0.40	31.98	3.95	0.04	8.75	1.04	1.87	0.03*	10.4	0.0	0.0
EL4													Duplicate
EL4	17803	34.35	0.77	33.24	5.08	0.00	6.84	1.17	1.50	0.04*	10.0	0.0	0.0
EL4	17805	34.53	1.03	33.25	8.13	0.09	4.48	0.43	1.75	0.05*	10.0	0.0	0.0
EL4	17805												Duplicate
EL4	17806	34.98	1.21	31.75	5.89	0.09	7.43	1.49	1.39	0.04*	10.1	0.0	0.0
EL4	17807	33.77	1.12	32.83	9.44	0.06	4.05	0.91	1.60	0.05*	9.8	0.0	0.0
EL4	17808	34.82	0.93	32.55	5.60	0.02	7.04	0.81	1.76	0.08*	10.1	0.0	0.0
EL4	17809	35.02	0.47	34.12	5.01	0.03	6.72	0.75	1.63	0.05*	10.1	0.0	0.0
EL4	17810	34.42	1.32	31.54	5.87	0.04	7.16	1.12	1.80	0.06*	10.0	0.3	0.0
EL4	17811	34.24	1.01	31.32	7.54	0.07	6.08	1.17	1.80	0.06*	9.9	0.0	0.0
EL4	17812	34.73	0.65	28.11	8.55	0.00	8.31	1.91	1.62	0.01*	10.1	0.0	0.0
EL4	17813	34.26	0.77	33.03	8.08	0.03	4.78	0.44	1.86	0.05*	9.9	0.0	0.0
EL4	17814	34.56	0.46	33.37	9.35	0.12	3.48	0.20	1.67	0.03*	10.0	0.0	0.0
JK2	04110	35.21	0.04	35.26	12.95	0.19	1.03	0.05	1.40	0.02*	10.4	0.0	0.0
JK2	0.4111	35.98	1.26	28.87	9.24	0.04	7.25	1.10	2.20	0.02*	10.4	0.0	0.0
JK2	04112	35.12	0.64	32.57	9.84	0.06	4.80	0.79	1.84	0.06*	10.4	0.1	0.0
JK2	04113	37.09	0.20	34.31	4.27	0.19	8.03	0.33	2.12	0.04*	10.9	0.0	0.0
JK2	04114	34.56	0.51	32.62	12.06	0.06	3.47	0.55	1.98	0.06*	10.3	0.5	0.0
JK2	04118	35.03	0.49	31.83	12.41	0.22	3.31	0.13	2.17	0.06*	10.3	0.2	0.0
JK2	04119	37.37	1.32	28.33	2.92	0.00	12.62	2.58	1.67	0.03*	10.8	0.6	0.0
PC65	04108	36.27	0.80	33.61	7.46	0.00	5.66	0.24	1.96	0.02*	10.7	0.0	0.0
PC65	04108												Duplicate
PC65	04109	36.14	0.87	34.16	8.00	0.04	4.94	0.35	1.70	0.02	10.7	0.0	0.0
PC65	04116	35.02	1.05	32.81	7.82	0.05	5.90	1.36	1.59	0.05*	10.5	0.1	0.3
PC65	04117	35.03	0.95	33.50	9.01	0.00	4.46	0.64	1.81	0.05*	10.5	0.1	0.0
PO1	22316	35.60	0.80	34.26	5.89	0.06	5.79	0.35	1.78	0.03*	10.3	0.0	0.0
PO1	22317	35.20	0.70	34.06	6.45	0.09	5.85	0.31	1.78	0.03*	10.2	0.0	0.0
PO1	22318	34.74	0.77	34.12	7.72	0.05	4.65	0.44	1.93	0.05*	10.1	0.0	0.0
PO1	22319	34.37	0.70	33.89	6.36	0.00	6.28	1.27	1.56	0.06*	10.0	0.0	0.0
PO1	22320	35.00	0.42	32.99	8.28	0.05	5.38	0.26	2.09	0.04*	10.1	0.0	0.0
PO1	22321	34.94	0.80	30.24	9.09	0.02	7.06	1.68	1.58	0.06*	10.1	0.0	0.0
PO1	22322	34.99	0.78	31.14	8.26	0.00	6.36	1.11	2.06	0.07*	10.1	0.0	0.0
PO1	22323	35.68	0.58	33.43	5.36	0.04	7.23	0.30	2.09	0.02*	10.3	0.0	0.0
PO1	22324	35.40	0.20	32.86	4.97	0.07	8.52	0.71	2.06	0.05*	10.3	0.0	0.0
PO1	22325	35.18	1.05	30.89	8.37	0.07	6.65	1.10	1.98	0.07*	10.2	0.0	0.0
PO1	22326	35.94	0.47	32.90	5.38	0.04	7.29	0.38	1.91	0.02*	10.4	0.0	0.0
PO1	22327	35.73	0.31	33.74	5.86	0.10	6.47	0.62	1.90	0.04*	10.4	0.0	0.0
PO1	22328	35.38	0.74	34.17	4.13	0.07	7.05	0.69	1.82	0.04*	10.3	0.0	0.0
PO1	22329	35.44	0.78	33.71	6.08	0.07	6.53	0.52	1.94	0.05*	10.3	0.0	0.0
PO2	22330	35.34	0.62	30.71	7.84	0.04	7.04	0.79	2.00	0.02*	10.2	0.0	0.0
PO5	22331	34.11	0.80	31.72	8.77	0.11	5.56	0.55	2.09	0.05*	9.9	0.0	0.0
PO5	22332	35.16	0.88	33.73	5.96	0.06	6.33	0.54	2.04	0.05*	10.2	0.0	0.0
PO5	22333	35.46	0.53	33.47	6.06	0.00	6.61	0.44	2.08	0.04*	10.3	0.0	0.0
PO5	22335	35.04	0.95	34.30	5.93	0.01	6.25	0.78	1.67	0.05*	10.2	0.0	0.0
SK1	04121	35.59	0.11	34.57	11.15	0.02	2.69	0.05	1.52	0.02*	10.5	0.0	0.0
SK1	04123	34.61	0.81	32.64	12.51	0.09	3.06	0.51	1.91	0.05*	10.3	0.0	0.0
SK1	04124	35.50	0.16	33.64	10.54	0.28	3.41	0.12	1.93	0.04*	10.4	0.0	0.0
SK1	04125	35.98	0.05	37.01	7.15	1.87	0.21	0.20	2.20	0.03	10.5	1.0	nd
SK1	04126	35.48	0.35	34.23	11.40	0.06	2.91	0.22	1.85	0.02*	10.5	0.0	0.0

