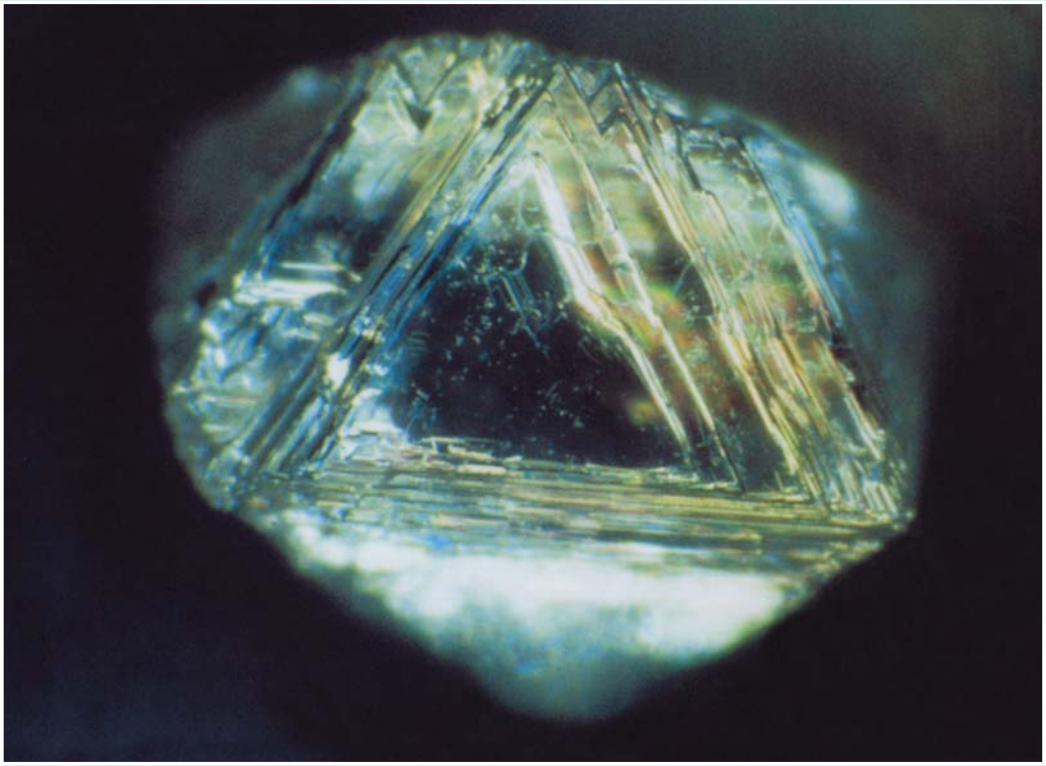
GEOLOGICAL SURVEY OF CANADA
BULLETIN 423

# DIAMOND EXPLORATION TECHNIQUES EMPHASISING INDICATOR MINERAL GEOCHEMISTRY AND CANADIAN EXAMPLES

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



1995

Natural Resources Canada    Ressources naturelles Canada

Canada

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**

Catalogue No. M42-423E
ISBN 0-660-16203-2

Available in Canada from
Geological Survey of Canada offices:

601 Booth Street
Ottawa, Ontario K1A 0E8

3303-33rd Street, N.W.
Calgary, Alberta T2L 2A7

101-605 Robson Street
Vancouver, B.C. V6B 5J3

or from

Canada Communications Group – Publishing
Ottawa, Canada K1A 0S9

A deposit copy of this publication is also available for reference in public libraries across Canada

Price subject to change without notice

**Reprinted 1997**
**Reprinted 2002**
**Reprinted 2006**

**Cover illustration**

A 1.1 mm gem quality, flawless natural octahedral diamond from the 1991 discovery core hole at Point Lake, N.W.T. Photograph by Julius Weber, N.Y.

**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*

*Original manuscript submitted: 94-06-20*
*Final version approved for publication: 95-07-24*

# 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

# CONTENTS

**Figures**

**Tables**

**Plates**

# 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'activite 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 donnés 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** |

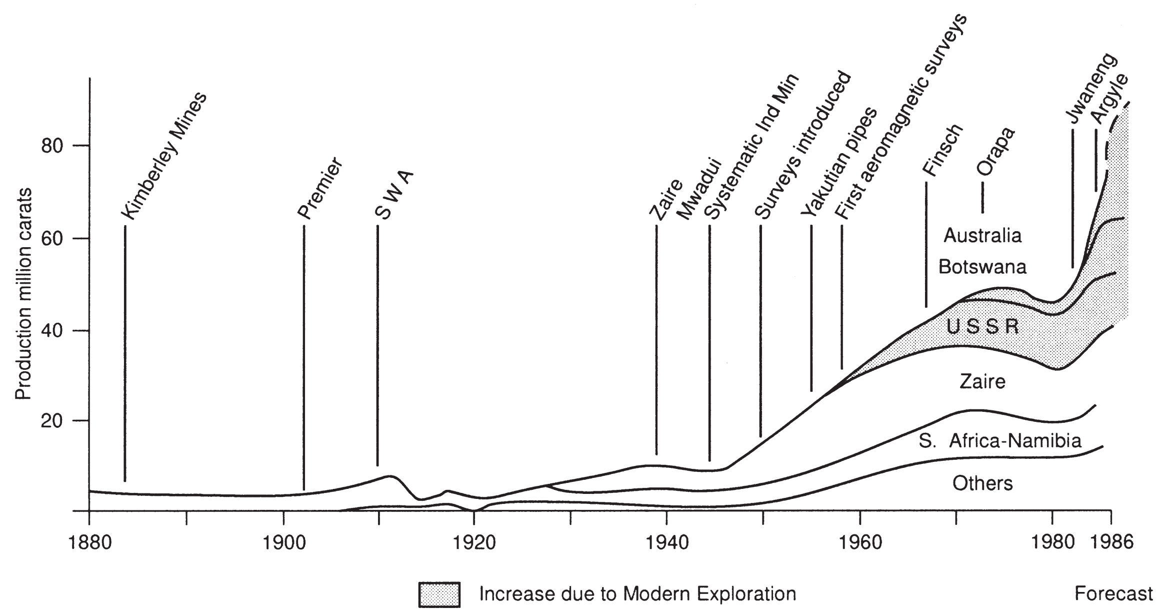


***Figure 1.** Growth in world diamond production (After Atkinson, 1989).*

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).

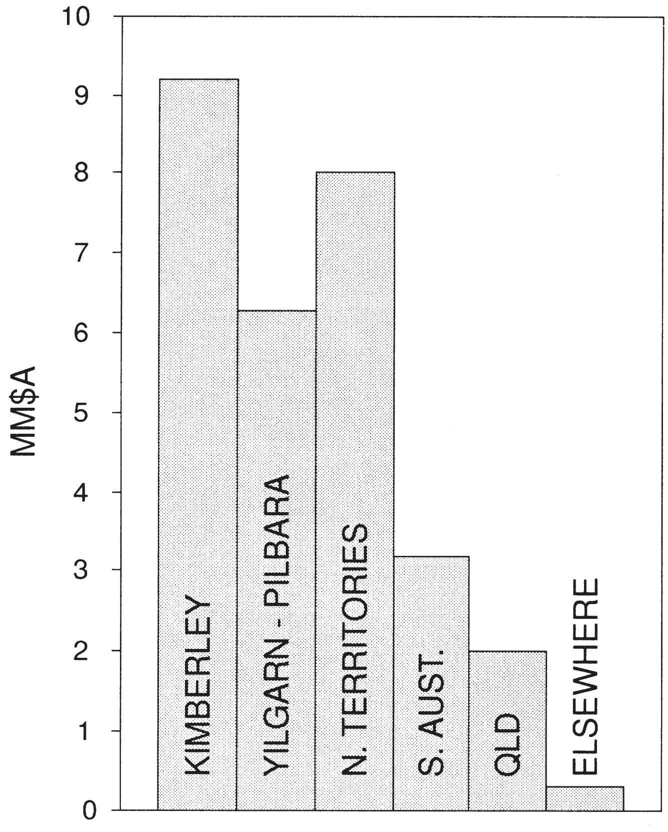


***Figure 2.** Estimated expenditure for diamond exploration in Australia for 1984 (after Atkinson, 1989).*

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 |

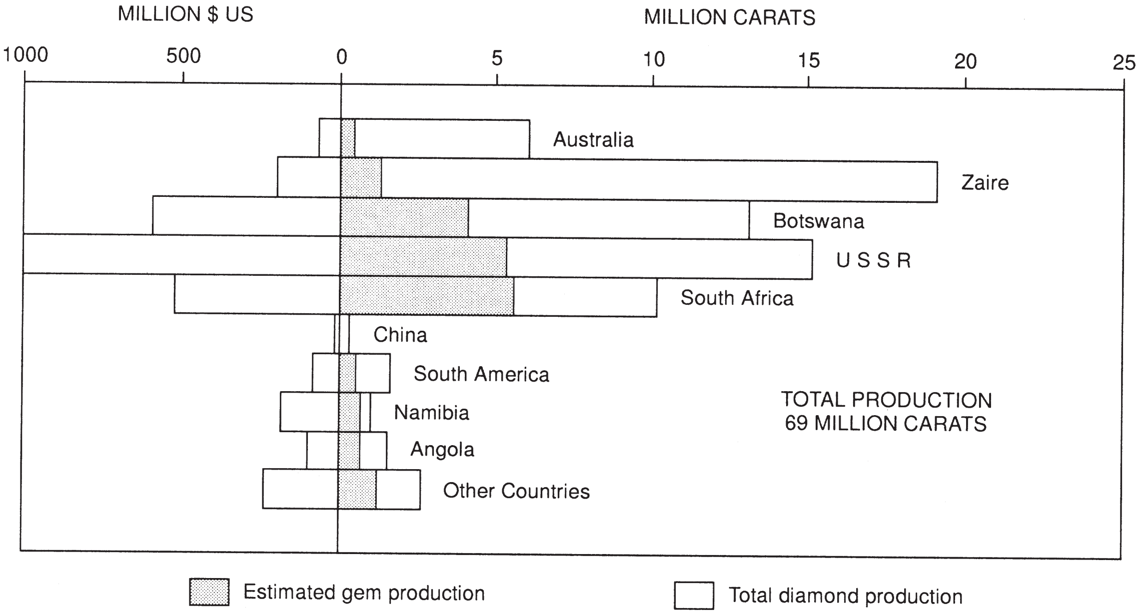


***Figure 3.** World diamond production for 1984, separated into gem and industrial categories (after Atkinson, 1989).*

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 microdiamonds. 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-pyrope 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 Eggler, 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<br>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, Tennesse | 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 Tyalor (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 $CO_2$, $TiO_2$, $K_2O$ and $P_2O_5$. 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 $CO_2$

## 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 |
| $Al_2O_3$ | 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 |
| $Cr_2O_3$ | 0.22 | 0.23 | 0.15 | – | – | – | – | 0.10 | 0.31 | – | – | – | – | – |
| $Fe_2O_3$ | 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 |
| $Na_2O$ | 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 |
| $K_2O$ | 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 |
| $P_2O_5$ | 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 |
| $H_2O+$ | 8.70 | 7.56 | 6.25 | – | 2.75 | 1.15 | 5.13 | 2.34 | – | 4.89 | – | 3.16 | 5.64 | 3.16 |
| $H_2O-$ | 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, Malibamatso 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 Hawthrone, 1973); **6**, composite sample of Benfontein sill (Dawson and Hawthrone, 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 $Fe_2O_3$; 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.

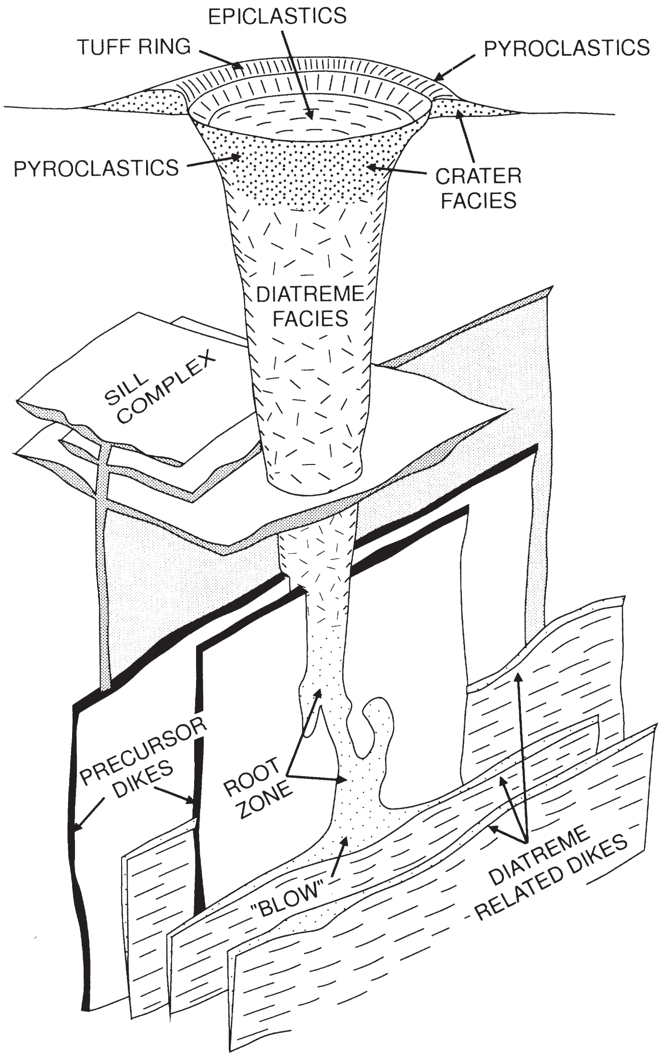


***Figure 5.*** *Model of an idealised kimberlite magmatic system, illustrating the relationship between crater, diatreme, and hypabyssal facies (not to scale). Hypabyssal facies include sills, dykes, root zone and "blow". Reproduced from Mitchell (1986).*

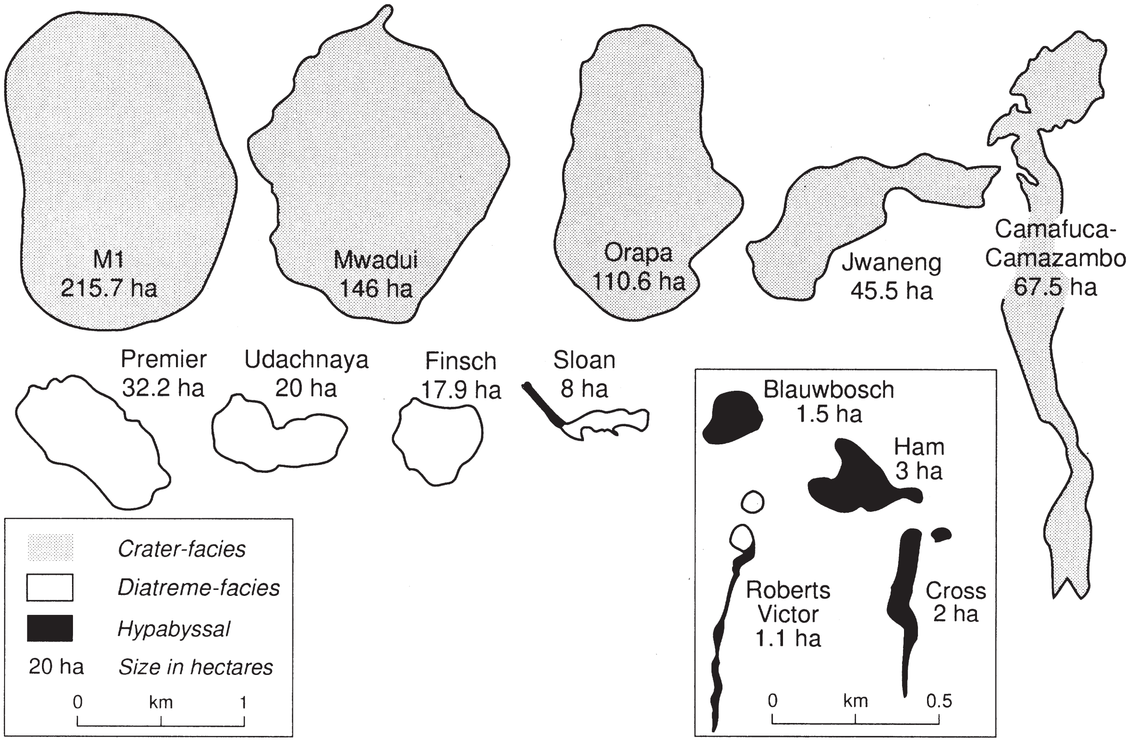


***Figure 6a.*** *Kimberlites: Plan views. Reproduced from Scott-Smith (1992).*

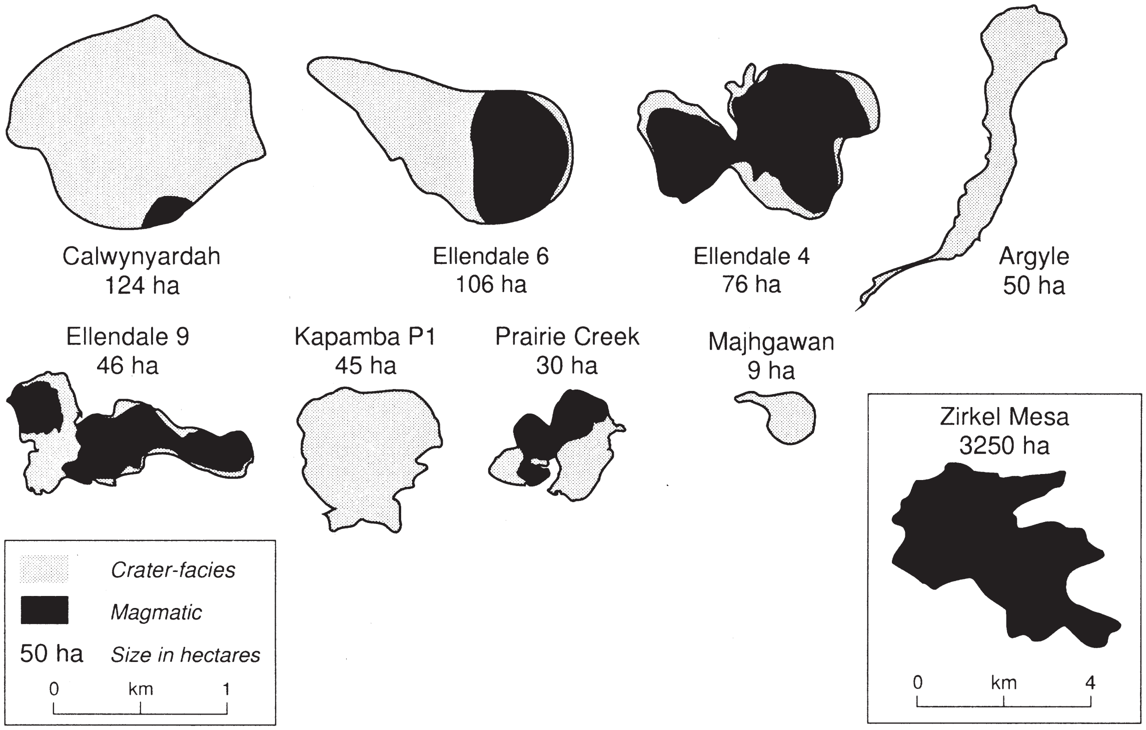


***Figure 6b.*** *Lamproites: Plan views. Reproduced from Scott-Smith (1992).*

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 $CO_2$. 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.

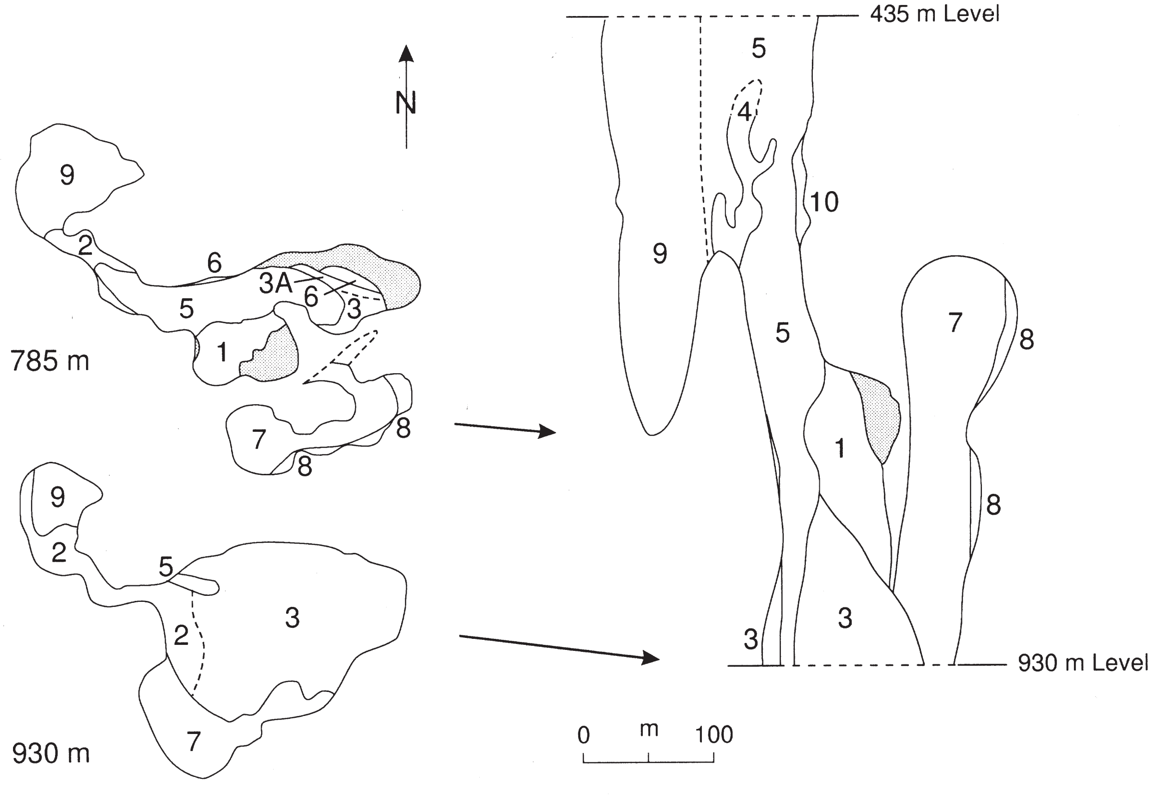


*Figure 7. Vertical and horizontal cross-sections of the root zones of the Wesselton diatreme (Clement, 1982; Shee, 1984). Numbers signify petrographically distinct varieties of kimberlite (not in sequence of intrusion). Diagonal shading indicates contact breccias. Note the blind diatreme represented 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/carat, whereas at others it can exceed \$300/carat. 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.

