GEOLOGICAL SURVEY OF CANADA
COMMISSION GEOLOGIQUE DU CANADA
OPEN FILE 2124

THE DEVELOPMENT OF ADVANCED TECHNOLOGY TO DISTINGUISH BETWEEN DIAMONDIFEROUS AND BARREN DIATREMES

INSTITUTE OF SEDIMENTARY
AND PETROLEUM GEOLOGY

Canadä

GEOLOGICAL SURVEY OF CANADA
COMMISSION GEOLOGIQUE DU CANADA
OPEN FILE 2124

THE DEVELOPMENT OF ADVANCED TECHNOLOGY TO DISTINGUISH BETWEEN DIAMONDIFEROUS AND BARREN DIATREMES

PART 1

A Review of Geological Material Relevant to Diamond Exploration and a Summary of Results

October, 1989

TABLE OF CONTENTS

ACKNOWLEDGMENTS

ACKNOWLEDGMENTS

Principal Sponsors

The Institute of Sedimentary and Petroleum Geology, Geological Survey of Canada (GSC), Calgary, Alberta.

Supply and Services Canada, Hull, Quebec.

C.F. Mineral Research Ltd., Kelowna, British Columbia.

Scientific Authority

Dr. W.W. Nassichuk, Director, Institute of Sedimentary and Petroleum Geology, Geological Survey of Canada, Calgary, Alberta.

Project Co-ordinator

Mr. C.E. Fipke, C.F. Mineral Research Ltd., Kelowna, B.C.

Contributing Scientists (listed in alphabetical order)

Mr. A. Bentzen, C.F. Mineral Research, Kelowna, BC.
Mr. H. Dummett, Tuscon, Arizona.
Mr. C.E. Fipke, C.F. Mineral Research, Kelowna, BC.
Dr. H.H.J. Geldsetzer, Geological Survey of Canada, Calgary, AB.
Dr. P.E. Grattan-Bellew, National Research Council Canada, Ottawa, ON.
Mr. A. Heinrich, I.S.P.G., Geological Survey of Canada, Calgary, AB.
Dr. A.L. Jaques, Bureau of Mineral Resources, Canberra, Australia.
Mr. R. King, University of Saskatchewan, Saskatoon, SK.
Dr. P. Kresten, Geological Survey of Sweden, Uppsala, Sweden
Mr. M. Labonte, I.S.P.G., Geological Survey of Canada, Calgary, AB.
Dr. O.P. Lavin, Kingston, ON.
Dr. M.E. McCallum, Colorado State University, Fort Collins, CO.
Mr. F. Meister, (Project Manager), Austin, Texas.
Dr. C.W. Naeser, U.S. Geological Survey, Denver, CO.
Dr. D.K. Norris, Kelowna, BC.
Dr. R. Parrish, Geological Survey of Canada, Ottawa, ON.
Dr. G. Poling, University of British Columbia, Vancouver, BC.
Ms. I. Reichenbach, Ottawa, ON.
Dr. E.A. Schiller, Calgary, AB.
Dr. B.H. Scott-Smith, Scott-Smith Petrology, Vancouver, BC.
Dr. C.B. Smith, CRA Exploration, Perth, Western Australia.
Dr. J. Utting, I.S.P.G., Geological Survey of Canada, Calgary, AB.
Mr. M. A. Waldman, LAC Minerals, Fort Collins, CO.
Dr. J.O. Wheeler, Geological Survey of Canada, Vancouver, BC.
Dr. S.A. Williams, Globo De Plomo Enterprises, Douglas, AZ.

Technical Assistance

The staff of C.F. Mineral Research Ltd.: Dr. Forough Hobuti, David Thompson, Rosemary Capell, Steve Maltby, Arnold Bauslaugh, Gwyneth Bruce, Rick Froment, Fred Basson, Norm Oftedal, Marilyn Trenn, Sheila Axten, Eva Horak, Mark Fipke, Steve Marsh, Claire Bruce, James Suggit, Marlene Fipke, Stan Emerson, Dan Tomelin, Christine Yoshimura, Lynn Lashuk, Ken Heaton, Brent Carr, Pat Leishman.

Contributions and assistance from the following are acknowledged

* Mr. Dan Hora and Dr. Jennifer Pell, British Columbia Ministry of Energy, Mines and Petroleum Resources, Victoria, BC.
* Dr. Eric Hoffman, Activation Laboratories Ltd., Brantford, ON.
* AAR Resources Ltd., 100 Mile House, British Columbia.
* Dia Met Minerals Ltd., Kelowna, British Columbia.
* Mr. R. B. Barlow, The Ontario Department of Mines, Toronto, ON
* CRA Exploration Pty Ltd., Belmont, Western Australia.
* Elemental Research Ltd., Vancouver, BC.
* Dr. H. Helmstaedt, Queens University, ON.
* Beverly and Fred Meister, Austin, Texas.
* Dr. S.E. Haggerty, University of Massachusetts, Amherst, MA.
* Dr. T.E. Krogh, Royal Ontario Museum, Toronto, ON.
* Mr. Carlos Bertoni, Montreal, PQ.
* Mr. Gary Grabowski, Mr. Howard Lovell, Mr. Dave Guindon, Mrs. Fay Boucher and Mr. Mike Woods, The Ontario Ministry of Northern Development and Mines, Kirkland Lake, ON.
* Rudy Gertsch Mountaineering, Golden, BC.
* Mr. Jerry Scheltgen, Lake City Technical, Kelowna, BC.
* Mr. Allan Hill, Okanagan College, Kelowna, BC.
* Dr. M.J. Orchard, Geological Survey of Canada, Vancouver, B.C.
* Dr. Eugene Jarosewich, National Museum of Natural History, Smithsonian Institution, Washingtion, D.C.

1. INTRODUCTION

1.1 Aims of the Project

A geological fact kept classified by a few major companies is that a number of diamondiferous diatremes have been located in rock underlain by the Archean Canadian Shield Craton. In fact, a large number of microdiamonds and some large (up to 40.8 carat) gem and industrial quality diamonds have been recovered from kimberlitic and lamproitic pipes in the Rocky Mountains of British Columbia; in the Mackenzie Mountains, NWT; on Somerset Island, NWT; in Ontario and possibly Quebec; in Colorado and Wyoming and in Arkansas. The Prairie Creek lamproite pipe in Arkansas would possibly be mined today if it was not in a state park.

Considering that the vast Canadian Shield is a desireable geological environment for locating diamondiferous diatremes, very little serious exploration has been undertaken by Canadian companies. A major cause of this is believed to be the lack of evaluation technology available as compared with the expertise of a few specialised companies. A fact that is often not appreciated is that on a global scale, only one in about three hundred kimberlite pipes is sufficiently diamondiferous to be an economic proposition. The application of sophisticated technology would enable a company to differentiate potentially mineable pipes from the many unmineable pipes at an early stage of the evaluation process, thereby eliminating the considerable expense of processing hundreds of tons of rock with no economic potential. As a result of the lack of technology, domestic and international diamond exploration expenditures by Canadian Companies have not resulted in any profitable return on investment. Consequently, Canadian management is reluctant to invest in diamond exploration regardless of the potential for diamond profits in Canada. If one mineable discovery is found in Canada, exploration activity should exponentially accelerate to the very high levels of activity that Austalia is presently experiencing. However, without an increase in exploration effort, it is unlikely that such a mine will be established.

The application of modern concepts to diamond exploration has had some success in the areas of established diamond deposits such as

South Africa as witnessed by the discovery of Venetia in the Northern Transvaal. However, it has been even more successful in countries with previously minor roles as diamond producers such as the USSR, Botswana and Australia (see Fig. 1). The relatively recent commissioning of producing mines at Mir and Udachnaya (USSR); Orapa, Letlhakane and Jwaneng (Botswana) and Argyle in Australia has resulted in these three countries now being responsible for more than half the world's annual production of natural diamond (Fig. 2). These enormous successes have promoted intense exploration interest in the areas concerned as evidenced by the exploration expenditure for diamonds in Australia for the decade 1975-84 (Fig. 3) (Atkinson, 1989).

The finding of Argyle in the north of Western Australia with its' current production of 30 million carats/year has further widened the scope for locating a major mine by demonstrating the viability of an additional rock-type, olivine lamproite. This exciting discovery not only widens the number of potential diamond occurrences throughout the world, but because of the distribution pattern of olivine lamproite, it increases the areas of the earth that can be considered prospective. It has also unlocked the minds of explorationists who had no reason to believe that a primary diamond mine could ever be found in any rock type other than kimberlite. Most people would now accept that further discoveries in additional rock types are quite possible.

Since diamond is a very important strategic mineral for which new uses are being continually discovered, but for which there are no mined sources on the North American continent, there are strong reasons to promote exploration in Canada. This is accentuated by the huge areas of the continental land mass within the country that were cratonised before 1.5 b.y. and which, therefore, present prime target areas.

As diamond prospecting has become more sophisticated, it has become apparent that although diamond deposits around the world have certain basic similarities, there are regional differences as well. 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. This project was initiated to establish

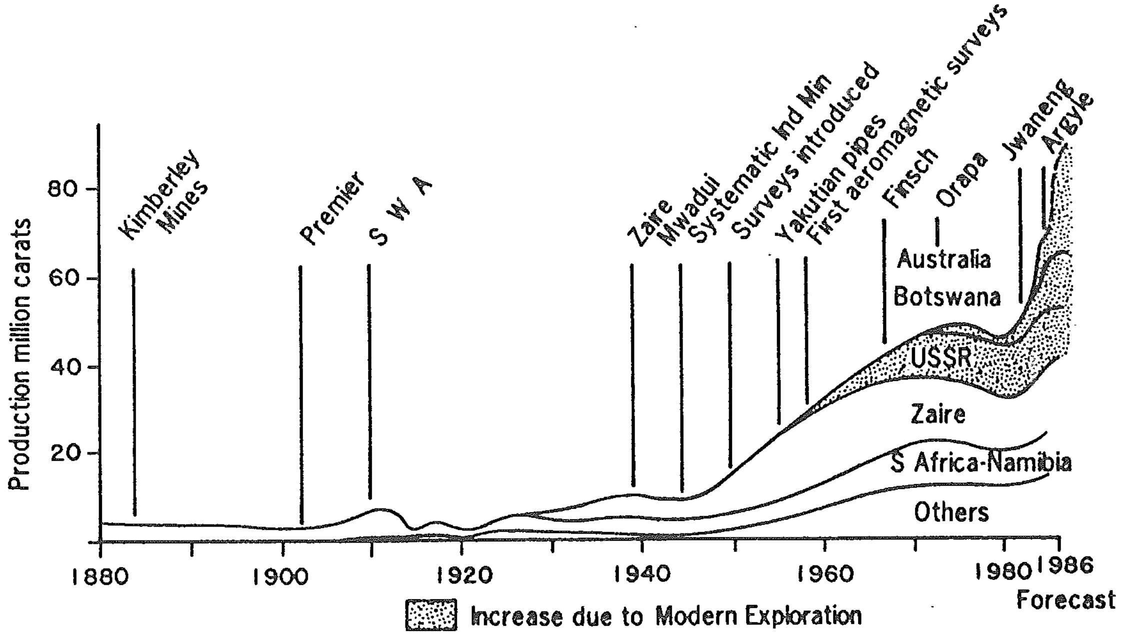


FIGURE 1: Growth in world diamond production (after Atkinson, 1989)

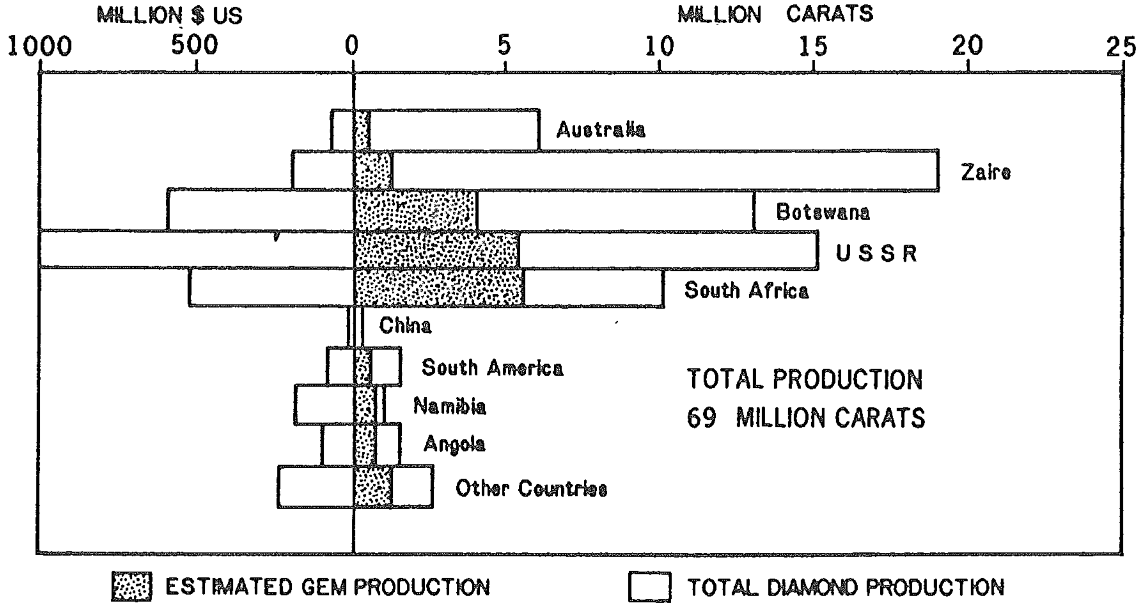


FIGURE 2: World diamond production for 1984 separated into gem and industrial categories (after Atkinson, 1989).

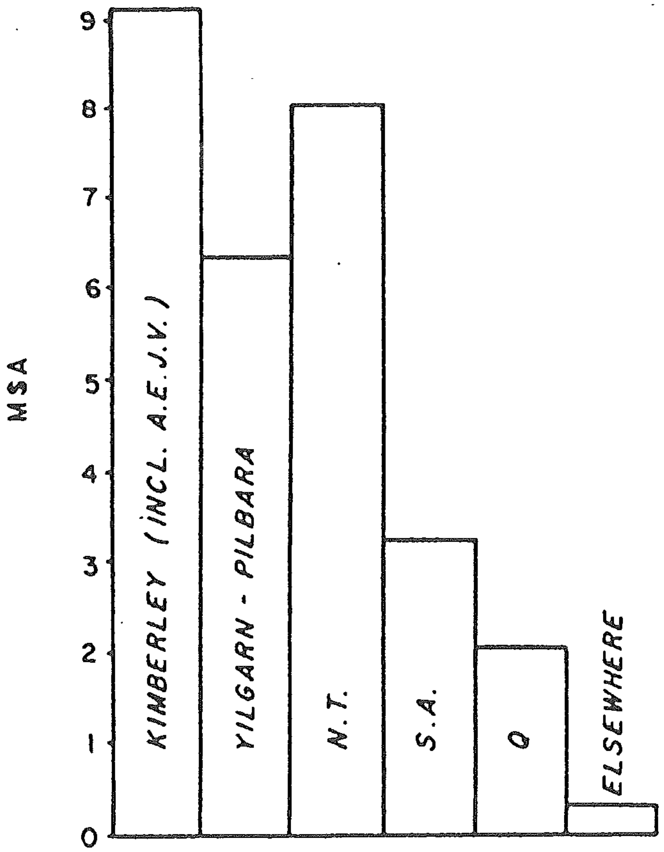


FIGURE 3: Estimated expenditure for diamond exploration in Australia for 1984 (after Atkinson, 1989).

criteria that can be applied to diamond exploration in North America to promote investment in diamond exploration in Canada.

It is a particularly opportune time to attract attention to diamond prospecting. The diamond market has survived a slump in the early 1980's promoted by speculative investment in the commodity that lead to rapid price increases that could not be sustained. The ensuing slump in both prices and sales had not ended when the Argyle production started to enter the market, but now, in 1989, record volumes of diamonds are being traded at steadily increasing prices even though Argyle has added 50% to the previous levels of diamond production (~60 m.cts - > 90 m.cts). No new source of natural diamonds comparable to this is on the horizon. Venetia may produce 4-5 m.cts/year if brought to production. The USSR may set up a kimberlite mine in a new area in the Baltic Shield, and open another (Zarnitsa) in Siberia. The cessation of civil war in Angola opens up real possibilities for increased diamond production from that country. However, one would expect all of these sources to enter the market in an orderly fashion in their own interests. Offsetting this potential increase in production will be the decline in importance of the Mir kimberlite in the USSR, the kimberlite mines in Kimberley, R.S.A. and in the medium term, the alluvial beach deposits at C.D.M. in Namibia.

The Central Selling Organisation has recently reported sales from the diamond stockpile accumulated mainly during the most recent slump and it is clear that in certain types of diamond the market is currently undersupplied.

At the same time huge advances have been made in the manufacture of diamonds. Small synthetic stones dominate the industrial market and Sumitomo are now producing larger diamonds (>1 carat) for industrial purposes on a commercial basis for the first time. Therefore the demand for natural diamonds for industrial purposes may be insufficient to promote growth. Exploration activities will depend for success on finding deposits with sufficient high quality diamonds to make them viable. With this proviso, it is currently an excellent time to find new supplies of the mineral.

However, in Canada, where there are no producing diamond mines, there are no established criteria by which to search for and identify primary ore bodies. The Australian record shows that whilst what applies elsewhere in the world may be useful in a new environment, not all the rules can simply be adopted without modification.

The objective of this report is to provide information and ideas that could contribute to diamond exploration programmes in Canada.

1.2 Methodology

In order to achieve the objective outlined above, eighteen individual diatremes (including both kimberlites and lamproites) were selected for detailed study. These include thirteen from Canada, two from the USA, two from South Africa and one from Australia (Table 1).

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) provide examples of diamondiferous kimberlites, while Argyle (Australia) is a richly diamondiferous lamproite. The latter two localities are currently successfully mined for diamonds.

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.

Four major phases of work were involved in the project. A brief outline of these is provided here and further details are supplied in the relevant sections of the report.

A. Fieldwork

* A 32 kg bulk sample was collected from each locality.

* Six of the recently discovered diatremes in British Columbia were mapped for the first time:- Blackfoot, HP, Jack, Larry, Mark and Mike diatremes.

TABLE 1: THE DIATREMES INVESTIGATED

DIATREME	GEOGRAPHIC LOCATION	ROCK TYPE
Argyle	Kimberley Province, Australia	Lamproite
* Batty	Somerset Island, NWT	Kimberlite
* Blackfoot	Elkford, B.C.	Lamprophyre
* Cross	Elkford, B.C.	Kimberlite
* HP	Golden, B.C.	Lamprophyre
* Ile Bizard	Montreal, Quebec	Alnoite
* Jack	Golden, B.C.	Lamproite
* Joff	Elkford, B.C.	Kimberlite
* Kirkland Lake	Bisley Township, Ontario	Kimberlite
* Larry	Golden, B.C.	Lamproitic
* Mark	Golden, B.C.	Lamproitic
* Mike	Golden, B.C.	Lamproitic
* Mountain	Mackenzie Mountains, NWT	Kimberlite
New Elands	O.F.S., South Africa	Kimberlite
Prairie Creek	Pike County, Arkansas, USA	Lamproite
* Sturgeon Lake	Prince Albert, Saskatchewan	Kimberlite
Sloan	Larimer County, Colorado, USA	Kimberlite
Sover	Cape Province, South Africa	Kimberlite

* Canadian Diatremes

B. Sample Preparation and Data Collection

* A representative set of thin sections was prepared for each locality and despatched to three independant petrographers (M.A. McCallum, B.H. Scott Smith and S.A. Williams) for examination. Thin sections were prepared by Quality Thin Sections in Tucson, Arizona.

* Carefully selected material from each bulk sample was submitted to L. Heinrichs of the Geological Survey of Canada (Calgary) for whole rock geochemical analysis.

* Heavy mineral concentrates were prepared from the remaining material which usually represented about 95% of the original bulk sample. This was undertaken in the laboratories of C.F. Minerals Research according to the procedure outlined in Appendix 1.

* The mineralogy of each heavy mineral concentrate was documented and a representative number of the diamond indicator minerals (chromite, pyrope and pyrope-almandine garnet, picro-ilmenite and chrome diopside) present were selected for quantitative analysis (details of the analytical techniques adopted are outlined in Appendix 2). Representative examples of non-indicator minerals were analysed for a select number of localities.

* The heavy non-magnetic fraction of each concentrate was processed for microdiamonds. Details of the techniques adopted are outlined in Appendices 1 and 9.8.

1.3 The Structure of this Report

The report consists of three components as outlined below:

Part 1:- provides the background material necessary for the understanding of the report by providing brief reviews of the petrology of kimberlites and lamproites, diamond genesis and diamond exploration techniques. It addresses the various topics investigated in the project (as outlined in the Table of Contents) and summarises the results, conclusions and recommendations.

Part 2:- consists of a series of individual reports for each of the localities investigated. A considerable amount of material covered in these reports has been obtained from publications and sources unrelated to the project. In all cases the source of information is fully acknowledged.

Part 3:- a comprehensive appendix volume containing the following information and data:

- details of analytical techniques adopted.
- an outline of laboratory procedures.
- a complete listing of all mineral chemistry and whole rock geochemical data.
- petrographic descriptions of all thin sections examined.
- mineralogical descriptions of heavy mineral concentrates.
- reports submitted by contributing scientists.

2. THE PETROLOGY OF KIMBERLITES

In view of the fact that not all readers of this report will be kimberlite specialists, some of the common nomenclature used in the fields of kimberlite and lamproite petrology and diamond research is defined in Table 2.

2.1 The Nature of Kimberlite

Kimberlites are a rare and volumetrically insignificant variety of alkalic (usually potassic) volcanic rock. They are

TABLE 2: GLOSSARY OF SOME COMMON NOMENCLATURE

Petrographic terms:

Megacryst - a coarse single crystal (discrete nodule).
Macrocryst - nongenetic term to include phenocryst and xenocryst.
Phenocryst - relatively large crystal set in a fine-grained groundmass to which it is genetically related.
Xenocryst - fragment of a crystal enclosed by a magma and foreign to it.
Metasomatism - process by which one mineral is replaced by another of different chemical composition owing to reactions set up by the introduction of material from external sources.

Tectonic Terms:

Lithosphere - that portion of the uppper mantle that moves as a coherent mechanical unit with a velocity similar to the surface crustal plate.

Asthenosphere - less rigid than lithospheric upper mantle and capable of internal convective motion by plastic flow.

Rock Nomenclature:

Peridotites:-

Lherzolite - olivine + orthopyroxene + clinopyroxene.
Harzburgite - olivine + orthopyroxene >50 vol% of the rock.
Wehrlite - olivine + clinopyroxene.

Pyroxenite - clinopyroxene ± orthopyroxene.

Eclogite - typically a bimineralic rock consisting of pyrope-almandine and clinopyroxene. Accessory minerals include rutile, kyanite, coesite, sanidine, graphite and diamond.

Glimmerite - a rock consisting predominately of mica.

MARID - a rock consisting of an assemblage of mica ± amphibole ± rutile ± ilmenite ± diopside.

petrographically and geochemically complex because: (a) they are hybrid rocks that contain minerals, rock fragments and magmatic components that formed in diverse physical and chemical environments; and (b) they show an enormous range in modal composition.

Several definitions of kimberlite are firmly entrenched in the literature which has not only led to terminological confusion, but has also resulted in unwarranted implications regarding the possible petrogenetic associations between kimberlites and other rock types (Mitchell, 1970, 1979). This confusion has, however, largely been overcome by the widely accepted formal definition of kimberlite proposed by Clement et al. (1984).

> 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.

As mentioned above, a wide range of foreign rock fragments (xenoliths) are usually hosted within kimberlite intrusions. Xenoliths from five different sources may be recognised (Dawson, 1980):

1. Fragments from the immediate wall-rock of the intrusion.

2. Fragments derived from earlier formations, existing at the time of kimberlite emplacement, which have subsequently been removed by erosion.
3. Blocks from buried formations.
4. Granulites derived from deep-seated metamorphic terrains.
5. Xenoliths of rock-types believed to be derived from the earth's upper mantle.

The upper mantle xenoliths are important from both an academic and a commercial viewpoint and these are described in more detail in Section 2.3.

Two distinct varieties of kimberlite (termed Group I and Group II) have been recognized in southern Africa on the basis of petrographic and isotopic criteria (Smith, 1983; Smith et al., 1985 and Skinner, 1989). Petrographically Group I kimberlites are characterised by the presence of olivine, phlogopite, monticellite, calcite and serpentine and the absence of groundmass diopside, and they usually host at least some megacryst phases. In contrast, Group II kimberlites are dominated by phlogopite both as a groundmass and macrocryst constituent. Primary diopside is common and groundmass monticellite is typically absent. Group II kimberlites are typically poor in megacrysts and magnesian ilmenite is characteristically absent (Skinner, 1989). Micaceous Group II kimberlites have thus far only been recognised in southern Africa.

2.2 Styles of Kimberlite Magmatism

Early studies of kimberlite (e.g. Wagner, 1914) demonstrated that they occur as carrot-shaped vertical intrusions termed pipes or diatremes and as tabular dykes (fissures). Because of their economic importance, the diatremes attracted more attention than the dykes, and as a consequence, kimberlites became regarded as fragmental rocks and the existence of kimberlite magma was doubted (Mitchell, 1986). However, modern studies have revealed that three textural genetic groups of kimberlites, each associated with a particular style of magmatic activity can be recognised: (1) crater facies, (2) diatreme facies, and (3) hypabyssal facies (Hawthorne, 1975; Clement and Skinner, 1979, 1985). Figure 4 illustrates an idealized kimberlite magmatic system while Fig. 5 outlines details of their classification.