Table 21 (cont'd.)

CSIRO Proton Probe Analysis in ppm															
Cr	Ni	Cu	Zn	Ga	Ge	Rb	Sr	Y	Zr	Nb	Mo	Ba	Pb	TH	U
512	75	nd	236	76	nd	nd	51	45	99	nd	nd	116	18	76	22
nd	nd	nd	401	104	nd	nd	11	nd	3	nd	nd	nd	nd	nd	nd
nd	42	nd	269	79	nd	nd	31	nd	nd	nd	nd	nd	nd	nd	nd
nd	30	nd	476	78	nd	4	10	nd	1	nd	nd	nd	nd	nd	nd
nd	34	15	522	68	nd	8	4	nd	nd	nd	nd	nd	nd	nd	nd
nd	34	48	541	63	nd	9	5	nd	nd	nd	nd	nd	15	nd	nd
nd	nd	nd	546	81	nd	nd	14	nd	0	nd	nd	nd	nd	nd	5
411	nd	nd	1140	41	nd	nd	23	nd	nd	nd	nd	nd	nd	6	nd
411	nd	nd	1120	43	nd	nd	20	nd	nd	nd	nd	nd	nd	nd	6
nd	nd	nd	276	29	nd	nd	180	nd	nd	nd	nd	nd	5	nd	nd
616	196	nd	95	49	nd	nd	113	nd	nd	nd	nd	nd	12	nd	nd
616	210	nd	94	50	nd	nd	116	nd	nd	nd	nd	nd	15	nd	nd
684	22	nd	139	56	nd	nd	51	nd	nd	nd	nd	nd	nd	nd	nd
nd	nd	nd	437	106	nd	nd	nd	nd	nd	nd	nd	99	nd	nd	nd
nd	nd	nd	426	11	nd	nd	nd	nd	nd	nd	nd	121	nd	nd	nd
nd	nd	nd	237	88	nd	nd	83	nd	nd	nd	nd	nd	nd	nd	nd
nd	nd	nd	528	104	nd	nd	13	nd	nd	nd	nd	88	nd	nd	nd
nd	59	nd	193	61	nd	nd	111	nd	nd	nd	nd	nd	9	nd	nd
298	nd	nd	152	115	nd	nd	88	nd	nd	nd	nd	nd	5	nd	nd
411	nd	nd	167	106	nd	nd	24	nd	nd	nd	nd	nd	7	nd	nd
68.4	nd	nd	202	97	nd	nd	90	nd	nd	nd	nd	146	9	nd	nd
137	82	nd	80	24	nd	nd	488	nd	nd	nd	nd	nd	nd	nd	nd
nd	15	nd	224	107	nd	nd	6	nd	nd	nd	nd	nd	nd	nd	nd
479	nd	nd	409	54	nd	nd	3	nd	nd	nd	nd	nd	nd	nd	nd
nd	nd	nd	634	67	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
nd	21	nd	191	40	nd	nd	453	nd	4	nd	nd	nd	9	nd	6
nd	nd	nd	304	80	nd	nd	22	nd	5	nd	nd	119	nd	nd	nd
nd	nd	nd	93	82	nd	nd	nd	nd	4	1.9	nd	99	nd	nd	nd
nd	nd	nd	622	112	nd	nd	13	nd	nd	nd	nd	191	nd	nd	1
nd	nd	36	586	85	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
205	58	nd	nd	45	nd	nd	50	nd	nd	nd	nd	nd	nd	nd	nd
60	27	7	144	30	nd	nd	79	nd	nd	nd	nd	80	nd	nd	nd
nd	154	nd	172	21	nd	nd	122	7	265	nd	nd	nd	nd	nd	nd
nd	nd	335	256	nd	nd	116	270	nd	1030	nd	nd	nd	nd	nd	nd
nd	17	nd	161	42	nd	nd	124	nd	nd	nd	4	nd	9	nd	7
274	nd	9	381	70	nd	nd	19	nd	nd	nd	nd	nd	nd	nd	nd
nd	59	nd	154	54	nd	nd	33	3	nd	nd	nd	nd	nd	nd	6
274	76	nd	149	47	nd	nd	147	5	231	nd	nd	nd	6	nd	nd
nd	nd	nd	330	110	nd	nd	15	nd	nd	nd	nd	nd	nd	nd	nd
342	73	nd	133	48	nd	nd	149	nd	nd	nd	nd	87	7	nd	nd
nd	nd	nd	405	64	nd	nd	3	nd	nd	nd	nd	nd	nd	nd	nd
958	56	nd	135	55	nd	nd	198	nd	nd	nd	nd	nd	7	nd	nd
nd	16	nd	205	37	nd	nd	101	nd	nd	nd	nd	nd	41	nd	nd
547	36	nd	83	48	nd	nd	73	nd	nd	3.4	nd	nd	7	nd	nd
nd	12	nd	121	61	nd	nd	24	nd	nd	nd	4	nd	nd	nd	nd
nd	26	nd	249	94	nd	nd	14	nd	nd	nd	nd	nd	nd	nd	nd
342	21	nd	148	43	nd	nd	105	9	272	nd	nd	nd	13	nd	nd
nd	46	nd	145	33	nd	nd	70	nd	nd	nd	nd	nd	7	nd	nd
nd	12	nd	158	51	nd	nd	44	nd	nd	nd	nd	nd	nd	nd	nd
479	49	nd	136	47	nd	nd	52	nd	nd	nd	nd	nd	nd	5	nd
68.4	66	nd	333	33	md	nd	230	nd	nd	nd	nd	nd	10	nd	8
205	81	14	252	64	nd	nd	19	nd	11	nd	50	nd	nd	nd	nd
nd	11	nd	359	67	nd	nd	19	nd	nd	nd	nd	nd	nd	nd	nd
274	68	nd	142	38	nd	nd	61	nd	nd	nd	nd	nd	nd	nd	nd
342	14	nd	220	72	nd	nd	46	nd	nd	nd	nd	nd	nd	1	nd
nd	nd	nd	911	99	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
nd	53	nd	703	65	nd	nd	81	nd	4	nd	nd	nd	nd	nd	nd
nd	nd	nd	1030	73	nd	nd	nd	nd	nd	nd	nd	147	nd	nd	nd
nd	nd	9	4800	216	nd	nd	9	nd	nd	nd	nd	nd	11	nd	nd
nd	nd	nd	672	80	nd	nd	11	3	nd	nd	nd	145	nd	nd	nd

tourmaline analyses that plot within the elevated K_2O - TiO_2 field of Figure 31 show positive correlation with the known grades of diamonds within the pipes (Table 17). About two-thirds of the rounded tourmalines from the PO1 pipe located near President Oligario, Brazil, also plot within the elevated field.