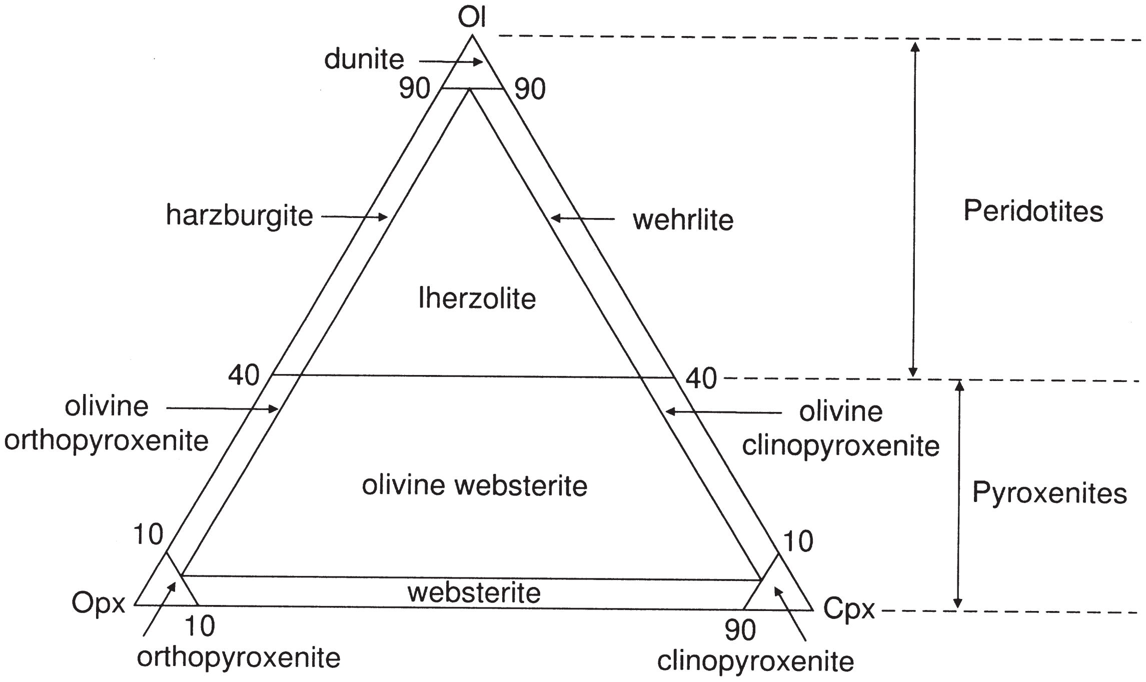


***Figure 8.*** *Classification of peridotites and pyroxenites as recommended by the International Union of Geological Sciences. Modal proportions are in volume percent. Reproduced from Dawson (1980).*

**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 (Bostwana), Lesotho, Gross Brukkaros (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 Merchimdem (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:

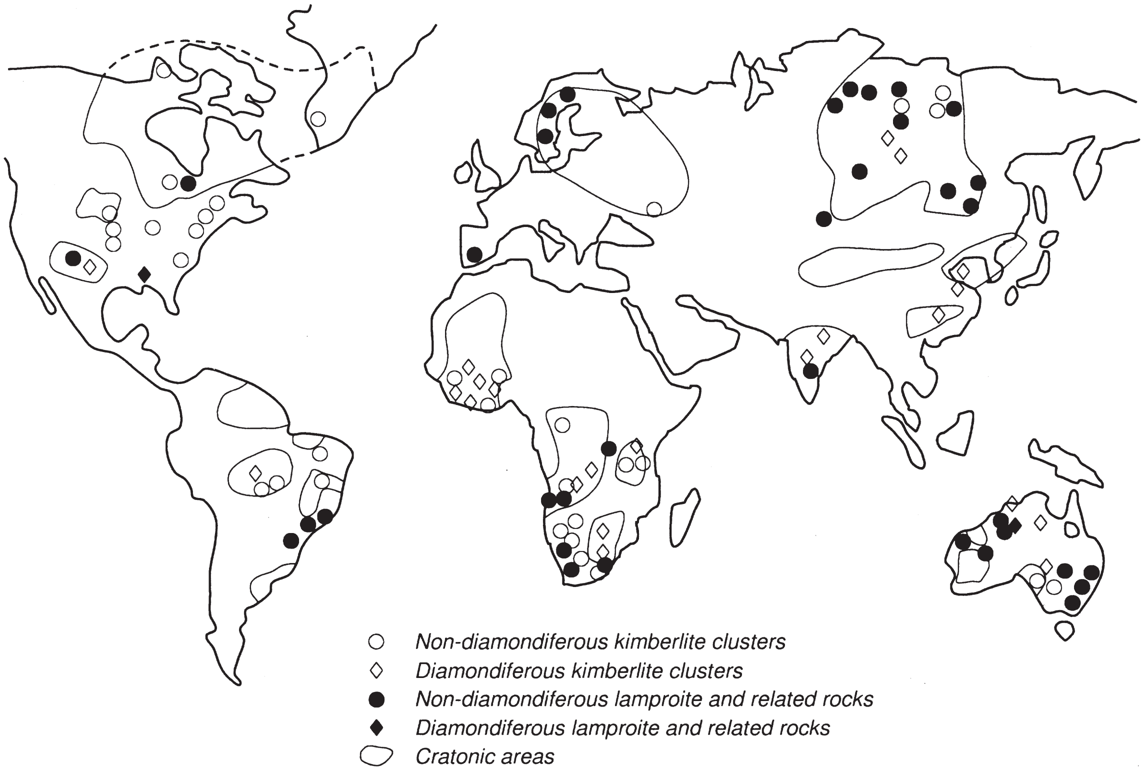


***Figure 9.*** *World distribution of kimberlites and lamproites in relation to Archean cratons. From Atkinson (1989); adapted from Janse (1984).*

> 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.

**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

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 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 $CO_2$ 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).

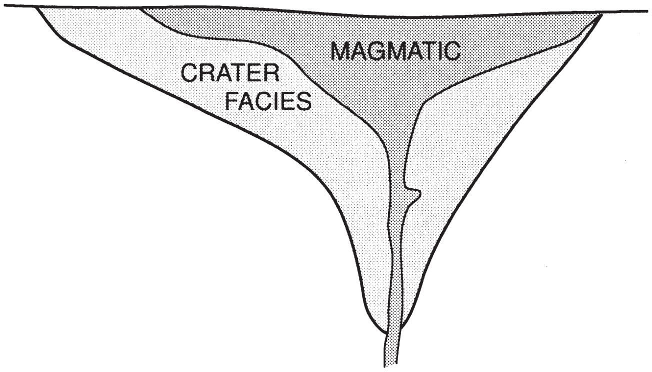


***Figure 10.*** *Schematic cross-section of a lamproite pipe illustrating the characteristic champagne glass shape. Note that the magmatic lamproite (hypabyssal facies) intrudes the crater facies pyroclastic material. After Scott-Smith and Skinner (1984b).*

Lamproite craters are infilled with volcaniclastic 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 volcaniclastic 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 $SiO_2$, $Al_2O_3$, $K_2O$, Rb, Ba, Sr, Zr and LREE and poorer in MgO, CaO, $H_2O$, $CO_2$, 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 Eggler, 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 |
| $Al_2O_3$ | 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 |
| $Na_2O$ | 1.3 ± 0.5 | 0.5 ± 0.3 | 2.0 ± 1.0 | 1.4 ± 1.0 |
| $K_2O$ | 10.4 ± 2.4 | 8.3 ± 2.9 | 6.6 ± 2.2 | 6.9 ± 2.8 |
| $P_2O_5$ | 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%) | | |
| $H_2O+$ | 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 |
|---|---|---|
| Ag | 0.134* | – |
| As | – | – |
| Au | (0.012)* | – |
| B | (36)* | – |
| Ba | 1100 | 5120 |
| Be | 1.6* | 8 |
| Bi | (0.024)* | – |
| Br | – | – |
| Cd | (0.073) | – |
| Ce | (200) | 400 |
| Cl | 202 | – |
| Co | 65 | 37 |
| Cr | 893 | 580 |
| Cs | 2.2* | 1.7 |
| Cu | 93 | 52 |
| Dy | – | 6.3 |
| Eu | (3.0) | 4.8 |
| Er | (1.45) | 2.4 |
| F | 2774 | – |
| Ga | 5.7* | 15 |
| Gd | (8.0) | 13 |
| Ge | 0.5* | – |
| Hf | 5.6 | 39 |
| Hg | (0.008)* | – |
| Ho | (0.55) | 1.1 |
| I | – | – |
| In | – | – |
| Ir | 0.003* | – |
| La | (150) | 240 |
| Li | 29 | 31 |
| Lu | (0.16) | 0.23 |
| Mn | (1160) | – |
| Mo | 1.7* | – |
| Nb | 141 | 95 |
| Nd | (85) | 207 |
| Ni | 965 | 420 |
| Os | 1.34* | – |
| P | (3880) | – |
| Pb | 15.3 | 44 |
| Pd | 0.0081* | – |
| Pr | (22) | – |
| Pt | (0.19)* | – |
| Rb | 73 | 272 |
| Re | 0.069* | – |
| Rh | 0.0071* | – |
| Ru | 0.065* | – |
| S | 1687 | – |
| Sb | – | – |
| Sc | 14 | 17 |
| Se | 0.15* | – |
| Sm | (13) | 24 |
| Sn | 5.4* | – |
| Sr | 851 | 1530 |
| Ta | 11 | 47 |
| Tb | (1.0) | 1.4 |
| Te | – | – |
| Th | 17 | 46 |
| Ti | (11800) | – |
| Tl | (0.219)* | – |
| Tm | (0.23) | – |
| U | 3.1 | 4.9 |
| V | 100 | 123 |
| W | – | – |
| Y | 22 | 27 |
| Yb | (1.2) | 1.7 |
| Zn | 69 | 84 |
| Zr | 184 | 922 |

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

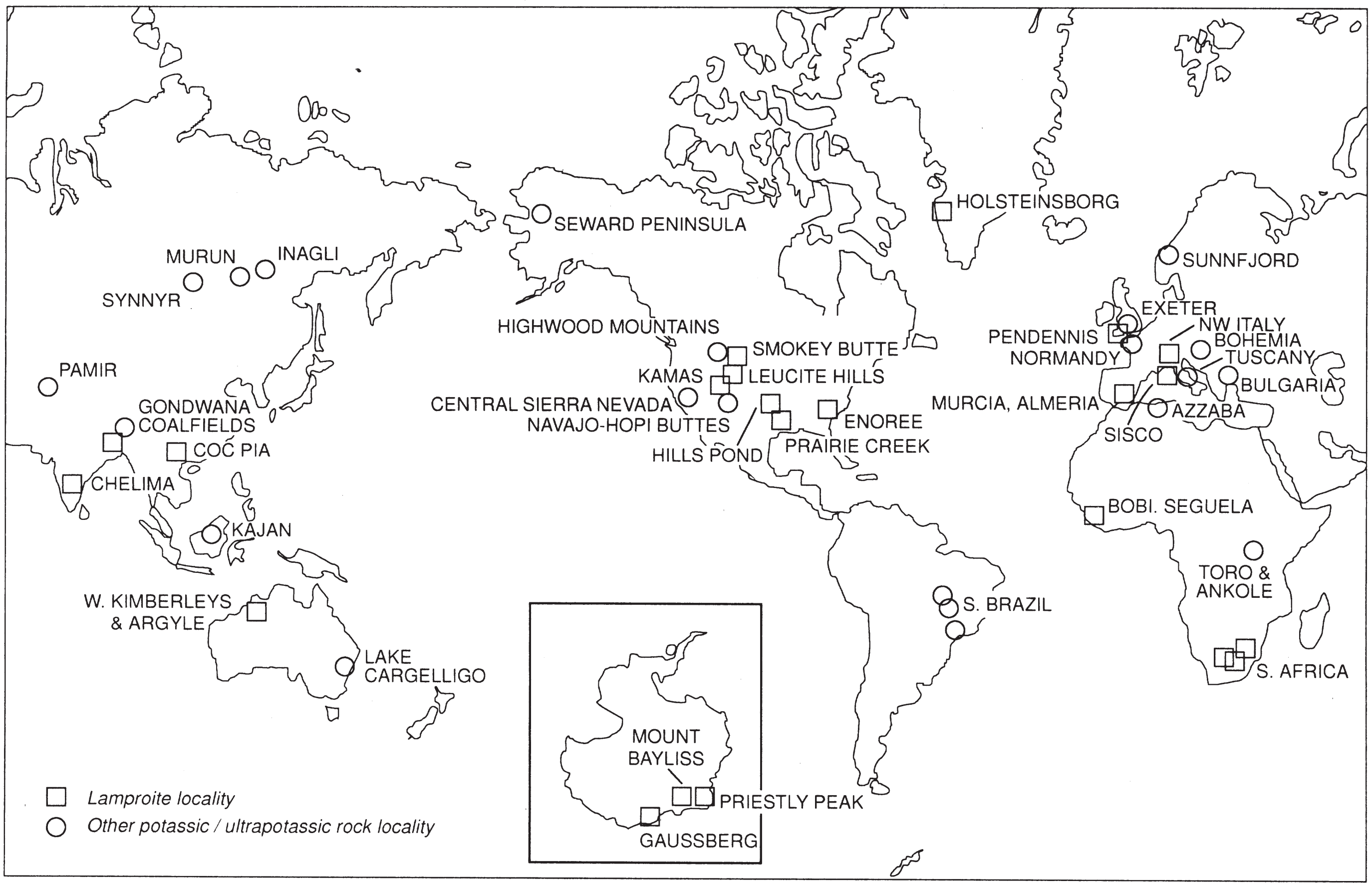


***Figure 11.*** *Map showing the locations of lamproite suites and some compositionally similar potassic-ultrapotassic rock suites. Reproduced from Bergman (1987).*

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/m$^2$ 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 $\delta^{13}C$ is +5 per mil to -34.4 per mil (Fig. 12; Harris, 1987). Diamonds of peridotitic paragenesis are largely confined to $\delta^{13}C$ 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 $\delta^{13}C$).

Several studies have shown that the carbon isotopic composition of diamonds may be inhomogeneous and complex. Variations of $\delta^{13}C$ 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;

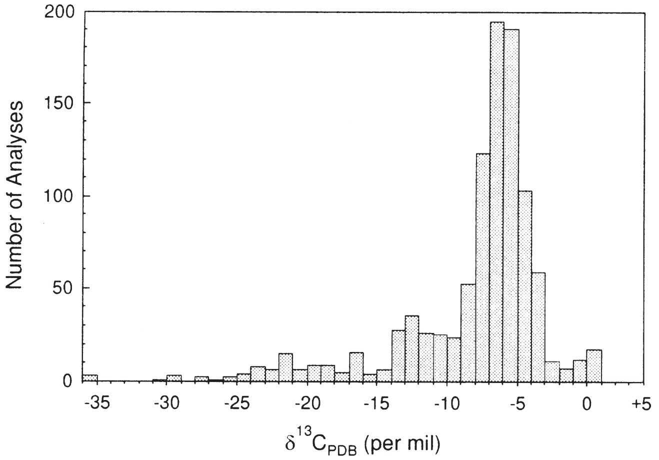


***Figure 12.*** *Histogram of the carbon isotopic compositions displayed by diamonds from worldwide sources. Peridotitic diamonds show a very restricted range in C-isotopic compositions which corresponds to the major abundance peak observed in this diagram (between -3 and -9 per mil). In contrast, eclogitic 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 $\delta^{13}C$ 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 $\delta^{13}C$ 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 Premierof 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 assignation 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.

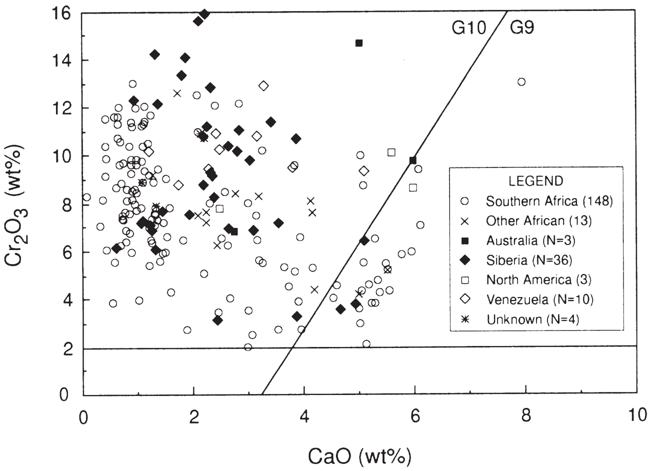


***Figure 13.*** *$Cr_2O_3$–CaO plots for peridotitic garnet inclusions in diamonds from worldwide localities. Eighty-five percent of the garnets plot on the CaO-poor side of the inclined line which was defined by Gurney (1984). These subcalcic compositions are referred to as G10 garnets. The horizontal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

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.

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).

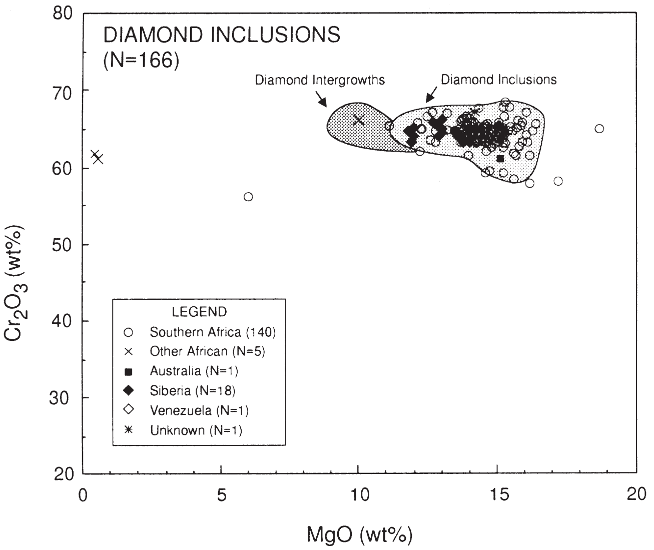


***Figure 14.*** *MgO–$Cr_2O_3$ plots for chromite inclusions in diamonds from worldwide localities. Note the highly restricted, chrome-rich character of the inclusions. The preferred compositional field indicated includes >98% of the data points.*

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 $Cr_2O_3$ compositions characteristic of chromites included or intergrown with diamond (Fig. 15). DI chromites generally contain <0.6 $TiO_2$ wt% whilst Cr-Ti chromites contain >0.8 wt% $TiO_2$ 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 $Cr_2O_3$–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 $Cr_2O_3$–$TiO_2$ 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).

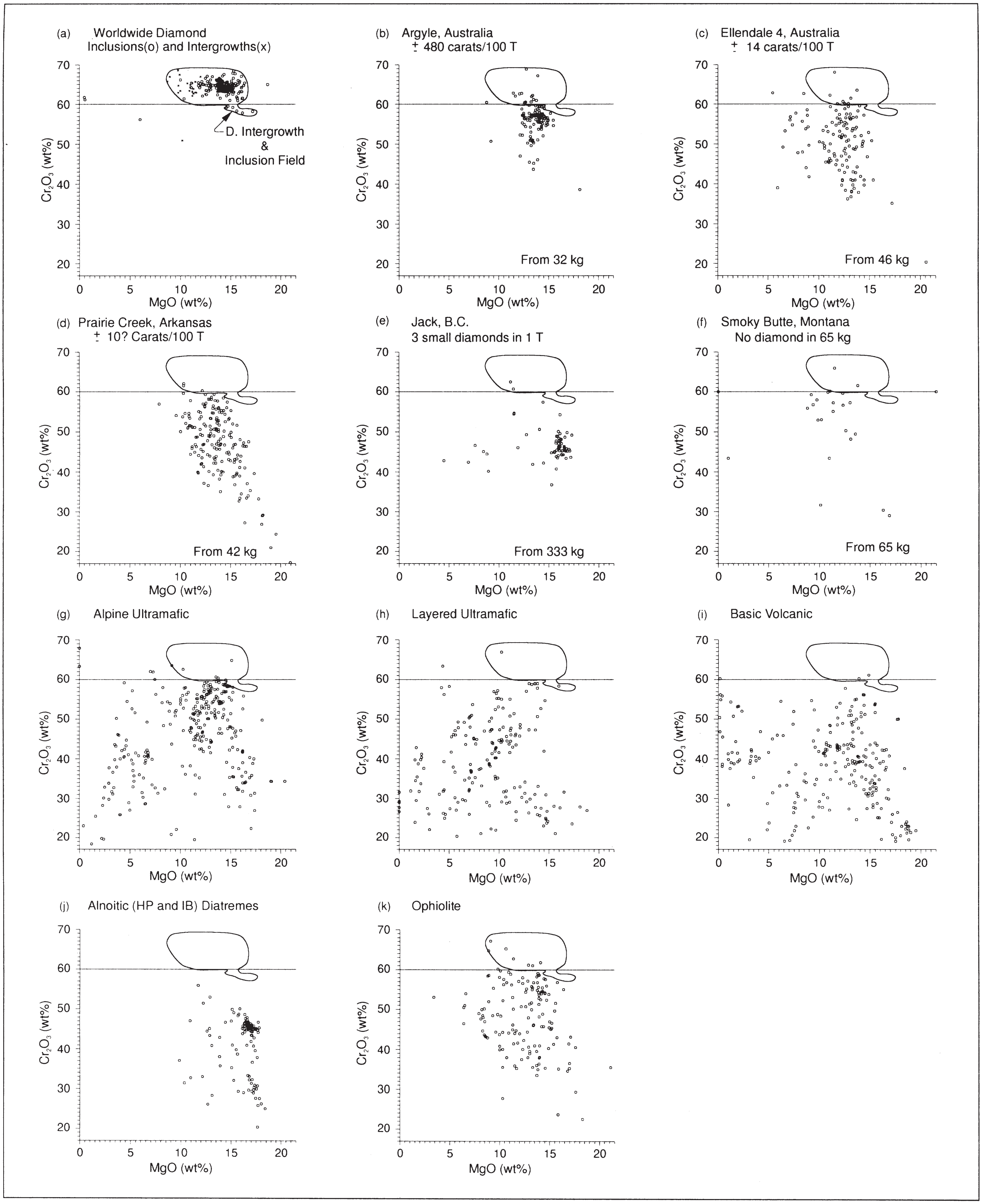


*Figure 15(a-k). $Cr_2O_3$–MgO plots for chromites from lamproite sources.*

## Table 15a

### Typical compositional ranges of chromites

| | DI chromites | Cr-Ti chromites | Al/Fe chromites |
|---|---|---|---|
| $Cr_2O_3$ | 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 |
| $Al_2O_3$ | 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 |

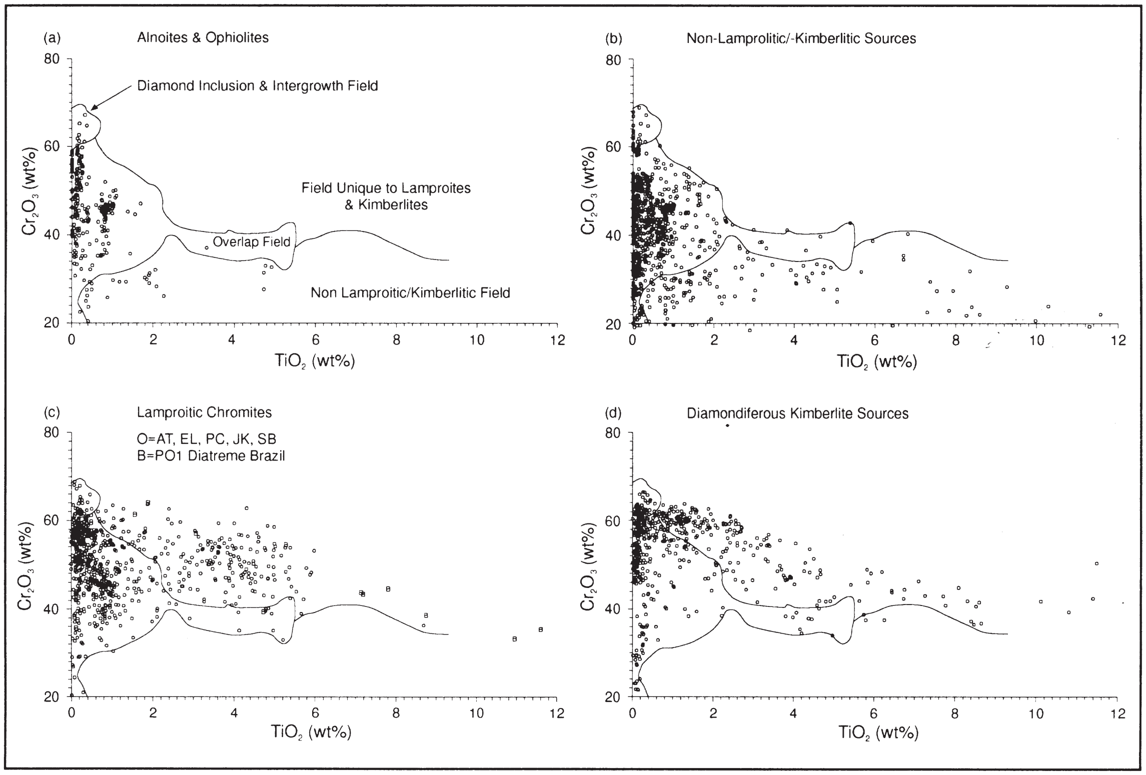


*Figure 16(a-d). Comparison of $Cr_2O_3$–$TiO_2$ plots of chromites from lamproites and kimberlites with chromites from non-diatreme sources. Data from 1006 analyses.*

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 $TiO_2$ (Danchin and Wyatt, 1979). Figure 17 is a plot of $TiO_2$–$Na_2O$ 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% $Na_2O$. 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% $Na_2O$ 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 $TiO_2$, 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).