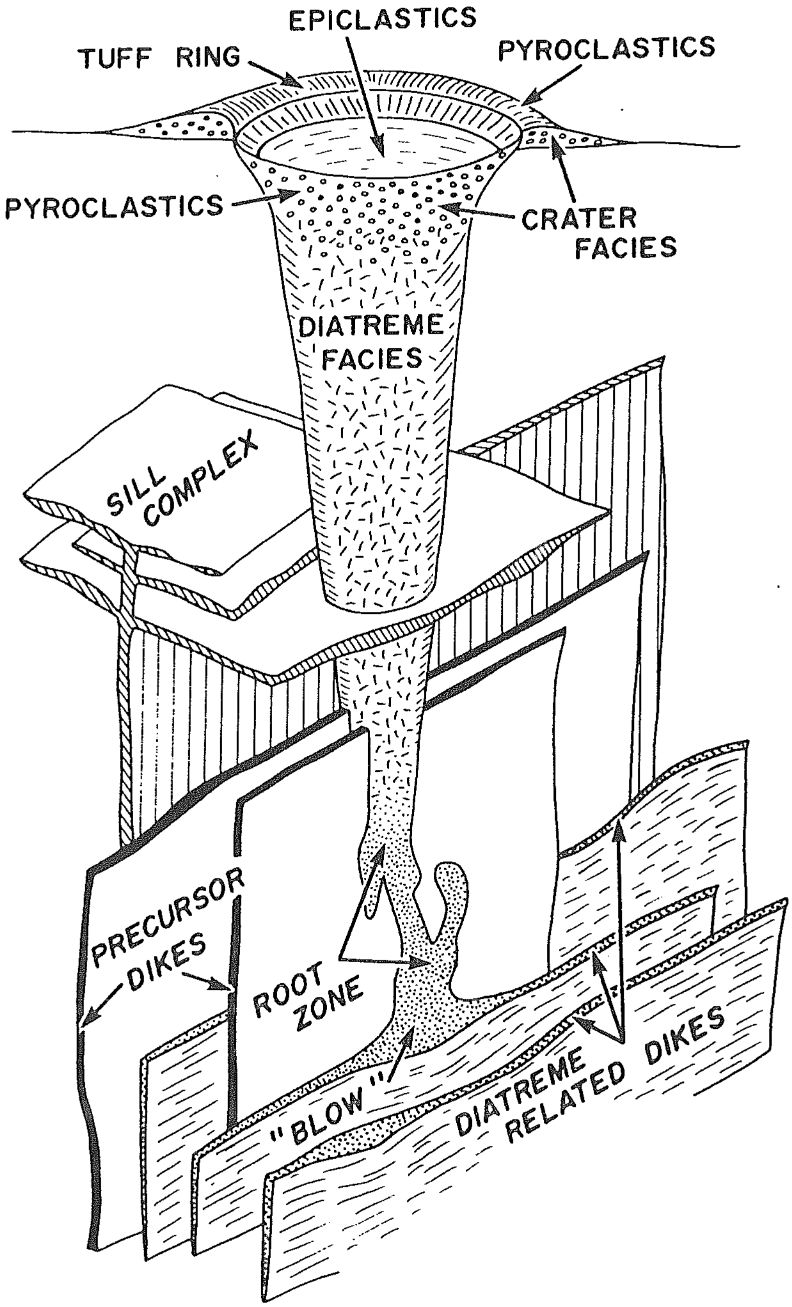


FIGURE 4: Model of an idealised kimberlite magmatic system, illustrating the relationship between crater, diatreme, and hypabyssal facies rocks (not to scale). Hypabyssal facies rocks include sills, dykes, root zone and "blow". Reproduced from Mitchell (1986).

2.1.1 Crater Facies Kimberlites

Crater facies kimberlites have only been preserved in a few areas where erosion has been negligible e.g. the Orapa pipe in Botswana. They may be divided into lavas, pyroclastic and epiclastic rocks. There is some doubt as to whether any genuine examples of uncontaminated extrusive kimberlite lavas exist.

Pyroclastic kimberlite represents the explosive ejecta such as kimberlite tuff or agglomerate deposited around and within the crater, while epiclastic kimberlites are produced by the fluviatile re-working and redeposition of kimberlite tuffs in crater lakes (maars) formed above diatremes. Epiclastic kimberlites are named according to standard sedimentological terminology (e.g. kimberlitic sandstone, kimberlitic shales etc). Crater facies kimberlites are typically very altered by weathering processes and could easily go unrecognized if not for the presence of resistant and distinctive macrocrystic minerals such as garnet, Cr-diopside, ilmenite and chromite.

2.1.2 Diatreme Facies Kimberlite

The diatreme zone is the long funnel-shape body of kimberlite that links the surface crater to the root zone of the pipe (Fig. 4). Although near surface the crater flares out rapidly, the margins of the diatremes show a consistent inward dip of 82^{o} (Hawthorne, 1975).

Diatreme facies kimberlites are fragmental rocks which represent the end products of complex vapour-rich fluidized intrusive systems. They have been classified as tuffisitic kimberlites and tuffisitic kimberlite breccias (Clement and Skinner, 1979; Clement, 1985). The two varieties are distinguished on the basis of xenolith content and further subdivisions can be made based upon the clasts and the inter-clast matrix (Fig. 5).

Tuffisitic kimberlite breccias (TKB) are the commonest rocks of the diatreme zone. They contain abundant (>15 vol%) country rock fragments, cognate clasts, and mantle-derived xenoliths and xenocrysts. The breccia fragments are cemented by microlitic diopside and serpentine which represent the quench products of

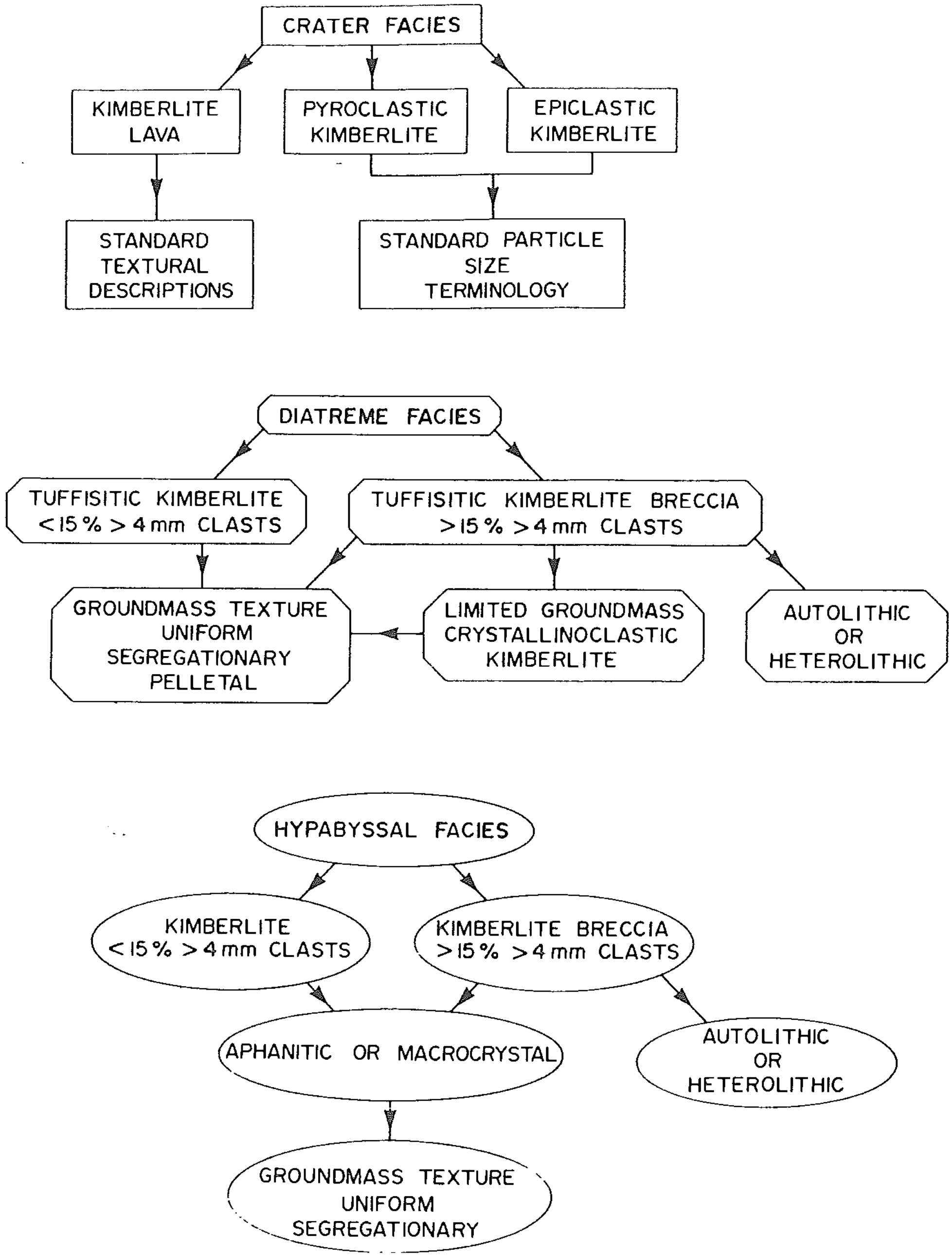


FIGURE 5: Textural genetic classification of kimberlite. Reproduced from Mitchell (1986). Modified from Clement and Skinner (1979) and Clement (1982).

the transporting fluid. Primary calcite is rare in most diatreme facies kimberlites and it appears likely that CO_2 is largely lost to the atmosphere during emplacement. Many TKBs contain abundant small (microscopic to several cm in diameter), spherical to subspherical, fine grained kimberlite lapilli. These lapilli probably represent magma droplets which coalesced around preexisting fragments or crystals during emplacement.

2.1.3 Hypabyssal Facies Kimberlite

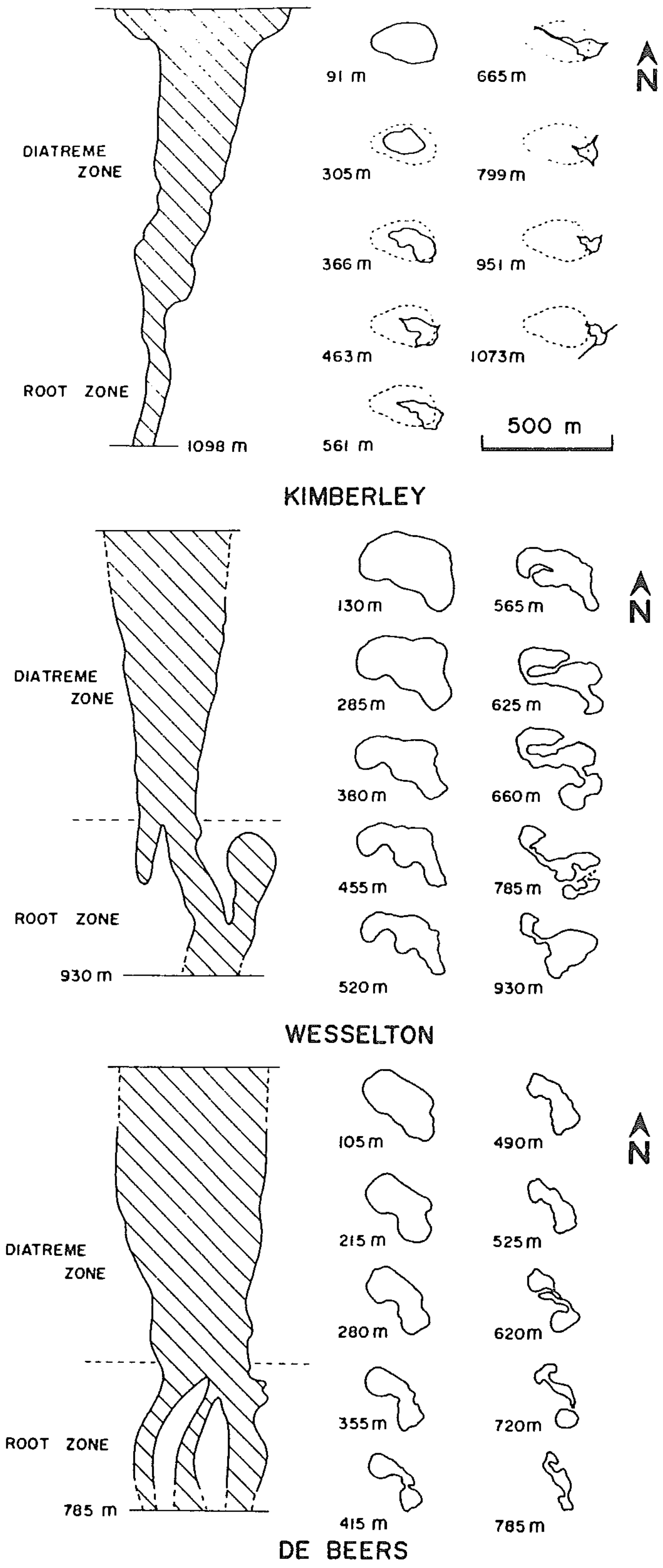
Hypabyssal facies kimberlites form the root zones of diatremes, and occur as dykes and sills (see Fig. 4). This variety of kimberlite displays igneous textures and has formed by crystallization of a volatile rich magma. Hypabyssal kimberlites can be subdivided into kimberlites and kimberlite breccias on the basis of xenolith content (see Fig. 5).

In contrast to the regular shape of the diatreme zone, the root zones of pipes are characteristically highly irregular and often extremely complex in shape (Figs. 6 & 7). Contacts between kimberlite and host rocks may vary from vertical to horizontal, with apophyses branching off from the main intrusion. Several intrusive pulses of kimberlite with different mineralogical characteristics, and particularly with different diamond grades, are recognizable (Fig. 7). By contrast, the diatreme facies kimberlites are far more homogeneous (due to mixing during intrusion) and consequently show far less fluctuation in diamond grade (Clement, 1982).

2.3 Upper Mantle Xenoliths in Kimberlite

Most kimberlites contain fragments of rock whose mineralogy and composition indicates derivation from the upper mantle. Five broad categories of rock types are present:

1. The peridotite-pyroxenite suite.
2. Eclogites.
3. Megacrysts
4. Metasomatised peridotites, rich in amphibole and/or mica.
5. Glimmerites and MARID-suite rocks.



KIMBERLEY

WESSELTON

DE BEERS

FIGURE 6: Vertical and horizontal cross sections of the Kimberley (Williams, 1932), Wesselton (Clement, 1982) and De Beers (Clement, 1982) diatremes. Reproduced from Mitchell (1986).

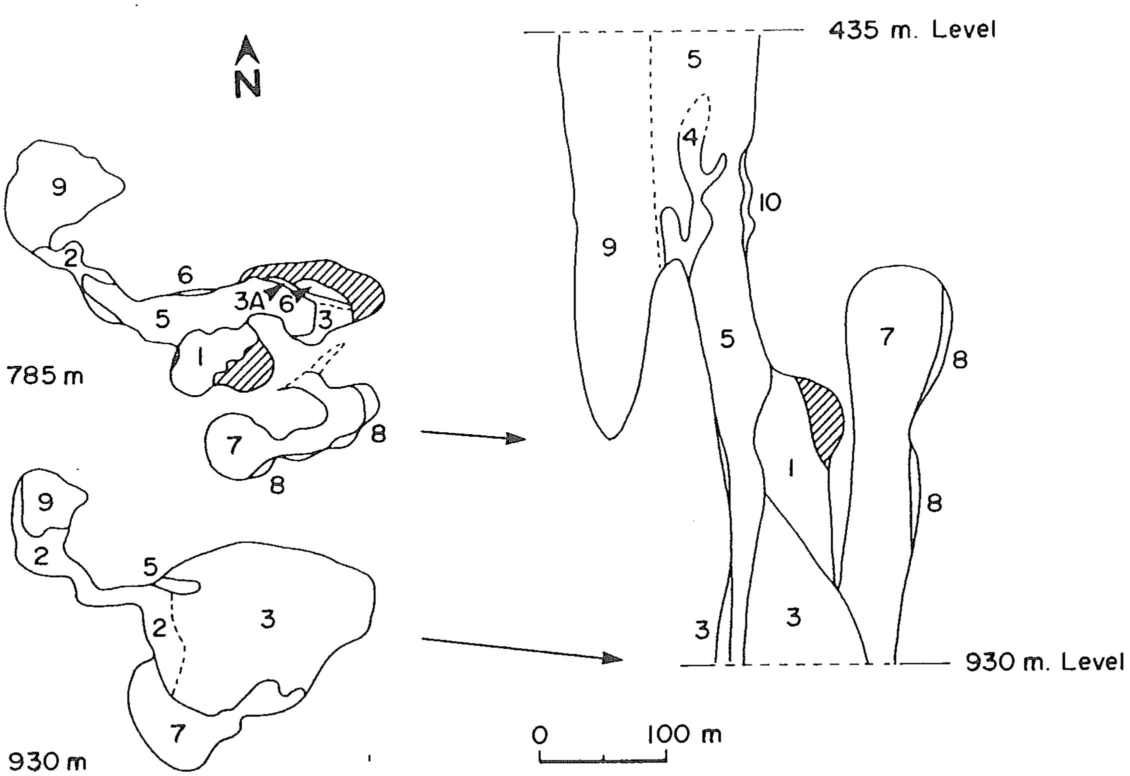


FIGURE 7: Vertical and horizontal cross sections of the root zones of the Wesselton diatreme (Clement, 1982; Shee, 1984). Numbers signify petrographically distinct varieties of kimberlite (not in sequence of intrusion). Diagonal shading indicates contact breccias. Note the blind diatreme represented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

Further details on the definition and classification of these rock types is summarised in Table 2 and Fig. 8.

Lherzolites and harzburgites of the peridotite-pyroxenite suite usually predominate, but megacrysts and eclogites may be locally abundant. Fragmentation of mantle-derived xenoliths during transportation in the kimberlite results in the addition of xenocrysts to the magma. The usefulness of specific varieties of the deep-seated xenoliths and xenocrysts in diamond exploration is outlined in subsequent sections.

2.4 Worldwide Distribution of Kimberlites

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

Kimberlites are widely distributed throughout Africa; in the south (S.Africa, Namibia, Botswana, Swaziland, Lesotho and Angola), central (Zaire, Central African Republic and Tanzania) and west (Ghana, Guinea, Ivory Coast, Liberia, Mali, Gabon and Sierra Leone). The Yakutian Province within the East Siberian Platform of the USSR is also a major region of kimberlite occurrence. Other important kimberlite provinces include the Brazilian Province and the Southern and Central Indian Provinces. Isolated occurrences of kimberlites are found within the USA, Canada, Greenland, Finland, USSR, China, Argentina, Australia and Malatia in the Solomon Islands. A comprehensive review of these occurrences is beyond the scope of this report and the reader is referred to Dawson (1980), Janse (1984) and Mitchell (1986) for further details. Mitchell (1986) also provides an excellent review of the various tectonic settings in which kimberlites are found.

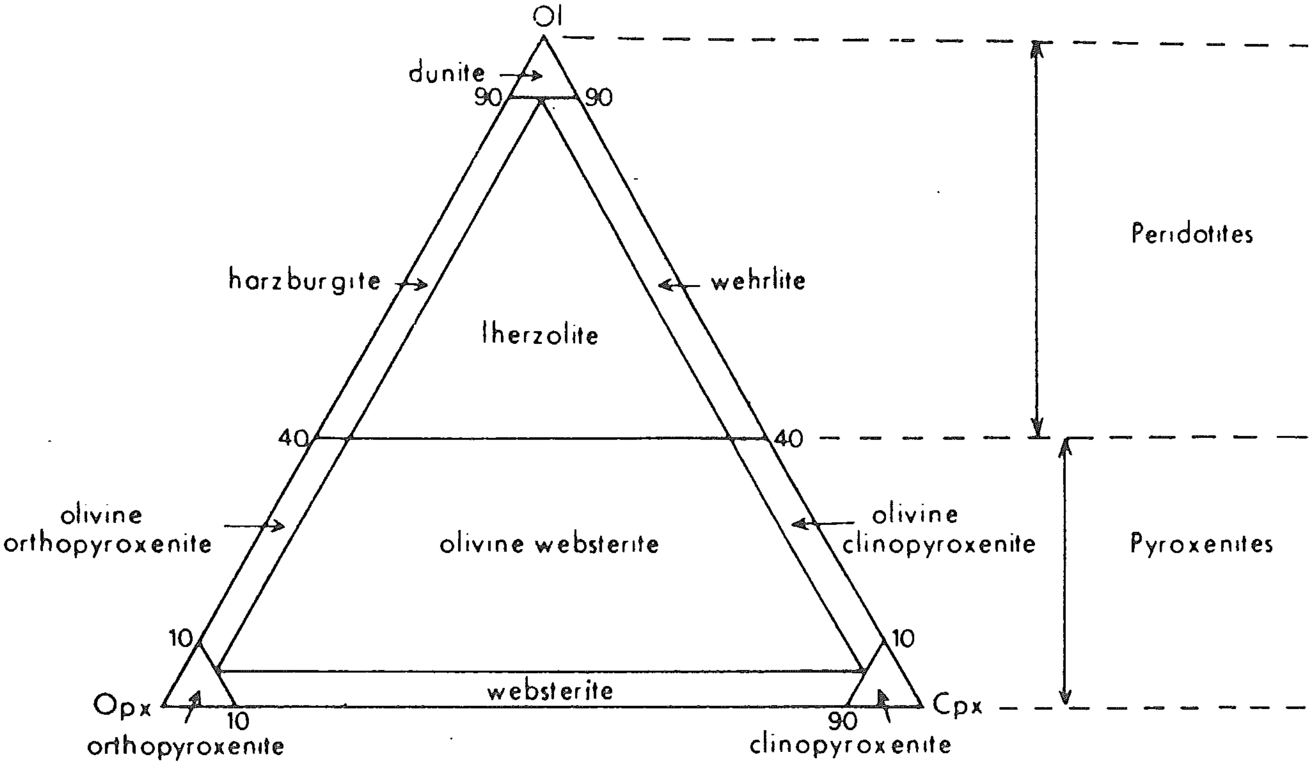


FIGURE 8: Classification of peridotites and pyroxenites as recommended by the International Union of Geological Sciences). Modal proportions are in volume percent. Reproduced from Dawson (1980).

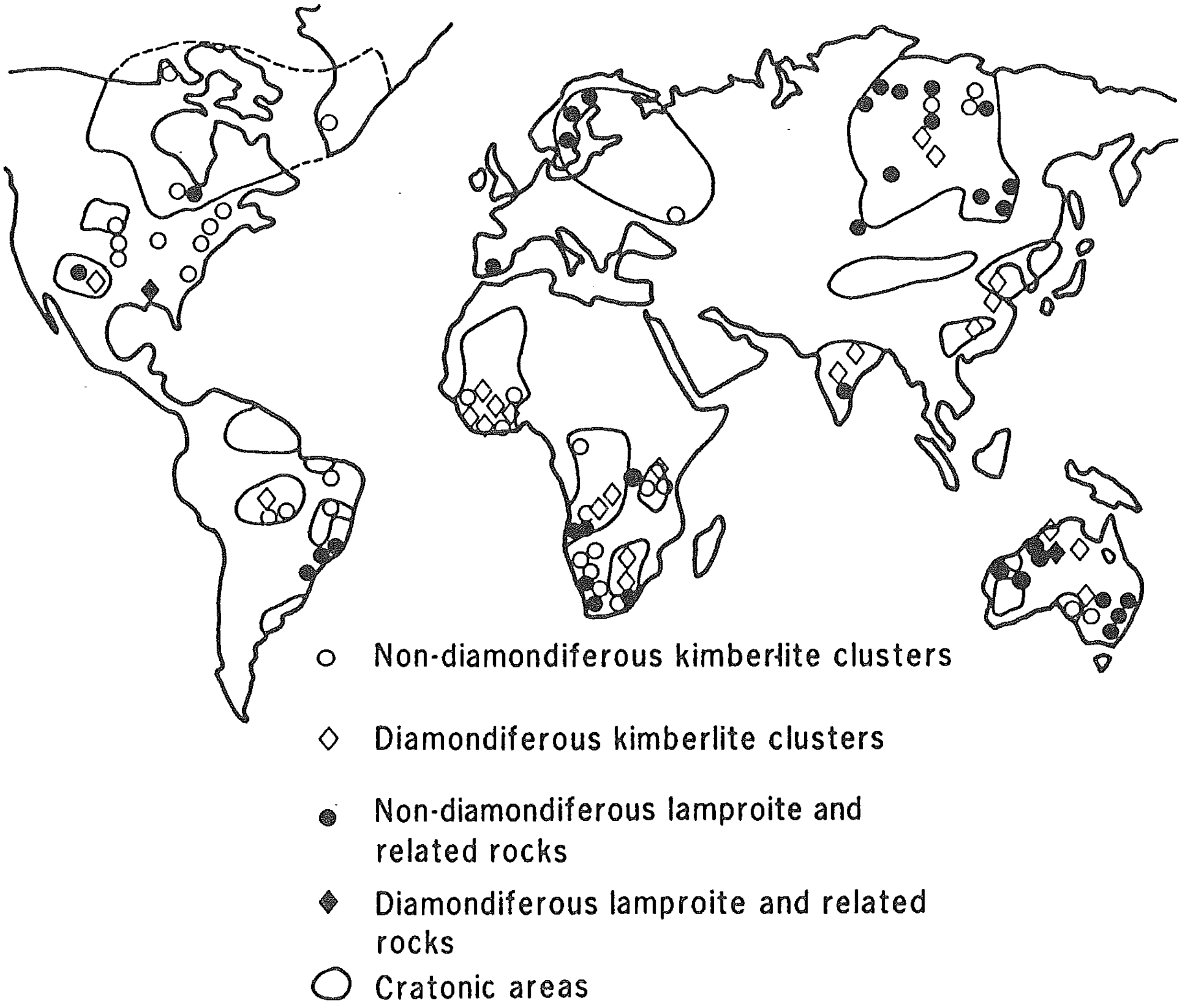


FIGURE 9: World distribution of kimberlites and lamproites in relation to Archean cratons. From Atkinson (1989); adapted after Janse (1984).