The majority of the regional tourmalines with "positive" compositions are of magmatic derivation and therefore can be distinguished from the rounded diatreme tourmalines on the basis of color, zonation and crystal form. However, it is probable that diatreme tourmalines would not be distinguished from rounded tourmalines of magmatic derivation eroded from clastic sandstone units in many areas of Australia, southern Africa and elsewhere.

Fipke (1991) suggests that tourmaline could be a useful aid in prospecting for lamproites in areas devoid of round clastic tourmalines, but a wider database is needed to assess this possibility.

Other lamproite minerals

Other minerals recovered and identified from the lamproite samples investigated include: phlogopite, Ti-phlogopite, diopside, diopsidic augite, alkali

amphibole, leucite pseudomorphs, sanidine, Sr-rich apatite, sphene, Sr-rich barite, perovskite, and ankeritic, as well as dolomitic carbonate. Of these, phlogopite, K-feldspar, apatite, sphene, and barite have been identified as epigenetic (secondary) inclusions in Argyle and/or Ellendale diamonds (Jaques et al., 1989).

Most of the low specific gravity minerals recovered in the heavy mineral concentrates occur in this fraction because they were either intergrown with, or coated by, a heavy-mineral phase (e.g., limonite). Although the above mentioned minerals have assisted in characterizing lamproite from other diatreme rocks, they have limited application as tools for detecting lamproite in regional heavy-mineral sampling programs. This is because they are difficult to concentrate and generally cannot be distinguished from common regional minerals. Furthermore, these minerals are so fragile and easily altered that they will not survive any significant detrital transport.

Many minerals such as K-Ti richterite, K-riebeckite, K-arfvedsonite, priderite, wadeite, shcherbakovite, and armalcolite, which are commonly present in hypabyssal and late stage (i.e., Smoky Butte) lamproite, were not identified in either the early crater-infill or the diatreme facies (diamondiferous lamproite) samples tested.