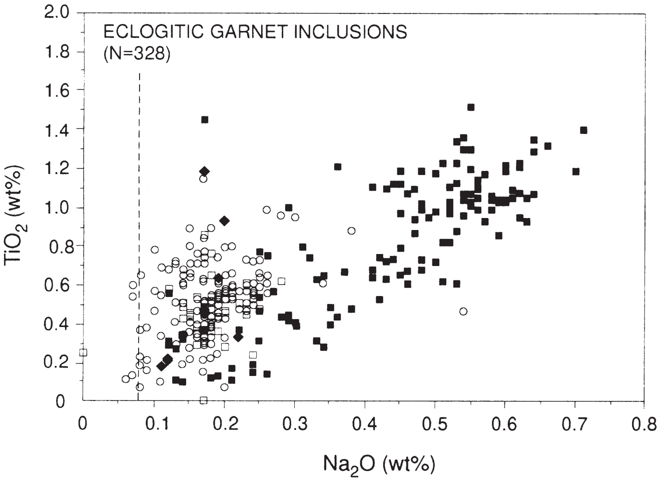


*Figure 17. $TiO_2$–$Na_2O$ plots for garnet inclusions in eclogitic diamonds from worldwide localities. For exploration evaluations, garnets with $Na_2O >$ 0.07 wt% are considered significant. Inclusion data plotted includes: southern Africa-149; Australia-134; Siberia-9; North America-36. Symbols as 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 $CO_2$ (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 $Fe^{3+}/Fe^{2+}$ 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 $Cr^{3+}$ can be found in either association. Droop (1987) has reviewed techniques for computing $Fe^{3+}/Fe^{2+}$ 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.

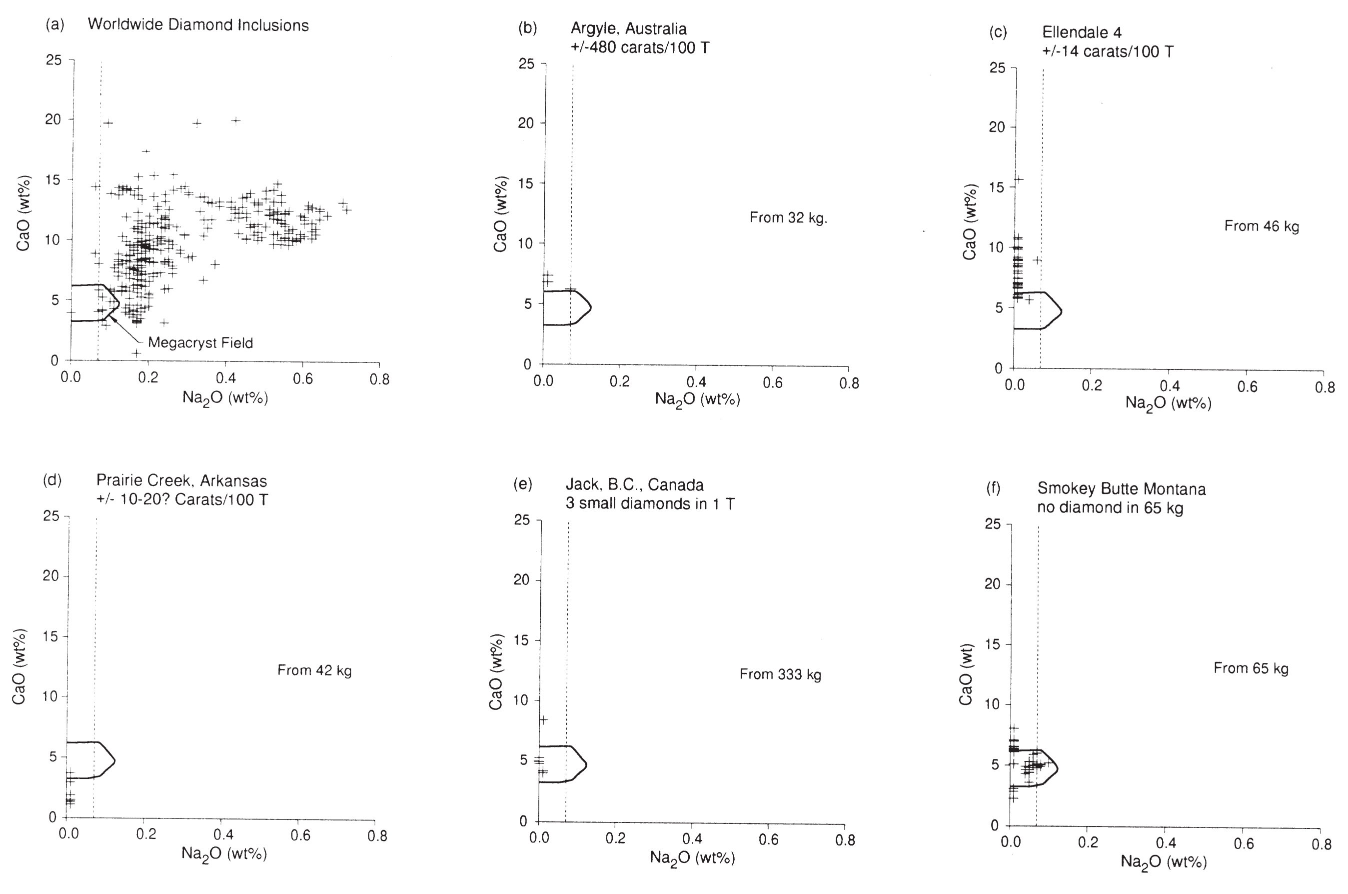


***Figure 18(a-f).*** *CaO-$Na_2O$ plots for Cr-poor garnets from lamproites and inclusions in diamonds.*

## 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

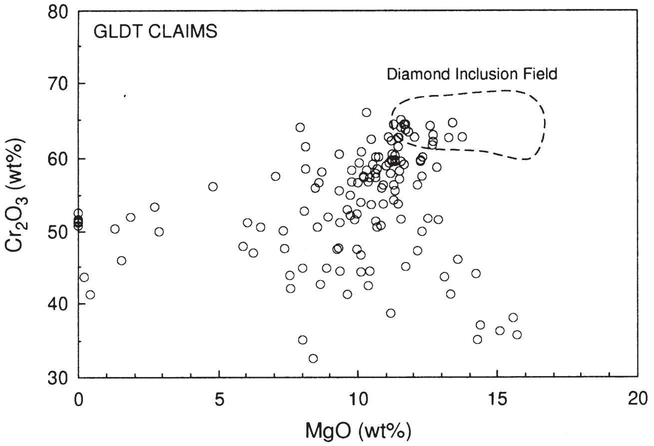


***Figure 19.** Chromites composition plot. Reproduced from Minerale Dienste "GLDT" report on claims in DiaMet's property block, N.W.T., 1990. (see text)*

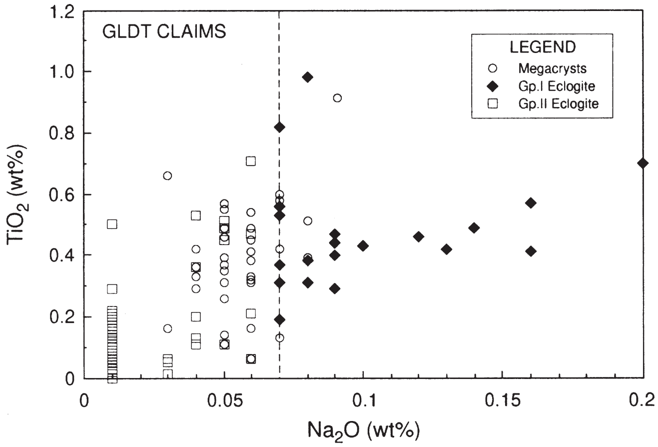


***Figure 21.** Low-Cr garnet composition plot. Reproduced from Minerale Dienste "GLDT" report on claims in DiaMet's property block, N.W.T., 1990. (see text)*

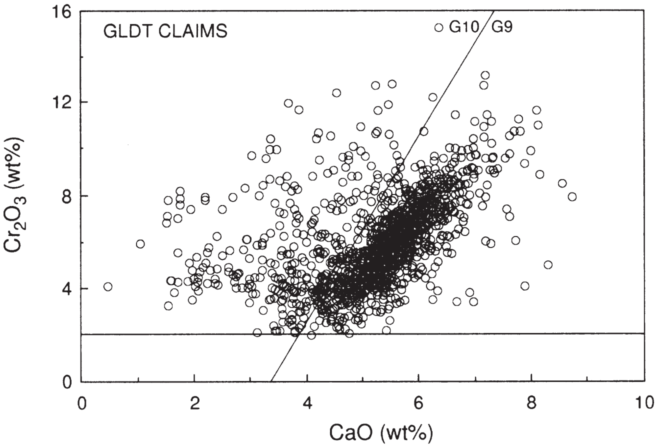


***Figure 20.** Peridotitic garnet composition plot. Reproduced from Minerale Dienste "GLDT" report on claims in DiaMet's property block, N.W.T., 1990. (see text)*

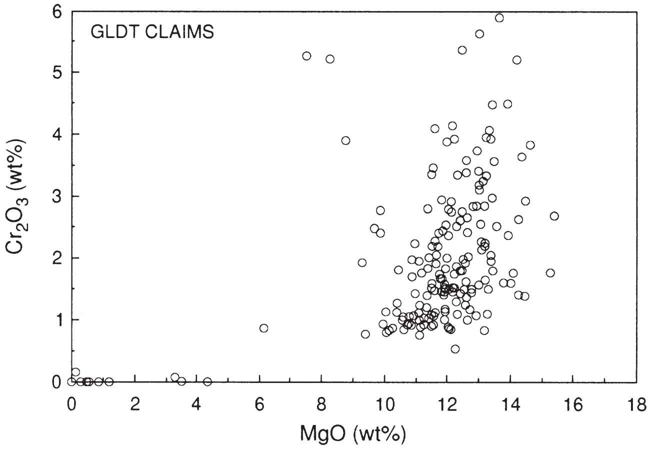


***Figure 22.** Ilmenite composition plot. Reproduced from Minerale Dienste "GLDT" report on claims in DiaMet's property block, N.W.T., 1990. (see text)*

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/m$^2$ 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°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°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/m$^2$ (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 | Hi-P macrocrysts | Magmatic | Magmatic | Lo-P macrocrysts | Harz + Lherz | Harzburgitic |
| $Cr_2O_3$ | 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% |
| $Al_2O_3$ | 5–11 wt% | bimodal: 7–9&2–4% | 10–18 wt% | 15–22 wt% | 4-20 wt% | 4–10 wt% |
| $Fe_2O_3$ | 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% $Cr_2O_3$; Cr-poor garnets <2 wt% $Cr_2O_3$; Cr-rich cpx 0.5 wt% $Cr_2O_3$; Cr-poor cpx <0.5 wt% $Cr_2O_3$.
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% $Cr_2O_3$ (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% $Cr_2O_3$ 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 sources[1]

| ID | DIA. Macro and Micro | Rock type | Orig. wt/kg | Zircon amt. | Tourmaline amt. | Chromite %$Cr_2O_3$ | | Ilmenite | | GARNETS CFM MODIFICATION OF DAWSON CLASS- | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Norm. | | | >60 | 60 | PL | IL | G1 | G2 | G3 | G4 | G5 | G6 | G7 | G8 |
| | | | | | | | | | | P&M | P&E | E&R | | | E | P | E |
| AT | Vab | L | 32 | ab | mod | +13 | +100 | +8 | +13 | 0 | 2 | 2 | 0 | 8 | 0 | 0 | 0 |
| | | | | | | 21 | 159 | 13 | 21 | 0 | 3 | 3 | 0 | 13 | 0 | 0 | 0 |
| EL4 | mod | L | 46 | ab | Vab | 8 | +69 | +3 | +44 | 0 | 0 | 34 | 1 | 25 | 0 | 0 | 0 |
| | | | | | | 9 | 76 | 3 | 48 | 0 | 0 | 37 | 1 | 27 | 0 | 0 | 0 |
| JKM | tr | L | 180 | ab | ab | 2 | 12 | 48 | 11 | 6 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 1 | 3 | 13 | 3 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| JK2 | tr | L | 90 | mod | mod | 0 | +21 | 2 | 13 | 1 | 0 | 1 | 0 | 3 | 0 | 0 | 0 |
| | | | | | | 0 | 12 | 1 | 7 | 1 | 0 | 1 | 0 | 2 | 0 | 0 | 0 |
| JK3 | nil | L | 63 | min | min | 0 | +41 | 0 | 8 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 |
| | | | | | | 0 | 32 | 0 | 6 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 |
| PC64 | min | L | 21 | ab | min | 1 | +116 | 5 | 4 | 0 | 0 | 1 | 0 | 40 | 0 | 0 | 0 |
| | | | | | | 2 | 272 | 12 | 9 | 0 | 0 | 2 | 0 | 94 | 0 | 0 | 0 |
| PC65 | mod | L | 21 | ab | mod | 2 | +79 | 15 | 0 | 0 | 0 | 1 | 0 | 20 | 0 | 0 | 0 |
| | | | | | | 5 | 189 | 36 | 0 | 0 | 0 | 2 | 0 | 48 | 0 | 0 | 0 |
| SB | nil | L | 65 | tr | nil | 3 | 20 | +75 | 7 | 30 | 6 | 6 | 0 | 16 | 0 | 0 | 0 |
| | | | | | | 2 | 16 | 58 | 5 | 23 | 5 | 5 | 0 | 12 | 0 | 0 | 0 |
| SF1 | nil | L | 22 | min | nil | 0 | 32 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 0 | 73 | 9 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| LRO | nil | PL | 31.4 | min | nil | 0 | +91 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 0 | 145 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| LRD | nil | PL | 45.9 | tr | nil | 0 | +99 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| | | | | | | 0 | 108 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| MR | nil | PL | 34 | min | tr | 0 | +66 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 0 | 97 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| MK | tr | PL | 30.1 | min | tr | 0 | +114 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 0 | 189 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| PO1 | nil | PL | 16.7 | min | min | 1 | 16 | 40 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 3 | 48 | 120 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BT | tr | K | 73.7 | min | nil | 2 | 39 | +17 | 1 | 13 | 0 | 0 | 0 | 3 | 0 | 0 | 0 |
| | | | | | | 1 | 26 | 12 | 1 | 9 | 0 | 0 | 0 | 2 | 0 | 0 | 0 |
| CC | nil | K | 62.5 | tr | nil | 1 | +139 | 1 | 1 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 1 | 111 | 1 | 1 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| JF | nil | K | 64.3 | min | tr | 0 | +82 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 0 | 64 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| KL1 | tr | K | 23.2 | min | nil | 0 | 32 | +28 | 0 | 1 | 0 | 5 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 0 | 69 | 60 | 0 | 2 | 0 | 11 | 0 | 0 | 0 | 0 | 0 |
| KL5 | tr | K | 4.7 | tr | nil | 3 | +92 | +54 | 0 | 1 | 2 | 1 | 0 | 1 | 0 | 0 | 0 |
| | | | | | | 32 | 979 | 574 | 0 | 11 | 21 | 11 | 0 | 11 | 0 | 0 | 0 |
| NE | ab | K | 20.8 | min | nil | 40 | +79 | 1 | 5 | 2 | 0 | 7 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 96 | 190 | 2 | 12 | 5 | 0 | 17 | 0 | 0 | 0 | 0 | 0 |
| SK | tr | K | 36 | min | min | 1 | 47 | +40 | 0 | 28 | 6 | 16 | 1 | 0 | 1 | 0 | 0 |
| | | | | | | 1 | 65 | 56 | 0 | 39 | 8 | 22 | 1 | 0 | 1 | 0 | 0 |
| SL | mod | K | 44.2 | min | nil | 1 | +65 | +36 | 0 | 9 | 2 | 41 | 0 | 0 | 1 | 0 | 0 |
| | | | | | | 1 | 74 | 41 | 0 | 10 | 2 | 46 | 0 | 0 | 1 | 0 | 0 |
| SV | ab | K | 9.5 | tr | nil | +70 | 28 | 2 | 1 | 14 | 0 | 50 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 368 | 147 | 11 | 5 | 74 | 0 | 263 | 0 | 0 | 0 | 0 | 0 |
| BF | nil | AL | 70.5 | min | nil | 0 | +180 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 0 | 128 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| HP | nil | AL | 60.2 | tr | nil | 0 | +85 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 0 | 71 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IB | nil | AL | 65.2 | tr | nil | 0 | 44 | +25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 0 | 34 | 19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| MD | nil | OM | 100 | mod | nil | 0 | 32 | 10 | 9 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | 0 | 16 | 5 | 5 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| DIAMOND INCLUSIONS: | | | | | | | | | | | | | | | | | |
| South Africa | | | | | | 132 | 6 | 3 | 0 | 3 | 1 | 75 | 62 | 4 | 7 | 2 | 0 |
| North America | | | | | | 1 | 0 | 2 | 2 | 0 | 0 | 28 | 5 | 3 | 0 | 0 | 0 |
| Australia | | | | | | 1 | 0 | 0 | 1 | 1 | 0 | 6 | 93 | 0 | 34 | 0 | 0 |
| USSR | | | | | | 8 | 0 | 1 | 0 | 3 | 0 | 6 | 4 | 0 | 0 | 0 | 0 |

[1] Values 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 melilite, M: megacryst, E: eclogitic, P: peridotitic, R: regional, V: volcanic, C: clinopyroxene, +: additional unanalysed present, IL: Ilmenite, PL: picroilmenite.

## Table 17 (cont'd.)

| | | | | | | | CLINOPYROXENES | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IFICATIONS | | | | MOORE CLASS | | | DAWSON | | | | | | | | | MOORE | | CFM |
| G9 | G10 | G11 | G12 | | | | CP1 | CP2 | CP3 | CP4 | CP5 | CP6 | CP8 | CP9 | CP10 | | | |
| P | | | | E | P | R | P&E | | | E | P | | E | | | CE | CP | CV |
| 0 | 0 | 1 | 0 | 3 | 3 | 49 | 1 | 2 | 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 | 29 | 6 | 3 |
| 16 | 8 | 6 | 0 | 54 | +28 | 23 | 0 | 0 | 0 | 0 | 35 | 1 | 0 | 0 | 0 | 0 | +37 | +1 |
| 18 | 9 | 7 | 0 | 59 | 31 | 25 | 0 | 0 | 0 | 0 | 38 | 1 | 0 | 0 | 0 | 0 | 41 | 1 |
| 4 | 1 | 20 | 0 | 3 | 34 | 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 | ? | ? | ? |
| 2 | 4 | 5 | 0 | 3 | 10 | 39 | 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 | 1 | 0 | 2 |
| 0 | 0 | 1 | 0 | 3 | 1 | 13 | 0 | 3 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 19 | 5 | 9 |
| 0 | 0 | 1 | 0 | 2 | 1 | 10 | 0 | 2 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 15 | 4 | 7 |
| 3 | 0 | 0 | 0 | 3 | 3 | 51 | 0 | 6 | 0 | 0 | 26 | 3 | 0 | 0 | 0 | +1 | +32 | +6 |
| 7 | 0 | 0 | 0 | 7 | 7 | 120 | 0 | 14 | 0 | 0 | 61 | 7 | 0 | 0 | 0 | 2 | 75 | 14 |
| 0 | 0 | 0 | 1 | 6 | 1 | 23 | 1 | 7 | 1 | 0 | 36 | 1 | 0 | 0 | 0 | +15 | +37 | +39 |
| 0 | 0 | 0 | 2 | 14 | 2 | 55 | 2 | 17 | 2 | 0 | 86 | 2 | 0 | 0 | 0 | 36 | 89 | 93 |
| 21 | 1 | 35 | 0 | 50 | 76 | 13 | 0 | 1 | 0 | 0 | 5 | 7 | 0 | 0 | 0 | 8 | 19 | 2 |
| 16 | 1 | 27 | 0 | 39 | 59 | 10 | 0 | 1 | 0 | 0 | 4 | 5 | 0 | 0 | 0 | 6 | 15 | 2 |
| 10 | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 2 | 5 |
| 23 | 0 | 0 | 0 | 0 | 23 | 0 | 0 | 0 | 0 | 0 | 5 | 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 | 1 | 0 | 9 | 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 | 1 | 0 | 1 |
| 0 | 0 | 0 | 0 | 1 | 0 | 23 | 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 | 1 |
| 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 | 2 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 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 | 6 | 0 | 0 |
| 28 | 0 | 17 | 0 | 15 | 43 | 12 | 0 | 3 | 1 | 0 | 8 | 4 | 0 | 0 | 0 | +5 | +17 | +1 |
| 19 | 0 | 12 | 0 | 10 | 29 | 8 | 0 | 2 | 1 | 0 | 5 | 3 | 0 | 0 | 0 | 3 | 12 | 1 |
| 43 | 3 | 30 | 0 | 16 | +71 | 0 | 0 | 1 | 2 | 0 | 17 | 1 | 0 | 0 | 0 | 0 | +7 | +14 |
| 34 | 2 | 24 | 0 | 13 | 57 | 0 | 0 | 1 | 2 | 0 | 14 | 1 | 0 | 0 | 0 | 0 | 6 | 11 |
| 1 | 0 | 0 | 0 | 3 | 0 | 5 | 0 | 6 | 2 | 0 | 15 | 0 | 0 | 0 | 0 | 2 | 9 | +20 |
| 1 | 0 | 0 | 0 | 2 | 0 | 4 | 0 | 5 | 2 | 0 | 12 | 0 | 0 | 0 | 0 | 2 | 7 | 16 |
| 14 | 7 | 17 | 0 | 5 | +39 | 0 | 0 | 2 | 0 | 0 | 7 | 22 | 0 | 0 | 0 | 1 | 34 | 0 |
| 30 | 15 | 37 | 0 | 11 | 84 | 0 | 0 | 4 | 0 | 0 | 15 | 47 | 0 | 0 | 0 | 2 | 73 | 0 |
| 32 | 12 | 47 | 0 | 2 | +98 | 0 | 0 | 8 | 1 | 1 | 16 | 3 | 0 | 0 | 0 | 13 | 29 | 1 |
| 340 | 128 | 500 | 0 | 21 | 0 | 0 | 0 | 85 | 11 | 11 | 170 | 32 | 0 | 0 | 0 | 138 | 309 | 11 |
| 26 | 77 | 30 | 3 | 1 | +127 | 0 | 0 | 1 | 0 | 0 | 12 | 26 | 0 | 0 | 0 | +1 | +42 | 0 |
| 63 | 185 | 72 | 7 | 2 | 305 | 0 | 0 | 2 | 0 | 0 | 29 | 63 | 0 | 0 | 0 | 2 | 101 | 0 |
| 28 | 1 | 24 | 0 | 36 | +68 | 0 | 0 | 0 | 0 | 0 | 16 | 1 | 0 | 0 | 0 | 0 | +18 | +1 |
| 39 | 1 | 33 | 0 | 50 | 94 | 0 | 0 | 0 | 0 | 0 | 22 | 1 | 0 | 0 | 0 | 0 | 25 | 1 |
| 22 | 11 | 80 | 0 | 57 | +107 | 4 | 0 | 7 | 0 | 0 | 32 | 2 | 0 | 0 | 0 | 0 | +42 | 0 |
| 25 | 12 | 90 | 0 | 64 | 121 | 5 | 0 | 8 | 0 | 0 | 36 | 2 | 0 | 0 | 0 | 0 | 48 | 0 |
| 26 | 33 | 4 | 0 | 87 | +40 | 1 | 0 | 0 | 0 | 0 | 6 | 34 | 0 | 0 | 0 | 0 | 41 | +1 |
| 137 | 174 | 21 | 0 | 458 | 211 | 5 | 0 | 0 | 0 | 0 | 32 | 179 | 0 | 0 | 0 | 0 | 216 | 5 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 9 | 0 | 52 | 2 | 0 | 0 | 0 | 1 | 8 | +75 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 6 | 0 | 37 | 1 | 0 | 0 | 0 | 1 | 6 | 53 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 0 | 34 | 2 | 0 | 0 | 0 | 3 | 4 | +49 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 0 | 28 | 2 | 0 | 0 | 0 | 2 | 3 | 41 |
| 36 | 0 | 0 | 0 | 0 | 36 | 0 | 0 | 11 | 7 | 8 | 11 | 1 | 0 | 0 | 0 | +25 | +28 | +45 |
| 28 | 0 | 0 | 0 | 0 | 28 | 0 | 0 | 8 | 5 | 6 | 8 | 1 | 0 | 0 | 0 | 19 | 21 | 35 |
| 1 | 0 | 0 | 0 | 0 | 2 | 5 | 6 | 3 | 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 | 5 | 1 | 1 |
| 5 | 97 | 8 | 1 | 149 | 114 | 0 | 0 | 5 | 0 | 0 | 5 | 4 | 48 | 10 | 6 | 132 | 17 | 0 |
| 0 | 3 | 1 | 0 | 36 | 4 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 15 | 3 | 1 | 21 | 4 | 0 |
| 0 | 2 | 0 | 0 | 133 | 3 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 16 | 4 | 6 | 43 | 3 | 0 |
| 0 | 26 | 4 | 0 | 13 | 30 | 0 | 0 | 2 | 0 | 0 | 6 | 2 | 3 | 1 | 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 ($Cr_2O_3$ >6 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