2.5 Geochemistry of Kimberlites

The major element composition of kimberlites are broadly similar to those of normal olivine-rich ultramafic rocks, except that kimberlites are usually enriched in TiO_2, K_2O and P_2O_5 and have an extremely high volatile component (see Table 3). While it is recognised that the concept of an average chemical composition of kimberlite may be misleading (because of their extreme variability in composition), a comparison of the average kimberlite composition with the average ultramafic composition compiled by Wedepohl and Muramatsu (1979) (see Table 4) serves to illustrate the most important geochemical characteristic of kimberlites. Table 4 shows that Li, F, P, K, Ti, Rb, Sr, Zr, Nb, Sn, Ba, Pr, Nd, Sm, Eu, Gd, Hf, Ta, Tl, and Pb are enriched in the "average kimberlite" by a factor of between 10 and 100 and C, Cs, La, Ce, Th and U by a factor greater than 100 compared to the average ultramafic composition. Kimberlites thus have major element compositions which are similar to normal olivine-rich ultramafic rocks, but they are highly enriched in volatiles and incompatible elements.

2.6 Kimberlite Genesis

In his book on kimberlites and their xenoliths, Dawson (1980) discusses three hypotheses for the origin of kimberlite. These are zone refining (Harris, 1957, Harris and Middlemost, 1969), the residual process (O'Hara and Yoder, 1967) and the small volume partial melt hypothesis. None of these three hypotheses is entirely satisfactory for a variety of reasons, some of which are discussed in Dawson (1980). Zone refining is not currently a favoured model for kimberlite genesis and the residual melting theory is confounded by the non-genetic relationship between kimberlite and eclogite. Moreover, no single mantle rock has been identified that produces kimberlite on partial melting, with its exceptionally high volatiles, incompatible trace elements, K and Ti.

Based primarily on his studies in East Africa, Bailey has maintained since 1964 (e.g. Bailey, 1964, 1984) that the source of alkaline magmas including kimberlite is within the lithosphere, where they are generated by a process of volatile

TABLE 3: REPRESENTATIVE COMPOSITIONS OF KIMBERLITES

	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	11.85[b]	4.02	3.72	7.04	19.66	8.57[b]	6.80	8.90[b]	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

[a] 1, Shandong, China (Zhang and Liu 1983); 2, Dike 202, Malibamatso River, Lesotho (Gurney and Ebrahim 1973); 3, Pipe 200, Lesotho (Gurney and Ebrahim 1973); 4, base of macrocrystal-rich sill, Mayeng (Apter *et al.* 1984); 5, olivine-magnetite-perovskite cumulate, Benfontein (Dawson and Hawthorne 1973); 6, composite sample of Benfontein sill (Dawson and Hawthorne 1973); 7, magnétite-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).

[b] Total Fe calculated as Fe_2O_3; L.O.I. = loss on ignition.

(Reproduced from Mitchell, 1986)

TABLE 4: THE CHEMICAL COMPOSITION OF "AVERAGE KIMBERLITE" COMPARED WITH THAT OF "AVERAGE ULTRAMAFIC ROCK"

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

(Reproduced from Middlemost, 1986; After Wedepohl & Muramati (1979) fluxing. For kimberlites it is clear that there is a deep lithospheric component involving metasomatised rocks including carbonated peridotite, that there is crustal contamination and that deep sourced partial melting is involved. However, it is apparent too that some, maybe all kimberlites must have an origin in the asthenosphere. Small degrees of partial melting are favoured over extensive fractionation.

The model of Nixon et al., (1981) that suggests that kimberlites are hybrid magmas by virtue of the incorporation of incompatible rich melt at the base of the continental mantle is another version of the "conditioning process" envisioned by Bailey, and once again supports the idea that kimberlite as seen at the surface is not generated in any single mantle location. Rather, proto-kimberlites evolve into kimberlite by assimilation of components from several sources en route from the asthenosphere to the surface through the lithospheric mantle and the crust. Wyllie (1989) has recently suggested that kimberlite intrusion is preceded by a period of "conditioning" in the lower lithospheric mantle by asthenospheric volatile rich fluids. He suggests that there are many "failed" kimberlites in this zone that are emplaced during the conditioning period.

Currently there is no universally accepted model for kimberlite genesis.

3. THE PETROLOGY OF LAMPROITES

Niggli (1923) introduced the term "lamproite" to describe "volcanic rocks rich in potassium and magnesium". Subsequently, authors such as Troger (1935) and Wade and Prider (1940) broadened the term to encompass a wide variety of ultrapotassic leucite-bearing rocks, commonly of lamprophyric aspect (Mitchell, 1989). Prior to the 1970s very little was known about lamproites, but the discovery of the diamond-bearing lamproites in north-western 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 now given the group a status that is second only to kimberlite as a primary source of diamond (Mitchell, 1989).

3.1 The Nature of Lamproite

The petrographic and geochemical diversity of lamproites precludes any simple definition based on modal mineralogy. Consequently, the term lamproite as currently used refers to a clan of rocks and not a specific rock variety. Scott Smith and Skinner, (1984a) recently proposed the following definition for lamproites:

> 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 richertite), olivine and sanidine. Other primary minerals may include priderite, perovskite, apatite, wadeite, spinel and nepheline. Other minerals such as carbonate, chlorite and zeolite, if present, may not be primary.
>
> Upper mantle-derived xenocrysts or xenoliths may or may not be present.

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

The mineralogy of lamproites and kimberlites are compared and contrasted in Table 5. The presence of amphibole, sanidine and glass distinguishes lamproite from kimberlite. In addition, leucite, priderite, wadeite and nepheline are not found in kimberlites and lamproites lack the primary serpentine and/or carbonate which reflect the volatile-rich nature of kimberlites. Minerals which are characteristically absent from lamproites are nepheline, sodalite, hauyn, nosean, kalsilite, melilite,

TABLE 5: SUMMARY 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		

NOTES:

* Phase unique to lamproites compared with kimberlites
\+ Phase unique to kimberlite compared with lamproite

plagioclase, monticellite, and melanite (Bergman, 1987). The absence of these minerals serves to set members of the lamproite clan apart from potassic rocks such as leucitites, katungites, mafurites etc. and other undersaturated alkaline rocks such as nephelinites, melilitites and alnoites (Mitchell, 1989).

Lamproite terminology has historically been one of the most complex and disjointed for any group of igneous rocks (Bergman, 1987). Petrological relationships between lamproites were obscured by the confusing type locality nomenclature applied indiscriminantly to individual lamproite suites without consideration of lamproites elsewhere in the world. Consequently 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, akin to that utilized for kimberlites was introduced by Scott Smith and Skinner (1984a), and subsequently modified by Mitchell (1985) and Jaques et al. (1984). Lamproites are classified into groups that are named on the basis of modally dominant minerals. The major divisions are based upon the the predominance of phlogopite, richterite, olivine, diopside, sanidine and leucite e.g. olivine lamproite or leucite lamproite. Further subdivisions are made by the use of an appropriate modifier(s) to the basic name to reflect the relative abundance of other phases e.g. diopside phlogopite lamproite (Mitchell, 1989). The existing lamproite terminology recast into the revised terminolgy is summarised in Table 6. Diamonds in commercial quantities have thus far only been found in olivine lamproites (Atkinson et al., 1984).

3.2 Model of a Lamproite Pipe

Lamproites have been reported to occur in nearly every igneous form possible, the most common being dykes and sills (Bergman, 1987). However, those occuring as diatremes or pipes have the greatest potential for possessing a diamondiferous olivine lamproite phase such as found at Prairie Creek and Argyle.

In contrast to the carrot-like shape of kimberlite diatremes which show 2 to 3 km of vertical flaring, lamproite pipes are

TABLE 6: 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
fitzroyite	leucite phlogopite lamproite
cedricite	leucite diopside lamproite
wolgidite	diopside leucite richterite madupitic lamproite
mamillite	leucite richterite lamproite
gaussbergite	hyalo-olivine leucite lamproite

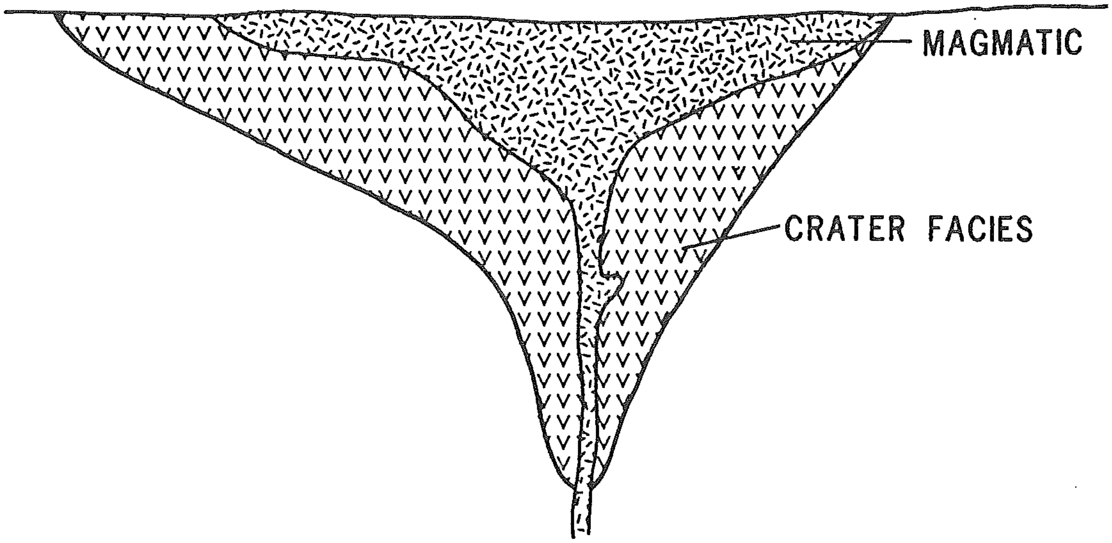


FIGURE 10: Schematic cross-section of a lamproite pipe illustrating the characteristic champagne glass shape. Note that the magmatic lamproite (hypabyssal facies) intrudes the crater facies pyroclastic material. After Scott Smith and Skinner (1984b).

usually more champagne-glass shaped bodies with less than 0.1 to 0.5 km of vertical flaring (Fig. 10). This contrast has important diamond-exploration implications (i.e. ore volume calculations and magnetic modelling) and can be reconciled by contrasting intrusion styles caused by the different volatile budgets of the two intrusive systems (Bergman, 1987). The larger proportions of both CO_2 and H_2O in kimberlites results in the final explosive phase of intrusion originating at greater depths than is the case for lamproites.

The crater walls of lamproite pipes typically slope inward at 30 degrees (Atkinson et al., 1984) and the crater zones are filled with airfall and water-lain tuffs and epiclastic sediments. Unlike kimberlites, where hyabyssal material occurs as dykes, sills and pipe root zones, magmatic, hypabyssal lamproite rises to the surface and intrudes and overlies the lamproite crater sediments (see Fig. 10).

Detailed textural-genetic classifications analagous to those developed for kimberlites have not been developed as yet. However, Scott Smith and Skinner (1984a) consider the pyroclastic components of diatremes to belong to a lamproite crater facies and the magmatic rocks to a hypabyssal facies. Neither of these categories are equivalent in texture or petrography to rocks of the kimberlite facies of the same name.

3.3 Distribution of Lamproites

Bergman (1987) provides an excellent and comprehensive review of the global distribution of lamproites and his location map is reproduced as Fig. 11. Only a very brief summary is provided here, and the reader is referred to Bergman (op cit) for further details.

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

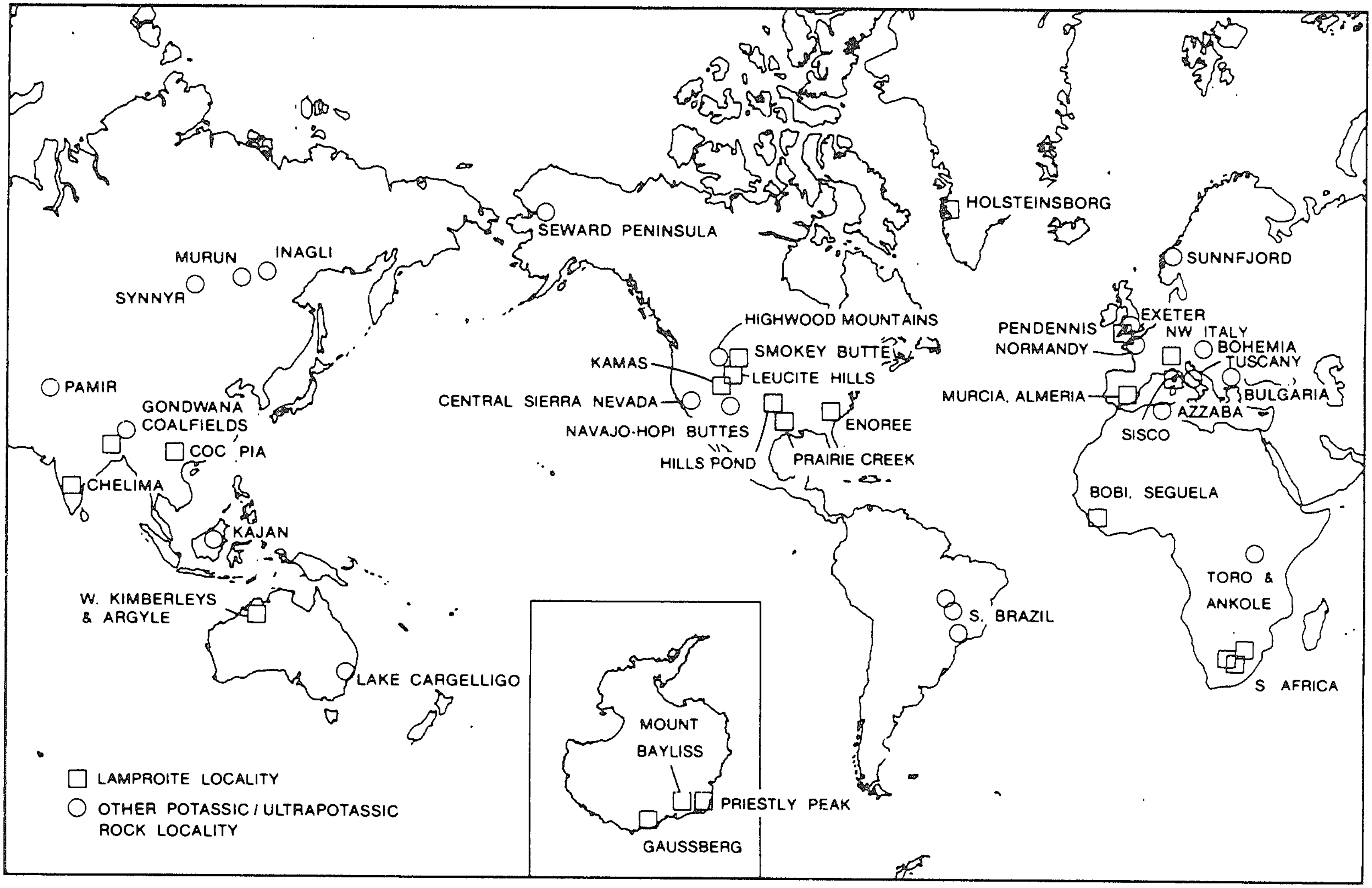


FIGURE 11: World map showing the locations of lamproite suites and some compositionally similar potassic-ultrapotassic rock suites. Reproduced from Bergman (1987).

well off-craton in the Gulf Coastal Plains of south central U.S.A.

Other varieties of lamproites occur toward the margins or off the edges of the Kaapvaal, Congo and Tanzania Cratons in southern Africa, and the Guapore and Sao Francisco cratons of South America (Janse, 1984). They occur with diamondiferous kimberlites in India, West Africa, East Siberia, Wyoming (North America) and West Australia, and with non-diamondiferous kimberlites in the Superior-Churchill and Northern Europe/Western Russia cratons (Janse, 1984).

3.4 The Geochemistry of Lamproites

The major and trace element geochemistry of lamproites has been discussed in detail by Bergman (1987) 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 taken from Bergman (1987) are summarised in Tables 7 and 8. As noted for kimberlites, the average compositions may have little geochemical significance, but they 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).

3.5 Lamproite Genesis

A wide variety of models have been advocated for the genesis of lamproites and these have been reviewed by Bergman (1987). Many of the models are broadly to similar to those put forward for kimberlites and most fit one of three broad groups (Bergman, 1987).

1. Partial melting of mantle material that has been metasomatically (or otherwise) enriched in phlogopite and

TABLE 7: REPRESENTATIVE RANGES AND AVERAGE COMPOSITION OF LAMPROITES (After Bergman, 1987)

	1	2	3	4
		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	7.4 ± 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 ± 0.03	0.09 ± 0.03	0.08 ± 0.05	0.10 ± 0.05
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	0.08 ± 0.04	0.13 ± 0.07
		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
	(24)	(51)	(98)	(309)

* Total Fe calculated as FeO

Notes:
1 Leucite Hills, U.S.A.
2 Murcia-Almeira, Spain
3 West Kimberley, Australia
4 Average lamproite (worldwide)

Number of samples in parentheses.

TABLE 8: AVERAGE TRACE ELEMENT ABUNDANCES IN KIMBERLITES AND LAMPROITES (ppm) (Adapted from Mitchell, 1989)

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

Notes:

1 worldwide kimberlites (Mitchell, 1986), values in parentheses after Muramatsu (1983)

2 worldwide lamproites from Bergman (1987)

* unreliable data or inadequate data base

other LIL-element-enriched minor phases (e.g. apatite, zircon, sphene etc), the melt may be subject to variable amounts of fractionation but does not undergo substantial assimilation of crustal material.

2. Assimilation of continental crustal material by "normal" mantle-derived alkali-basaltic, carbonatitic or alkali-ultramafic rocks.

3. Evolution involving processes such as zone refining, fractional resorption, gaseous transport etc. in otherwise typical mantle-derived melts.

4. KIMBERLITES AND RELATED ROCKS OF NORTH AMERICA

Kimberlites, and rocks of kimberlitic affinity have a relatively wide distribution throughout north America (see Fig. 12 and Table 9). In the U.S.A. they occur in the western margin of the Appalachians from New York to Tennessee; in the central region of the the U.S. including Kentucky, southern Illinois, Missouri, Kansas and Arkansas, and in the Western States of Montana, Wyoming, Colorado, Utah, Arizona and the New Mexico. In Canada, they have been documented on Somerset Island, NWT, the Mackenzie Mountains, NWT, in parts of Saskatchewan, Ontario and Quebec and in the Rocky Mountains in the region of the British Columbia-Alberta border.

A comprehensive review of these occurrences is beyond the scope of this report. In fact, no up to date summary is available at the present time. Meyer (1976), Watson (1967a, 1973), Brummer (1978) and Dawson (1980) present the most recent general accounts of the North American localities, but these contributions are now considerably out of date. Some more modern information is available in a number of papers published in a recent book edited by P.H. Nixon (Nixon, 1987), but these articles deal primarily with xenoliths rather than the host volcanic rocks.

Key references to the localities plotted on Fig. 12 are listed in Table 9 so that individual localities of interest may be pursued. However, the reader is cautioned that the terminology used in a number of the older papers may not be accurate. In particular,

FIGURE 12: Kimberlites and related rocks of North America. A full listing of the localities is presented in Table 9.

TABLE 9: KIMBERLITES AND RELATED ROCKS OF NORTH AMERICA

#	LOCALITY	TYPE	REFERENCE
CANADA			
1	Somerset Island, NWT	K	This Report
2	Mountain Diatreme, NWT	K	This Report
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	Ile Bizard, Quebec	A	This Report
8	Bachelor Lake, Quebec	K,La?	Dawson (1967); Watson (1967a)
9	Picton & Varty Lake, Ont.	K	Arima & Kerrich (1988)
10	Kirkland Lake, Ontario	K	This Report
11	Michaud Township, Ontario	K	Watson (1973)
12	Coral Rapids, Ontario	La,K?	Brown et al. (1967)
13	Hearst, Ontario	K	Nixon (1987)
14	Keith Township, Ontario	K	Watson (1973)
15	Wawa, Ontario	La	Mitchell & Janse (1982)
16	McKellar Harbour, Ontario	A	Platt & Mitchell (1982)
17	Sturgeon Lake, Saskatchewan	K	This Report
18	Golden Cluster, B.C.	K,L	This Report
19	Cranbrook Cluster, B.C.	K,B	This Report
UNITED STATES OF AMERICA			
20	North Montana	K,L	Mitchell & Hawkesworth (1984); He & McGee (1984)
21	Iron Mountain, Wyoming	K	McCallum et al. (1975)
22	State Line, Colorado/Wyoming	K	This Report
23	Green Mountain, Colorado	K	Meyer & Kridelbaugh (1977)
24	Mule Ear, Moses Rock, Utah	K	McGetchin & Silver (1970); Stuart Alexander et al. (1972)
25	Garnet Ridge, Arizona	M	Watson (1967b)
26	Buell Park, Arizona	M	Roden & Smith (1979); Smith (1979
27	Green Knobs, New Mexico	M,K	Smith (1979)
28	Riley County, Kansas	K	Brookins (1970 a,b); Berendson et al. (1985)
29	Murfreesboro, Arkansas	L	This Report
30	South Eastern Missouri	La?	Mansker (1973)
31	W.Kentucky & S.Illinois	La?	Koenig (1956)
32	Elliot County, Kentucky	K	Boliver (1972), Hunt & Boliver (1972); Garrison & Taylor (1980); Schulze (1984)
33	Norris Kimberlite, Tennesse	K	Meyer (1975)
34	Mt Horeb, Virginia	K?	Young & Bailey (1955); Sears & Bilbert (1973)
35	Masontown, Pennsylvania	K	Alibert & Albarede (1988); Hunter Taylor (1984)
36	Dixonville, Pennsylvania	K	Hunter & Taylor (1984)
37	Syracuse, New York State	La?	Apfel et al. (1951)
38	Lake Ellen, Michigan	K	McGee & Hearn (1984)

Codes For Rock Types:

K = Kimberlite
L = Lamproite
La = Lamprophyric
A = Alnoite
B = Basaltic
C = Carbonatitic
M = Minette

lamprophyric rocks have often been incorrectly classified as kimberlites. In a number of cases modern follow up studies have yet to be undertaken.

5. DIAMOND GENESIS:

As already mentioned, 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 economically viable diamond deposits have so far been found. There are however examples of other rocks which have been reported to contain traces of diamond (e.g. lamprophyres, ophiolites, garnet granulites and tectonically emplaced ultramafics).

In both kimberlites and lamproites the diamonds range in size from micro-crystals < 50 microns to macro-crystals occasionally > 1 cm in size. It is clear that the full diamond suite incorporates several overlapping populations with diverse origins, though how many is not certain. Every diamond-bearing locality has diamonds of eclogitic and peridotitic paragenesis as judged by the mineral inclusions in the diamonds and occasionally confirmed by the finding of diamond-bearing xenoliths. Diamond-bearing eclogites are found quite easily, particularly at some of the localities where eclogitic diamonds are common like Orapa in Botswana. These xenoliths are not cognate to the host volcanic rock, but have clearly been sampled in the upper mantle and transported to the earth's surface fairly rapidly. Diamond-bearing peridotites are much scarcer than diamond eclogites although judged by inclusions, peridotitic diamonds are more abundant than those formed in eclogite. However, xenocrysts of disaggregated peridotites including harzburgite (see Table 2 for explanation of terminology) are found in diamondiferous diatremes. Some of these xenocrysts have the right composition to be derived from diamond-bearing garnet harzburgites (Gurney, 1984). This rock is considered to be preferentially disaggregated on sampling and transport to the surface due to the presence of a carbonate phase that dissociates in response to reducing pressure whilst temperature remains relatively high (Boyd and Gurney, 1982). This phenomenon introduces the constituent minerals of the harzburgite as dispersed phases into the host volcanic magma.

Consequently, primary harzburgite minerals constitute a small portion of the secondary heavy mineral dispersal train.

Eclogitic diamonds display a wide range of carbon isotope compositions ($-34 < \delta\ ^{13}C < +3$; see Fig. 13). It could be derived from an upper mantle that has retained a primary heterogeneity, or from crustal sources subducted into the mantle. We favour mixing models involving recycled carbon and a primary mantle source that is fairly homogeneous. At least some eclogitic diamonds are therefore thought to be related to processes active during subduction events and plate movements. In contrast, peridotitic diamonds have a more restricted range in carbon isotope composition ($-9 < \delta\ ^{13}C < +2$) which is thought to be derived from a more homogeneous asthenospheric source for the carbon.

The peridotitic diamonds often have formed in association with a chromite or garnet harzburgite assemblage with very magnesian mineral components. In contrast to their refractory residual major element compositions, these minerals are enriched in large ion lithophile trace elements and this phenomenon is interpreted to be due to ancient (>3 b.y.) metasomatic processes. Whatever the source of the enrichment, it is clear that the eclogitic minerals associated with diamonds cannot be derived by partial melting processes that leave the diamond-bearing harzburgites as residua. For instance, the high REE concentration and LREE enrichment patterns in harzburgite garnets (Shimizu and Richardson, 1987) are quite irreconcilable with the low REE concentrations and HREE enrichment patterns in eclogitic diamonds at Finsch.