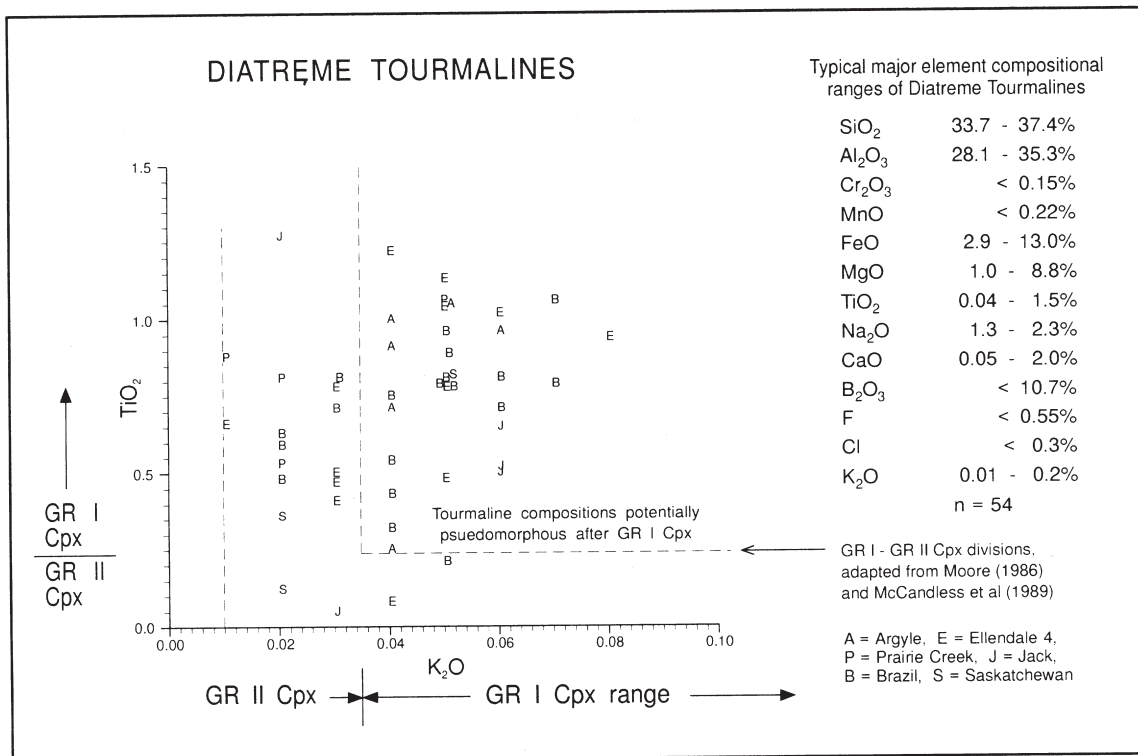


Figure 31. TiO_2 - K_2O plot for diatreme tourmalines.

These findings are in agreement with those of C.B. Smith (CRA, Australia) who reports that these minerals have not been detected in the most diamondiferous sandy breccia tuff phase of the Argyle lamproite.

Discussion

Jaques et al. (1989) demonstrated that minerals of eclogitic paragenesis are the predominant syngenetic inclusions in Argyle diamonds, but both eclogitic and peridotitic minerals are included in approximately equal proportions in Ellendale lamproite diamonds. However, the major constituents of both the eclogitic and peridotitic source rocks to the diamonds are either absent or rare in samples of the five lamproite diatremes tested in our study. This observation implies that the most important silicate indicator minerals, which have been so successfully utilized in the discovery and assessment of kimberlites, do not survive in abundance in lamproite magmatic systems.

This rarity of conventional indicator minerals prompted investigation into other minerals related to diamond genesis, which may be more common. These include rutile, corundum, kyanite, and magnetite, which commonly are present in rare to minor amounts. Unfortunately, the major and trace element compositions of these minerals cannot presently be distinguished with certainty from regional varieties, and their low abundance renders them hard to recover in useful quantities.

Spherical, rounded, frosted, light to dark brown, unzoned, dravitic tourmalines were detected in minor to abundant quantities in all diamondiferous lamproites tested. Such tourmalines may represent pseudomorphs after the jadeitic diopside components of Group I or Group II eclogite intruded by lamproite magmas. However, tourmalines of magmatic paragenesis have similar compositions. Consequently, there is presently insufficient data to prove the pseudomorph model with any certainty. Such rounded, frosted tourmalines were mistaken for brown E garnets and were consequently utilized to discover the diamond-bearing Jack lamproite. If one assumes the proposed model to be correct, rounded, high- K_2O - TiO_2 , dravitic tourmaline would be the only major constituent mineral species available for the detection of the most important (Group I eclogite) source of lamproite diamonds. Consequently, recording the presence of such rounded tourmalines in heavy mineral concentrates should be considered, particularly when exploring areas devoid of regional tourmalines.