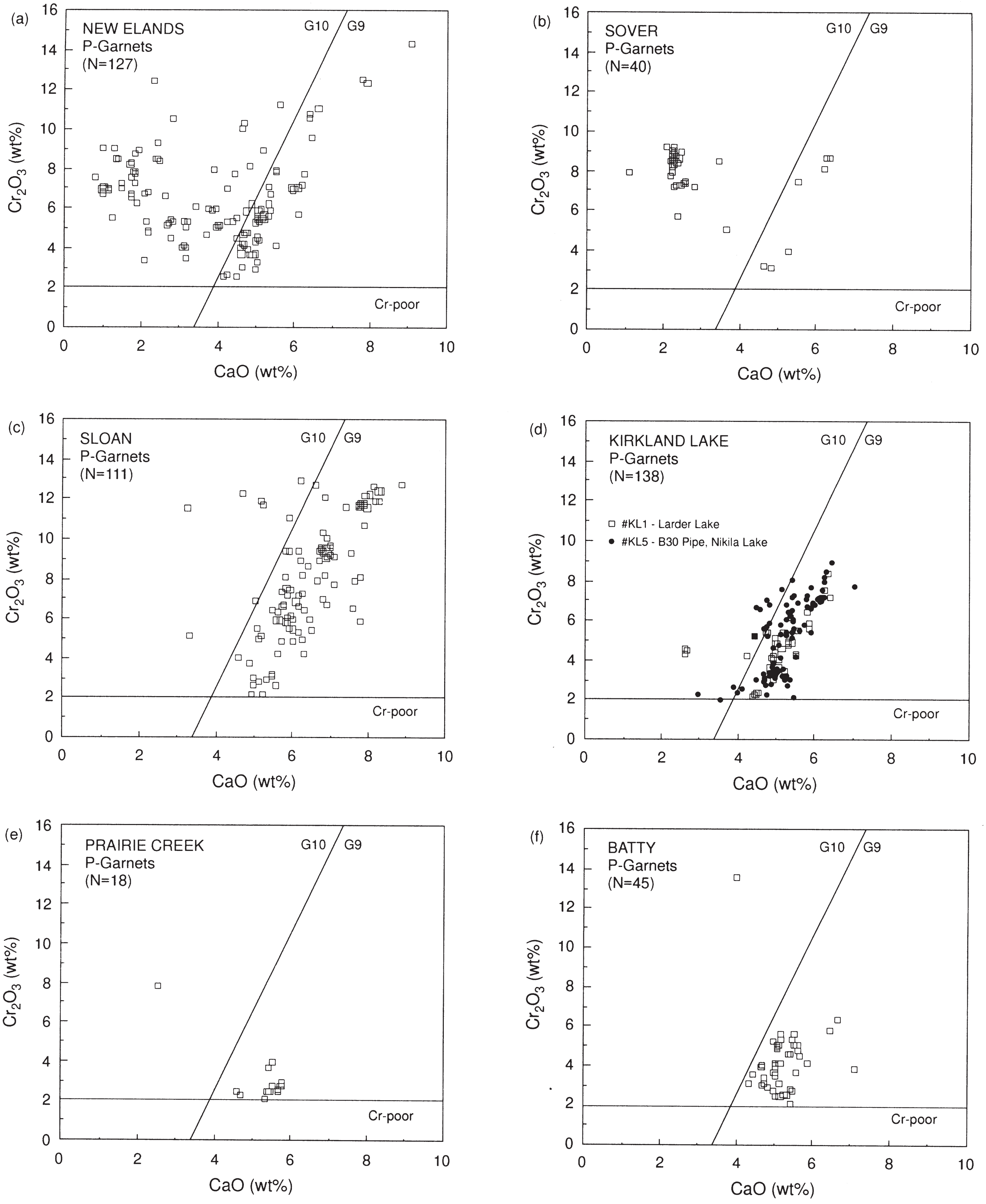


*Figure 23(a-f). Peridotitic garnet compositions for the localities investigated.*

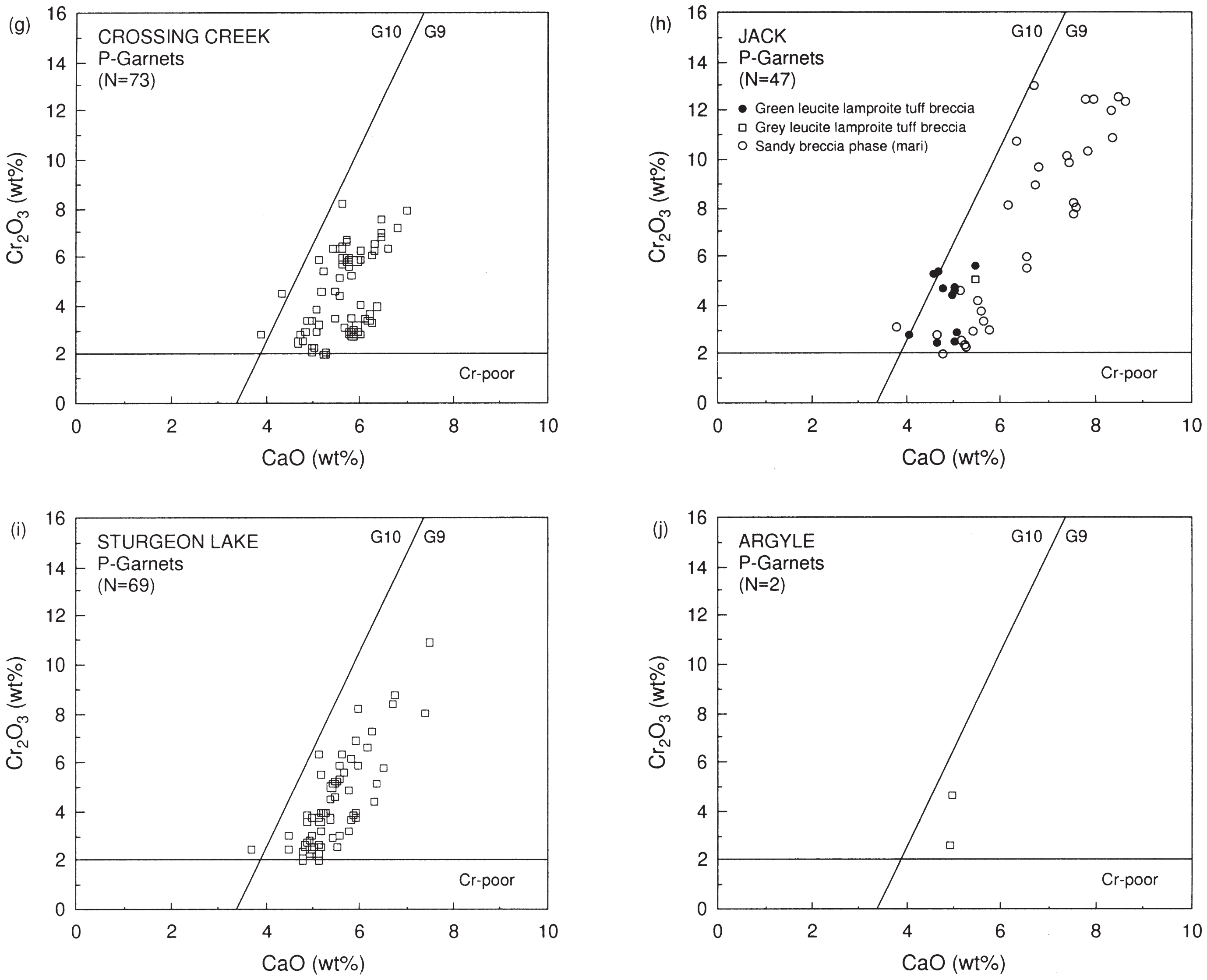


*Figure 23(g-j). (cont'd.)*

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., $TiO_2$-Ni, $Cr_2O_3$-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 ($\sim 40$ $mWm^{-2}$), 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

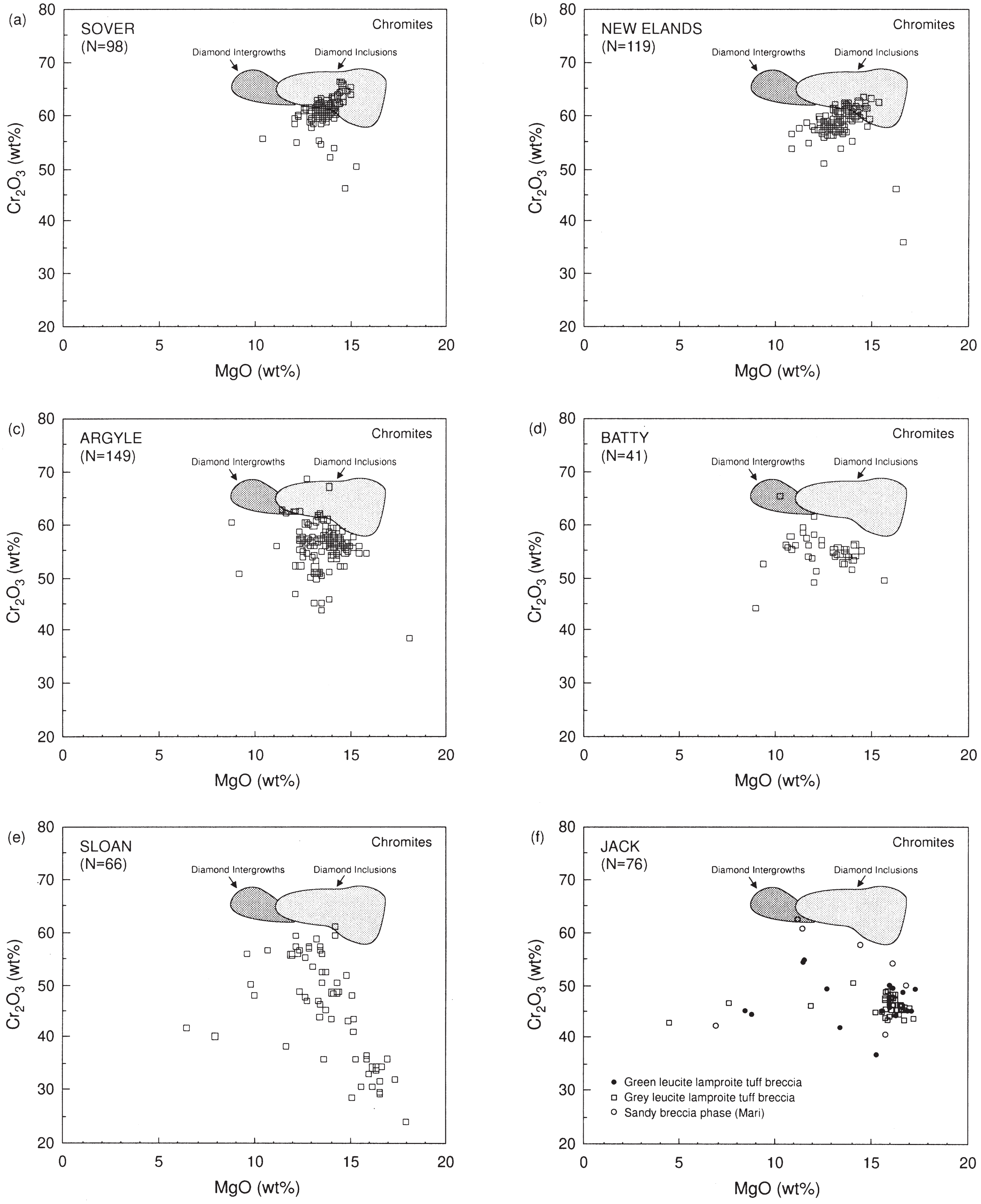


***Figure 24(a-f).*** *Chromite compositions for the localities investigated.*

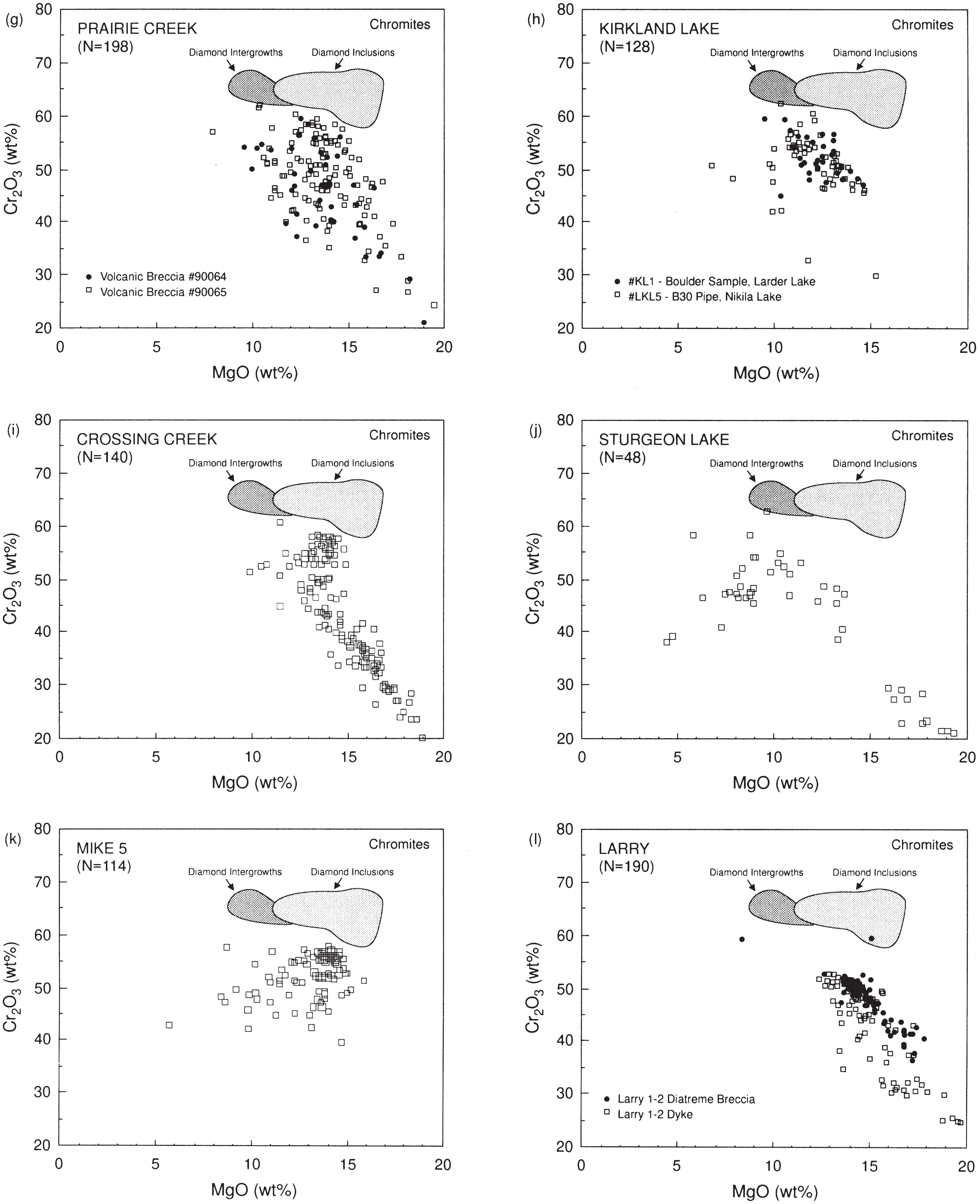


***Figure 24(g-l). (cont'd.)***

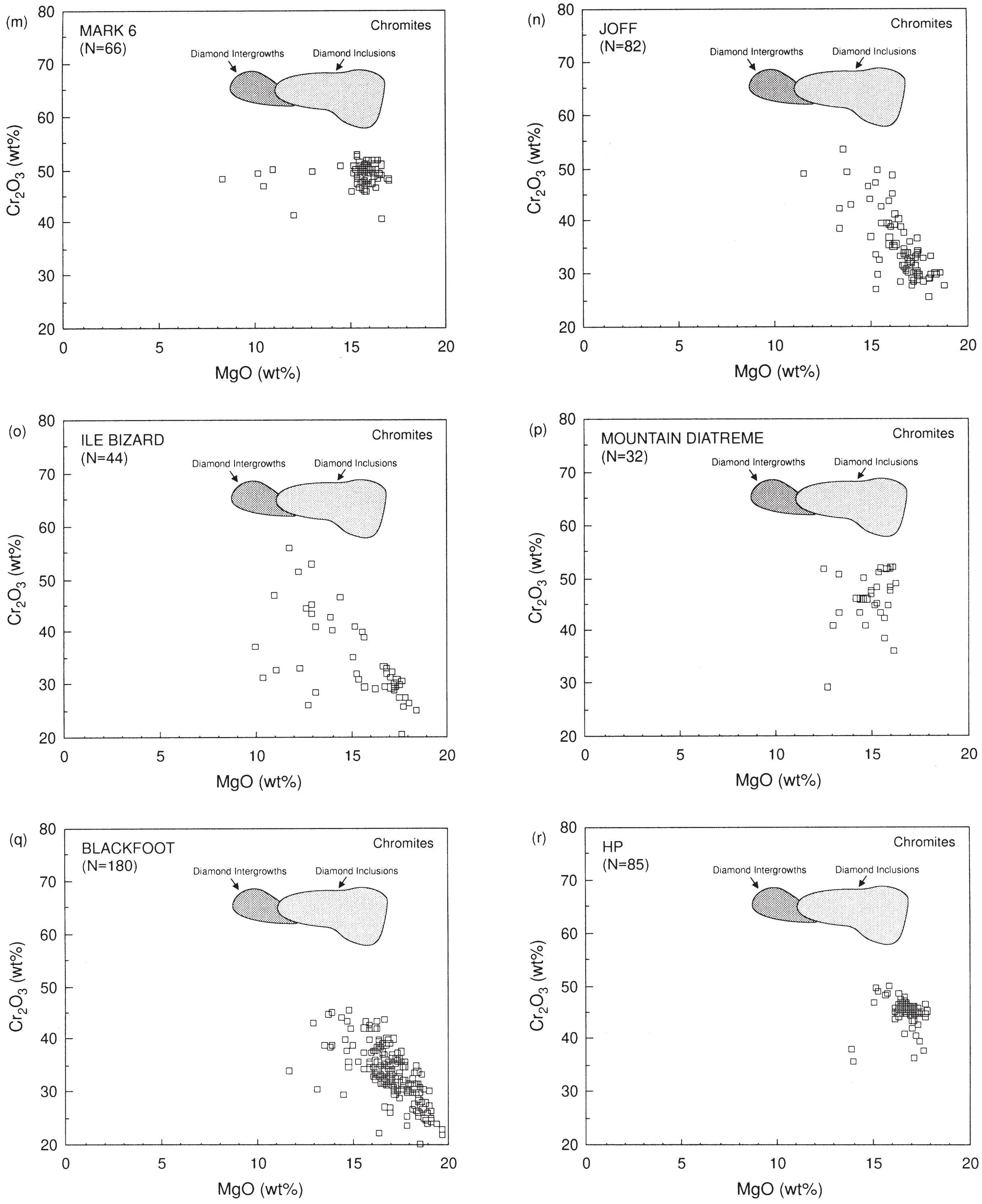


*Figure 24(m-r). (cont'd.)*

## Table 18

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

| ID | Grain | Min | $TiO_2$ | $Al_2O_3$ | $Cr_2O_3$ | 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* |

[1] Additional 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.)**

| | | | | | | | | | CSIRO Proton Probe Analysis | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Grain | Min | $TiO_2$ | $Al_2O_3$ | $Cr_2O_3$ | FeO | MnO | MgO | 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 $\mu$m 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 $\mu$m 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% $Cr_2O_3$. 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 $TiO_2$ versus $Na_2O$ for the suites recovered from the localities investigated are presented in Figure 25.

Garnets showing significant trace enrichments of sodium (>0.07 wt% $Na_2O$) 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-$Na_2O$ 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 ecologitic 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 $Cr_2O_3$ versus MgO for the ilmenites recovered from each locality are plotted in Figure 26.