Peridotitic and eclogitic diamonds are quite clearly unrelated populations. The proportions present in one locality can vary widely, from at least 82% eclogitic (Orapa, Botswana) to at least 99% peridotitic (Mir, U.S.S.R.). Overall, however, peridotitic diamonds appear to be more common.

The majority of natural diamonds could have been formed at depths between 150-180 km below the earth's surface, often at quite low temperatures for such depths (< 1200°C). At Monastery Mine, however, eclogitic garnet inclusions from some diamonds show extensive pyroxene solid solution and appear to have a much

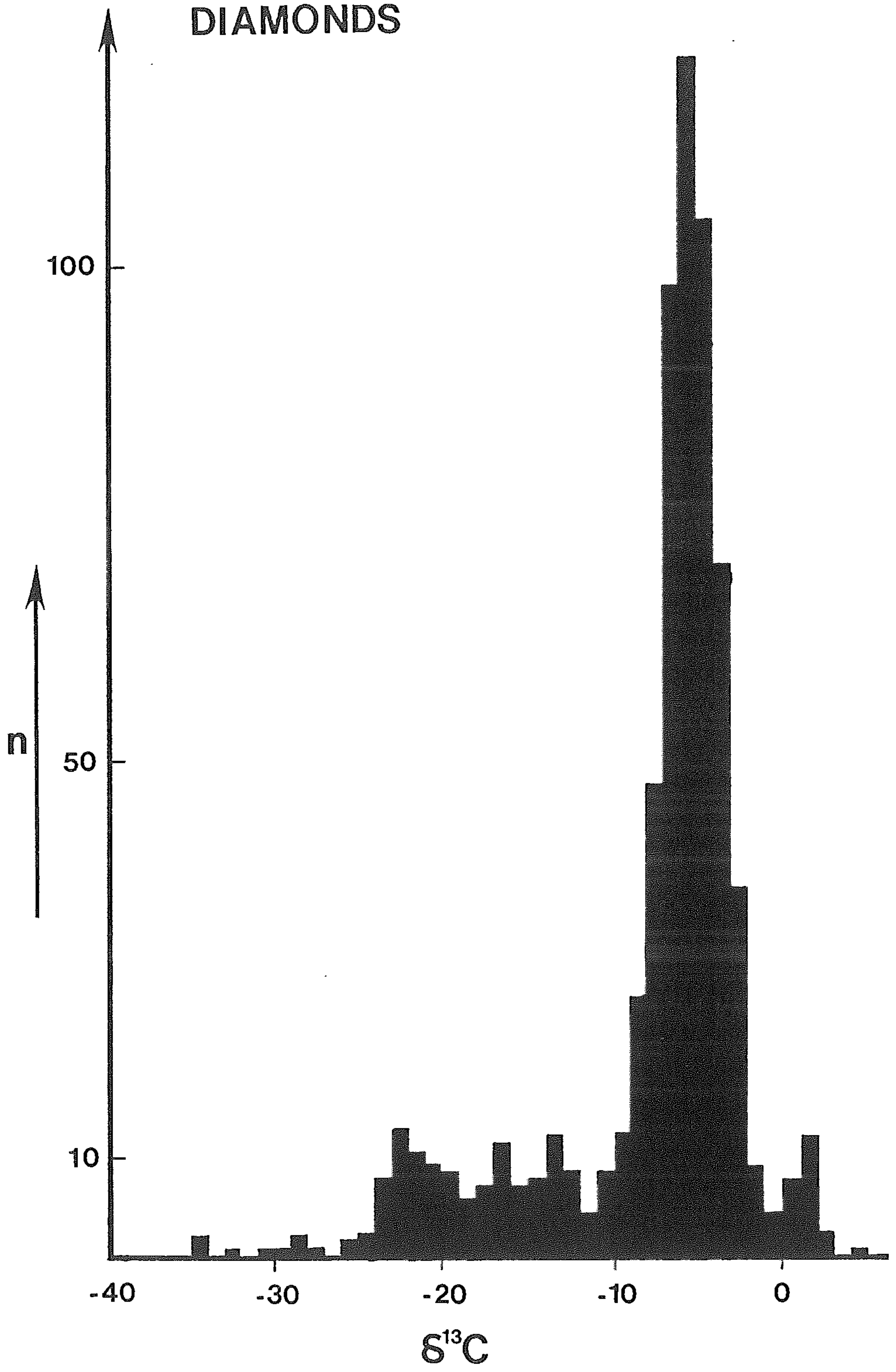


FIGURE 13: Histogram of the carbon isotopic compositions displayed by diamonds from worldwide sources. Peridotitic diamonds show a very restricted range in C-isotopic compositions which corresponds to the major abundance peak observed in this diagram (between -3 and -9 per mil). In contrast, eclogitic diamonds show C-isotopic compositions which range between +5 and -35 per mil. After Gurney (1989).

deeper (300 km?) origin (Moore and Gurney, 1985, 1989). Similar garnets are common in diamonds from Jagersfontein (Gurney, unpublished data) and Brazil (Wilding et al., 1989).

The minerals closely associated with diamonds have well defined ranges in composition. In the cases of garnets and chromites which are analysed during heavy mineral prospecting programmes, the specific compositions can be an aid to ascertaining that a particular (possibly as yet unfound) source will be diamond-bearing. For peridotitic diamonds, the garnets (termed G10) are high in MgO and Cr_2O_3 and low in CaO (Gurney, 1984). The chromites show a high average Cr_2O_3 content and some xenocrysts have $Cr_2O_3 > 62.5$ wt%. In the eclogitic paragenesis, the most diagnostic chemical parameter is the trace amount of Na_2O in garnet ($Na_2O > 0.07$ wt%), but TiO_2 is also characteristically high (Danchin and Wyatt, 1979).

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 (Gurney. 1989).

Inclusions of diamond in diamond and the common occurrence of coated stones at M'buji Mayi, Zaire, show that more than one phase of diamond growth takes place within suites of diamonds from one locality (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).

It has also been comprehensively proven that many diamonds are partially resorbed en route to the earth's surface from the upper mantle (Robinson, 1979). This process is sufficiently common and significant that many diamonds assume a rounded dodecahedral morphology from their original octahedral shape, implying a weight loss of the order of at least 45% in macro-stones. Under such oxidising conditions it is considered probable that many micro-diamonds would be completely resorbed and therefore disappear. This, in turn, coupled with their euhedral shape has lead to the proposal that micro-diamonds may be mainly a separate population on their own, crystallising just prior to diatreme emplacement and unrelated to macro-diamond populations which appear much older (Haggerty, 1986). Fibrous overgrowths (skins) on previously formed diamonds have been highlighted as having a similar young origin. The presence of nitrogen in the single substitutional (Ib) form in such fibrous material strongly supports this interpretation of a young age.

In contrast, there is abundant evidence of the old age of both eclogitic and peridotitic diamonds (Kramers, 1979; Richardson et al., 1984; Richardson, 1986, 1989; Smith et al., 1989). Some of this is controversial, other components are circumstantial and virtually none is scientifically unassailable. Nevertheless, there are a number of independent lines of evidence that point to peridotitic diamonds being Archean, and eclogitic diamonds spanning an age from the Archean through at least most of the Proterozoic (Richardson, 1989; Smith et al., 1989).

Much of the evidence is provided by isotopic measurements on the diamonds themselves and their inclusions. Since such studies are often hard to assess, it is worth pointing out that diamonds are found in xenoliths of peridotite and eclogite where they are in general well preserved, showing predominantly growth forms. Secondly, many diamonds show direct evidence that they have been deformed under mantle conditions in a plastic manner. Thirdly, most diamonds show complex nitrogen aggregation patterns that would appear to need a billion or more years to develop at mantle temperatures and pressures. This already suggests that the reason diamonds are associated with ancient continental cratons (Fig. 9) is because they are sampled from old rocks. K/Ar, ^{3}He/^{4}He, ^{87}Sr/^{86}Sr, Pb/Pb and ^{143}Nd/^{144}Nd radiogenic isotope studies all provide evidence for the non-genetic relationship of eclogitic diamonds, peridotitic diamonds and the host kimberlite or lamproite. It is readily admitted that the K/Ar studies appear to be flawed, the helium data is hard to interpret and in general has been obtained on poorly characterised diamonds and the remaining studies are mainly based on composited inclusions from many diamonds and rely on model not isochron ages. Therefore, all the evidence can be validly criticised. Despite this, an old origin for many (most, all?) macrodiamonds is now widely accepted. Peridotitic diamonds are generally supposed to be Archean (~3.3 billion years - Richardson et al., 1984) while eclogitic diamond "ages" vary from ~990 m.y. (Orapa - Richardson,

1989) to ~1.2 b.y. (Premier - Richardson, 1986), through 1.7 b.y. (Finsch and Argyle - Richardson, 1986, Smith et al., 1989) to the 2.7 b.y. of the Rovic xenoliths (Kramers, 1978) that sometimes carry diamond.

The eclogitic host rocks vary widely in diamond content judged by eclogitic xenoliths found at mines such as Orapa and Rovic which show huge disparities in diamond content even within different portions of the same xenolith (e.g. Hatton and Gurney, 1979). Furthermore, the diamond-bearing rocks may form minor lenses and pods in the mantle if cognisance is taken of the evidence from the Beni Bouchera high temperature peridotite (Slodkevich, 1983). Here, octahedral graphite (formerly diamond) is irregularly distributed in igneous pyroxenite cumulate rocks of minor extent. Locally the original diamond content could have been as high as 15 to 20%.

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

(1) The macro-diamonds in economic deposits are derived from sometimes highly diamondiferous peridotitic and eclogitic rocks that formed in the lithospheric upper-mantle.

(2) Both peridotitic and eclogitic diamonds occur in every known diamond deposit world-wide.

(3) Peridotitic diamonds, which are rather more common than eclogitic diamonds are interpreted to be Archean in age (~3,300 m.y.).

(4) Eclogitic diamonds are old, but show a range of ages, all apparently rather younger than peridotitic diamonds (990 - 2,700 m.y.).

(5) As diamonds are released into the new host volcanic rock by the disaggregation of pre-existing diamond-bearing rocks, other constituent minerals of those rocks will be incorporated with the diamonds.

(6) Since some of these minerals (notably garnets and chromites) have very distinctive compositions, their presence can be detected and used as a strong diamond indicator.

(7) In a single diatreme, it is extremely reasonable to expect a roughly linear relationship between the amount of diamond present and abundance of fragments of the host diamondiferous rocks from the mantle.

(8) In different diatremes, such comparisons can never be expected to be as quantitative because of variations in diamond grade of the eclogite and peridotite sources, the superimposed reductions in diamond content due to resorption, and more speculatively because of assimilation of the diamond source rock in the magma.

(9) Micro-diamond counts in the kimberlite or lamproite may show the relationship with macro-diamonds described under (7), but may not give good correlations with macro-grades in general due to the decoupling effects of resorption followed by subsequent growth of micro-diamonds described earlier.

(10) Both the relationships described in (8) and (9) can be semi-quantitative. Both can predict the presence of diamond with a high degree of certainty and both can give a "ball park" estimate of grade with some success. Neither provide information about diamond quality (value) (Gurney, 1984 and unpublished database).

(11) The heavy mineral geochemistry approach gives the earliest possible signal about the diamond potential of the source in an exploration programme (except for finding diamond itself).

(12) It is perhaps more likely to go wrong in terms of predicting the presence of diamonds that are not there, than to miss out on predicting their presence when they are there.

(13) Macro-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. Complex structural

settings where overthrusting will allow old keels to survive underneath younger rocks are not ruled out of contention.

(14) Transport to the surface from depths of diamond stability must be rapid and thus far has proven to involve highly volatile, ultrapotassic, ultrabasic volcanics, with only minor exceptions.

6. EXPLORATION TECHNIQUES

6.1 General Statement

Recent advances in knowledge about diamonds and their host rocks has focussed attention on the extraordinary variability of diamond deposits. Kimberlite, which has historically been the major source rock of diamonds since its discovery over 100 years ago, is so extremely wide ranging in physical and chemical properties that there is still debate about a satisfactory definition for the rock. The recognition of a second important primary source of diamonds in the rock type olivine lamproite expands this diversity considerably. The understanding that, at the very least, many of the macro-diamonds recovered from these so called "primary" host rocks actually formed in eclogite and peridotite within the upper mantle has destroyed the previously widely accepted idea that kimberlite and diamond were genetically related. A lamproite such as Argyle which produces 30 million carats or one third of the world 1989 diamond production is a mega-demonstration of this diversity of source and undoubtedly should change explorationists' attitudes towards a more open minded approach with respect to alternative deep sourced host rocks which in term expands even further the options that must be investigated in any global diamond exploration strategy.

It has already been established on a worldwide basis that a variety of exploration techniques can be advantageously integrated into a diamond exploration programme. These include aspects of petrology, mineralogy, geochemistry, geophysics, geobotany and remote sensing. The most recent and comprehensive review of diamond exploration philosophy, practice and case histories is that of Atkinson (1989). The selection of the appropriate techniques for a particular prospecting programme is governed by a large number of variables. Amongst these will be the range in types of deposit sought, the physical and chemical properties of the country rocks, the geomorphological 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. Many of these variables apply only to the area where the exploration programme is to be undertaken, which cannot be generalised. In this report emphasis is therefore given to investigating the type of target that has been found on the North American continent and trying to find a signature that can be applied regionally to cost effective diamond exploration. Indicative costs of exploration techniques in Australia are summarised in Table 10.

The review by Atkinson provides a wealth of useful information such as:-

(a) Indicator mineral dispersion patterns (Figs. 14, 15 and 16).
(b) Magnetic suseptibilities of kimberlite, lamproite and other rock (Table 11).
(c) Ground magnetic contours (Fig. 17).
(d) Gravity responses from kimberlite (Fig. 18).
(e) Electrical responses over kimberlites (Fig. 19).

However, these serve to highlight the individuality of the targets in many instances rather than providing ground rules and therefore demonstrate the need for orientation programmes to be designed for local conditions.

Much of the Australian interior is geologically favourable craton for instance, but it has old, flat low lying land surfaces that are extensively lateritised. Very few minerals survive the acid conditions associated with the formation of these oxidised surface deposits, not even garnets or ilmenites. 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 bedrock greenstone belt ultramafics. In contrast, both ilmenite and garnet survive the development of, and work their way through over 100 metres of the shallow lake, surficial and aeolian deposits of the Kalahari formation in Botswana. Extrapolation of these results or of those

TABLE 10: INDICATIVE COST OF EXPLORATION TECHNIQUES IN AUSTRALIA ($A\$ \ km^{-2}$) (From Atkinson, 1989)

		REGIONAL RECONNAISSANCE	MORE DETAILED
1	Remote sensing (LANDSAT, SLAR, MSS, etc)	0 - 20	-
2	Air photo	1	n.a.
3	Drainage	15	
4	Aeromagnetics/ Radiometrics	5 - 10	35
5	Input	-	100
6	Loaming	25 - 100	1000
7	Drilling	n.a.	very high

Variables:
Processing cost
Scale
Sample spacing
Standards
Flight line spacing
Overburden

TABLE 11: COMPARISON OF THE MAGNETIC SUSCEPTIBILITY OF KIMBERLITE LAMPROITE AND OTHER ROCKS (From Atkinson, 1979; After Gregory, 1984)

	SUSCEPTIBILITY x 10^{-6} emu)	
ROCK	RANGE	AVERAGE
Kimberlite (1)	10-10 000	Typically (200-2000)
Lamproite	180- 1 800	650
Granite (3)	0- 4 000	200
Dolerite	100- 3 000	1 400
Porphyry	20-16 700	5 000
Gabbro	80- 7 200	6 000
Basalts	20-14 500	6 000
Diorite	50-10 000	7 000
Peridotite	7 600-15 600	13 000
Andesite		13 500
Amphibolite		60
Schist	25- 240	120
Gneiss	10- 2 000	-
Quartzite	-	350
Serpentine	250- 1 400	-
Slate	0- 3 000	500
Dolostones	0- 75	10
Limestones	2 280	25
Sandstones	0- 1 660	30
Shales	5- 1 480	50

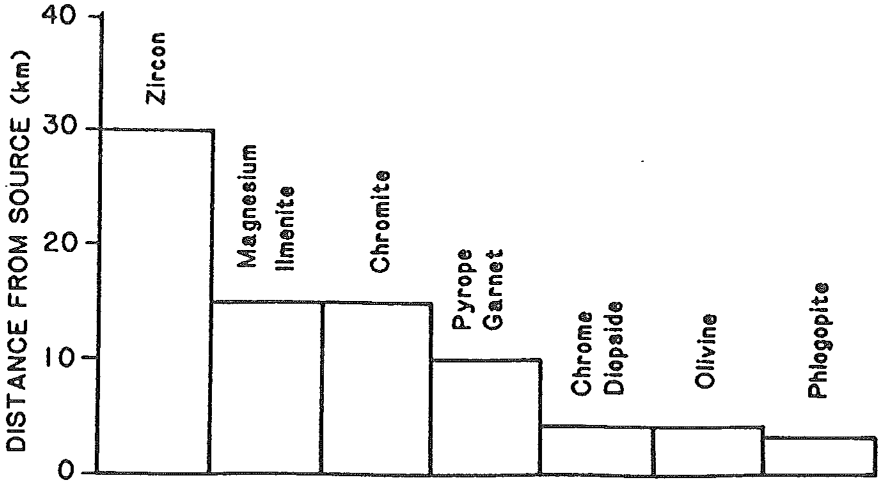


FIGURE 14: Detrital trains of indicator minerals under Australia
conditions. After Atkinson (1989).

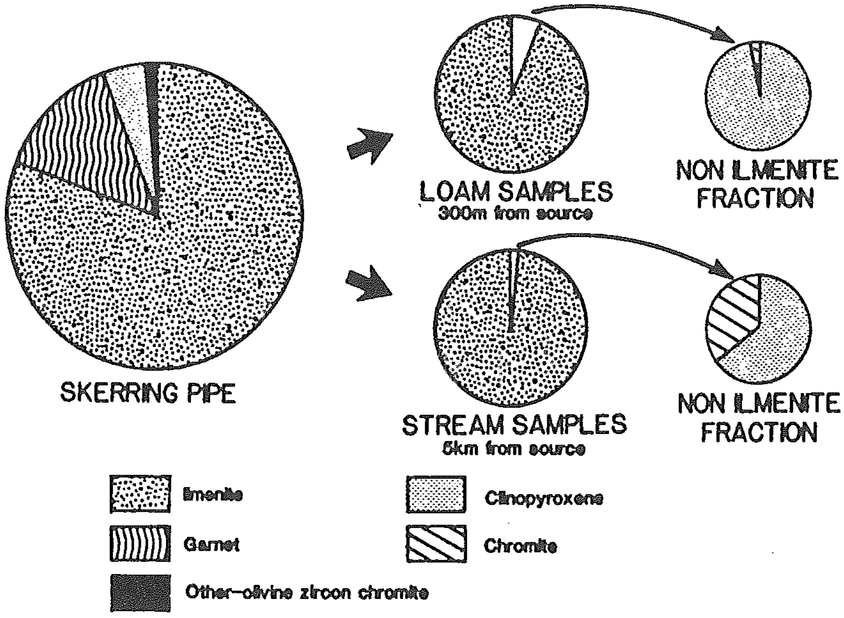


FIGURE 15: Indicator mineral dispersion for the Skerring Pipe, Australia. After Atkinson (1989).

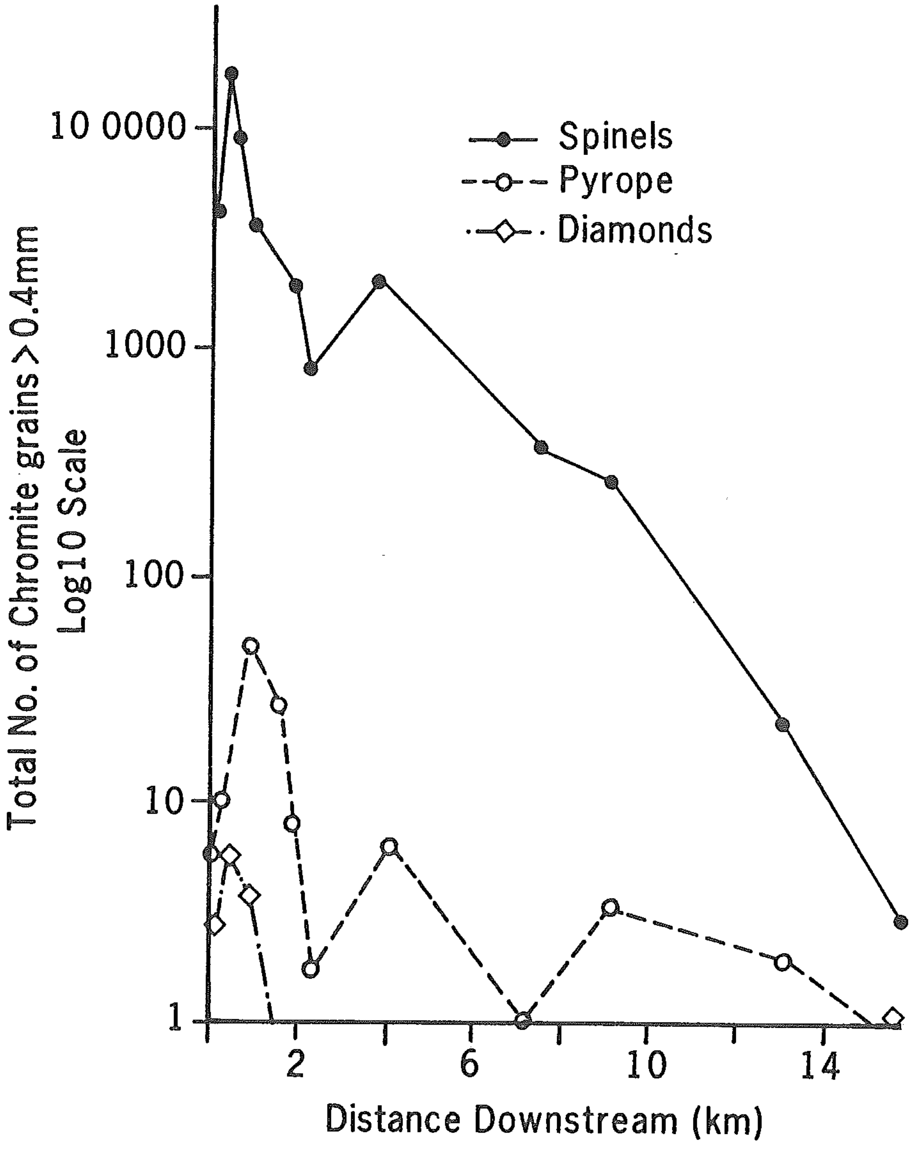
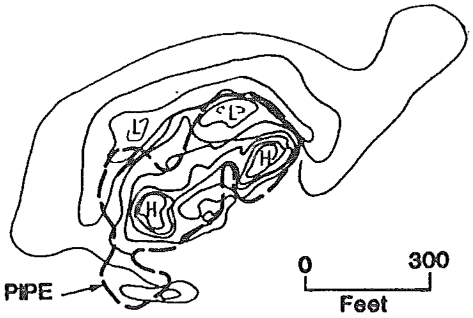
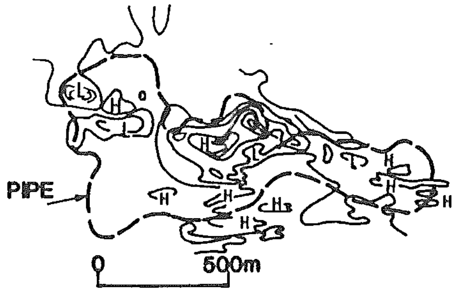


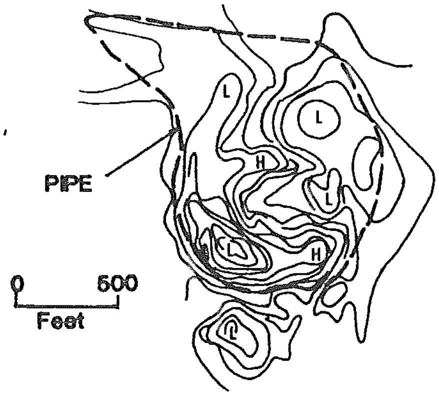
FIGURE 16: Alluvial dispersion train of diamond, spinel and pyrope from the Ellendale lamproite pipe. After Atkinson (1989).