Even though picroilmenites, as well as pure and Mn-ilmenites, occur only in trace to minor amounts in lamproite, the characteristic “flying saucer” morphology of these diatreme ilmenites makes for rapid, cost-effective identification. Because picroilmenites are also an effective indicator of the presence of Group I kimberlite (and other diatremes), as well as a potential guide to diamond preservation (Gurney and Moore, 1989), this mineral should be routinely used in reconnaissance and follow-up surveys for lamproite.

DI and Cr-Ti chromites are generally the most useful indicator minerals in exploration programs for lamproite. When present, Cr-diopside, garnets, and possibly olivine, orthopyroxene, Nb-rutile, and zircon also may be useful pathfinder minerals for the location of lamproite diatremes (Fipke, 1991).

DIAMOND EXPLORATION: SUMMARY OF IMPORTANT POINTS

1. Diamonds are likely to be found in regions of the earth with thick cool lithospheric keels where old rocks are preserved. Consequently, continental cratons may be prime targets if they are thick enough to intersect the diamond stability field (~150 km). Complex structural settings where overthrusting allows old cool keels to survive underneath younger rocks also are possible exploration areas.
2. Based on the features in point 1 above, the vast Canadian Shield is a highly desirable geological environment for locating diamondiferous diatremes.
3. The macrodiamonds in economic deposits are derived from peridotitic and eclogitic source rocks that formed in the lithospheric upper mantle. Both types of paragenesis occur in every known diamond deposit.
4. As diamonds are released into the host volcanic rock by the disaggregation of pre-existing diamond-bearing rocks, other constituent minerals of those rocks will be incorporated with the diamonds.
5. Since some of these minerals (most notably garnets and chromites) have very distinctive compositions, their presence can be detected and used as diamond indicators.
6. In a single diatreme, it is reasonable to expect a roughly linear relationship between the amount of

diamonds present and the abundance of fragments of the host diamondiferous rocks from the mantle. Exceptions obviously occur.