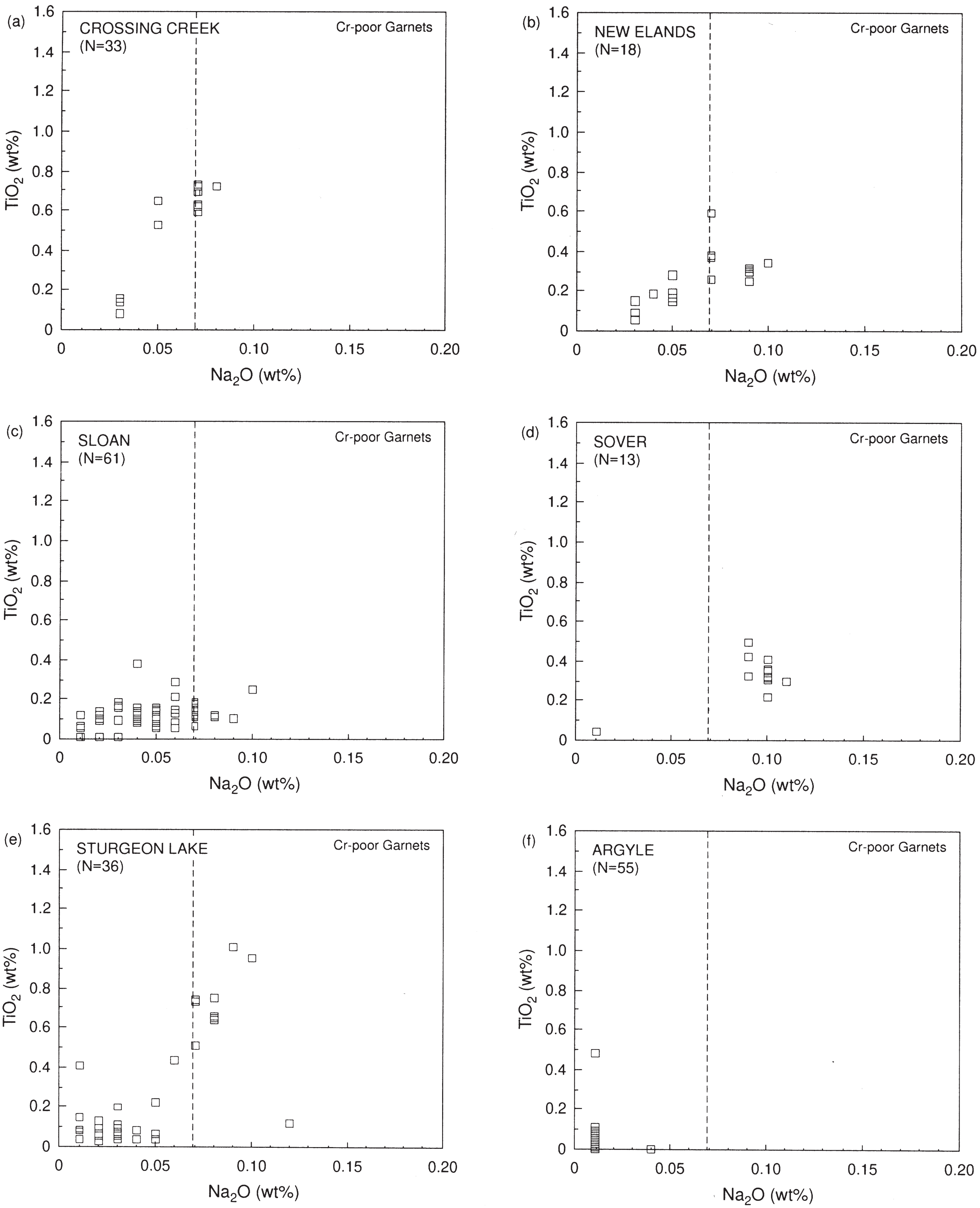


***Figure 25(a-f).*** *Cr-poor garnet compositions for the localities investigated.*

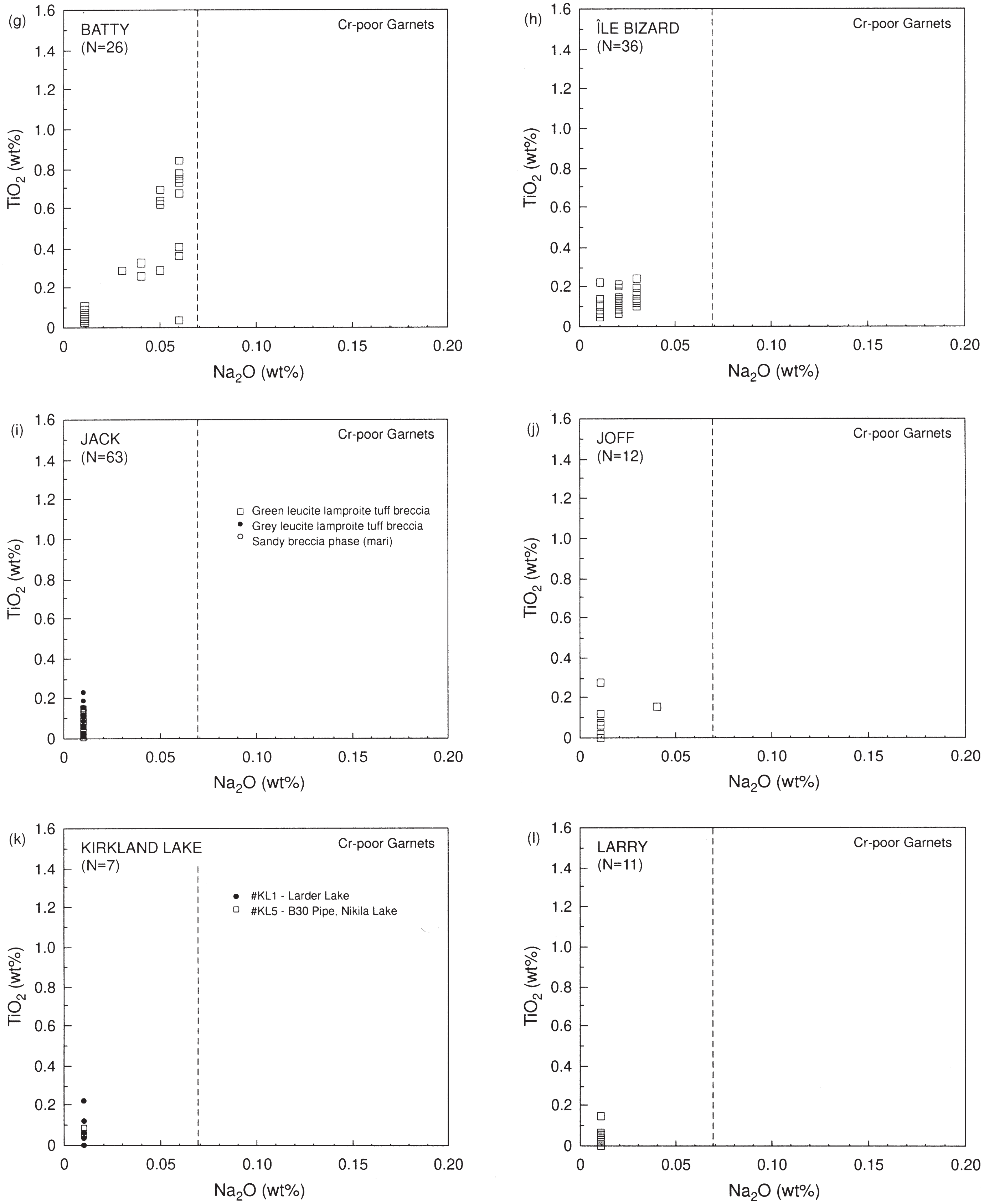


***Figure 25(g-l). (cont'd.)***

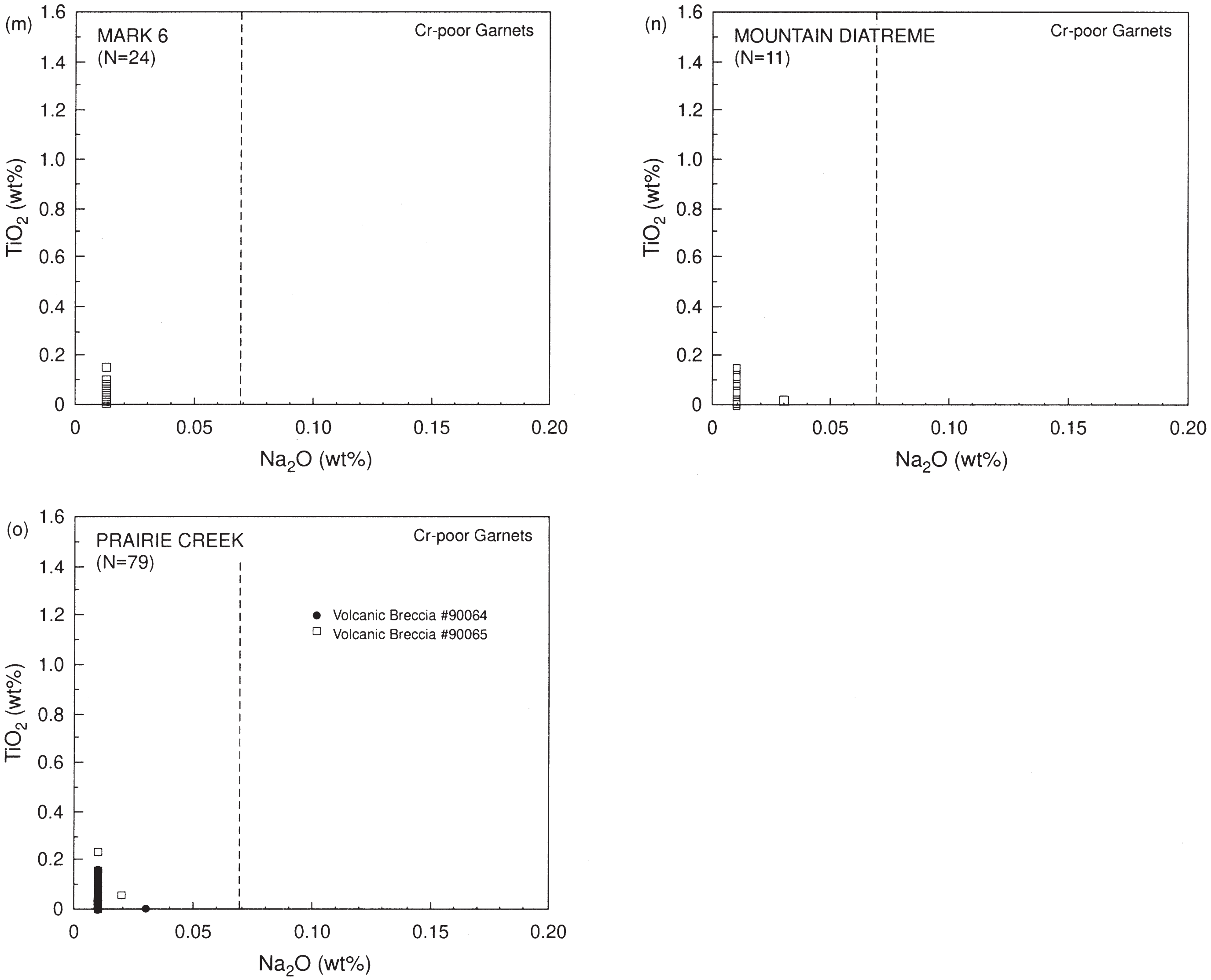


***Figure 25(m-o). (cont'd.)***

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 $Fe^{3+}$ content and lower magnesium content ($\sim$4.5 wt% MgO). In addition, chrome content increases at the low MgO end of the trend. These features are thought to accompany increased $Fe^{3+}$.

The ilmenites from Ile Bizard (Fig. 26h) show a range in MgO content from $\sim$6.5 to 11 wt%, but all have very low concentrations of $Cr_2O_3$. A low DPP is forecast.

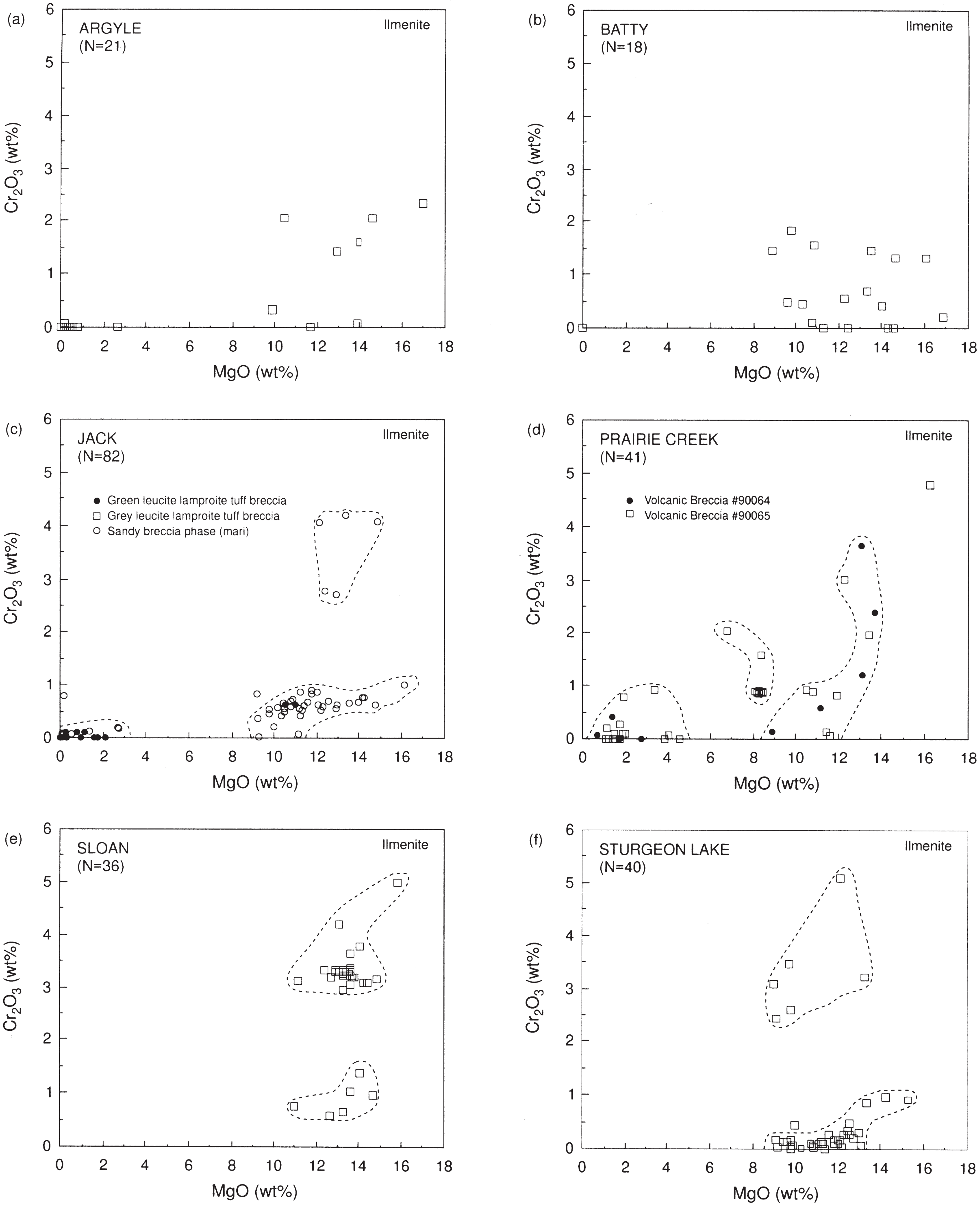


***Figure 26(a-f).*** *Ilmenite compositions for the localities investigated.*

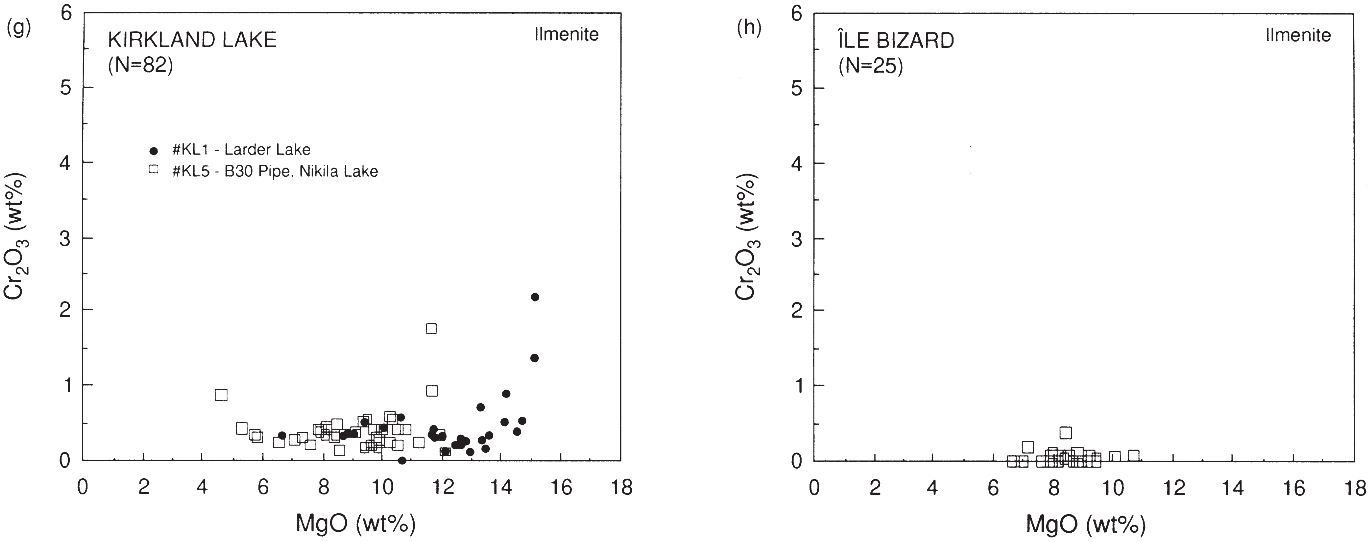


***Figure 26(g-h).*** *(cont'd.)*

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 $Na_2O$ 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.

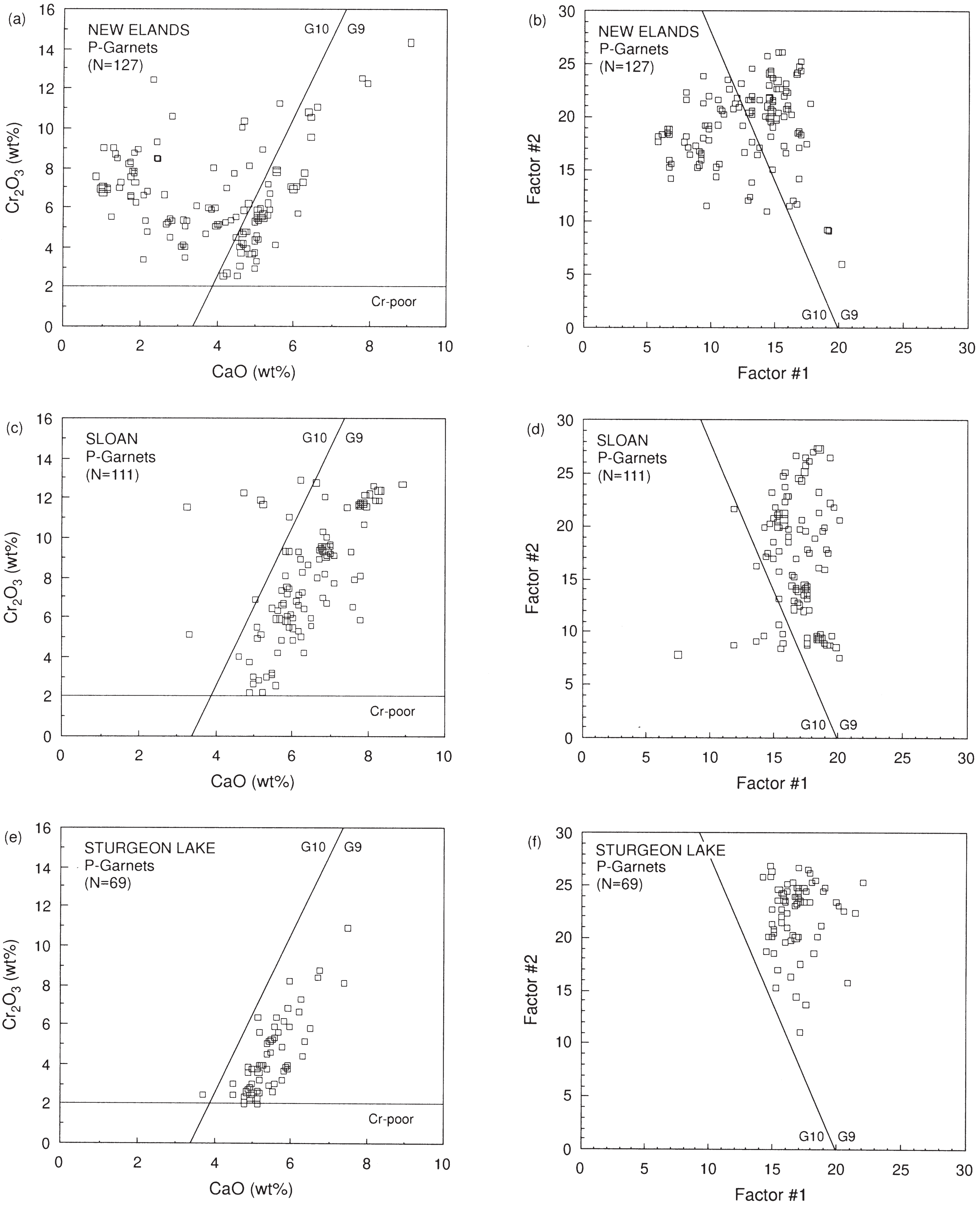


***Figure 27(a-f).*** *Comparison of selected peridotitic garnet factor plots against major element equivalents.*

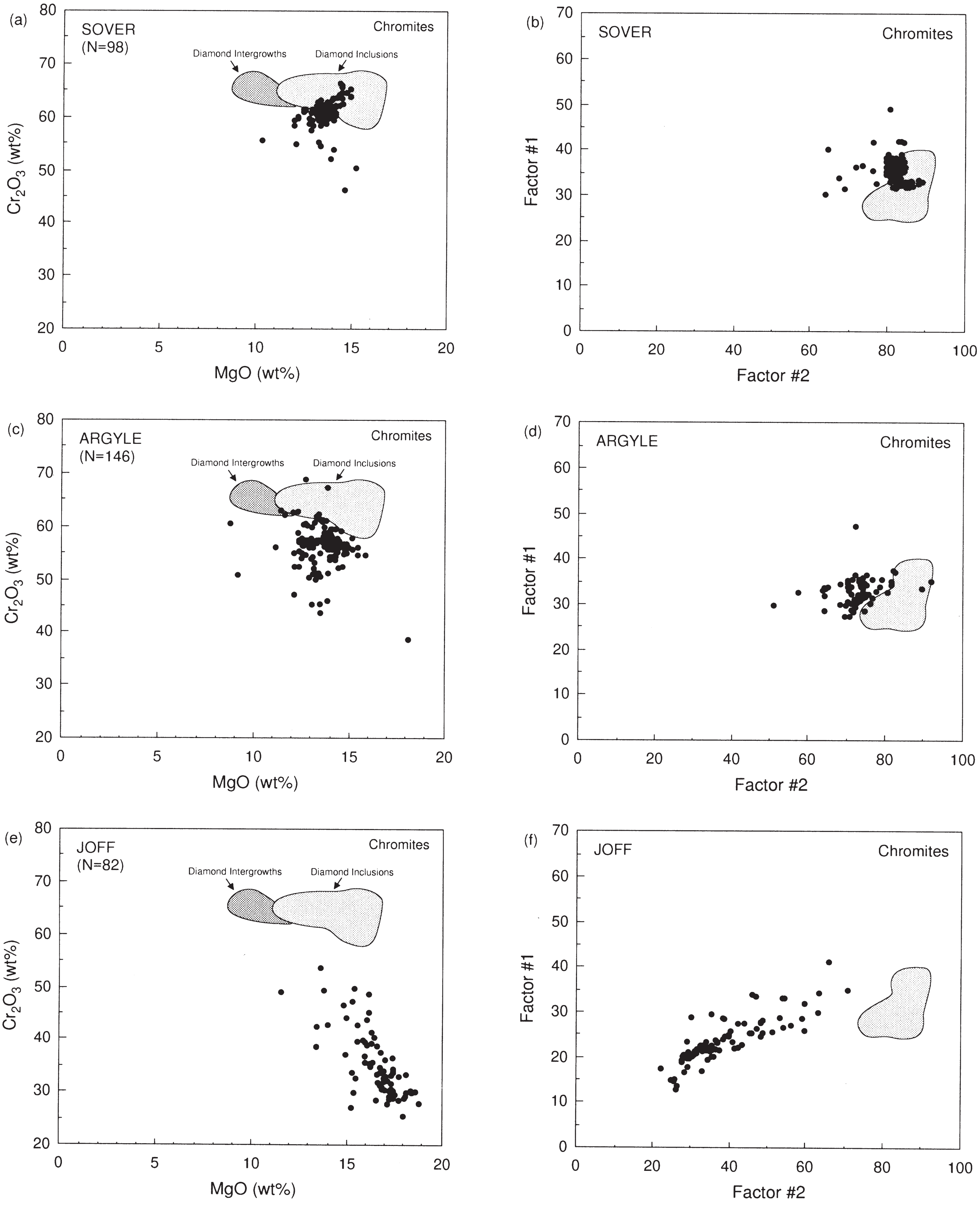


***Figure 28(a-f).*** *Comparison of selected chromite factor plots against major element equivalents.*

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 ($<0.5$mm), 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 | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Cr_2O_3$ | FeO | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | NiO | $Nb_2O_3$ | $ZrO_2$ | 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, $Al_2O_3$, CaO, and $Na_2O$ compared to other orthopyroxenes. The low CaO and $Al_2O_3$ 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 $K_2O$ 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.