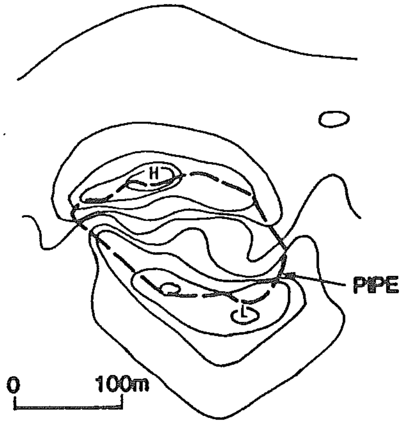
PRAIRIE CREEK LAMPROITE PIPE
(after Bolivar and Brookins 1979)



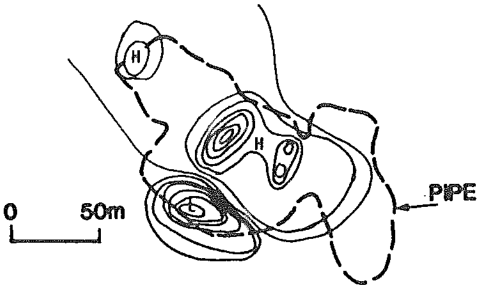
ELLENDALE No. 9 LAMPROITE PIPE
(after Jenke 1983)



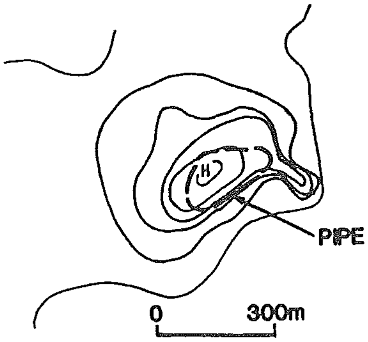
MAJHGAWAN KIMBERLITE PIPE
CENTRAL INDIA
(after Sharma and Nandi 1964)



KIMBERLITE PIPE
MALI, WEST AFRICA
(after Gerryts 1967)

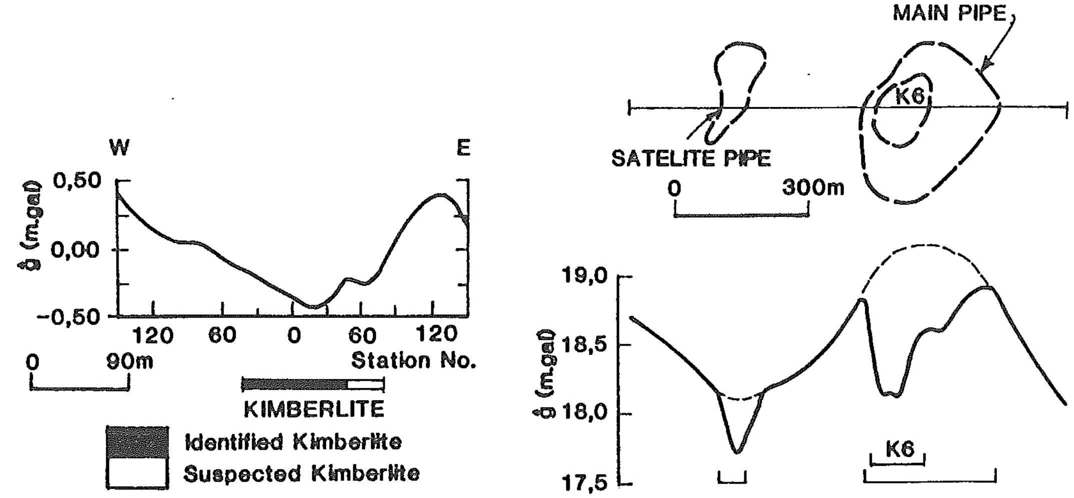


KOLO KIMBERLITE PIPE
(after Burley and Greenwood 1972)



KIMBERLITE PIPE, JWANENG AREA
(after Lock 1985)

FIGURE 17: Ground magnetic contours over kimberlite and lamproite pipes. After Atkinson (1989).

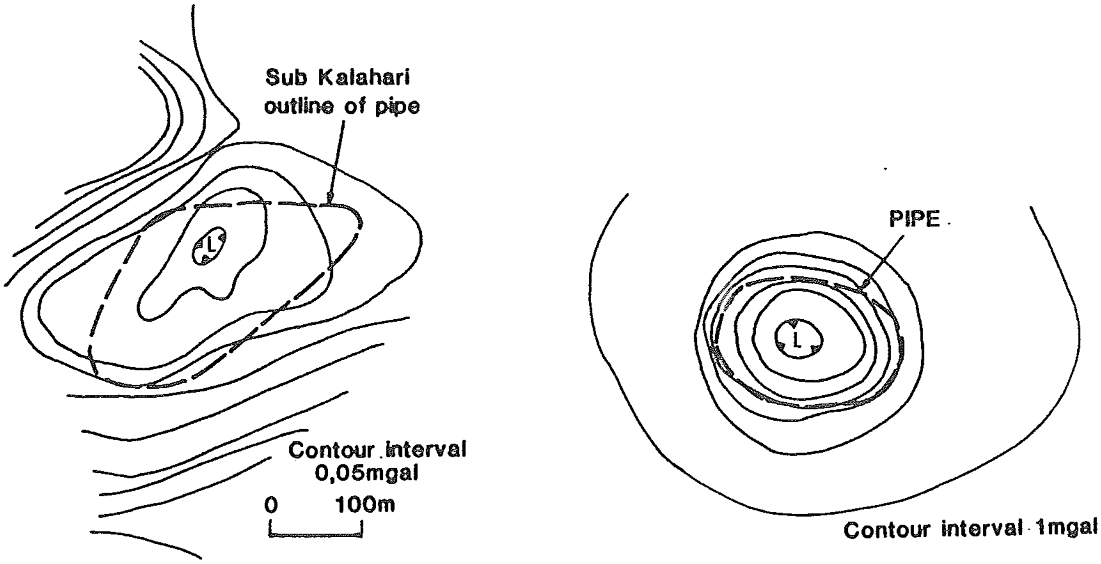


GRAVITY SURVEY OF MAXWELL No. I KIMBELITE PIPE

(after Carlsen et al. 1984)

GRAVITY SURVEY OF KIMBERLITE PIPE–SEKAMENG, LESOTHO

(after Burley and Greenwood 1972)



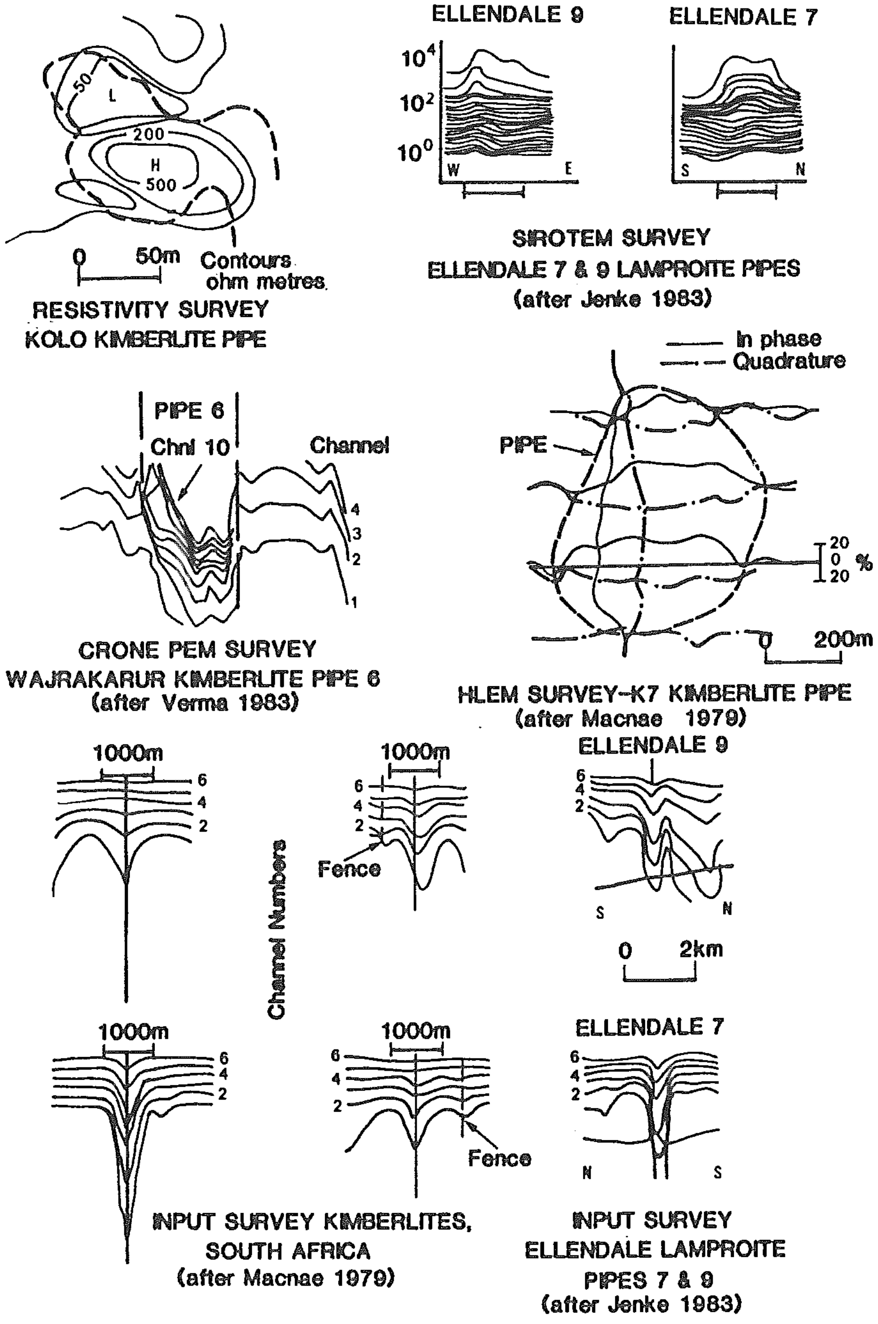
GRAVITY SURVEY OF KIMBERLITE PIPE – JWANENG AREA

(after Lock 1985)

GRAVITY SURVEY OF MWADUI KIMBERLITE PIPE

(after Gerryts 1970)

<u>FIGURE 18</u>: Typical gravity responses from kimberlites. After Atkinson (1989).



RESISTIVITY SURVEY
KOLO KIMBERLITE PIPE

SIROTEM SURVEY
ELLENDALE 7 & 9 LAMPROITE PIPES
(after Jenke 1983)

CRONE PEM SURVEY
WAJRAKARUR KIMBERLITE PIPE 6
(after Verma 1983)

HLEM SURVEY-K7 KIMBERLITE PIPE
(after Macnae 1979)

INPUT SURVEY KIMBERLITES,
SOUTH AFRICA
(after Macnae 1979)

INPUT SURVEY
ELLENDALE LAMPROITE
PIPES 7 & 9
(after Jenke 1983)

<u>FIGURE 19</u>: Responses from electrical prospecting methods applied over kimberlite and lamproite pipes. After Atkinson (1989).

obtained in tropical climates such as west Africa to the Canadian shield must be potentially misleading in the extreme. Therefore, case histories are badly needed in the local areas, taking cognisance of the regional problems. This survey therefore represents a first attempt to assemble the foundations of a database for North America, particularly Canada. It is not complete because it has been compiled from relatively few occurrences, none of which have proved commercially viable. It will require continual updating as new discoveries are made and more is known about exploration techniques. It is intended to provide a starting point by investigating how various deposits were found, which methods were useful and how future programmes can be improved.

Providing the problems of surficial glaciation can be successfully dealt with, there is no doubt that the heavy mineral indicator methods will be very important for locating kimberlites in Canada's cold climate because they will not be rapidly altered by chemical attack.

In addition to the wealth of general information provided by Atkinson (1989), he also makes the directly relevant point to Canadian diamond explorationists that modern discoveries have been primary deposits in new production centres away from historically important diamond mining centres. These have been in geologically favourable areas that have been relatively inaccessible because of geographic isolation, climate or surficial cover. Canada clearly qualifies as a top aspirant for future honours, whilst the USSR, Botswana and Australia now provide more than half of the world's annual supply of diamonds whether viewed by weight or value (Fig. 1).

6.2 The Geochemistry of Indicator Minerals

A substantial portion of the work completed in this project has been directed at recovering and defining the compositions of suites of high pressure macrocrysts from the diatremes. The more resistant macrocrysts of garnet, chromite and ilmenite are sought in streams and soils on a world-wide basis as evidence for the proximity of a kimberlite. This has been the practice for more than one hundred years virtually since kimberlite was first recognised as a host for diamond in South Africa. In the past two decades the use of heavy minerals in diamond exploration has been refined to permit an assessment of the diamond potential of the source. This is routinely applied in various major diamond exploration programmes and relies on the interpretation of the composition of the so called "indicator minerals" mentioned above. The criteria used vary widely and can 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 project 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 and Gurney. The method was designed specifically for kimberlite occurrences in southern Africa, where it has been very profitably applied in many instances. It has also been applied on other continents as well, including North America (e.g. Carlson and Marsh, 1989; Dummett et al., 1986).

First it is necessary to explain the basis for the method, describe how it is applied and then interpret the mineral compositions at the localities dealt with in this project. It should be noted right at the outset that the scheme was empirically derived and the localities constituting the orientation survey did not include lamproites. It has been apparent for some time that it is not directly applicable to olivine lamproites in Australia. The results of this project strengthen that perception, as will become apparant.

The model on which the method is based considers that macro-diamonds are xenocrysts in the volcanic diatremes from which they are recovered, and that they are derived from disaggregated mantle equilibrated peridotites and eclogites that pre-date the age of emplacement of the volcanic intrusion (see review by Gurney, 1989).

Some diamonds contain mineral inclusions that can clearly be assigned to an eclogitic or peridotitic source, a few are found in xenoliths of eclogite, or more rarely peridotite. There is abundant evidence from many sources that such diamonds did not form in the kimberlite or lamproite from which they are recovered in mining operations. The unequivocal assignation of the paragenesis of most diamonds is, however, not possible because they are recovered as single crystals and are often without any definitive inclusions. It is assumed that these diamonds have the same origins as the minority that can be defined. It should be noted that <u>on a world wide basis</u> more than 98% of the apparently syngenetic inclusions reported from diamonds can be confidently assigned to the peridotitic and eclogitic parageneses. 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 logical. The volcanic host rock is therefore seen only as a transporting agent for macro-diamonds from the upper mantle to the earth's surface. The amount of diamond it contains will depend on at least six variables:-

(i) How much diamond peridotite did it sample?
(ii) What was the average grade of the diamond peridotite?
(iii) How much diamond eclogite did it sample?
(iv) What was the grade of the diamond eclogite?
(v) How well were the diamonds preserved during transportation?
(vi) How efficiently were the diamonds transported to the earth's surface?

The amount of diamond peridotite or diamond eclogite that has been sampled (i & iii) should be reflected in the amount of disaggregated mineral grains and/or xenoliths in the diatreme. If these can be identified it should be possible to forecast whether diamond could be present or not. Identification of garnets and chromites that have specific compositions has indeed turned out to be a useful diamond indicator (e.g. Gurney, 1989). Forecasting accurately the diamond content of a rock that is in the mantle and cannot be directly sampled is unfortunately impossible, so that variations in (ii) and (iv) cannot be quantified in any rigorous way. Fortunately the diamond indicator minerals can be identified by certain compositional parameters and the higher the abundance of these minerals that are present in kimberlites, the better the diamond content of the body usually is. However, there are exceptions as must be expected from considerations I - VI above.

Diamond, it has already been stated, is derived from peridotite and eclogite. The requirement for prospecting purposes is to be able to identify fragments of these diamond-bearing rocks which means discriminating between them and other rocks including non-diamond bearing peridotites and eclogites, of which there are a large variety (see Table 2 and Fig. 8). This can be done in various ways. Cluster and multiple component discriminant analysis 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 (1986) advocate a classification technique that combines cluster and discriminant analysis. In this project both a geostatistical and simple graphical approach have been applied. However the data is assessed, the essential discriminating criteria come down to a few simple facts.

In the peridotitic diamond paragenesis three sub-groupings are apparent: garnet harzburgite, chromite harzburgite and garnet lherzolite. The harzburgites are depleted in calcium relative to the lherzolites in three ways: the absence of a calcium saturated phase (diopside), a low bulk rock calcium content and low mineral content of calcium. As with most classification schemes there is a little 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 incompatible: for instance a sub-calcic garnet can not be in equilibrium with diopside and is therefore never found in a lherzolite. It has been established that the relative importance with respect to diamonds is: garnet harzburgite > chromite harzburgite > garnet lherzolite. In addition 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 there is no simple way to differentiate between a diamond-bearing and a barren garnet lherzolite (see Gurney, 1985 for more detailed discussion). Therefore garnets of lherzolitic composition have to be discriminated against in an exploration programme. The method described by Gurney (1985) has been used in this project because it has been repeatedly proved to be useful in exploration programmes on several continents.

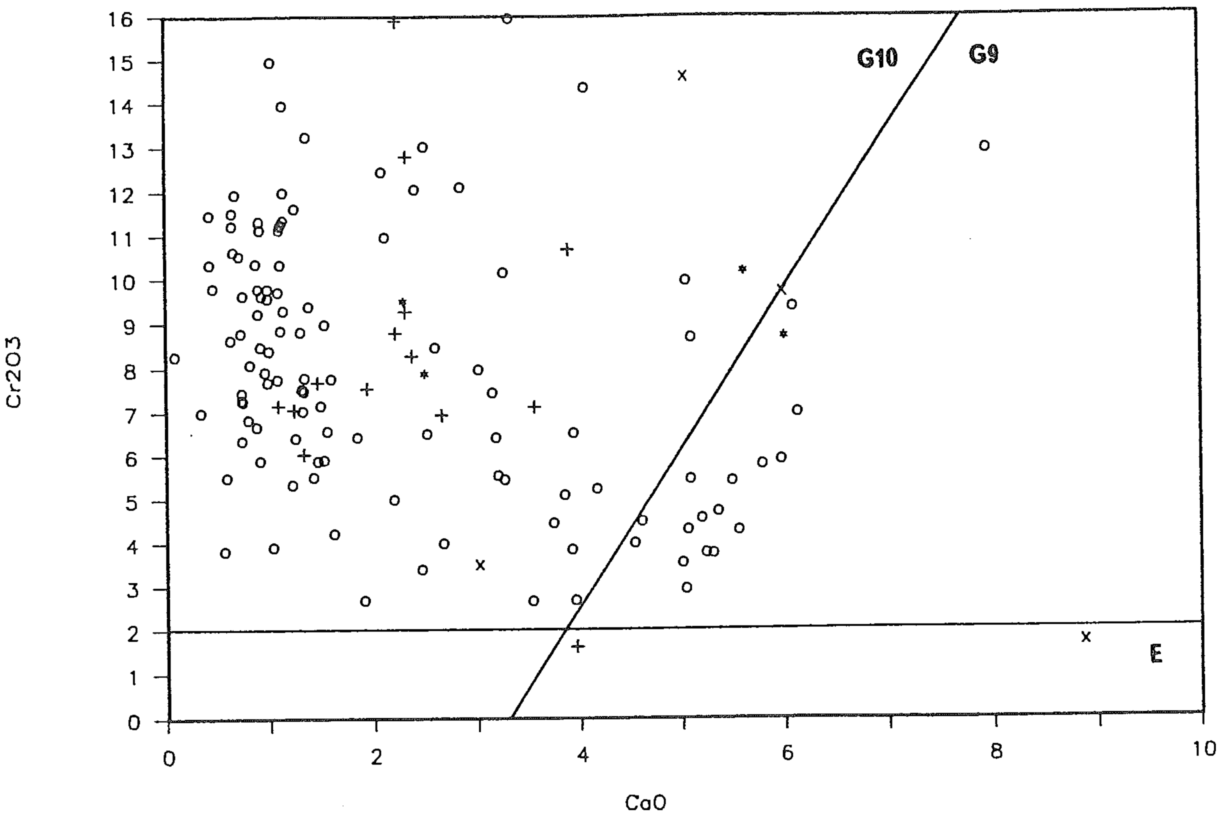
The component of diamonds derived from garnet harzburgite is assessed by considering both the number of sub-calcic garnets found in a diatreme and their degree of calcium depletion. Whilst not strictly correct in terms of the Dawson and Stephens (1975) classification, these garnets are referred to as G10 garnets in this text and associated figures whilst lherzolitic garnets are referred to as G9. The fields are defined in Fig. 20 and used throughout the plots for peridotitic garnets.

Chromite is used in a similar manner to garnet to provide an indication of the amount of diamond in the diatreme derived from disaggregated chromite harzburgite. The useful chromite compositions are defined in Fig. 21 and the "diamond chromite" field is plotted on the subsequent chromite plots for each locality in Part II of this report.

In respect of eclogitic sources for diamonds the most diagnostic features of the eclogite garnets are the amounts of Na_2O (first noted by Sobolev and Lavrent'ev, (1971)) and TiO_2 (Danchin and Wyatt, 1979) in the high pressure eclogite garnets associated with diamonds. The composition of eclogitic garnets associated with diamonds worldwide with respect to these two key oxides is presented in Fig. 22.

At each locality the contribution to the overall diamond population from each of the garnet harzburgite, chromite harzburgite and eclogite parageneses is assessed by establishing the abundance of the garnets and chromites derived from disaggregation of the mantle host rock. It should be clearly realised that these three diamond sources are additive and that a really good contribution from any one of them could be sufficient to provide an economic grade in a diatreme. It should also be apparent from this discussion that it is necessary to establish both the compositions of the indicator minerals and their relative abundances.

Having sampled a diamondiferous rock or rocks in the mantle, an igneous intrusion must carry the mantle sample to the surface.



<u>FIGURE 20</u>: A plot of Cr_2O_3 against CaO for peridotitic diamond inclusion garnets from worldwide localities. 85% of the diamond inclusion compositions plot on the CaO-poor side of the inclined line which was defined by Gurney (1984). These subcalcic sompositions are referred to as G10 garnets. The 2 wt% Cr_2O_3 is used as an arbitary division between eclogitic garnets below the line and peridotitic garnets above it. Symbols: o = southern Africa; x Australia; * North America; + USSR. A full listing of data is presented in Appendix 3.

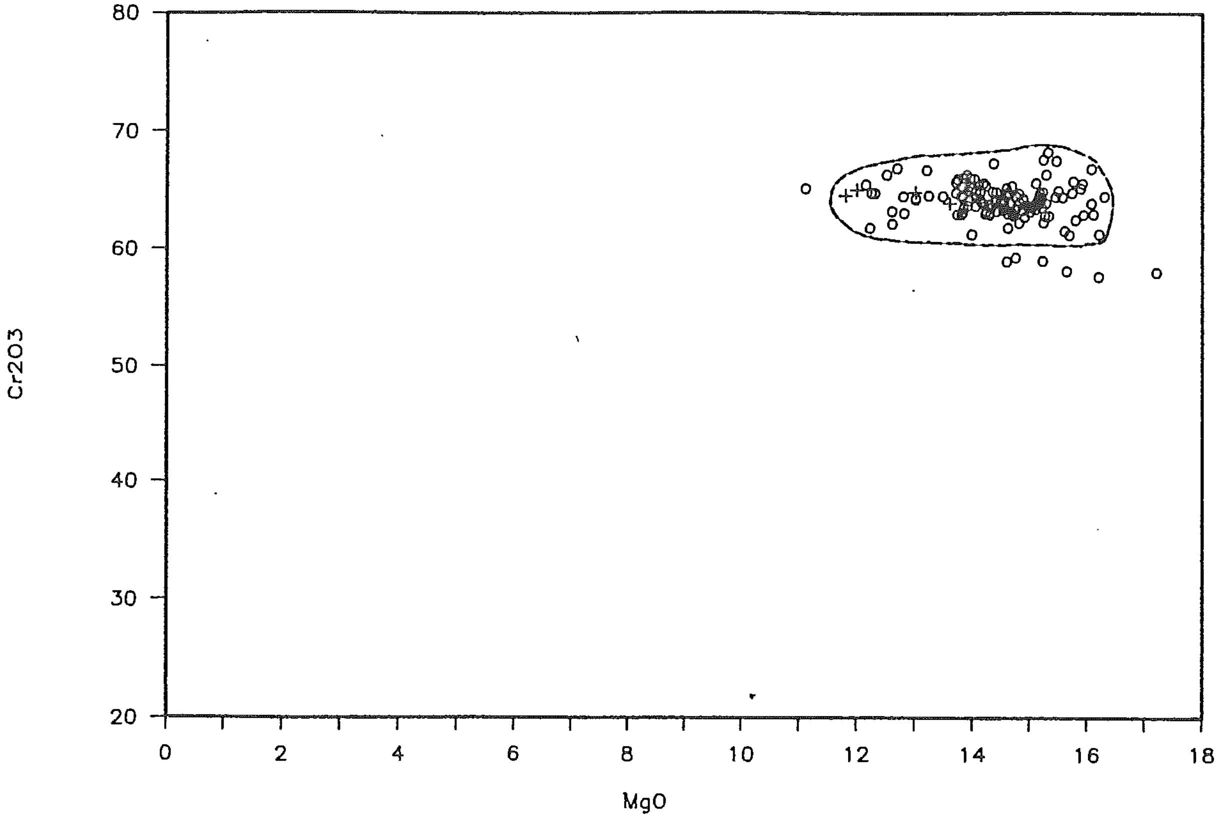


FIGURE 21: A plot of MgO versus Cr_2O_3 for chromite diamond inclusions from worldwide localities. Note the highly restricted, Cr_2O_3-rich character of the inclusions. The preferred compositional field indicated includes >90% of the data points. Symbols: o = southern Africa; x Australia; * North America; + USSR. A full listing of data is presented in Appendix 3.