7. Climatic conditions in Canada are suited to the indicator mineral approach to diamond prospecting.
8. The "traditional" indicator mineral approach does not appear to be as reliable for lamproites as it is for kimberlites. Use of other minerals, such as olivines, tourmalines, orthopyroxenes, zircons, ilmenite, and Nb-rutile as pathfinders to lamproite has had some encouraging results and warrants consideration where compositional overlap with regional minerals is not extensive.
9. Cr-diopside is a useful mineral for detecting and tracking diatremes in regional sampling programs. Tourmalines, olivines, and zircons also may be useful for this purpose, particularly in the case of lamproites.
10. A multivariate statistical approach to evaluating the geochemistry of indicator minerals provides a viable alternative approach to the simpler graphical approach for chromites and peridotitic garnets, but it does not work for eclogitic garnets. The graphical approach is favored because it does not require much data manipulation, trends can be readily related to geological processes, interpretation can be adapted as the database for a particular region improves, and because it provides a strong distinction between barren and diamondiferous kimberlites.
11. Bulk-rock geochemical analyses of diatreme rocks are plagued by problems of xenolith contamination and alteration, which makes them difficult to interpret.
12. The emergence of lamproite as a major source of diamonds has considerably increased the importance of petrography in diamond exploration programs.

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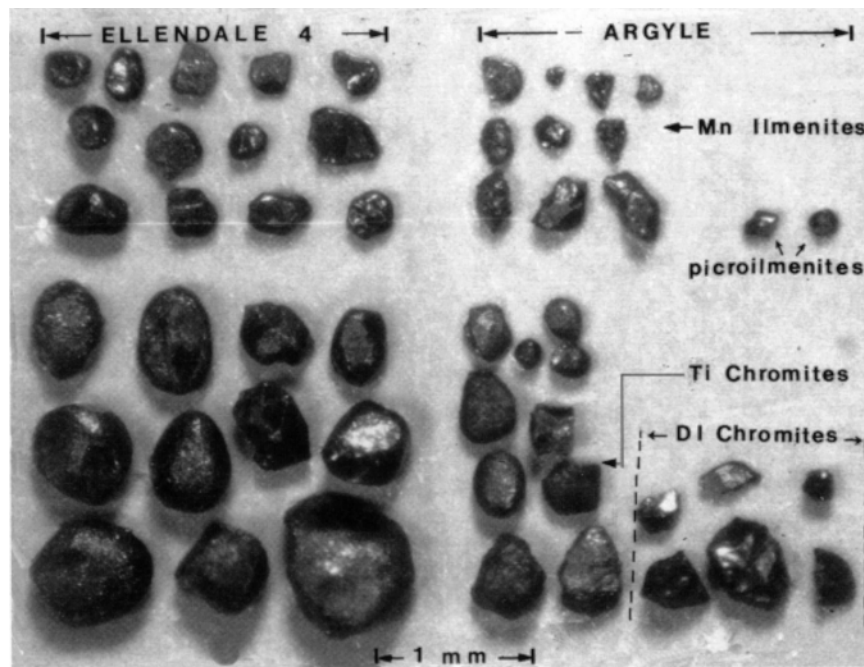


Plate 1. Photomicrograph of Mn ilmenite and Ti chromites from Argyle and Ellendale, Australia. Six DI chromites and two picroilmenites from Argyle are also illustrated.



Plate 2. Photomicrograph (25x) of minerals from till collected immediately down ice from the Point Lake kimberlite pipe, N.W.T., Canada. Pictured in groups of four, from upper left to lower right: Group 1 E garnets, picroilmenites, megacrystic E garnets, Cr diopsides, G10 P garnets, Ti-Cr chromites and a single DI chromite (lowest far right). Photograph by Julius Weber, N.Y.