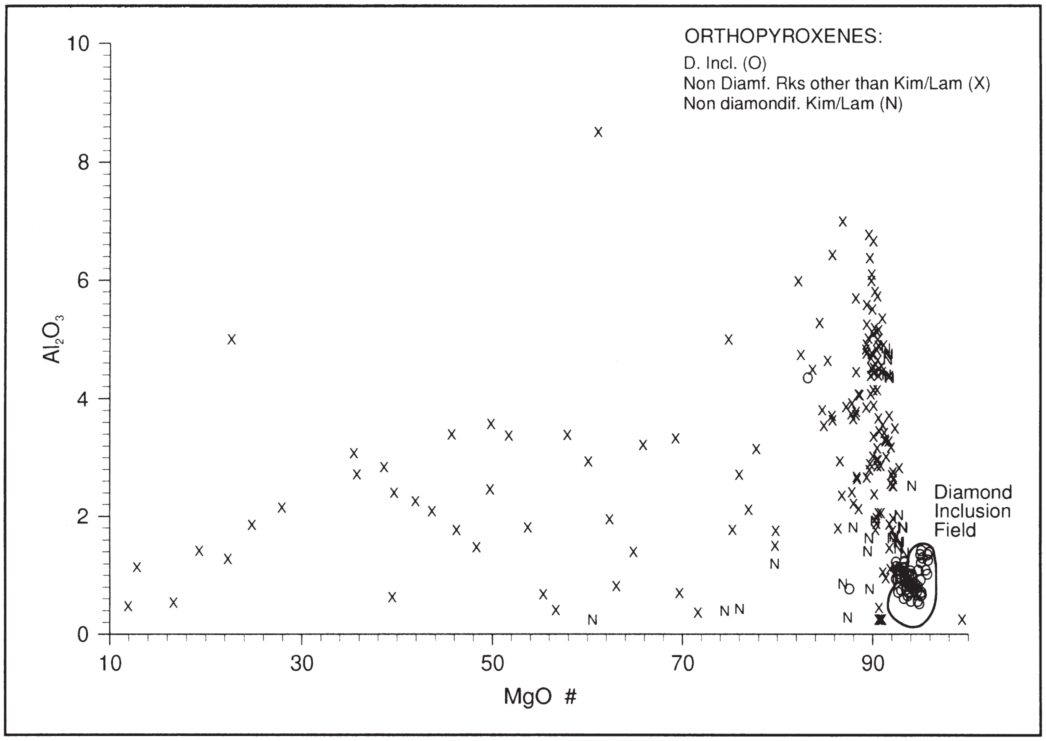


***Figure 29a.*** *Comparison of compositions of orthopyroxene from inclusions in diamond with other orthopyroxenes (data from literature sources).*

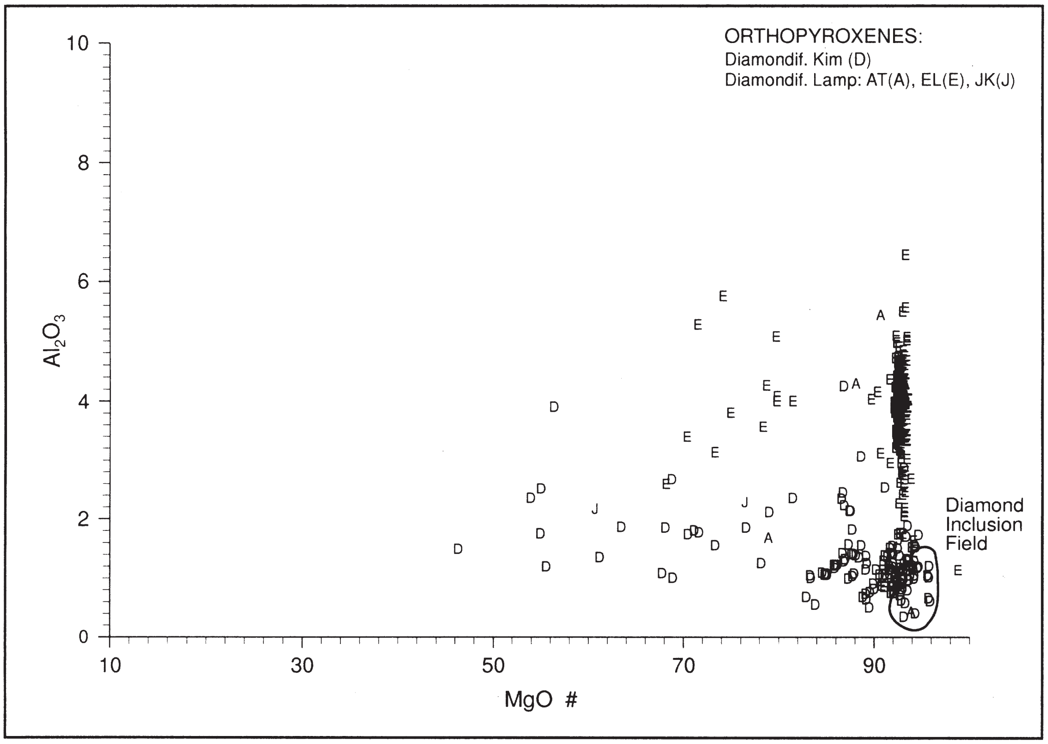


***Figure 29b.*** *Comparison of compositions of orthopyroxene from inclusions in diamond with orthopyroxenes from kimberlite sources.*

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 ($Fo_{90.2\text{-}96.6}$), 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% $Cr_2O_3$, 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% $Cr_2O_3$ 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% $TiO_2$ (Table 20). A ruby corundum inclusion reported by Meyer and Gubelin (1981) is low in titanium (0.09 wt% $TiO_2$) but contains 1.3 wt% $Cr_2O_3$.

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.

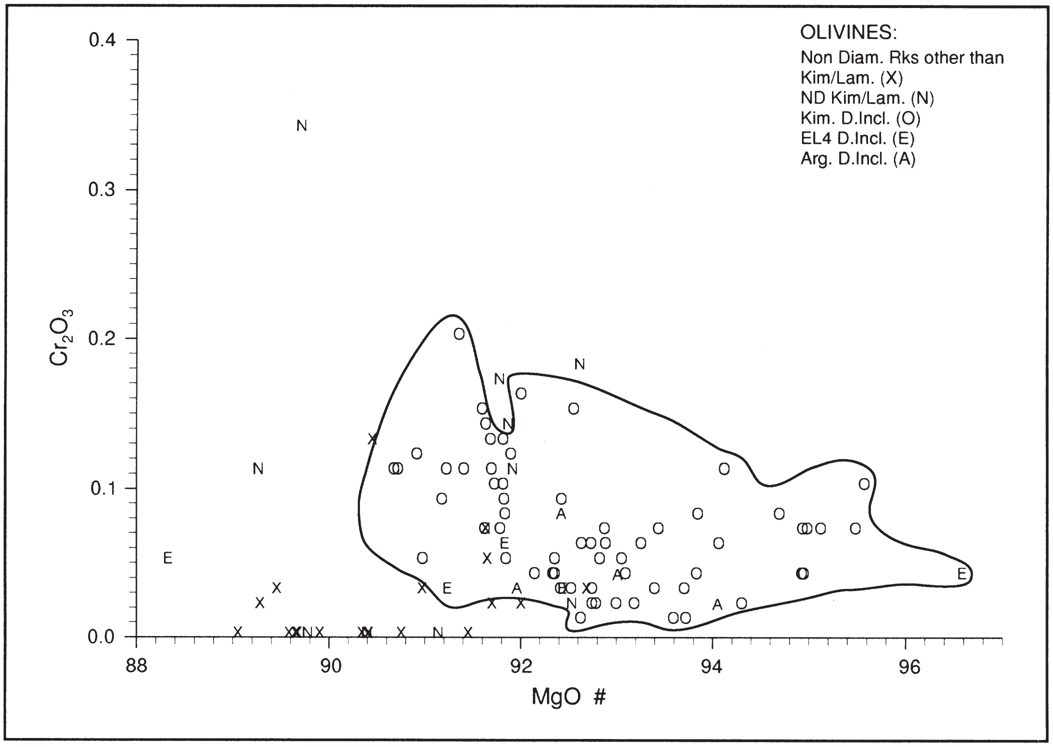


***Figure 30a.** Comparison of compositions of olivine from inclusions in diamond with other olivines (data from literature sources).*

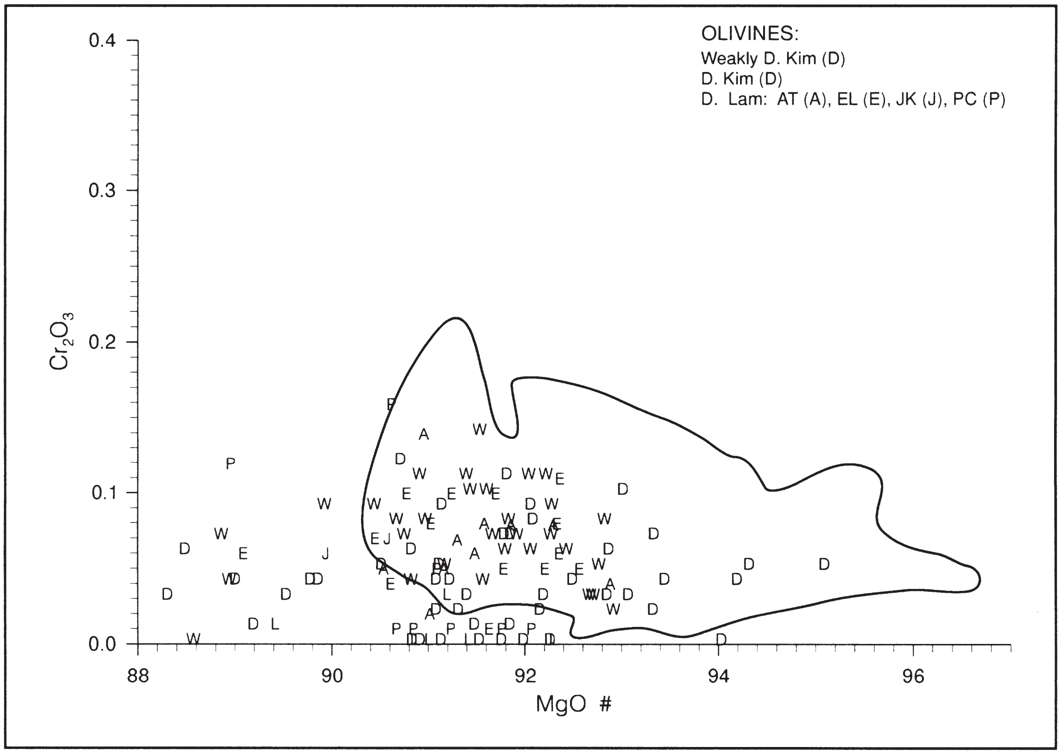


***Figure 30b.** Composition of olivine from diamondiferous kimberlite and diamondiferous lamproite sources.*

### *Rutile and related minerals*

The compositions of rutiles intergrown with diamonds from Mir, as well 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 $Nb_2O_3$ 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% $Nb_20_5$, 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 $\mu$m 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 $K_2O^*$ by University of Cape Town | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | FeO | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $B_2O_3$ | 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.

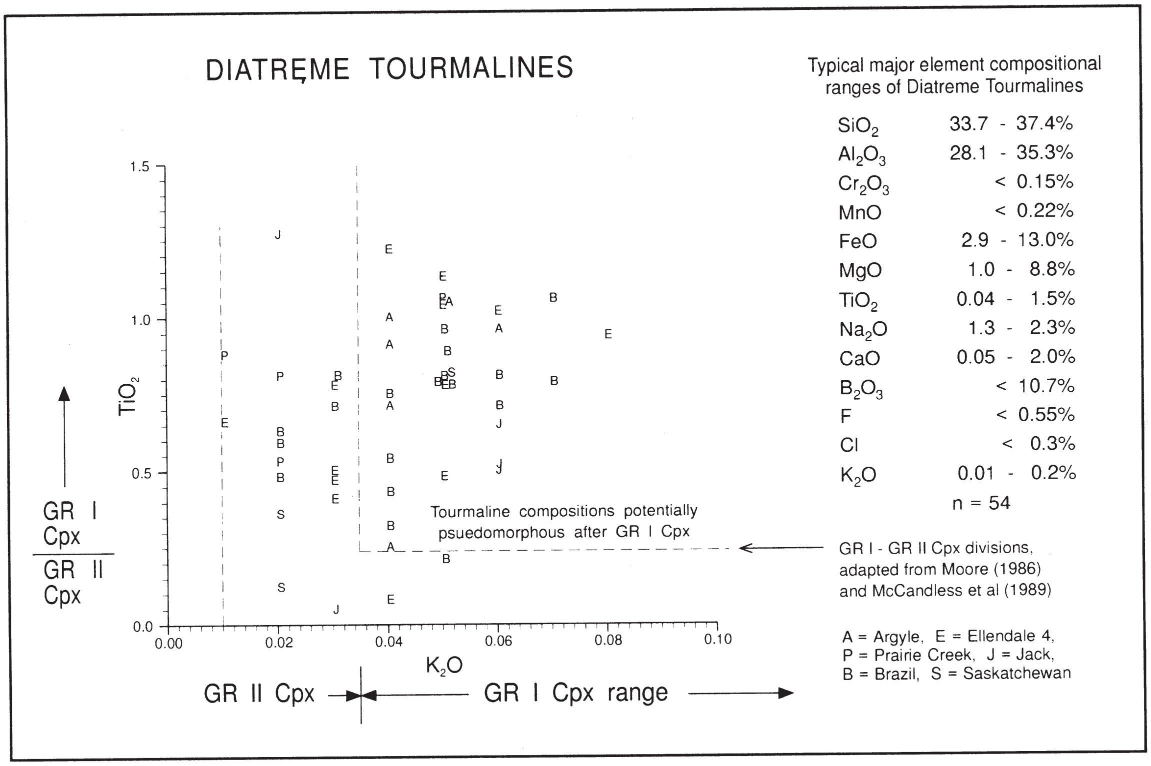


*Figure 31.* *$TiO_2$–$K_2O$ plot for diatreme tourmalines.*

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 ($\sim 150$ 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.

## ACKNOWLEDGMENTS

This bulletin represents a summary of certain aspects of Geological Survey of Canada (1989) which reported on the findings of a research project conducted over the period 1987 to 1989. The project was sponsored by the Institute of Sedimentary and Petroleum Geology, Geological Survey of Canada, Calgary, Alberta; Supply and Services Canada, Hull, Quebec; and C.F. Mineral Research Ltd, Kelowna, B.C. Dr. Walter W. Nassichuk was the principal scientist and project coordinator from the GSC. The numerous people who participated in the project are listed in the Open File Report and their contributions are gratefully acknowledged. Drs. M.A. McCallum and B.H. Scott-Smith undertook detailed petrographic studies on difficult rocks in the original study, and the latter assisted in preparing the overview of kimberlite and lamproite petrology in this bulletin. Technical reviews by Drs. B. Kjaarsgaard and T.E. McCandless assisted in improving the quality of the manuscript. James L. Gurney is gratefully acknowledged for the thankless task of editing the submitted manuscript.

## REFERENCES

**Afanasev, V.P., Varlamov, V.A., and Garanin, V.K.**
1984: The abrasion of minerals in kimberlites in relation to the conditions and distance of their transportation. Soviet Geology and Geophysics, v. 25, p. 119-125.

**Alexander, P.O.**
1986: Preliminary study of soil bacterial populations over and adjacent to three kimberlite diatremes. Extended Abstract, Fourth International Kimberlite Conference, Geological Society of Australia, Special Publication no. 16, p. 440-442.

**Alibert, C. and Albarede, F.**
1988: Relationships between mineralogical, chemical and isotopic properties of some North American kimberlites. Journal of Geophysical Research, v. 93, p. 7643-7671.

**Apfel, E.T., Maynard, J.E., and Ploger, L.W.**
1951: Possible diatremes in Syracuse, New York. Geological Society of America, Bulletin 62, 1421 p.

**Apter, D.B., Harper, F.J., Wyatt, B.A., and Smith, B.H.S.**
1984: The geology of the Mayeng Kimberlite sill complex, South Africa. In Kimberlites I: Kimberlites and Related Rocks, J. Kornprobst (ed.). Elsevier, p. 43-57.

**Arima, M. and Kerrich, R.**
1988: Jurassic kimberlites from Picton and Varty Lake, Ontario: Geochemical and stable isotope characteristics. Contributions to Mineralogy and Petrology, v. 99, p. 385-391.

**Atkinson, W.J.**
1989: Diamond exploration philosophy, practice, and promises: a review. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 1075-1107.

**Atkinson, W.J., Hughes, F.E., and Smith, C.B.**
1984: A review of the kimberlitic rocks of Western Australia. *In* Kimberlites I: Kimberlites and Related Rocks, J. Kornprobst (ed.). Elsevier, Amsterdam, p. 195-224.

**Bayly, B., Reid, A.M., and Gurney, J.J.**
1979: Zircon-bearing rocks from the Kimberley Mines. Extended abstract. Geocongress 1979, University of Port Elizabeth, South Africa.

**Berendson, P., Cullers, R.L, Mansker, W.L., and Cole, G.P.**
1985: Late Cretaceous kimberlite and lamproite occurrences in eastern Kansas, U.S.A. Geological Society of America, Program with Abstracts 17, 151 p.

**Bergman, S.C.**
1987: Lamproites and other potassium-rich igneous rocks: a review of their occurrence, mineralogy and geochemistry. *In* Alkaline Igneous Rocks, J.G. Fitton and B.G.J. Upton (eds.). Geological Society of London, Special Publication no. 30, p. 103-190.

**Bolivar, S.L.**
1972: Kimberlite of Elliott County, Kentucky. M.S. thesis, Eastern Kentucky University, 61 p.

**Botkunov, A.I., Garanin, V.K., Kudrjavtseva, G.P., and Perminova, M.S.**
1980: Mineral inclusions in olivine and zircon from the kimberlite pipe "Mir". Doklady Akademii Nauk SSSR, v. 251, p. 1233-1236.

**Boyd, F.R. and Gurney, J.J.**
1986: Diamonds and the African lithosphere. Science, v. 232, p. 472-477.

**Boyd, F.R. and Nixon, P.H.**
1989: The origin of low-Ca garnet harzburgites and their relationship to diamond crystallisation. Extended Abstract. Workshop on Diamonds, 28th International Geological Congress, Washington D.C., p. 4-7.

**Boyd, S.R., Seal, M., Mathey, D.P., Mendelssohn, M.J., Milledge, H.J., and Pillinger, C.T.**
1986: Zoned diamonds: records of mantle volatile activity. Terra Cognita, v. 6, p. 191.

**Brookins, D.G.**
1970a: Kimberlite at Winkler Crater, Kansas. Geological Society of America, Bulletin 81, p. 541-546.

1970b: The kimberlites of Riley County, Kansas. Kansas Geological Survey, Bulletin 200, p. 1-32.

**Brown, D.D.**
1967: The source of alluvial kimberlite indicator minerals in the James Bay Lowland. Ontario Department of Mines, Miscellaneous Paper MP-7, 35 p.

**Brummer, J.J.**
1978: Diamonds in Canada. The Canadian Mining and Metallurgical Bulletin, Oct. 1978, p. 1-16.

**Campbell, R.B.**
1972: Geologic map of the S.E. Cordillera. Field Guide AOI, 1972, International Geological Congress, Montreal.

**Canil, D.**
1994: An experimental calibration of the "Nickel in Garnet" geothermometer with applications. Contributions to Mineralogy and Petrology, v. 117, p. 410-420.

**Carlson, J.A. and Marsh, S.W.**
1989: Discovery of the George Creek kimberlite dikes, Colorado. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 1169-1178.

**Carswell, D.A. and Gibb, F.G.F.**
1984: Geothermometry of garnet lherzolite nodules with special reference to those from the kimberlites of Northern Lesotho. Contributions to Mineralogy and Petrology, v. 74, p. 403-416.

**Clarke, D.B. and Reardon, N.C.**
1989: Tourmaline composition as a guide to mineral exploration. Economic Geology and the Bulletin of the Society of Economic Geologists, v. 84, p. 1921-1935.

**Clement, C.R.**
1982: Comparative geological study of some major kimberlite pipes in the northern Cape and Orange Free State. Unpublished Ph.D. thesis, University of Cape Town, South Africa.

**Clement, C.R. and Reid, A.M.**
1989: The origin of kimberlite pipes: An interpretation based on a synthesis of geological features displayed by southern African occurrences. *In* Kimberlites and Related Rock, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 632-646.

**Clement, C.R. and Skinner, E.M.W.**
1985: Textural-genetic classification of kimberlites. Transactions of the Geological Society of South Africa, v. 88, p. 403-409.

**Clement, C.R., Skinner, E.M.W., and Scott-Smith, B.H.**
1984: Kimberlite redefined. Journal of Geology, v. 92, p. 223-228.

**Clifford, T.N.**
1966: Tectono-metallogenic units and metallogenic provinces of Africa. Earth and Planetary Science Letters, v. 1, p. 421-434.

1970: The structural framework of Africa. *In* African Magmatism and Tectonics, T.N. Clifford and I.G. Gass (eds). Oliver and Boyd, Edinburgh, p. 1-26.

**Collerson, K.D., Jesseau, C.W., and Bridgewater, D.**
1976: Contrasting types of banded olivine in ultramafic rocks from the Archean of Labrador. Canadian Journal of Earth Sciences, v. 13, p. 442-450.

**Coopersmith, H.G. and Mitchell, R.H.**
1989: Geology and exploration of the Rose lamproite, southeast Kansas, U.S.A. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 1179-1191.

**Cox, K.G., Gurney, J.J., and Harte, B.**
1973: Xenoliths from the Matsoku Pipe. *In* Lesotho Kimberlites, P.H. Nixon (ed.). Lesotho National Development Corp., p. 76-100.

**Cullers, R.L., Ramakrishnan, S., Berendsen, P., and Griffin, T.**
1985: Geochemistry and petrogenesis of lamproites, late Cretaceous age, Woodson County, Kansas, U.S.A. Geochimica et Cosmochimica Acta, v. 49, p. 1383-1402.

**Danchin, R.V. and Wyatt, B.A.**
1979: Statistical cluster analysis of garnets from kimberlites and their xenoliths. Kimberlite Symposium II, Cambridge, U.K., p. 22-27. Published privately by De Beers Consolidated Mines.

**Daniels, L.R.M.**
1991: Diamonds and related minerals from the Dokolwayo kimberlite, kingdom of Swaziland. Unpublished Ph.D thesis, University of Cape Town, South Africa, 109 p.

**Davis, G.L., Krogh, T.E., and Erlank, A.J.**
1976: The ages of zircons from kimberlites from South Africa. Carnegie Institute of Washington, Yearbook 75, p. 821-824.