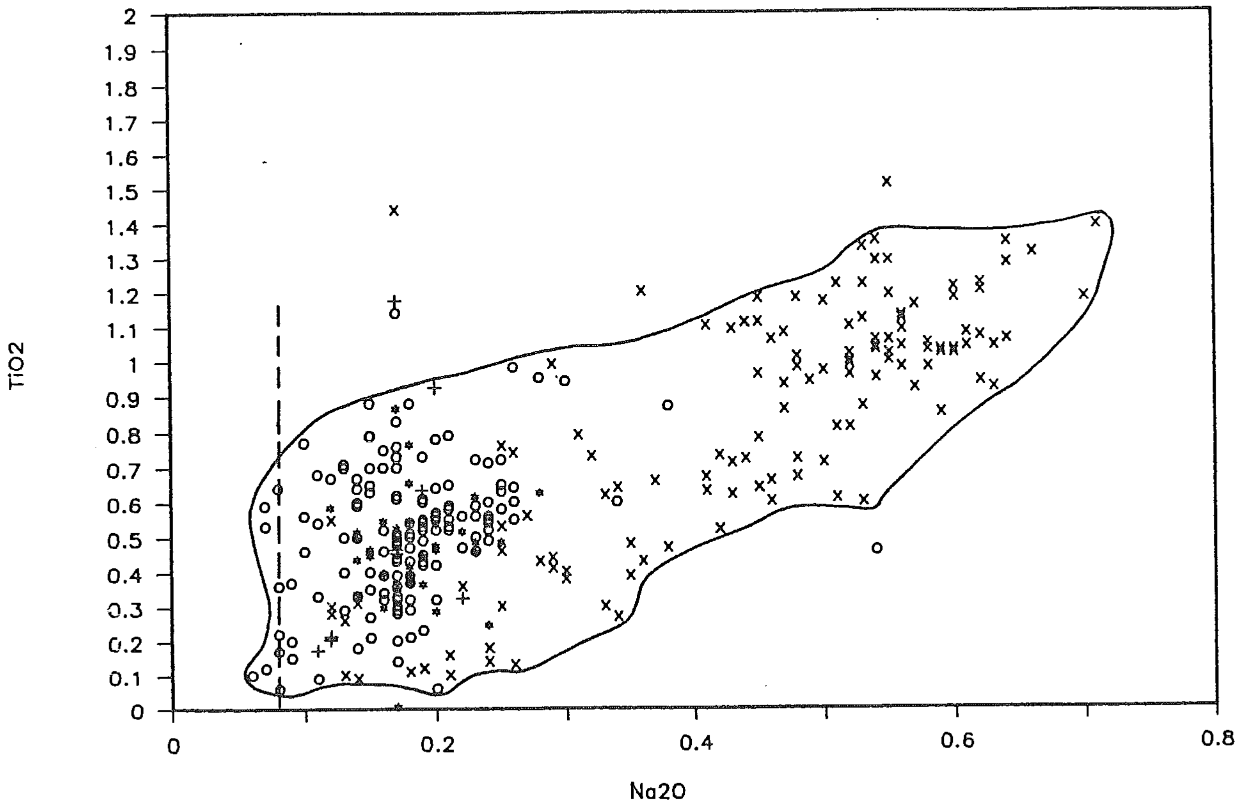


FIGURE 22: A plot of TiO_2 versus Na_2O eclogitic diamond inclusion garnets from worldwide localities. Note that the elevated levels of both these elements is characteristic of eclogitic garnets associated with diamonds. In prospecting samples, garnets with $Na_2O > 0.07$ wt% are considered significant. Symbols: o = southern Africa; x Australia * North America; + USSR. A full listing of data is presented in Appendix 3.

Whilst so doing it is quite clear that conditions within the magma en route upwards must eventually 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. The latter will happen more rapidly as a result of higher oxygen activity in the magma. The effect of this resorption on the diamond content of an intrusion can be large. In the model developed for southern Africa, it appears that ilmenite compositions give some measure of these redox conditions. Ilmenite with low Fe^{3+}/Fe^{2+} ratios are associated with higher diamond contents than those with more Fe^{3+}, whilst diamonds are not associated with ilmenites with high Fe^{3+} contents at all. In kimberlitic ilmenites, high Fe^{3+} is associated with low MgO. High Cr^{3+} can be found in either association but is only a positive factor when it occurs with high Mg.

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 as detractors do not hesitate to point out whenever a locality is discovered that does not fit the model. The kimberlites in the Kuruman area, South Africa or at Skerring in Australia are examples to add to the lamproite localities mentioned earlier. However, the authors experience is that the system is a major aid to exploration programmes. In Botswana, where it was applied to several tens of kimberlites discovered under Kalahari cover in the early 1980's, the heavy mineral analysis correctly identified all the barren kimberlites, all the diamond-bearing kimberlites and had flagged the best ore bearing body found (GO25) immediately the first batch of heavy minerals from that source passed in front of the microprobe. In this environment of hidden ore bodies, it was an unqualified success.

In a Venezuelan stream sampling programme in 1975, the presence of G10 garnets from a nearby diamond source was picked up in the Guaniamo region where the primary source of some of the alluvial diamonds has now been found (Nixon et al., 1989). Earlier than that, the system was used to demonstrate the proximity of a then unknown primary source (Dokolwayo) to the Hlane alluvial diamonds in Swaziland.

Accurate forecasts about the presence or absence of diamonds has also been made for Brazilian kimberlites and for numerous localities in southern Africa both barren and diamond-bearing which now constitute the database mentioned earlier. The method has also been successfully applied in the Banankaro region in Guinea, West Africa. In North America, it was used to find the Georges Creek dyke in the Colorado/Wyoming State Line District, provided acceptable forecasts for the nearby Schaffer and Sloan 2/5 diatremes, and predicts the absence of diamonds at Iron Mountain. The heavy mineral assessment of the kimberlites in the Upper Peninsula, Michigan is again in good accord with the known facts in that area. The authors therefore feel that the heavy mineral forecasts are a valuable aid to assessing the potential of a possible diamond source on a world-wide scale. 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 surface the relationship may hold.

Where they do not, further geochemical detective work may reveal relevant clues. The diamonds may not have been preserved en-route to surface, the lithosphere may not have been thick enough or the geothermal gradient sufficiently low to permit diamond formation and/or storage to have occurred. The apparently necessary metasomatic activity that may have a particularly important role in the formation of peridotitic diamonds may never have occurred and a suitable carbon source may therefore not be available. There may be clues available to these facts, some of them in the major and trace element contents of other mantle minerals such as orthopyroxene that occur in the diatreme under investigation. Given the wide range of uncertainties, a balanced view has to be permissive of exceptions to the rules since these are obviously certain to occur. At the end of the day, however, an explorationist who does not place the target with the best G10 garnets, the highest chrome chromites, the biggest population of high sodium eclogitic garnets and the most magnesian ilmenites at the top of his priority list of sampling, has spent too long in the bush. 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 rankest of outsiders.

The survey undertaken in this project covers a relatively small number of largely low grade or barren occurrences that make it difficult to judge the applicability of the heavy mineral geochemistry from this suite alone (see subsequent section). The above discussion has been aimed at putting this into perspective.

7. THE DIATREMES INVESTIGATED IN THIS PROJECT

7.1 General Statement

Individual reports on each locality investigated are presented in Part II of this report and readers are referred to these for specific details. Results of the indicator mineral and whole rock geochemistry investigations are summarised in subsequent sections. A number of other important points worth highlighting are briefly outlined below.

The emergence of lamproites as a second major primary source of diamonds has considerably increased the importance of petrography in diamond exploration programs. The differences noted for the indicator mineral characteristics of kimberlites and lamproites (discussed in more detail in Section 7.2), implies that the correct identification of any one diatreme may be vitally important to subsequent exploration philosophy. Since the petrographic differences between kimberlites, lamproites and some lamprophyres are subtle and most often masked by a high degree of alteration, it is absolutely critical that the petrography is undertaken by an experienced expert. The misidentification of a diatreme early in a program may ultimately cost an exploration company a considerable amount of money and/or lead to the overlooking of a potential orebody.

One of the objectives of this project was to map and evaluate a selection of the numerous diatremes located in the Rocky Mountains on the British Columbia-Alberta border. A highlight of this investigation, has been the identification of some of these diatremes as being lamproitic. The fact that the Jack diatreme had been core-drilled by a joint venture syndicate in 1986, allowed for a detailed petrographic and mineralogical investigation to be undertaken. Results of these studies are to be found in reports by M.E. McCallum and C.E. Fipke in Parts II and III of this report. Petrographic and mineralogical evidence in support of the Jack being a lamproite includes the presence of sanidine, glass, high Ti-phlogopite, Sr-barite and pseudomorphs after leucite. In addition, the breccia phases are noted to be distinctly ultrapotassic (see Section 7.3.3).

Some of the other B.C. diatremes, notably the Larry, Mark and Mike also show petrographic features such as the presence of sanidine and pseudomorphs after leucite which are consistent with them being lamproites. However, in the absence of detailed mineralogical investigations and in view of their slightly less convincing whole rock compositions (see Section 7.3.3), these diatremes are conservatively classified as lamproitic at this stage. However, it is believed that should follow up work be undertaken, they will also prove to be true lamproites.

7.2 Indicator Mineral Geochemistry

Using the criteria outlined in Section 6.2, the indicator minerals recovered in this project (see Table 12 for summary) have been assessed and interpreted with respect to diamond potential. In addition, a multivariate statistical approach was developed and tested.

The potential advantage of a multivariate statistical approach, is that the covariance of a number of compositional variables can be simultaneously assessed. In simple terms, the technique involves expressing diamond inclusion compositions in terms of two multi-element equations (factors) by subjecting them to a factor analysis. The indicator minerals are then expressed in terms of these factors and graphically assessed for similarities with diamond inclusion compositions. The diamond inclusion datasets used in the factor analyses are listed in Appendix 3.

A more rigorous explanation of the theoretical background to the statistical technique adopted is as follows. The method of principal factor analysis as it is found in the "SAS Software Package" was utilised to perform an R-mode factor analysis on the indicator mineral compositions. The similarity matrix used was a correlation matrix, and the resultant factor pattern values were

TABLE 12: SUMMARY OF INDICATOR MINERALS RECOVERED

	INDICATOR MINERALS					
LOCALITY	Chrom	Hi-Cr Garnet	Low-Cr Garnet	Ilmnt	Hi-Cr Cpx	Low-Cr Cpx
ARGYLE	113	3	55	21	4	18
BATTY	41	45	26	18	18	6
BLACKFOOT	180	0	0	3	63	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

applied as discriminant functions, making use of the Eckart-Young theorem (Davis, 1986).

The factor pattern produced by factor analysis is a result of a transformation of the eigenvectors which are obtained by the spectral decomposition of the similarity matrix. These factor pattern results can be utilised as one given matrix in the product decomposition to which the data is to be expressed (as in Malinkowski and Howery, 1980). The other matrix can then be deduced by the method outlined below. There is no unique mathematical solution to decomposing a matrix into a product of two factor matrices. This is the reason for alluding to the Eckart and Young theorem (Davis, 1986) which provides a general setting for obtaining a solution expressed in terms of orthonormal matrices.

The size of each component (and also their very nature) in this matrix product is dictated by the number of factors which are judged as applicable in a given factor analysis. In the case of the indicator minerals, only two factors were deemed significant enough to be retained, as was indicated by the eigenvalue analysis incorporated in the principal factor analysis method (i.e in all cases, > 85% of the variance is explained by the first two factors).

A detailed account of the properties of factor analysis are covered by Davis (1986) and Malinkowski and Howery (1980). The latter author is particularly useful with regards to the practical decomposition of data-set matrices into factor matrices. In particular, the column matrix to which the factor pattern matrix can be assimilated, possess the property of orthonormality. This translates into the fact that its transpose is equivalent to its inverse. As it is shown in Malinkowski and Howery (1980), the following applies:

$$D = R \cdot C' + E$$

where: D - is the original data matrix
R - is the row matrix
C′ - is the transpose of the column matrix which is obtained from the eigenvector matrix. Modifications to the matrix made from the

eigenvectors as columns include: multiplication by the square root of the pertinent eigenvalue, and also the Kaiser (Varimax) rotation of the factor axes, also the method of normalization varies between the different implementations of the algorithms performing the spectral decompositions.

E - is an error matrix incorporating the measurement errors, etc.

If we neglect the error matrix E and postmultiply the above equation by C, we get the following:

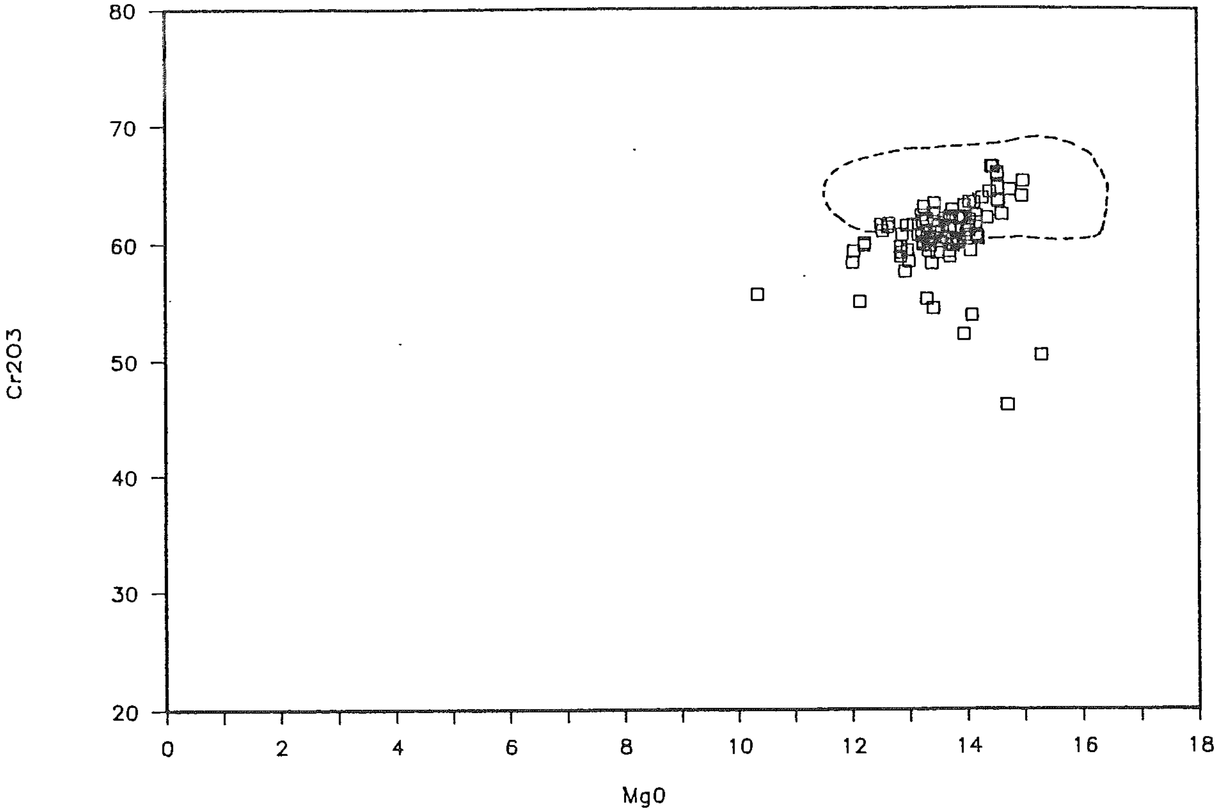
$$D . C = R . C' . C = R$$

Because: $C' . C = I$

This matrix R has as many columns as the number of factors that were preserved in the factor analysis (in this case two). It is thus possible to graphically display these two columns on two dimensional X-Y plots.

It was found that the results of the statistical approach where generally in full agreement with the more simple "key elements" geochemical approach outlined in Section 6.2. To demonstrate this and reinforce the basic principles involved in the interpretation of the indicator minerals, example suites of chromites and peridotitic garnets from high grade, low grade and barren pipes are presented in Figures 23 and 24. No good examples of eclogitic diamond sources were found in the project so a similar exercise is not possible for this paragenesis of diamonds. It should however be noted that 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 out 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 simpler 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.



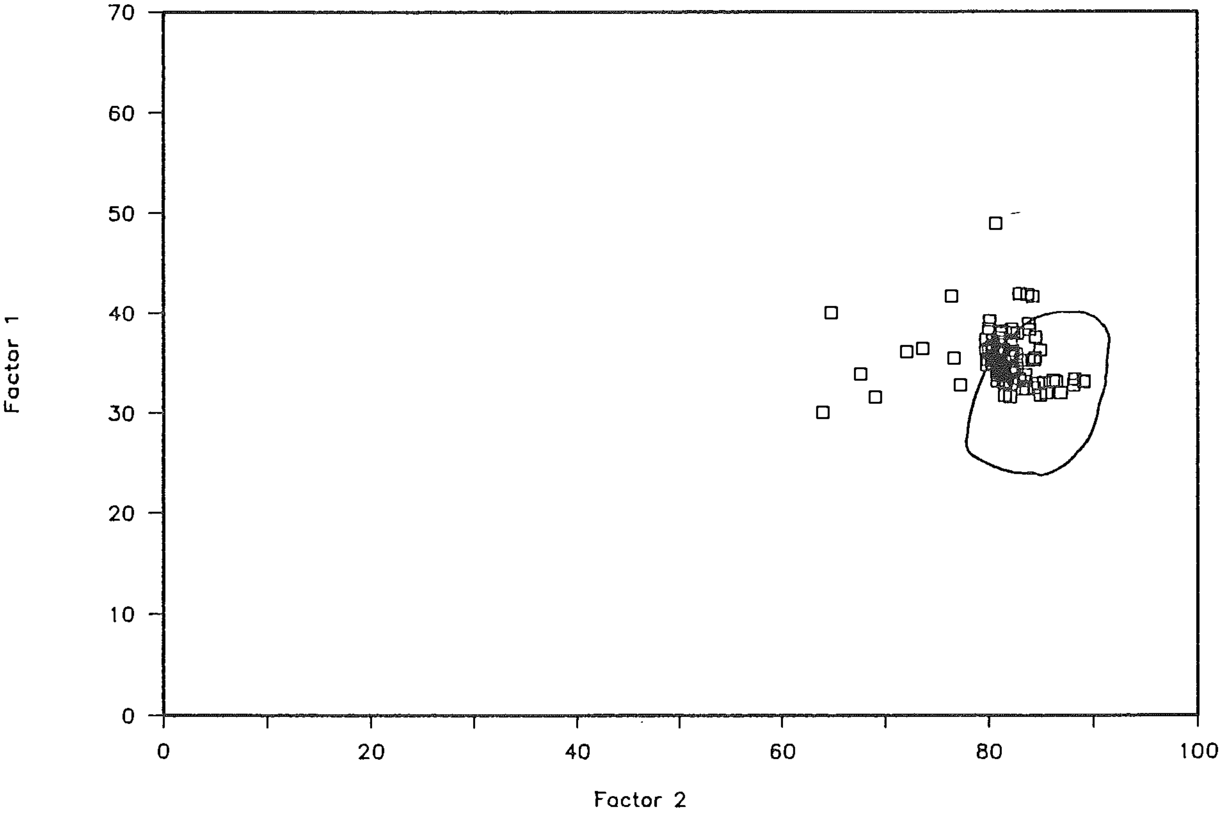
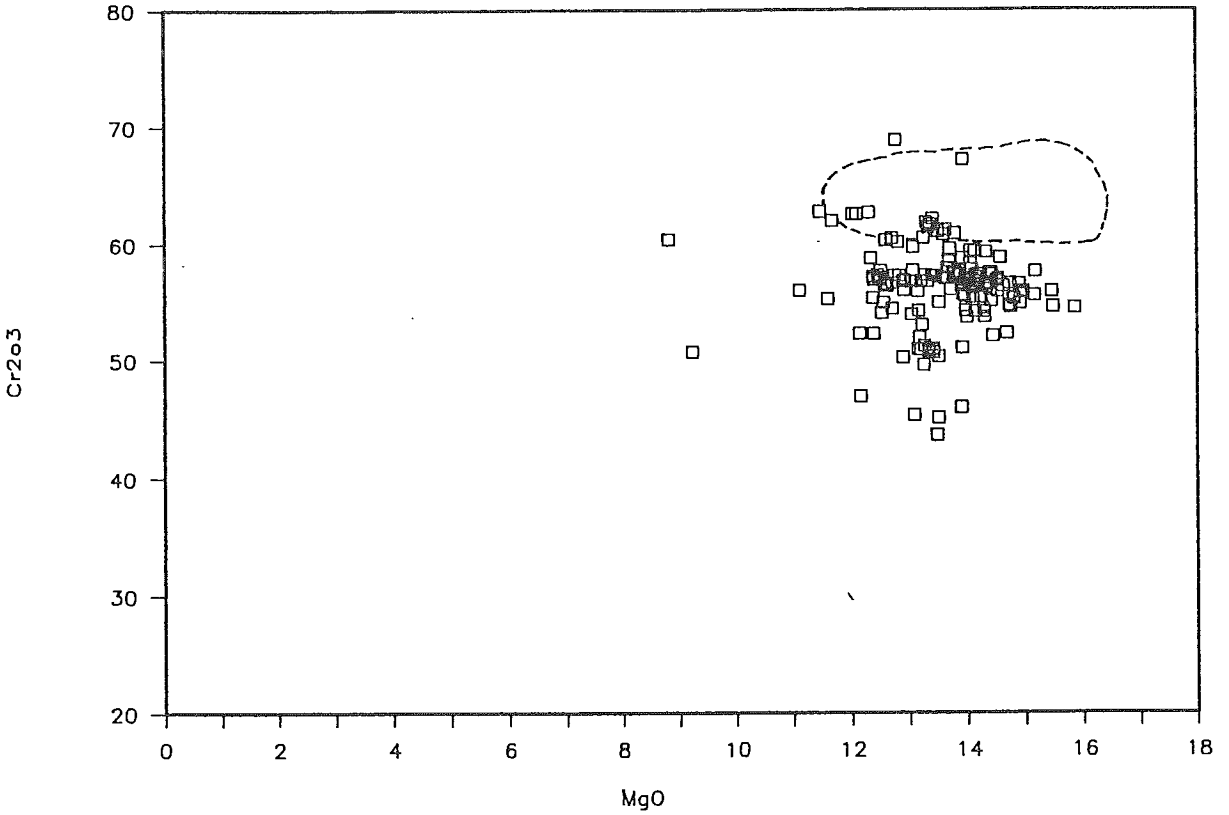


FIGURE 23 a: Chromites from the Sover kimberlite, South Africa. The high number of data points which plot in the preferred diamond inclusion field is indicative of a high grade of diamonds from a chromite harzburgite source rock. Note the good agreement between the factor and the simple "key element" approach. Factors are defined in Part II of this report.



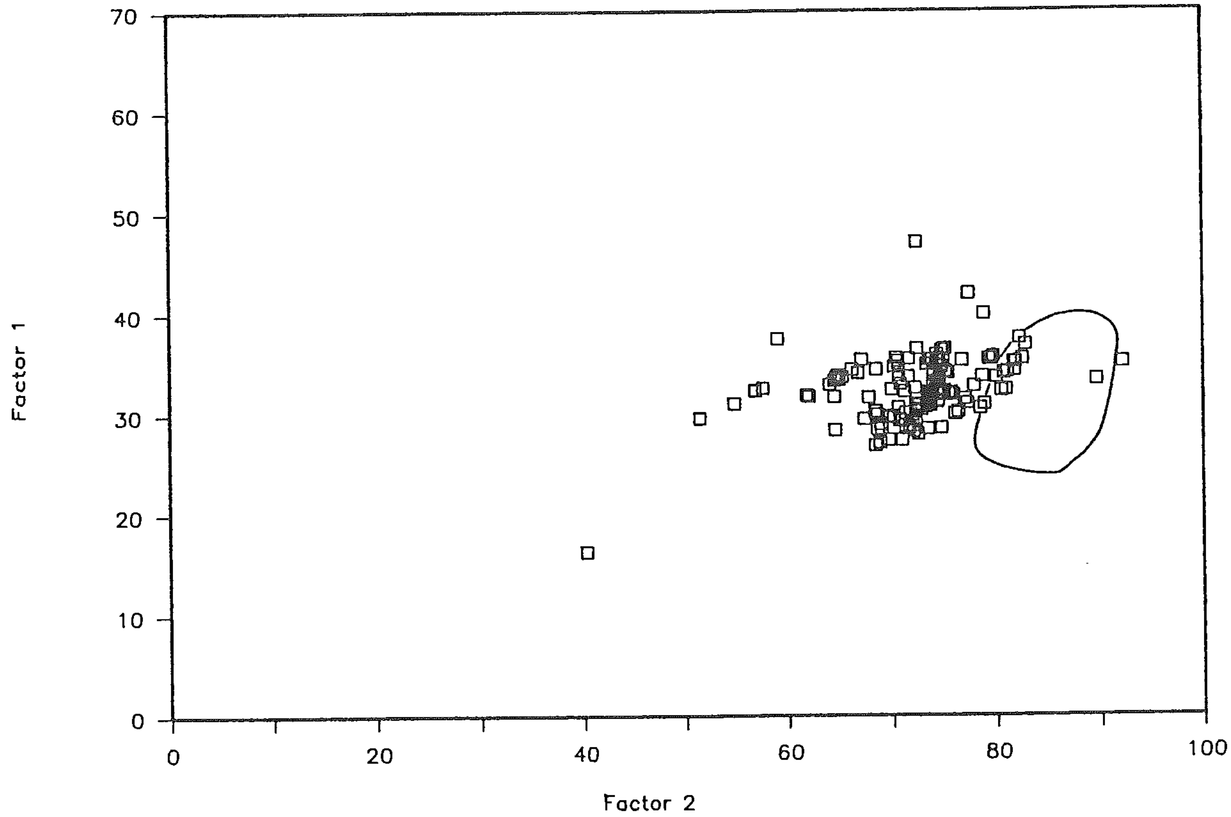
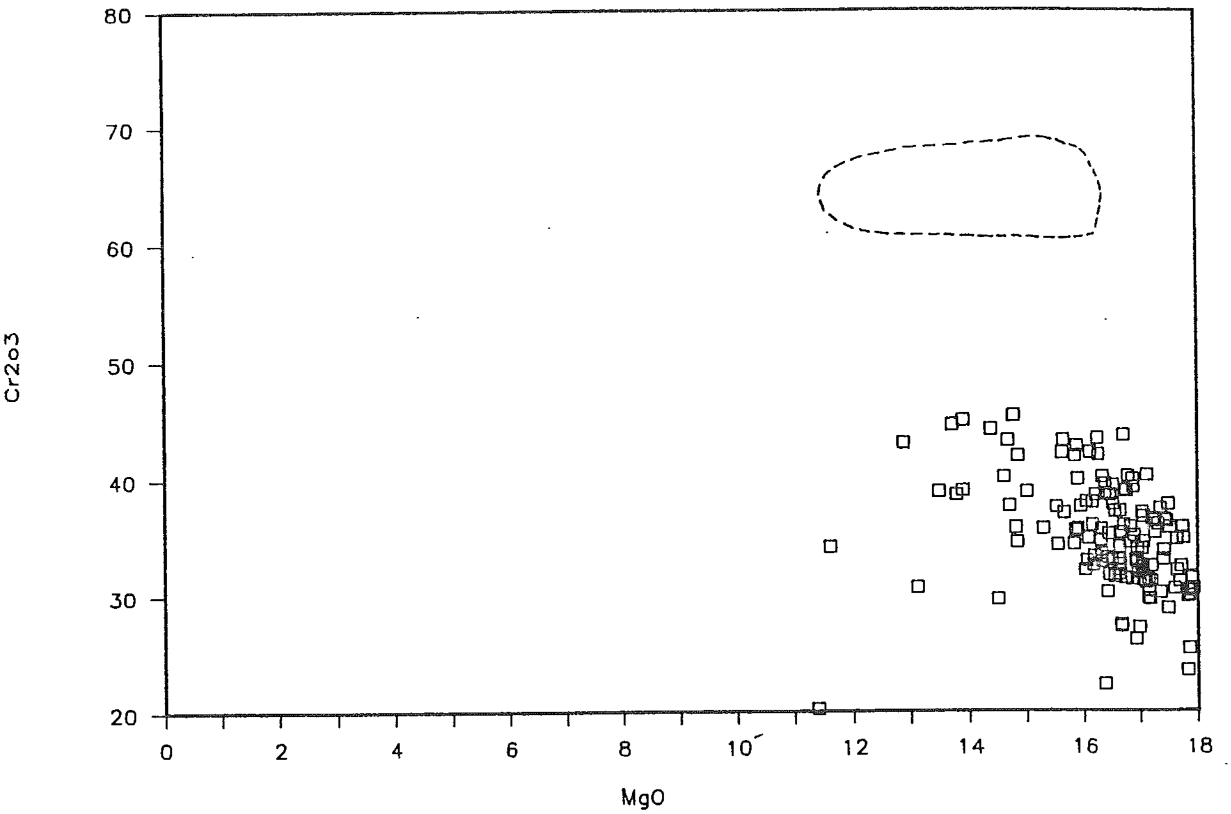


FIGURE 23 b: Chromites from the Argyle lamproite, Australia. The moderate number of data points which plot in the preferred diamond inclusion field is indicative of a low grade of diamonds from a chromite harzburgite source rock. Note the good agreement between the factor and the simple "key element" approach. Factors are defined in Part II of this report.