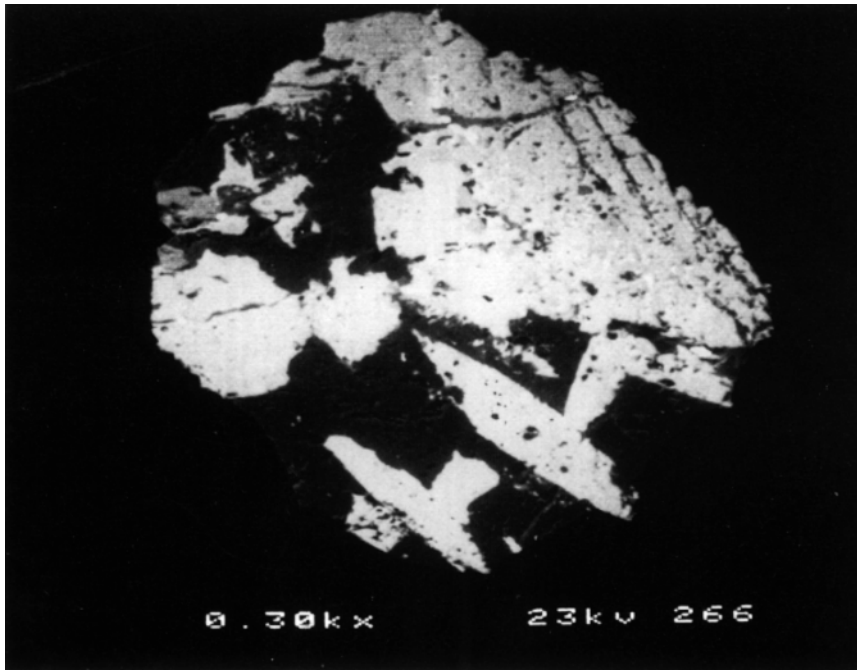


Plate 3. SEM backscatter photomicrograph (300x) of intergrowth of niobium rutile (light grey) and titaniferous dolomite (dark) from Jack, B.C. phase 2 lamproites. The rutile contains tiny (whitish) blebs of unidentified Nb-Ti-W-Fe and Zr-Ti-Fe silicate minerals.



Plate 4. X-ray scan of Plate 3 (300x) illustrating distribution of Nb minerals (black) Ti minerals, rutile (red) and of Ca minerals-dolomite (yellow).

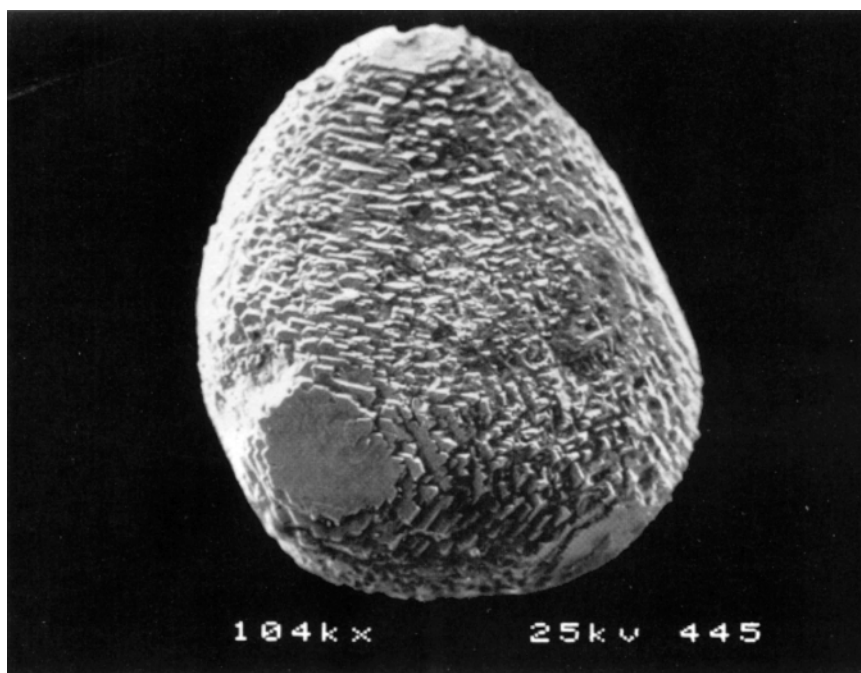


Plate 5. SEM microphotograph (104x) of Cr-Ti chromite from Ellendale 4. Note the round shape and resorption on the octahedral parting.



Plate 6. Photomicrograph of light to dark brown, glassy to frosted, spheroidal tourmalines from the Ellendale 4, Australia, Jack, B.C., Prairie Creek, Arkansas, and Argyle, Australia diamondiferous lamproites.