**Dawson, J.B.**
1967: A review of the geology of kimberlite. *In* Ultramafic and Related Rocks, P.J. Wyllie (ed.). Wiley, New York, p. 241-251.

1972: Kimberlites and their relation to the mantle. Philosophical Transactions of the Royal Society of London, v. A271, p. 297-311.

1980: Kimberlites and their Xenoliths. Springer-Verlag, Berlin, 252 p.

**Dawson, J.B. and Hawthorne, J.B.**
1973: Magmatic sedimentation and carbonatitic differentiation in kimberlite sills at Benfontein, South Africa. Geological Society of London, v. 129, p. 61-85.

**Dawson, J.B. and Smith, J.V.**
1975: Occurrence of diamond in a mica-garnet lherzolite xenolith from kimberlite. Nature, v. 254, p. 580-581.

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

**Deer, W.A., Howie, R.A., and Zussman, J.**
1963: The Rock Forming Minerals. Longman Group Ltd., London, U.K., Volumes 1 & 5.

**Deines, P., Gurney, J.J. and Harris, J.W.**
1984: Associated chemical and carbon isotopic composition variations in diamonds from Finsch and Premier kimberlite, South Africa. Geochimica et Cosmochimica Acta, v. 48, p. 325-342.

**Deines, P., Harris, J.W., and Gurney, J.J.**
1987: Carbon isotopic composition, nitrogen content and inclusion composition of diamonds from Roberts Victor kimberlite, South Africa: Evidence for $^{13}$C depletion in the mantle. Geochimica et Cosmochimica Acta, v. 51, p. 1227-1243.

**Demaiffe, D., Fieremans, M., and Fieremans, C.**
1991: The kimberlites of central Africa: A review. *In* Magmatism in Extensional Structural Settings. The Phanerozoic Plate, A.B. Kampunzu and R.T. Lubala (eds.). Springer Verlag, p. 537-559.

**Dimroth, E.**
1970: Meimechites and carbonatites of the Castignon Lake complex, New Quebec. Neues Jahrbuch für Mineralogie, Abhandlungen, v. 112, p. 239-278.

**Droop, G.T.R.**
1987: A general equation for estimating $Fe^{3+}$ concentrations in ferromagnesian silicates and oxides from microprobe analyses using stoichiometric criteria. Mineralogical Magazine, v. 51, p. 431-435.

**Dummett, H.T., Fipke, C.E., and Blusson, S.L.**
1986: Diamond exploration in the North American Cordillera. *In* Proceedings Volume of Geoexpo/86, Exploration in the North American Cordillera, I.L. Elliot and B.W. Smee (eds.). Joint publication of the Association of Exploration Geochemists and the Geological Association of Canada, p. 168-176.

**Eggler, D.H.**
1989: Kimberlites: How do they form? *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 323-342.

**Erlank, A.J. and Kushiro, I.**
1970: Potassium contents of synthetic pyroxenes at high temperatures and pressures. Carnegie Institute Yearbook 68, p. 433-439.

**Erlank, A.J., Waters, F.G., Hawkesworth, C.J., Haggerty, S.E., Allsopp, H.L., Rickard, R.S., and Menzies, M.A.**
1987: Evidence for mantle metasomatism in peridotite nodules from the Kimberley pipes, South Africa. *In* Mantle Metasomatism, M.A. Menzies and C.J. Hawkesworth (eds). Academic Press, London, p. 221-311.

**Evans, T. and Qi, Z.**
1982: The kinetics of aggregation of nitrogen in diamond. Proceedings of the Royal Society of London, A381, p. 159-178.

**Finnerty, A.A. and Boyd, F.R.**
1984: Evaluation of thermobarometers for garnet peridotites. Geochimica et Cosmochimica Acta, v. 48, p. 15-27.

**Fipke, C.E.**
1991: Significance of chromite, ilmenite, G5 Mg-almandine garnet, zircon and tourmaline in heavy mineral detection of diamond bearing lamproite. *In* Fifth International Kimberlite Conference, Brazil, 1991. Comphania de Pequisa de Rescursos Minerais, Special Publication 2/91, p. 97-100.

**Fipke, C.E., Gurney, J.J., Moore, R.O., and Nassichuk, W.W.**
1989: The development of advanced technology to distinguish between productive diamondiferous and barren diatremes. Geological Survey of Canada, Open File 2124, v. 1, v. 3, p. 1-621.

**Fisher, R.V. and Schmincke, H.U.**
1984: Pyroclastic Rocks. Springer Verlag, 472 p.

**Frank, F.C.**
1969: Diamond and deep fluids in the mantle. *In* The Application of Modern Physics to Earth and Planetary

Interiors, S.K. Runcorn (ed). John Wiley and Sons, New York, p. 247-250.

**Galimov, E.M. and Kaminsky, F.V.**
1982: On the isotopic composition of carbon from ballas. Doklady Akademii Nauk SSSR, v. 267, p. 156.

**Garanin, V.K. and Kudryavtseva, G.P.**
1990: Morphology, physical properties and paragenesis of inclusion-bearing diamonds from Yakutian kimberlites. Lithos, v. 25, p. 211-217.

**Garrison, J.R. Jr. and Taylor, L.A.**
1980: Megacrysts and xenoliths in kimberlite, Elliott County, Kentucky: a mantle sample from beneath the Appalachian Plateau. Contributions to Mineralogy and Petrology v. 75, p. 27–42.

**Geological Survey of Canada**
1989: The development of advanced technology to distinguish between productive diamondiferous and barren diatremes. Geological Survey of Canada, Open File 2124, 1183 p.

**Gregory, G.P. and White, D.R.**
1989: Collection and treatment of diamond exploration samples. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 1123–1134.

**Griffin, W.L., Cousins, D.R., Ryan, C.G., Sie, S.H. and Suter,G.F.**
1989: Ni in chrome pyrope garnets: a new thermometer. Contributions to Mineralogy and Petrology, v. 103, p. 199–203.

**Griffin, W.L., Gurney, J.J., and Ryan, C.G.**
1992: Variations in trapping temperatures and trace elements in peridotite-suite inclusions from African diamonds: evidence for two inclusion suites, and implications for lithosphere stratigraphy. Contributions to Mineralogy and Petrology, v. 110, p. 1–15.

**Griffin, W.L. and Ryan, C.G.**
1992: Trace elements in garnets and chromites: their use in diamond exploration. International Round Table Conference on Diamond Exploration and Mining, New Delhi, p. 24–57.

**Griffin, W.L., Ryan, C.G., Fisher, N.I., and Friedman, J.H.**
1991: Trace Elements in Garnets and Chromites: Their Use in Diamond Exploration. CSIRO Division of Exploration Geoscience.

**Griffin, W.L., Ryan, C.G., Gurney, J.J., Sobolev, N.V., and Win, T.T.**
1991: Chromite macrocrysts in kimberlites and lamproites: geochemistry and origin. *In* Fifth International Kimberlite Conference, Brazil, 1991. Comphania de Pequisa de Recursos Minerais, Special Publication 2/91, p. 142-144.

**Gurney, J.J.**
1984: A correlation between garnets and diamonds in kimberlites. *In* Kimberlite Occurrence and Origin: A basis for conceptual models in exploration, J.E. Glover and P.G. Harris (eds.). Geology Department and University Extension, University of Western Australia, Publication No. 8, p. 143–166.

1989: Diamonds. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 935–965.

**Gurney, J.J. and Ebrahim, S.**
1973: Chemical composition of Lesotho kimberlites. *In* Lesotho Kimberlites, P.H. Nixon (ed.). Lesotho National Development Corporation, p. 280–293.

**Gurney, J.J., Helmstaedt, H.H., and Moore, R.O.**
1993: A review of the use and application of mantle mineral geochemistry in diamond exploration. Pure and Applied Chemistry, v. 65, p. 2423–2442.

**Gurney, J.J. and Moore, R.O.**
1989: The development of advanced technology to distinguish between productive diamondiferous and barren diatremes. Geological Survey of Canada, Open File 2124, v. 1, p. 1–90.

1991a: Geochemical correlations between kimberlitic indicator minerals and diamonds on the Kalahari Craton. Proceedings of the International Field Seminar, Deep Seated Magmatism and Evolution of the Lithosphere of the Siberian Platform, Novosibirsk, Mirny, Udachnaya, Sobolev, N.V. (ed.).

1991b: Geochemical correlations between kimberlitic indicator minerals and diamonds as applied to exploration. Extended Abstract. *In* Fifth International Kimberlite Conference, Brazil, 1991. Comphania de Pequisa de Recursos Minerasis, Special Publication 2/91, p. 125–126.

**Gurney, J.J., Moore, R.O., Otter, M.L., Kirkley, M.B., Hops, J.J., and McCandless, T.E.**
1991: Southern African kimberlites and their xenoliths. *In* Magmatism in Extensional Structural Settings: the Phanerozoic African Plate, A.B. Kampunzu and R.T. Lubala (ed.). Springer-Verlag, Berlin, p. 495–536.

**Gurney, J.J. and Switzer, G.S.**
1973: The discovery of garnets closely related to diamonds in the Finsch Pipe, S.A.., Contributions to Mineralogy and Petrology, v. 39, p. 103–116.

**Haggerty, S.E.**
1986: Diamond genesis in a multiply-constrained model. Nature, v. 320, p. 34–38.

1991: Emplacement and implications of ultra-deep xenoliths and diamonds from the transition zone. *In* Fifth International Kimberlite Conference, Brazil, 1991. Comphania de Pequisa de Recursos Minerais, Special Publication 2/91, p. 157–159.

**Halder, D. and Ghosh, D.B.**
1974: Tectonics of the kimberlites around Majhgawan, Madhya-Pradesh, India. *In* International Seminar on Tectonics and Metallogeny of Southeast Asia and Far East, M.V.N. Murty (ed.). Geology Survey of India, p. 47–48.

**Hall, A.E. and Smith, C.B.**
1985: Lamproite Diamonds – are they different? *In* Kimberlite Occurrence and Origin: A Basis for Conceptual Model in Exploration, J.E. Glover and P.G. Harris (eds.). University of Western Australia, p. 167–212.

**Harris, J.W.**
1987: Recent physical, chemical and isotopic research of diamond. *In* Mantle Xenoliths, P.H. Nixon (ed.). John Wiley and Sons, Chichester, England, p. 447-500.

**Harte, B. and Gurney, J.J.**
1975: Ore mineral and phlogopite mineralisation within ultramafic nodules from the Matsoku Kimberlite pipe, Lesotho. Carnegie Institute of Washington, Yearbook 74, p. 528-536.

**Hatton, C.J. and Gurney, J.J.**
1979: A diamond-graphite eclogite from the Roberts Victor mine. *In* The Mantle Sample: Inclusions in Kimberlites and other Volcanics, F.R. Boyd and H.O.A. Meyer (eds.). American Geophysical Union, Washington, p. 29-36.

**Hawkins, D.W.**
1976: Emplacement petrology and geochemistry of ultrabasic to basic intrusives at Aillik Bay, Labrador, Unpublished M.Sc. thesis, Memorial University, Newfoundland.

**Hawthorne, J.B.**
1975: Model of a kimberlite pipe. Physics and Chemistry of the Earth, v. 9, p. 1-15.

**Hearn, B.C. Jr.**
1968: Diatremes with kimberlitic affinites in north-central Montana. Science, v. 159, no. 3815, p. 622-625.

1989: Smoky Butte lamproite, Montana. *In* Volcanism and plutonism of western North Ameirca, Volume 2: Montana high-potassium igneous province. U.S. Geological Survey, Reston, VA, p. 75-78.

**Hearn, B.C., Jr. and McGee, E.S.**
1984: Garnet peridotites from Williams kimberlite, north-central Montana, U.S.A. *In* Kimberlites II: The mantle and crust-mantle relationships, J. Kornprobst (ed.). Elsevier, p. 57-70.

**Helmstaedt, H.H.**
1992: "Primary" diamond deposits: what controls their size, grade and location? Giant Ore Deposits Workshop, Kingston, Ontario, Canada.

**Helmstaedt, H.H. and Gurney, J.J.**
1984: Kimberlites of southern Africa - are they related to subduction processes? *In* Kimberlites I. - Kimberlites and Related Rocks, J. Kornprobst (ed.). Elsevier, Amsterdam, p. 425-434.

1994: Geotectonic controls on the formation of diamonds and their kimberlitic and their lamproitic host rocks: Applications to diamond exploration. *In* Proceedings Fifth International Kimberlite Conference, Brazil, H.O.A. Meyer and O. Leonardos (eds.). Companhia de Pesquisa de Recursos Minerals, v. 2, p. 236-250.

**Helmstaedt, H.H. and Schulze, D.J.**
1989: Southern African kimberlites and their mantle sample: implications for Archean tectonics and lithosphere evolution. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 358-368.

**Henry, D.J. and Guidotti, C.V.**
1985: Tourmaline as a petrogenetic indicator mineral: an example from the staurolite-grade metapelites of NW Maine. American Mineralogist, v. 70, p. 1-15.

**Hunt, G.H. and Bolivar, S.L.**
1972: Oxygen and carbon isotope ratios of carbonate from kimberlites in Elliot County, Kentucky. Geological Society of America, Programs with Abstracts, no. 4, 81 p.

**Hunter, R.H. and Taylor, L.A.**
1984: Magma-mixing in the low velocity zone: kimberlitic megacrysts from Fayette County, Pennsylvania. American Mineralogist, no. 69, p. 30-40.

**Ibarguchi, J.I.G., Miren, M., and Girardeau, J.**
1991: Mg- and Cr-rich staurolite and Cr-rich kyanite in high-pressure ultrabasic rocks (Cabo Ortegal, northwestern Spain). American Mineralogist, v. 76, p. 501-511.

**Jago, B. and Mitchell, R.H.**
1989: A new garnet classification technique: divisive cluster analysis applied to garnet populations from Somerset Island kimberlites. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 298-310.

**Janse, A.J.A.**
1985: Kimberlites - Where and When? *In* Kimberlite Occurrence and Origin: A Basis for Conceptual Models in Exploration, J.E. Glover and P.G. Harris (eds.). Geology Department and University Extension, University of Western Australia, Publication no. 8, p. 19-61.

**Janse, A.J.A., Downie, I.F., Reed, L.E., and Sinclair, I.G.L.**
1989: Alkaline intrusions in the Hudson Bay lowlands, Canada; exploration methods, petrology and geochemistry. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 1192-1203.

**Jaques, A.L., Hall, A.E., Sheraton, J.D., Smith, C.B., Sun, S-S, Drew, D.M., Foudoulis, C. and Ellingsen, K.**
1989: Composition of crystalline inclusions and C-isotopic composition of Argyle and Ellendale diamonds. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 966-989.

**Jaques, A.L., Lewis, J.D., and Smith, C.B.**
1986: The kimberlites and lamproites of Western Australia. Geological Survey of Western Australia, Bulletin 132, 268 p.

**Jaques, A.L., Lewis, J.D., Smith, C.B., Gregory, G.P., Ferguson, J., Chappell, B.W., and McCulloch, M.T.**
1984: The diamond-bearing ultrapotassic (lamproitic) rocks of the West Kimberley region, Western Australia. *In* Kimberlites I: Kimberlites and Related Rocks, J. Kornprobst (ed.). Elsevier, p. 225-254.

**Jaques, A.L., O'Neill, H.St.C., Smith, C.B., Moon, J., and Chappell, B.W.**
1990: Diamondiferous peridotite xenoliths from the Argyle (AK1) lamproite pipe, Western Australia. Contributions to Mineralogy and Petrology, v. 104, p. 255-276.

**Javoy, M., Pineau, F., and Demaiffe, D.**
1984: Nitrogen and carbon isotopic composition in diamonds from Mbuji Mayi (Zaire). Earth and Planetary Science Letters, v. 68, p. 399–412.

**Jennings, C.M.H.**
1990: Exploration for diamondiferous kimberlites and lamproites. *In* Modern Exploration Techniques, L.S. Beck and C.T. Harper (eds.). Special Publication no. 10, Saskatchewan Geological Society, Regina, p. 139–148.

**Kennedy, C.S. and Kennedy, G.C.**
1976: The equilibrium boundary between graphite and diamond. Journal of Geophysical Research, v. 81, p. 2467–2470.

**Kinny, P.D. and Dawson, J.B.**
1992: A mantle metasomatic injection event linked to Late Cretaceous kimberlite magmatism. Nature, v. 360, no. 6406, p. 723–726.

**Kirkley, M.B.**
1987: Aspects of the geochemistry of kimberlite carbonates. Unpublished Ph.D thesis, University of Cape Town, South Africa, 282 p.

**Kirkley, M.B., Gurney, J.J., and Levinson, A.A.**
1991: Age, origin and emplacement of diamonds: Scientific advances in the last decade. Gems and Gemology, v. 27, p. 465–479.

**Koenig, J.B.**
1956: The petrography of certain igneous dikes of Kentucky. Kentucky Geological Survey, Bulletin 21, 57 p.

**Kramers, J.D.**
1979: Lead, uranium, strontium, potassium and rubidium in inclusion-bearing diamonds and mantle-derived xenoliths from southern Africa. Earth and Planetary Science Letters, v. 65, p. 90–106.

**Kresten, P., Fels, P., and Berggren, G.**
1975: Kimberlitic zircons–A possible aid in prospecting for kimberlites, Mineralium Deposita, v. 10, p. 47–56.

**Kurz, M.D., Gurney, J.J., Jenkins, W.J., and Lott, D.E.**
1986: Helium isotopic variability within single diamonds from the Orapa kimberlite pipe. Earth and Planetary Science Letters, v. 86, p. 57–68.

**Lawless, P.J.**
1974: Some aspects of the geochemistry of kimberlite xenocrysts. Unpublished PhD thesis, University of Cape Town, South Africa.

**Lee, J.E.**
1993: Indicator mineral techniques in a diamond exploration programme at Kokong, Botswana; Prospectors and Developers Association of Canada Meeting, Diamond Exploration, Toronto, Canada, p. 1–21.

**Lehnert-Thiel, K., Loewer, R., Orr, R., and Robert-Shaw, P.**
1991: Diamond-bearing kimberlites in Saskatchewan, Canada: the Fort a la Corne case history. Abstract for the 1st Annual Field Conference of the Geological Section of Canadian Institute of Mining, Saskatoon, September 1991, p. 29–30.

**Levinson, A.A., Gurney, J.J., and Kirkley, M.B.**
1992: Diamond sources and production: Past, present and future. Gems and Gemology, Winter 1992, p. 234–253.

**Mansker, W.L.**
1973: Petrology of a south-eastern Missouri ultramafic pipe. M.S. Thesis, Univeristy of Missouri, Rolla, 53 p.

**McCallum, M.E. and Eggler, D.H.**
1976: Diamonds in an upper mantle peridotite nodule from kimberlite in southern Wyoming. Science, v. 192, no. 4236, p. 253–256.

**McCallum, M.E., Eggler, D.H., and Burns, L.K.**
1975: Kimberlite diatremes in northern Colorado and southern Wyoming. Physics and Chemistry of the Earth, v. 9, p. 149–162.

**McCandless, T.E.**
1990: Kimberlite xenocryst wear in high-energy fluvial systems: experimental studies, Journal of Geochemical Exploration, v. 37, p. 323–331.

**McCandless, T.E. and Gurney, J.J.**
1989: Sodium in garnet and potassium in clinopyroxene: criteria for classifying mantle eclogites. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 827–832.

**McGee, E.S. and Hearn, B.C. Jr.**
1984: The Lake Ellen Kimberlite, Michigan, U.S.A. *In* Kimberlites I: Kimberlites and Related Rocks, J. Kornprobst (ed.). Elsevier, p. 143–154.

**McGetchin, T.R. and Silver, L.T.**
1970: Compositional relations in minerals from kimberlite and related rocks in the Moses Rock dike, San Juan County, Utah. American Mineralogist, v. 55, p. 1738–1771.

**Melton, C.E. and Giardini, A.A.**
1980: The isotopic composition of argon included in an Arkansas diamond and its significance. Geophysical Research Letters, v. 7, p. 461–464.

**Meyer, H.O.A.**
1975: Kimberlite from Norris Lake, eastern Tennessee: mineralogy and petrology. Journal of Geology, v. 83, p. 518–526.

1987: Inclusions in diamond. *In* Mantle Xenoliths, P.H. Nixon (ed.). John Wiley and Sons, Chichester, England.

**Meyer, H.O.A. and Gubelin, E.**
1981: Ruby in diamond. Gems and Geology, Fall, p. 153–156.

**Meyer, H.O.A. and Kridelbaugh, S.J.**
1977: Green Mountain kimberlite, Colorado: mineralogy and petrology. Second International Kimberlite Conference, Sante Fe. Extended Abstracts, unpaginated.

**Meyer, H.O.A. and Svizero, D.P.**
1973: Mineral inclusions in Brazilian diamonds. Abstract Volume, International Conference on Kimberlites, Geological Society of South Africa, p. 225–228.

**Meyer, H.O.A. and Tsai H.M.**
1976: Mineral inclusions in diamond: Temperature and pressure of equilibration. Science 191, p. 849-851.

**Meyer de Stadhelhofen, C.**
1963: Les Breches kimberlitiques du Terratoire de Bakwanga (Congo). Archives des Science 16, fasc. 1, p. 87-144.

**Middlemost, E.A.K.**
1986: The nomenclature and origin of the noncumulate ultramafic rocks and the systematic position of kimberlites. Fourth International Kimberlite Conference. Geological Society of Australia, Abstract 16, p. 72-74.

**Milledge, H.J., Mendelssohn, M.J., Boyd, S.R., Pillinger, C.T., and Seal, M.**
1989: Infrared topography and carbon and nitrogen isotope distribution in natural and synthetic diamonds in relation to mantle processes. *In* 28th International Geological Congress, Workshop on Diamonds, Extended Abstracts, Washington, D.C., p. 55-60.

**Mitchell, R.H.**
1985: A review of the mineralogy of lamproites. Transactions of the Geological Society of South Africa, v. 88, p. 411-437.

1986: Kimberlites: Mineralogy, Geochemistry and Petrology. Plenum Press, New York. 442 p.

1989: Aspects of the petrology of kimberlites and lamproites: some definitions and distinctions. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 7-45.

**Mitchell, R.H. and Bergman,**
1991: Petrology of Lamproites. Plenum Press, New York, 447 p.

**Mitchell, R.H. and Hawkesworth, C.J.**
1984: Geochemistry of potassic lavas from Smoky Butte, Montana. Geological Society of America, Program with Abstracts 16, 494 p.

**Mitchell, R.H. and Janse, A.J.A.**
1982: A harzburgite-bearing monchifquite from Wawa, Ontario. Canadian Mineralogist, v. 20, p. 211-216.

**Moore, R.O.**
1986: A Study of the kimberlites, diamonds and associated rocks and minerals from the Monastery Mine, S.A. Unpublished PhD thesis, University of Cape Town, South Africa, v. 2, p. 1-359.

**Moore, R.O. and Gurney, J.J.**
1985: Pyroxene solid solution in garnets included in diamond. Nature, v. 318, p. 553-555.

1989: Mineral inclusions in diamonds from the Monastery kimberlite, South Africa. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 1029-1041.

**Muramatsu, Y.**
1983: Geochemical investigations of kimberlites from the Kimberley area, South Africa. Geochemical Journal, v. 17, no. 2, p. 71-86.

**Nielson, J.E.**
1989: Nature and sequence of mantle magmatic events indicated by compositional variations in a composite xenolith from Lashaine Volcano, Tanzania. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 700-708.

**Nixon, P.H.**
1980: Regional diamond exploration - theory and practice. *In* Kimberlites and Diamonds, L.E. Glover and D.I. Groves (eds.). University of Western Australia, Geology Department and University Extension, Publication no. 5, p. 65-80.