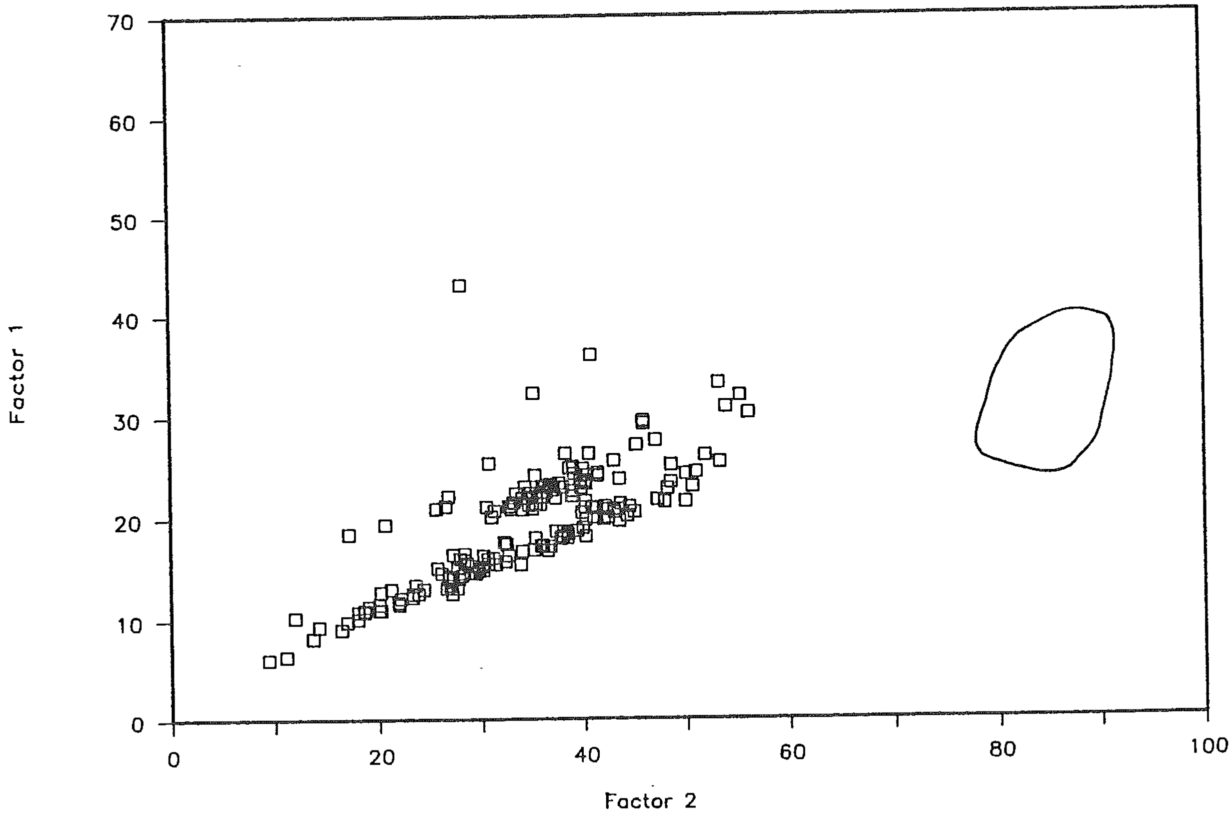


FIGURE 23 c: Chromites from the Blackfoot diatreme, British Columbia. The fact that the chromites show distinctly different compositions to those assocaited with diamonds implies that this diatreme is barren of diamonds from a chromite harzburgite source rock. Note the good agreement between the factor and the simple "key element" approach. Factors are defined in Part II of this report.

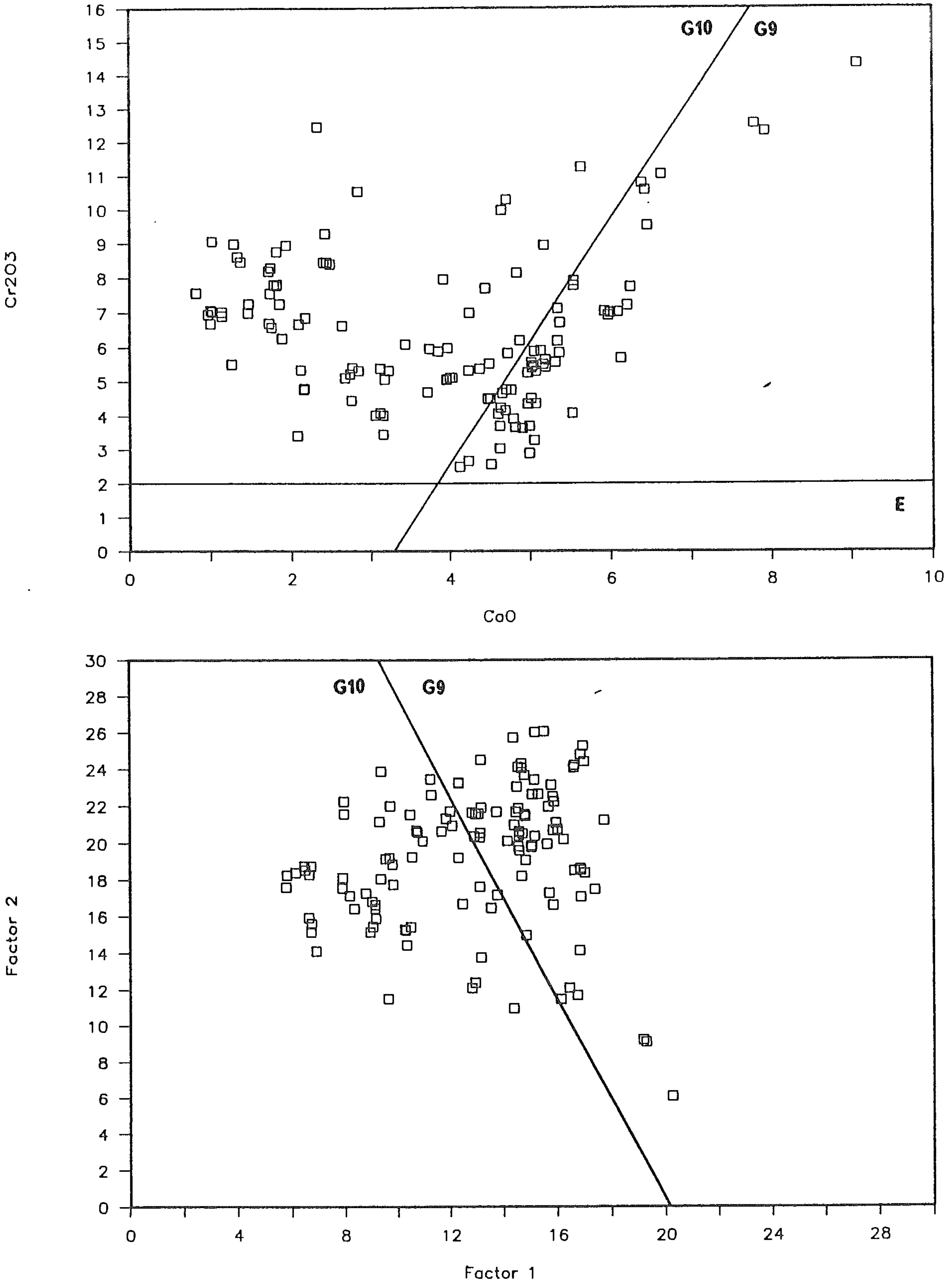
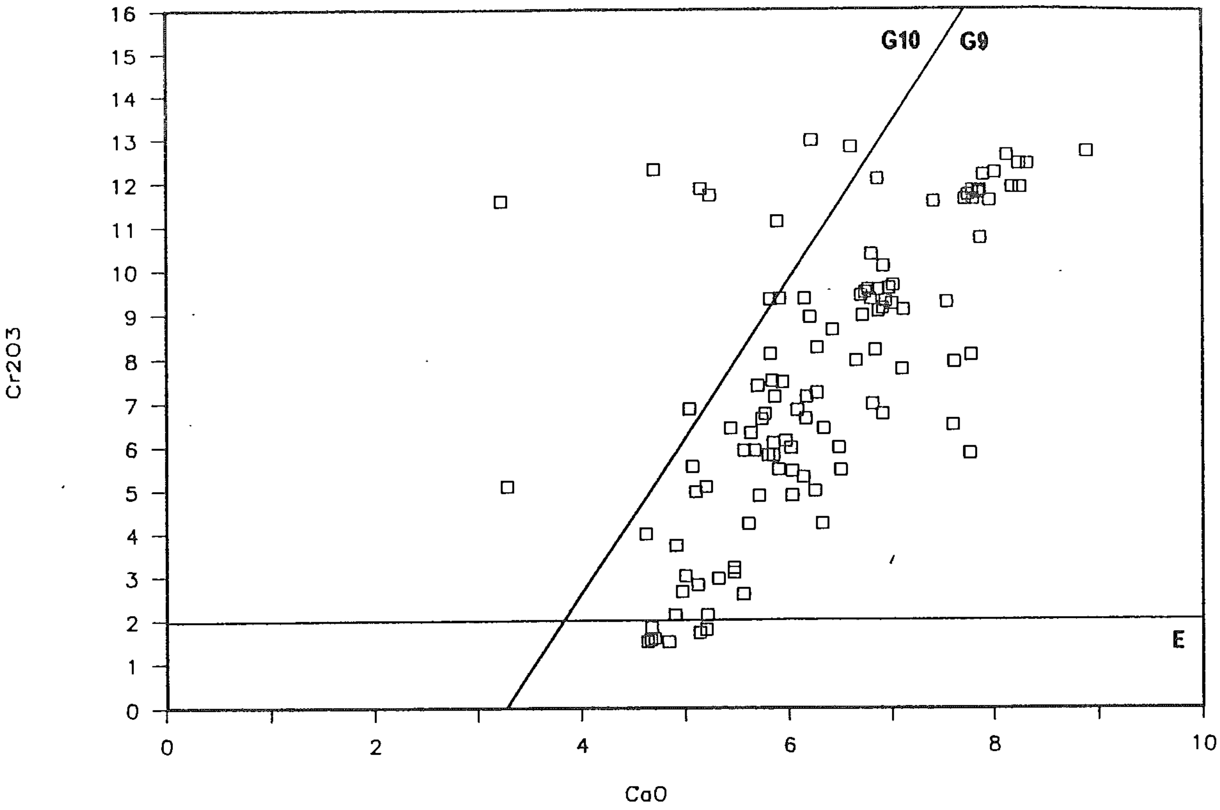


FIGURE 24 a: Peridotitic garnets from the New Elands kimberlite, South Africa. The high number of data points which plot on the subcalcic side of the 85% line (i.e. the high number of G10 compositions) is indicative of a high grade of diamonds from a garnet harzburgite source rock. Note the good agreement between the factor and the simple "key element" approach. Factors are defined in Part II of this report.



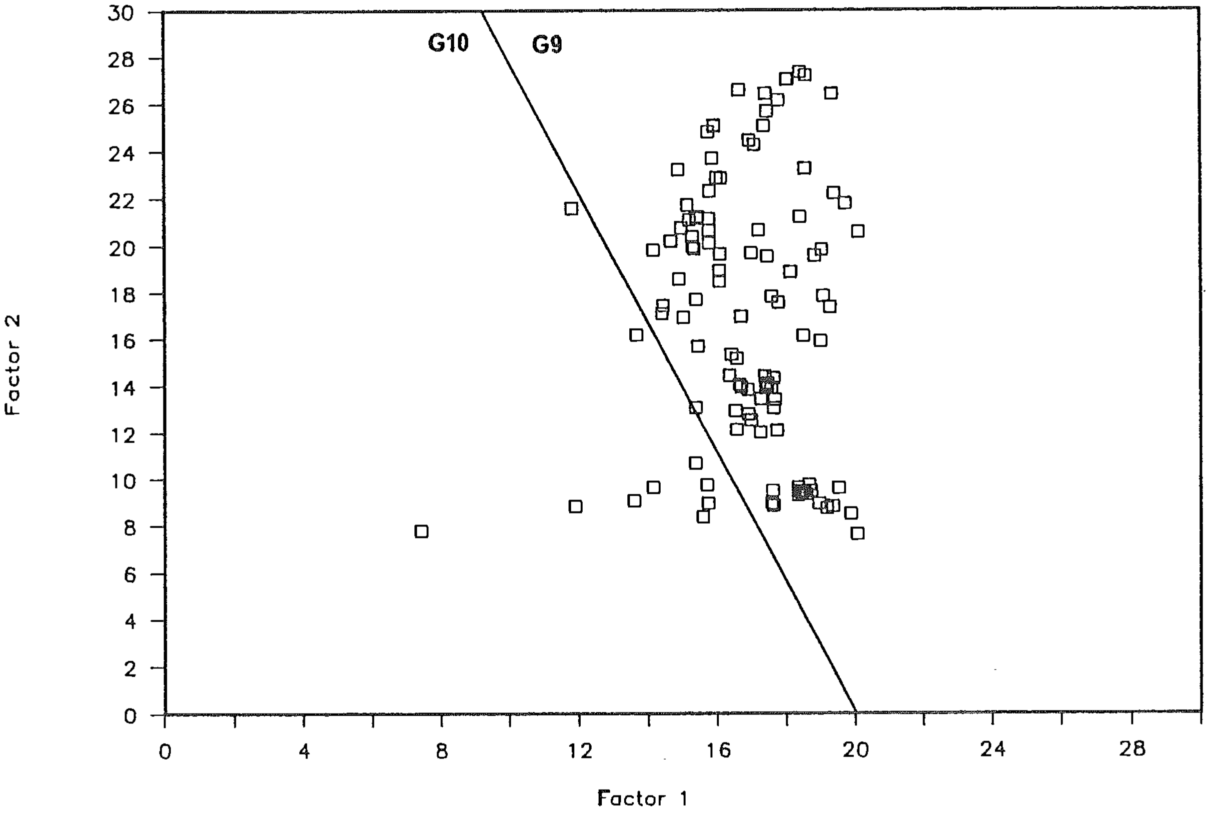
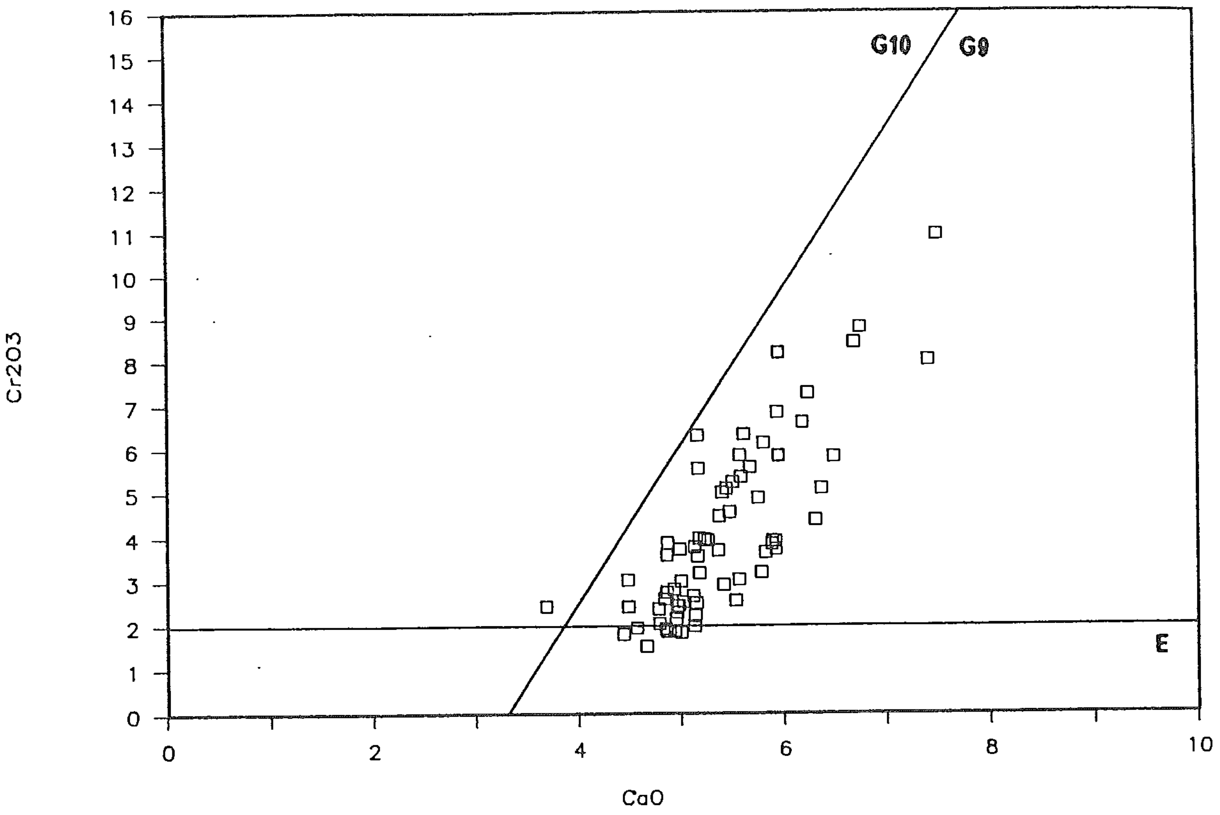


FIGURE 24 b: Peridotitic garnets from the Sloan kimberlite, Colorado. The moderate number of data points which plot on the subcalcic side of the 85% line (i.e. the moderate number of G10 compositions) is indicative of a low to medium grade of diamonds from a garnet harzburgite source rock. Note the good agreement between the factor and the simple "key element" approach. Factors are defined in Part II of this report.



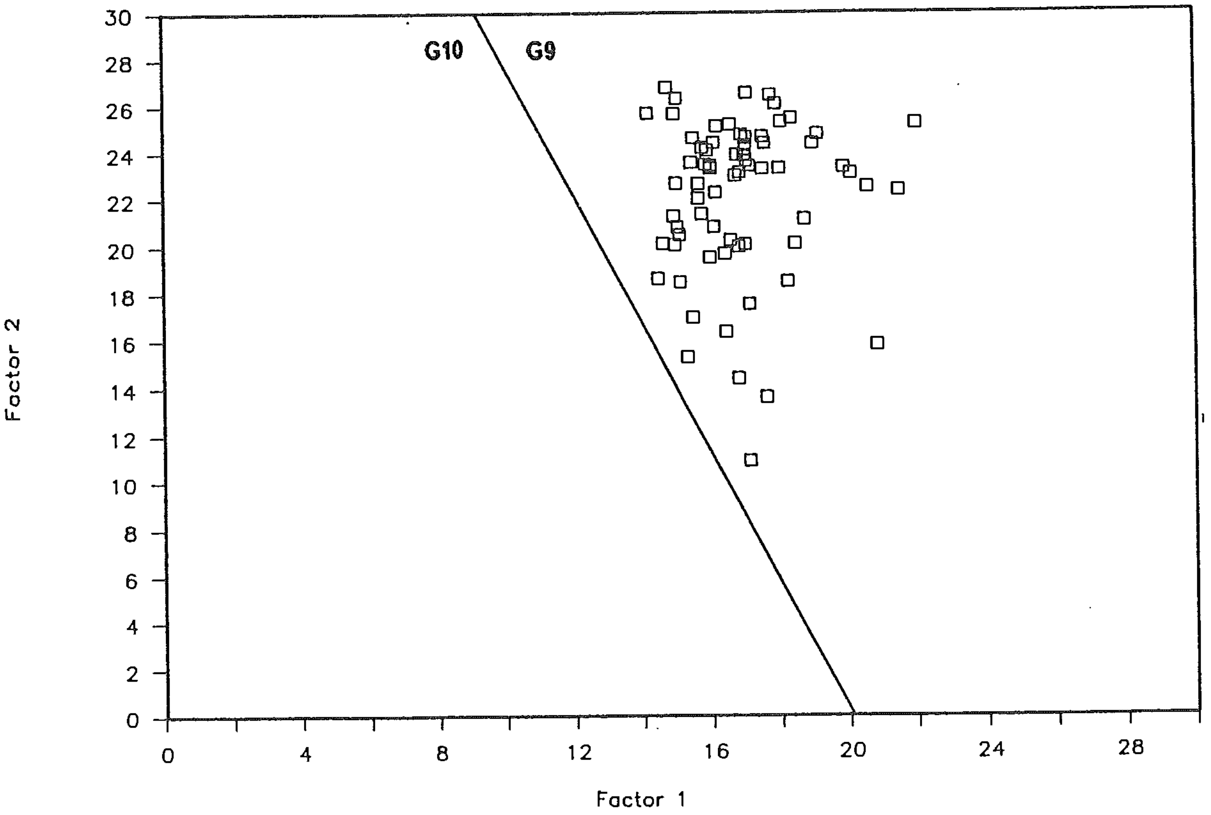


FIGURE 24 c: Peridotitic garnets from the Sturgeon Lake kimberlite, Saskatchewan. The fact that only one data point plots on the subcalcic side of the 85% line (i.e. essentially no G10 compositions) indicates that this pipe is barren of diamonds from a garnet harzburgite source rock. Note the good agreement between the factor and the simple "key element" approach. Factors are defined in Part II of this report.

Both peridotitic and eclogitic clinopyroxenes were found to be unsuitable as diamond indicators. However, it is important to note that Cr-diopside is a very useful mineral for detecting and tracking diatremes in regional sampling programmes. This is particularly true in Canada, where climatic conditions favour the preservation of this mineral in the secondary environment. Fipke has noted that tourmalines and zircons may also be useful for this purpose particularly in the case of lamproites (see Appendix 9.1).

Assessments of the diamond potential of the diatremes investigated are summarised in Table 13. A wide range of plots with associated comments are presented in Part II of this report and the report by C.E. Fipke included as Appendix 9 (Part III) discusses the lamproitic localities in some detail. Several noteworthy features require comment.