1987: The American plates-introduction. *In* Mantle Xenoliths, P.H. Nixon (ed.). John Wiley and Sons, New York, p. 13-22.

**Nixon, P.H., Davies, G.R., Condliffe, E., Baker, R., and Baxter Brown, R.**
1989: Discovery of ancient source rocks of Venezuela diamonds. 28th International Geological Congress, Workshop on Diamonds, Extended Abstract, p. 73-75.

**Ntanda, F.M., Moreau, J., and Meyer, H.O.A.**
1982: Particularites des Inclusions Cristallines Primaires des Diamants du Kasai, Zaire. American Mineralogist, v. 20, p. 217-230.

**Otter, M.L. and Gurney, J.J.**
1989: Mineral inclusions in diamonds from the Sloan diatremes, Colorado-Wyoming state line kimberlite district, North America. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 1042-1053.

**Ozima, M., Takaoka, N., Nito, S., and Zashu, S.**
1984: Ar isotopic ratios and K, Na and other trace element contents in Premier and Finsch Mine diamonds. *In* Materials Science of the Earth's Interior. I. Sunagawa (ed.). Tohoku University, Tohoku, Japan, p. 375-386.

**Ozima, M., Zashu, S., and Nito, O.**
1983: $^3$He/$^4$He ratio, noble gas abundance and K-Ar dating of diamonds - an attempt to search for the records of early terrestrial history. Geochimica et Cosmochimica Acta, v. 47, p. 2217-2224.

**Pearson, D.G., Davies, G.R., Nixon, P.H., and Milledge, H.J.**
1989: Graphite-bearing pyroxenites from Morocco: Evidence of recycled oceanic lithosphere and the origin of E-type diamonds. Nature, v. 338, p. 60-62.

**Pidgeon, R.T., Smith, C.B., and Fanning, C.M.**
1989: The ages of kimberlite and lamproite emplacement in Western Australia. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 369-381.

**Platt, R.G. and Mitchell, R.H.**
1982: The Marathon Dykes: ultrabasic lamprophyres from the vicinity of McKellar Harbour, N.W. Ontario. American Mineralogist, v. 67, p. 907-916.

**Pokhilenko, N.P., Sobolev, N.V., and Lavrent'yev, Yu. G.**
1977: Xenoliths of diamondiferous ultramafic rocks from Yakutian kimberlites. Extended Abstract, 2nd

International Kimberlite Conference, Santa Fe, American Geophysical Union, Washington (unpaginated).

**Raber, E. and Haggerty, S.E.**
1979: Zircon-oxide reactions in diamond-bearing kimberlites. *In* Kimberlites, Diatremes and Diamonds: Their Geology, Petrology and Geochemistry, F.R. Boyd and H.O.A. Meyer (eds.). American Geophysical Union, Washington, p. 229–240.

**Reid, A.M., Brown, R.W., Dawson, J.B., Whitfield, G.G., and Siebert, J.C.**
1976: Garnet and pyroxene compositions in some diamondiferous eclogites. Contributions to Mineralogy and Petrology, v. 58, p. 203–220.

**Richardson, S.H.**
1986a: Origin of diamonds of peridotitic and eclogitic parageneses. *In* 4th International Kimberlite Conference, Perth, Extended Abstracts, Geological Society of Australia, v. 16, p. 418–420.

1986b: Latter-day origin of diamonds of eclogitic paragenesis. Nature, v. 322, p. 623–626.

**Richardson, S.H., Erlank, A.J., Harris, J.W., and Hart, S.R.**
1990: Eclogitic diamonds of Proterozoic age from Cretaceous kimberlites. Nature, v. 346, p. 54–56.

**Richardson, S.H., Gurney, J.J., Erlank, A.J., and Harris, J.W.**
1984: Origin of diamonds in old enriched mantle. Nature, v. 310, p. 198–202.

**Rickwood, P.C., Gurney, J.J. and White-Cooper, D.R.**
1969: The nature and occurrence of eclogite xenoliths in the kimberlites of southern Africa. Geological Society of South Africa, Special Publication no. 2, p. 371–393.

**Robinson, D.N.**
1975: Magnetite-serpentine-calcite dykes at Premier Mine and aspects of their relationship to kimberlite and to carbonatite of alkalic carbonatite complexes. Physics and Chemistry of the Earth, p. 61–70.

1979: Surface textures and other features of diamonds. Unpublished Ph.D. thesis, University of Cape Town, South Africa, 221 p.

**Robinson, D.N., Gurney, J.J., and Shee, S.R.**
1984: Diamond eclogite and graphite eclogite xenoliths from Orapa, Botswana. *In* Kimberlites II, The Mantle and Crust-Mantle Relationships, J. Kornprobst (ed.). Elsevier, Amsterdam, p. 11–24.

**Robinson, D.N., Scott, J.A., Van Niekerk, A., and Anderson V.G.**
1989: The sequence of events reflected in the diamonds of some southern African kimberlites. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 980–990.

**Rock, N.M.S.**
1991: Lamprophyres. Blackie, Van Nostrand Reinhold, 285 p.

**Roden, M.F. and Smith, D.**
1979: Field geology, chemistry and petrology of the Buell Park minette diatreme, Apache County, Arizona. *In* Kimberlites, Diatremes and Diamonds: Their Geology, Petrology and Chemistry, F.R. Boyd and H.O.A. Meyer (eds.). American Geophysical Union, Washington, p. 364–381.

**Schroeder, D.A.**
1984: Geology of the Granby and Strawberry Lake 7-1/2' Quadrangles, Grand County, Colorado, Unpublished PhD thesis, University of Colorado, USA.

**Schulze, D.J.**
1984: Cr-poor megacrysts from the Hamilton Branch kimberlite, Elliot County, Kentucky. *In* Kimberlites II: Kimberlites and Related Rocks, J. Kornprobst (ed.). Elsevier, p. 255-284.

**Scott, B.H.**
1979: Petrogenesis of kimberlites and associated potassic lamprophyres from central West Greenland. *In* Kimberlites, Diatremes and Diamonds: Their Geology, Petrology and Geochemistry, F.R. Boyd and H.O.A. Meyer (eds.). Proceedings of the 2nd International Kimberlite Conference, no. 1, p. 190–205.

**Scott-Smith, B.H.**
1992: Contrasting kimberlites and lamproites. Exploration Mining Geology, v. 1, p. 371–381.

**Scott-Smith, B.H., Danchin, R.V., Harris, J.W., and Stracke, K.J.**
1984: Kimberlites near Orroroo, South Australia. *In* Kimberlites I: Kimberlites and Related Rocks, J. Kornprobst (ed.). Elsevier, p. 121–142.

**Scott-Smith, B.H. and Skinner, E.M.W.**
1984a: A new look at Prairie Creek, Arkansas. *In* Developments in Petrology 11A, Kimberlites I., Kimberlites and Related Rocks, J. Kornprobst, (ed). Elsevier Scientific Publications, Amsterdam, p. 255–284.

1984b: Diamondiferous lamproites. Journal of Geology, v. 92, p. 433–438.

**Sears, C.E. and Bilbert, M.C.**
1973: Petrography of the Mt. Horeb, Virginia kimberlite. Geological Society of America, Programs with Abstracts, no. 5, 434 p.

**Shatsky, V.S., Sobolev, N.V., and YeFimova, E.S.**
1989: Morphological features of accessary microdiamonds from metamorphic rocks of the earth's crust. Diamond Workshop, 28th International Geological Congress, Washington, D.C., p. 94, 95.

**Shaver, K.C.**
1988: Exploration of the Sloan Range complex: a diamondiferous kimberlite prospect in northern Colorado. Mining Engineering, January 1988, p. 45–48.

**Shee, S.R., Bristow, J.W., Bell, D.R., Smith, C.B., Allsopp, H.L., and Shee, P.B.**
1989: The petrology of kimberlites, related rocks and associated mantle xenoliths from the Kuruman Province, South Africa. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, v. 1, p. 60–82.

**Shee, S.R., Gurney, J.J., and Robinson, D.N.**
1982: Two diamond-bearing peridotite xenoliths from the Finsch kimberlite, South Africa. Contributions to Mineralogy and Petrology, v. 81, p. 79–87.

**Shimizu, N. and Richardson, S.H.**
1987: Trace element abundance patterns of garnet inclusions in peridotite-suite diamonds. Geochimica et Cosmochimica Acta, v. 51, p. 755–758.

**Skinner, E.M.W.**
1989: Contrasting Group I and Group II kimberlite petrology: towards a genetic model for kimberlite. *In* Kimberlites and Related Rocks, J. Ross (ed.). Geological Society of Australia, Special Publication no. 14, p. 528–544.

**Skinner, E.M.W. and Clement, C.R.**
1979: Mineralogical classification of southern African kimberlites. *In* Kimberlites, Diatremes and Diamonds: Their Geology, Petrology and Geochemistry, F.R. Boyd and H.O.A. Meyer (eds.). American Geophysical Union, Washington, p. 129–139.

**Smith, C.B.**
1983: Rubidium-strontium, uranium-lead and samarium-neodymium isotopic studies of kimberlite and selected mantle-derived xenoliths. Unpublished PhD thesis, University of the Witwatersrand, Johannesburg, South Africa, 436 p.

**Smith, C.B., Lucas, H., Hall, A.E., and Ramsay, R.R.**
1991: Diamond prospectivity and indicator mineral chemistry: A Western Australian perspective. *In* Fifth International Kimberlite Conference, Brazil, 1991. Comphania de Pequisa de Recursos Minerais, Special Publication 2/91, p. 380-382.

**Smith, D.**
1979: Hydrous minerals and carbonates in peridotitic inclusions from the Green Knobs and Buell Park kimberlite diatremes on the Colorado Plateau. *In* The Mantle Sample: Inclusions in Kimberlites and other Volcanics, F.R. Boyd and H.O.A. Meyer (eds.). American Geophysical Union, Washington, p. 345–356.

**Sobolev, N.V.**
1971: On mineralogy and criterions of diamond content of kimberlites. Geology and Geophysics, v. 3, p. 70–79.

1974: Deep seated inclusions in kimberlites and the problem of the composition of the upper mantle. Izdatel'stvo Nauka, SSSR. English translation by D.A. Brown, 1977, American Geophyical Union, Washington, D.C. USA.

1977: Deep seated inclusions in kimberlites and the problem of the composition of the upper mantle. American Geophysical Union, Washington, 279 p.

1985: Ultramafic and eclogitic types of paragenesis of diamonds. Extended Abstract. *In* Native Elements Formation in Endogenic Processes (no pagination). Academy of Sciences of the USSR, Siberian Division, Yakutsk.

**Sobolev, N.V., Galimov, E.M., Ivanovskaya I.N., and Yefimova E.S.**
1979: Isotope composition of carbon of diamonds containing crystalline inclusions. Doklady Akademii Nauk SSSR, v. 249, p. 1217–1220.

**Sobolev, N.V., Lavrent'yev, Yu G., Pokhilenko, N.P., and Usova, L.V.**
1973: Chrome-rich garnets from the kimberlites of Yakutia and their parageneses. Contributions to Mineralogy and Petrology, v. 40, p. 39–52.

**Sobolev, N.V., Lavrent'yev, Yu.G., Pospelova, L.N., and Sobolev, Ye. V.**
1969: Chrome pyropes from Yakutian diamonds. Doklady Akademii Nauk SSSR, v. 189, p. 162–165. (In Russian).

**Stephens, W.E. and Dawson, J.B.**
1977: Statistical comparison between pyroxenes from kimberlites and their associated xenoliths. Journal of Geology, v. 85, p. 433–449.

**Stuart-Alexander, D.E., Shoemaker, E.M., and Moore, H.J.**
1972: Geologic map of Mule Ear Diatreme, San Juan County, Utah. U.S. Geological Survey, Miscellaneous Geologic Investigations Map, I-674.

**Swart, P.K., Pillenger, C.T., Milledge, H.J., and Seal, M.**
1983: Carbon isotopic variation within individual diamonds. Nature, v. 303, p. 793–795.

**Switzer, G. and Melson, W.G.**
1969: Partially melted kyanite eclogite from the Roberts Victor Mine, South Africa. Smithsonian Contributions to Earth Sciences 1, 7 p.

**Takoaka, T. and Ozima, M.**
1978: Rare gas isotopic compositions in diamonds. Nature, v. 271, p. 45-46.

**Wagner, P.A.**
1914: The diamond fields of South Africa. Transvaal Leader, Johannesburg.

**Watson, K.D.**
1967a: Kimberlites of eastern North America. *In* Ultramafic and Related Rocks, P.J. Wyllie (ed.). Wiley, New York, p. 261–269.

1967b: Kimberlites pipes of northeastern Arizona. *In* Ultramafic and Related Rocks, P.J. Wyllie (ed.). Wiley, New York, p. 312–323.

1973: Kimberlites of the Superior Province, Canadian Shield. International Kimberlite Conference, Cape Town, South Africa, Extended Abstracts, p. 305–308.

**Wedepohl, K.H. and Muramatsu, Y.**
1979: The chemical composition of kimberlites compared with the average compositions of three basaltic magma types. *In* Kimberlites, Diatremes and Diamonds: Their Geology, Petrology and Geochemistry, F.R. Boyd and H.O.A. Meyer (eds.). Proceedings of the 2nd International Kimberlite Conference, no. 1, p. 300-312.

**Wilding, M.C., Harte, B., and Harris, J.W.**
1989: Evidence of asthenospheric source for diamonds from Brazil. 28th International Geological Congress, Abstracts Volume 3, Washington, D.C., p. 359-360.

**Woodzick, T.L. and McCallum, M.E.**
1984: A teledetective study of kimberlite regions in North America (Colorado-Wyoming), East Africa (Mwadui) and Siberia (Mir). *In* Kimberlites I: Kimberlites and Related Rocks, J. Kornprobst (ed.). Elsevier, Amsterdam, p. 5-20.

**Wyatt, B.A.**
1979: Manganoan ilmenite from the Premier kimberlite. Extended Abstract. Kimberlite Symposium II, Cambridge.

**Yefimova, E.S. and Sobolev, N.V.**
1977: Abundance of crystalline inclusions in diamonds of Yakutia. Doklady Akademii Nauk SSSR, v. 237, no. 6, p. 1475-1478. (In Russian).

**Young, R.S. and Bailey, R.A.**
1955: A mica peridotite dike near Fort Royal, Virginia. Virginia Journal of Science, v. 6, p. 282-283.

**Zhang, R. and Liu, B.**
1983: Kimberlites from North China. Geochemical Journal, no. 17, p. 209-220.

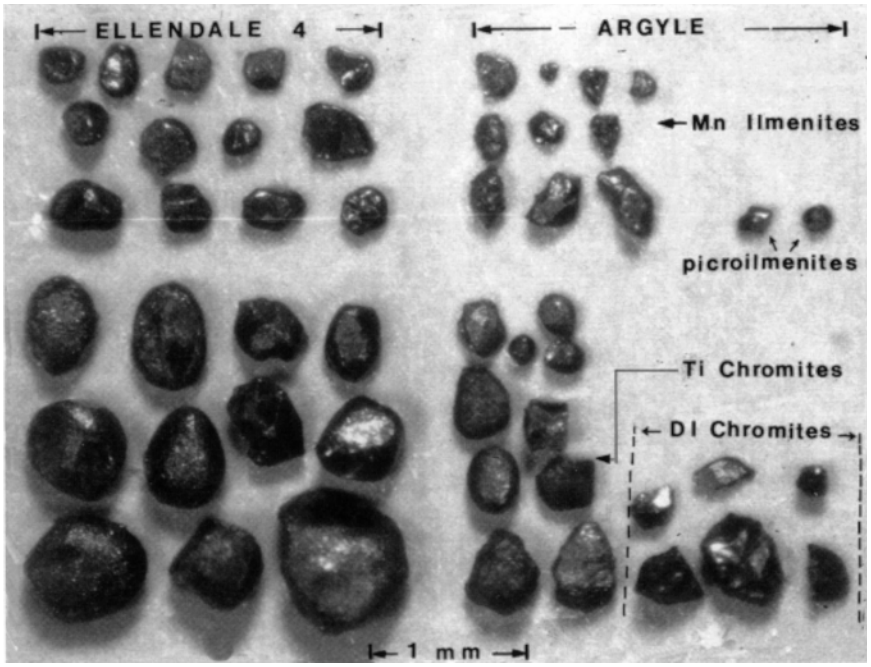


**Plate 1.** *Photomicrograph of Mn ilmenite and Ti chromites from Argyle and Ellendale, Australia. Six DI chromites and two picroilmenites from Argyle are also illustrated.*

**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.*

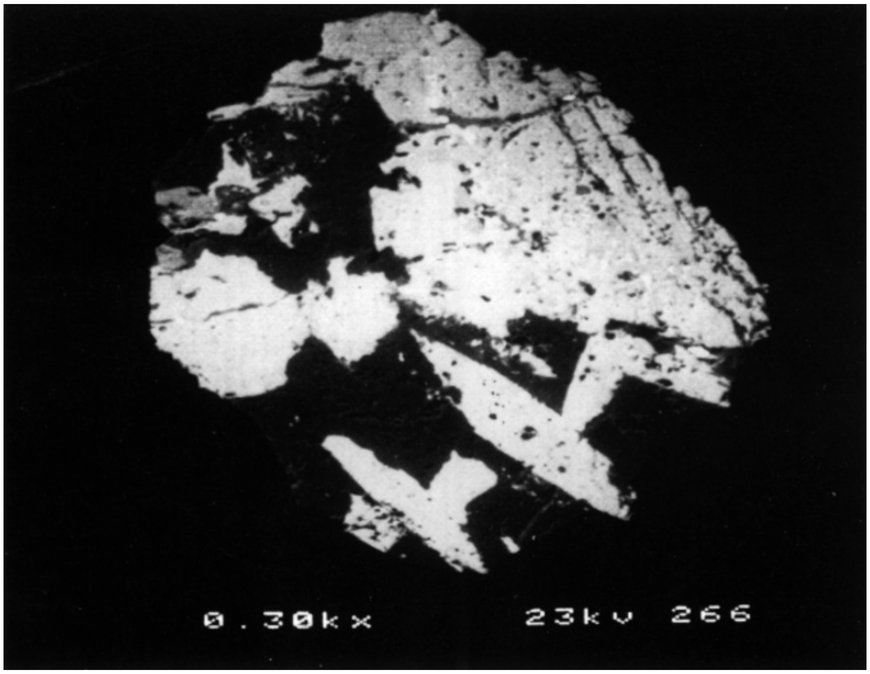


**Plate 3.** *SEM backscatter photomicrograph (300x) of intergrowth of niobium rutile (light grey) and titaniferous dolomite (dark) from Jack, B.C. phase 2 lamproites. The rutile contains tiny (whitish) blebs of unidentified Nb-Ti-W-Fe and Zr-Ti-Fe silicate minerals.*

**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).*

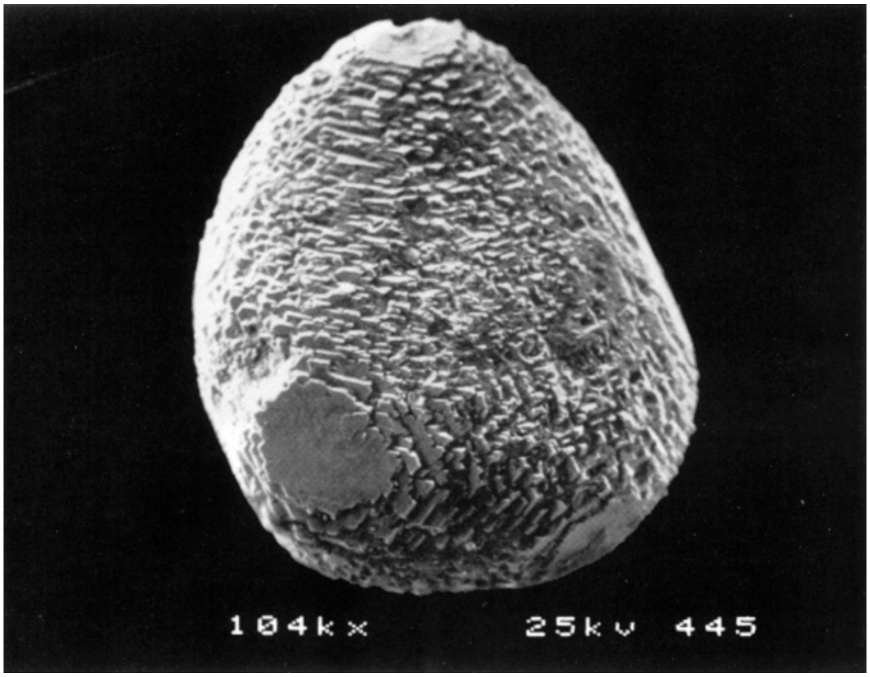


**Plate 5.** *SEM microphotograph (104x) of Cr-Ti chromite from Ellendale 4. Note the round shape and resorption on the octahedral parting.*

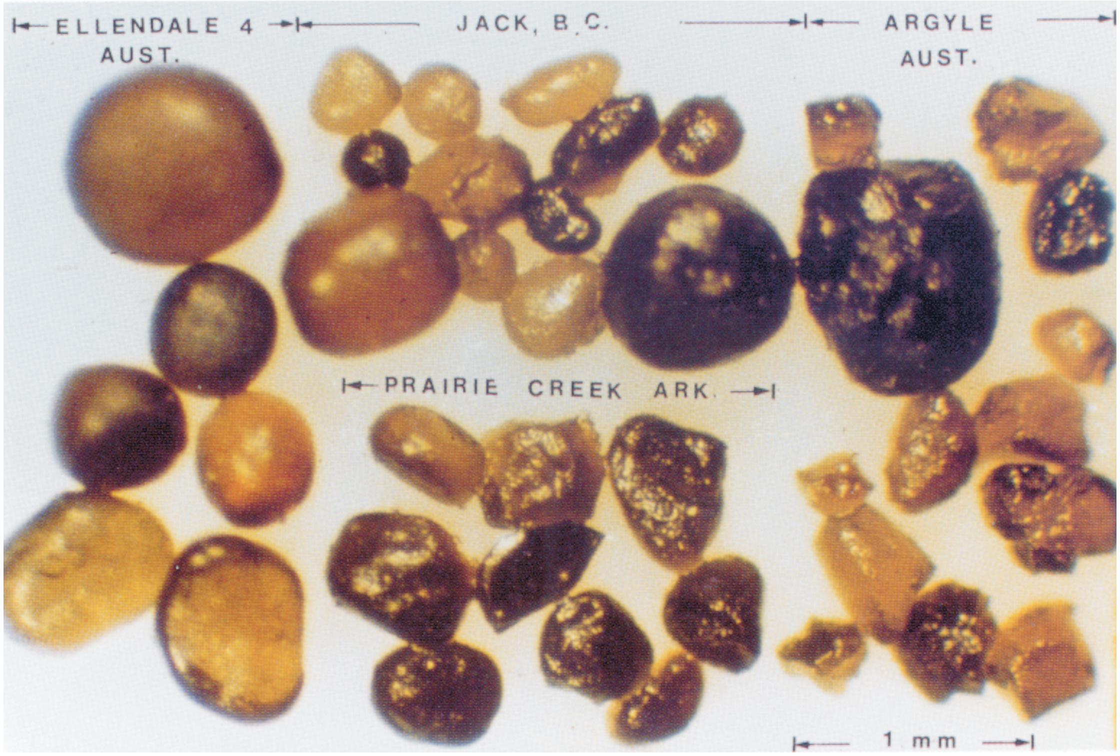


**Plate 6.** *Photomicrograph of light to dark brown, glassy to frosted, spheroidal tourmalines from the Ellendale 4, Australia, Jack, B.C., Prairie Creek, Arkansas, and Argyle, Australia diamondiferous lamproites.*