Firstly, 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 Prairie Creek and more significantly Argyle are both under-rated by the geochemical appraisal method. For kimberlites the method is much more successful. The limited number of localities with known diamond content in this study suggests this, but it was originally seen in a much larger sample of some 200 localities that form an unpublished database accessible to Gurney and Moore. Consequently, where the diamond host rock is a kimberlite, the diamond forecast is viewed with confidence. In the case of lamproites the situation at present strongly suggests that the same method is unsatisfactory. However, that is not because the diamonds have a different source. It is known at Argyle, Ellendale and Prairie Creek that they do not, since inclusions in the diamonds are eclogitic and peridotitic as for kimberlites. The problem is probably due to a different process or processes operating within lamproites compared to kimberlites. At Argyle it is known that garnet harzburgites or lherzolites have undergone retrograde metamorphism that has formed spinel at the expense of garnet. That spinel has not formed at the high pressures associated with diamond formation but rather en-route to the surface at shallower depths. The chromites therefore give no indication of having formed in the diamond stability field

TABLE 13: THE DIAMOND POTENTIAL OF THE LOCALITIES INVESTIGATED AS ASSESSED BY HEAVY MINERAL GEOCHEMISTRY

LOCALITY	GAR-HARZ DIAMONDS	CHR-HARZ DIAMONDS	ECLOGITE DIAMONDS	GROSS DIAMONDS	DIAMOND PRESERVE	NETT DIAMONDS	ACTUAL DIAMONDS	ROCK TYPE
Argyle	Nil	Low	Nil	V.Low	V.Good	V.Low	V.High sev/20	Lamproite
Batty	V.Low	V.Low	Nil	V.Low	Good	V.Low	Nil 0/0	Kimberlite
Blackfoot	Nil	Nil	Nil	Nil	Nil	Nil	Nil 0/0	Lamprophyre
Cross	V.Low	Nil	Nil	Almost Nil	No Data	Almost Nil	Nil 0/0	Kimberlite
HP	Nil	Nil	Nil	Nil	No Data	Nil	Nil 0/0	Lamprophyre
Ile Bizard	Nil	Nil	Nil	Nil	Nil	Nil	Nil 0/0	Alnoite
Jack	V.Low	Nil	Nil	Almost Nil	V.Good	Almost Nil	Almost Nil 1/1	Lamproite
Joff	Nil	Nil	Nil	Nil	No Data	Nil	Nil 0/0	Kimberlite
Kirkland Lake Sample KL5	Low	Nil	Nil	V.Low	Good	Low	Low 0/0	Kimberlite
Kirkland Lake Sample KL1	Low	Nil	Nil	V.Low	Poor	Almost Nil	Unknown 0/0	Kimberlite
Larry	Nil	Nil	Nil	Almost Nil	No Data	Almost Nil	Nil 0/0	Lamproitic
Mark	Nil	Nil	Nil	Nil	No Data	Nil	Nil 1/0	Lamproitic
Mike	Nil	Nil	Nil	Nil	No Data	Nil	Nil 0/0	Lamproitic
Mountain	Nil	Nil	Nil	Nil	Nil	Nil	Nil 0/0	Kimberlite
New Elands	V.High	High	Low	V.High	No Data	V.High	Mod sev./1	Kimberlite
Prairie Creek	V.Low	Nil	Nil	Almost Nil	No Data	Almost Nil	Low/Mod 0/0	Lamproite
Sturgeon Lake	V.Low	Nil	V.Low	V.Low	Good	V.Low	Unknown 0/0	Kimberlite
Sloan	Low	V.Low	Low	Low	V.Good	Low	Low/Mod sev./2	Kimberlite
Sover	High	V.High	V.High	V.High	No Data	V.High	High sev./1	Kimberlite

CATEGORIES FOR DIAMOND INDICATORS

Category	Estimated Grade
Nil	Barren
Almost Nil	Micro-diamonds only
V.Low	0 - 1 ct/100 tonnes
Low	1 - 10 cts/100 tonnes
Moderate	10 - 40 cts/100 tonnes
High	40 - 100 cts/100 tonnes
V.High	> 100 cts/100 tonnes

CATEGORIES FOR DIAMOND PRESERVATION

Category	Estimated Resorption
Nil	100%
Poor	70 - 99%
Good	30 - 70%
V.Good	10 - 30%
Excellent	0 - 10%

Nett Diamonds = Forecast for overall diamond grade

The figures under the "Actual Diamonds" column indicate the numbers of micro- and macro-diamonds recovered in the sample processed e.g. 2/1 indicates 2 microdiamonds and 1 macrodiamond recovered.

because they did not. In addition, no xenoliths of eclogite have yet been described from Prairie Creek, Ellendale or Argyle notwithstanding the fact that at the latter two localities at any rate, eclogite is a major source of the diamonds. Possibly eclogite is assimilated by lamproite magmas. Whatever the reason, it appears that the indicator forecasts can be misleading for lamproites and 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 micro-diamond recoveries. So whether fortuitously or not, the assessments in Table 13 might be close to the truth.

7.3 Whole Rock Geochemistry

7.3.1 General Statement

Several features of diatreme rocks make them highly unsatisfacory candidates for meaningful whole rock geochemical studies. The most important of these are that they usually contain high abundances of xenolithic material and they are characteristically highly altered. A further point worth noting is that kimberlites and lamproites are characteristically highly enriched in incompatible elements which necessitates the use of special analytical techniques (e.g. the low dilution technique in XRF) in order to obtain high precision data.

It is emphasised that since very few of the localities investigated in this study have been, or are being mined for diamonds, access to subsurface less altered material was generally not available. Consequently, the majority of samples analysed were highly altered. In an attempt to reduce the effects of contamination, considerable care was taken during sample preparation to remove xenolithic material (see Appendix 1, Part III). However, contamination due to the presence of microxenoliths and assimilated material cannot be avoided.

Due to the above considerations, very little emphasis is placed on the whole rock geochemistry results. In any event, only the broad compositional characteristics required for classifying the diatremes are of relevance to prospecting. Because of the complex and variable nature of alkaline rocks, diatremes can usually only be confidently classified after assessing a combination of petrographic, mineralogic and whole rock geochemical data.

Based on whole rock compositions, the diatremes investigated have been categorised into three groups which are briefly discussed below. The reader is referred to Tables 3, 4, 7 & 8 of this report and Appendix 5.1 (Part III) for general information on the composition of kimberlites and lamproites and details of the compositions for the samples analysed in the project.

7.3.2 Kimberlites

The following diatremes show the compositional characteristics of kimberlites: Batty, Crossing Creek, Joff, Kirkland Lake 1 & 2, Mountain Diatreme, New Elands, Sturgeon Lake, Sloan and Sover. As is typical of kimberlites, they show a wide range in compositions and some anomalous features were noted. The most noteworthy of these are:

(a) The Joff kimberlite shows low MgO and Ni (11.26 wt% and 305 ppm respectively) and is depleted in alkalis (Na_2O = 0.09; K_2O = 0.72 wt%) and incompatible elements compared to "average kimberlite".

(b) Sample KL5 from Kirkland Lake shows a highly aberrant composition. The high SiO_2 (49.9 wt%) and Al_2O_3 (16.65 wt%) and low MgO (5.36 wt%) is atypical of kimberlite. Moreover, this rock is substantially depleted in incompatible elements compared with "average kimberlite". These effects are most likely due to severe contamination by xenolithic material.

(c) The high LOI (26.57%) obtained for the Sturgeon Lake kimberlite is indicative of severe alteration. This sample also shows very low levels of alkalis (Na_2O = 0.04; K_2O = 0.01 wt%) and extreme depletions in incompatible elements (e.g. Zr = not detected, Ba = 174 ppm).

7.3.3 Lamproites

Because the samples analysed from both the Argyle and Prairie Creek lamproites were tuffaceous phases, the effects of contamination by fragmental quartz are evident. The most extreme example of this is noted for the Argyle sandy tuff sample which shows 82.01 wt% SiO_2. The high quartz component results in a considerable dilution of the lamproitic geochemical character of the rocks, which is particularly evident in the relatively low levels of Na_2O, K_2O, Rb, Sr and Ba observed for both diatremes. Sample 90065 from Prairie Creek shows the least contamination, but still shows lower than characteristic levels of K_2O (2.78 wt%) and only moderate enrichments in incompatible elements.

The two breccia phases from the Jack diatreme, British Columbia (P2 and P3) are similar in composition and show fairly high SiO_2 (~52 wt%), moderate Al_2O_3 (~19 wt%) and low MgO (~3 wt%). Their extremely ultrapotassic character (K_2O = ~10 wt%) and high K_2O/Na_2O ratios (~67) is characteristic of lamproites. The Jack breccias show moderate enrichments in incompatible elements (e.g. Zr ~200 ppm and Ba ~900 ppm) but these levels are considerably lower than is average for lamproites. However, taking cognisance of the independant petrographic and mineralogical evidence, the Jack diatreme classifies as a lamproite.

The Larry, Mark and Mike diatremes in British Columbia have variable compositions but generally show moderate levels of SiO_2 (~35 - 38 wt%), Al_2O_3 (~8 - 15 wt%) and MgO (~4 - 8 wt%). They do not show the same degree of alkali enrichment (K_2O ~2 - 7 wt%) as the Jack, and again the observed levels of incompatible elements such as Zr, Nb and Ba are substantially below those characteristic of lamproites. However, in view of the considerable error inherant in whole rock analyses of this kind (as discussed above) and considering the petrographic evidence, these rocks are considered to be lamproitic rather than lamprophyric.

7.3.4 Alkali Lamprophyres

Based on whole rock composition, the Blackfoot, HP and Ile Bizard diatremes can classified as alkali-lamprophyres. Lamprophyres are chemically very similar to lamproites except that the latter are characterised by higher K_2O (typically 4 to 12 wt%). Blackfoot and HP are very similar in composition. They show moderate levels of SiO_2 (~38 wt%), Al_2O_3 (~10 wt%) and MgO (~13 wt%) while being strongly potassic (K_2O ~4.5wt%) and enriched in incompatible elements such as Zr, Nb and Ba. Ile Bizard is essentially similar but has lower Al_2O_3 (5.2 wt%) and K_2O (3.7 wt%).

8. SUMMARY OF IMPORTANT POINTS

1. The vast Canadian Shield is a desirable geological environment for locating diamondiferous diatremes.

2. The international diamond market is currently sufficiently healthy to be attractive for the initiation of new exploration ventures.

3. The application of modern exploration techniques has been reponsible for a dramatic increase in the worlds diamond production over the past two decades.

4. 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 (~180 km). Complex structural settings where overthrusting will allow old keels to survive underneath younger rocks are not ruled out of contention.

5. The macro-diamonds in economic deposits are derived from peridotitic and eclogitic source rocks that formed in the lithospheric upper mantle. Both parageneses occur in every known diamond deposit worldwide.

6. 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.

7. Since some of these minerals (notably garnets and chromites) have very distinctive compositions, their presence can be detected and used as diamond indicators.

8. In a single diatreme, it is extremely reasonable to expect a roughly linear relationship between the amount of diamond

present and the abundance of fragments of the host diamondiferous rocks from the mantle.

9. Both peridotitic and eclogitic clinopyroxenes are unsuitable as diamond indicators. However, Cr-diopside is a very useful mineral for detecting and tracking diatremes in regional sampling programmes. Tourmalines and zircons may also be useful for this purpose particularly in the case of lamproites.

10. Climatic conditions in Canada are suited to the indicator mineral approach to diamond prospecting.

11. The indicator mineral approach does not appear to be reliable for lamproites. This is not because the diamonds have a different source, but must be due to a different process or processes operating in lamproites compared to kimberlites.

12. A multivariate statistical approach to evaluating the geochemistry of indicator minerals agrees with the more simplistic approach for chromites and peridotitic garnets, but it does not work for eclogitic garnets. The simple approach is favoured because it does not require data manipulation and trends can readily be related to geological processes.

13. The emergence of lamproites as a second major source of diamonds has considerably increased the importance of petrography in diamond exploration programmes.

14. The Jack diatreme in British Columbia has been positively identified as a lamproite. The Larry, Mark and Mike diatremes are most likely also lamproites but further evidence is required for an unequivocal classification.

15. Bulk-rock geochemical analyses of diatreme rocks are plagued by problems of xenolith contamination and alteration, which makes them difficult to interpret. However, only the broad geochemical features required for classification purposes are relevant to exploration.

9. REFERENCES CITED

ALIBERT C. and ALBAREDE F. 1988. Relationships between mineralogical, chemical, and isotopic properties of some North American kimberlites. Journal of Geophysical Research 93, 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.

ARIMA M. and KERRICH R. 1988. Jurassic kimberlites from Picton and Varty Lake, Ontario: Geochemical and stable isotope characteristics. Contributions to Mineralogy and Petrology 99, 385-391.

ATKINSON W.J. 1989. Diamond exploration philosophy, practice, and promises: a review. In: Kimberlites and related rocks 2: Their crust/mantle setting, diamonds and diamond exploration. Geological Society of Australia Special Publication 14, 1075-1107.

ATKINSON W.J., HUGHES F.E. and SMITH C.B. 1984. A review of the kimberlitic rocks of western Australia. In: Kornprobst J. ed., Kimberlites I: Kimberlites and related rocks, p195-224. Elsevier.

BAILEY D.K. 1964. Crustal warping - a possible tectonic control of alkaline magmatism. Journal of Geophysical Research 69, 1103-1111.

BAILEY D.K. 1984. Kimberlite: "The Mantle Sample" formed by ultrametasomatism. In: Kornprobst J. ed., Kimberlites I: Kimberlites and related rocks, p323-334. Elsevier.

BERENSENDSON 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.

BERGMAN S.C. 1987. Lamproites and other potassium-rich igneous rocks: a review of their occurrence, mineralogy and geochemistry. In: Fitton J.G. and Upton B.G.J. eds., Alkaline Igneous Rocks. Special Publication of the Geological Society of London 30, 103-190.

BOLIVAR S.L. 1972. Kimberlite of Eliott County, Kentucky. M.S. thesis, Eastern Kentucky University, 61p.

BOYD F.R. and GURNEY J.J. 1982. Low-calcium garnets: Keys to craton structure and diamond crystallization. Carnegie Institute of Washington Yearbook 81, 261-267.

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 6, 191.

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

BROOKINS D.G. 1970b. The kimberlites of Riley County, Kansas. Kansas Geological Survey Bulletin 200, 1-32.

CARLSON J.A. and MARSH S.W. 1989. Discovery of the George Creek, Colorado kimberlite dikes. In: Kimberlites and related rocks 2: Their mantle/crust setting, diamonds and diamond exploration. Geological Society of Australia Special Publication 14, 1169-1178.

CLEMENT C.R. 1982. A comparative geological study of some major kimberlite pipes in the northern Cape and Orange Free State. Unpublished Ph.D., University of Cape Town. 432p.

CLEMENT C.R. and SKINNER E.M.W. 1979. A textural-genetic classification of kimberlite rocks. Kimberlite Symposium II, Cambridge, U.K., p18-21.

CLEMENT C.R. and SKINNER E.M.W. 1985. A textural-genetic classification of kimberlites. Transactions of the Geological Society of South Africa 88, 403-409.

CLEMENT C.R., SKINNER E.M.W. and SCOTT-SMITH B.H. 1984. Kimberlite redefined. Journal of Geology 92, 223-228.

CLIFFORD T.N. 1966. Tectono-metallogenic units and metallogenic provinces of Africa. Earth and Planetary Science Letters 1, 421-434.

COLLERSON K.D., JESSEAU C.W. and BRIDGWATER D. 1976. Contrasting types of banded olivine in ultramafic rocks from the Archean of Labrador. Canadian Journal of Earth Sciences 13, 442-450.

DANCHIN R.V. and WYATT B.A. 1979. Statistical cluster analysis of garnets from kimberlites and their xenoliths. Kimberlite Symposium II, Cambridge, U.K., p22-27.

DANCHIN R.V., FERGUSON J., McIVER J.R. and NIXON P.H. 1975. THe composition of late-stage kimberlite liquids as revealed by nucleated autoliths. Physics and Chemistry of the Earth 9, 235-245.

DAVIS J.D. 1986. Statistics and data analysis in geology. John Wiley and Sons (2nd edition). 646p.

DAWSON J.B. 1967. A review of the geology of kimberlite. In: Wyllie P.J. ed., Utramafic and related rocks, p241-251. Wiley, New York.

DAWSON J.B. 1972. Kimberlites and their relation to the mantle. Philosophical Transactions of the Royal Society of London A271, 297-311.

DAWSON J.B. 1980. Kimberlites and their xenoliths. Springer-Verlag, Berlin. 252p.

DAWSON J.B. 1984. Contrasting types of upper-mantle metasomatism? In: Kornprobst J. ed., Kimberlites II: The mantle and crust-mantle relationships, p289-294. Elsevier.

DAWSON J.B. and STEPHENS W.E. 1975. Statistical classification of garnets from kimberlite and associated xenoliths. Journal of Geology 83, 589-607.

DIMROTH E. 1970. Meimechites and carbonatites of the Castignon Lake complex, New Quebec. Neues Jahrbuch fur Mineralogie. Abhandlungen 112, 239-278.

DUMMETT H.T., FIPKE C.E. and BLUSSON S.L. 1986. Diamond exploration in the North American Cordillera. 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 Society of Canada, 168-176.

FERGUSON J. and JAQUES A.L. 1984. Structural control of kimberlite. In: Glover J.E. and Harris P.G. eds., Kimberlite Occurrence and Origin: A basis for conceptual models in exploration. Geology Dept. and University Extension, University of Western Australia, Publication No. 8, 291-292.

FRASER K.J., HAWKESWORTH C.J., ERLANK A.J., MITCHELL R.H. and SCOTT-SMITH B.H. 1985/86. Sr, Nd and Pb isotope and minor element geochemistry of lamproites and kimberlites. Earth and Planetary Science Letters 76, 57-70.

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 75, 27-42.

GURNEY J.J. 1984. A correlation between garnets and diamonds in kimberlites. In: Glover J.E. and Harris P.G. eds., Kimberlite Occurrence and Origin: A basis for conceptual models in exploration. Geology Dept. and University Extension, University of Western Australia, Publication No. 8, 143-166.

GURNEY J.J. 1989. Diamonds. In: Kimberlites and related rocks 2: Their crust/mantle setting, diamonds and diamond exploration. Geological Society of Australia Special Publication 14, 935-965.

GURNEY J.J. and EBRAHIM S. 1973. Chemical composition of Lesotho kimberlites. In: Nixon P.H. ed., Lesotho Kimberlites, p280-293. Lesotho National Development Corporation.

HAGGERTY S.E. 1986. Diamond genesis in a multiply-constrained model. Nature 320, 34-38.

HARRIS P.G. 1957. Zone refining and the origin of potassic basalts. Geochimica et Cosmochimica Acta 12, 195-208.

HARRIS P.G. and MIDDLEMOST E.A.K. 1969. The evolution of kimberlites. Lithos 3, 77-88.

HATTON C.J. and GURNEY J.J. 1979. A diamond-graphite eclogite from the Roberts Victor mine. In: Boyd F.R. and Meyer H.O.A. eds., The Mantle Sample: Inclusions in kimberlites and other volcanics, p29-36. American Geophysical Union, Washington.

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

HAWTHORNE J.B. 1975. Model of a kimberlite pipe. Physics and Chemistry of the Earth 9, 1-15.

HEARN B.C. Jr. and McGEE E.S. 1984. Garnet peridotites from Williams kimberlite, north-central Montana, U.S.A. In: Kornprobst J. ed., Kimberlites II: The mantle and crust-mantle relationships, p57-70. Elsevier.

HUNT G.H. and BOLIVAR S.L. 1972. Oxygen and carbon isotope ratios of carbonate from kimberlites in Elliott County, Kentucky. Geological Society of America Programs with Abstracts 4, 81.

HUNTER R.H. and TAYLOR L.A. 1984. Magma-mixing in the low velocity zone: kimberlitic megacrysts from Fayette County, Pennsylvania. American Mineralogist 69, 30-40.

ILUPIN I.G. and LUTTS B.G. 1971. The chemical composition of kimberlite and questions on the origin of kimberlite magma (in Russian). Soretskaya Geol. 6, 61-73.

JAGO B.C. 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 1: Their composition, occurrence, origin and emplacement. Geological Society of Australia Special Publication 14, 298-310.

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: Kornprobst J. ed., Kimberlites I: Kimberlites and related rocks, 225-254. Elsevier.

JAQUES A.L., LEWIS J.D. and SMITH C.B. 1986. The kimberlites and lamproites of Western Australia. Geological Society of Western Australia, Bulletin 132.

JANSE A.J.A. 1984. Kimberlites - Where and When? In: Glover J.E. and Harris P.G. eds., Kimberlite Occurrence and Origin: A basis for conceptual models in exploration. Geology Dept. and University Extension, University of Western Australia, Publication No. 8, 19-61.

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

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 65, 90-106.

le ROEX A.P. 1986. Geochemical correlation between southern African kimberlites and South Atlantic hotspots. Nature 324, 243-245.

MALINKOWSKI E.R. and HOWERY D.G. 1980. Factor analysis in geology. John Wiley and Sons. 251p.

MANSKER W.L. 1973. Petrology of a south-eastern Missouri ultramafic pipe. M.S. thesis, University of Missouri, Rolla, 53p.

McCALLUM M.E., EGGLER D.H., BURNS L.K. 1975. Kimberlite diatremes in northern Colorado and southern Wyoming. Physics and Chemistry of the Earth 9, 149-162.

McGEE E.S. and HEARN B.C. Jr. 1984. The Lake Ellen Kimberlite, Michigan, U.S.A. In: Kornprobst J. ed., Kimberlites I: Kimberlites and related rocks, p143-154. Elsevier.

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 55, 1738-1771.

MEYER H.O.A. 1975. Kimberlite from Norris Lake, eastern Tennessee: mineralogy and petrology. Journal of Geology 83, 518-526.

MEYER H.O.A. and KRIDELBAUGH S.J. 1977. Green Mountain kimberlite, Colorado: mineralogy and petrology. Second International Kimberlite Conference, Sante Fe. Extended Abstracts, unpaged.

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. 28th I.G.C., Workshop on Diamonds, Extended Abstracts, 55-60.

MITCHELL R.H. 1970. Kimberlite and related rocks - a critical re-appraisal. Journal of Geology 78, 686-704.

MITCHELL R.H. 1979. The alleged kimberlite-carbonatite relationship: additional contrary mineralogical evidence. American Journal of Science 279, 570-589.

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

MITCHELL R.H. 1989. Aspects of the petrology of kimberlites and lamproites: some definitions and distinctions. In: Kimberlites and related rocks 1: Their composition, occurrence, origin and emplacement. Geological Society of Australia Special Publication 14, 7-45.

MITCHELL R.H. and HAWKESWORTH C.J. 1984. Geochemistry of potassic lavas from Smokey Butte, Montana. Geological Society of America Program with Abstracts 16, 494.

MITCHELL R.H. and JANSE A.J.A. 1982. A harzburgite-bearing monchiquite from Wawa, Ontario. Canadian Mineralogist 20, 211-216.

MOORE R.O. and GURNEY J.J. 1985. Pyroxene solid solution in garnets included in diamond. Nature 318, 553-555.

MOORE R.O. and GURNEY J.J 1989. Mineral inclusions in diamonds from the Monastery kimberlite, South Africa. In: Kimberlites and related rocks 2: Their crust/mantle setting, diamonds and diamond exploration. Geological Society of Australia Special Publication 14, 1029-1041.

MURAMATSU Y. 1983. Geochemical investigations of kimberlites from the Kimberley area, South Africa. Geochemical Journal 17, 71-86.

NIGGLI P. 1923. Gesteins- und Mineral provinzen I. Gebruder Borntraeger, Berlin.

NIXON P.H. 1987. Mantle Xenoliths. John Wiley & Sons, New York. 844p.

NIXON P.H. 1987. The American plates - introduction. In: Nixon P.H. ed., Mantle Xenoliths, p13-22. John Wiley & Sons, New York.

NIXON P.H., ROGERS N.W., GIBSON I.L. and GREY A. 1981. Depleted and fertile mantle xenoliths from southern African kimberlites. Annual Review of Earth and Planetary Sciences 9, 285-309.

NIXON P.H., DAVIES G.R., CONDLIFFE E., BAKER R. and BAXTER BROWN R. 1989. Discovery of ancient source rocks of Venezuela diamonds. 28th I.G.C., Workshop on Diamonds, Extended Abstracts, 73-75.

O'HARA M.J. and YODER H.S. 1967. Formation and fractionation of basic magmas at high pressures. Scottish Journal of Geology 3, 67-117.

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

RICHARDSON S.H. 1986. Latter-day origin of diamonds of eclogitic paragenesis. Nature 322, 623-626.

RICHARDSON S.H. 1989. Radiogenic isotope studies of diamond inclusions. 28th I.G.C., Workshop on Diamonds, Extended Abstracts, 87-90.

RICHARDSON S.H., GURNEY J.J., ERLANK A.J. and HARRIS J.W. 1984. Origin of diamonds in old enriched mantle. Nature 310, 198-202.

ROCK N.M.S. 1987. The nature and origin of lamprophyres: an overview. In: Fitton J.G. and Upton B.G.J. eds., Alkaline Igneous Rocks. Special Publication of the Geological Society of London 30, 191-226.

ROBINSON D.N. 1979. Surface textures and other features of diamonds. Unpublished Ph.D., University of Cape Town. 221p.

RODEN M.F. and SMITH D. 1979. Field geology, chemistry and petrology of the Buell Park minette diatreme, Apache County, Arizona. In: Boyd F.R. and Meyer H.O.A. eds., Kimberlites, diatremes and diamonds: their geology, petrology and chemistry, p364-381. American Geophysical Union, Washington.

SCHULZE D.J. 1984. Cr-poor megacrysts from the Hamilton Branch kimberlite, Elliott County, Kentucky. In: Kornprobst J. ed., Kimberlites II: The mantle and crust-mantle relationships, p 97-108. Elsevier.

SCOTT-SMITH B.H. and SKINNER E.M.W. 1984a. A new look at Prairie Creek, Arkansas. In: Kornprobst J. ed., Kimberlites I: Kimberlites and related rocks, 255-284. Elsevier.

SCOTT-SMITH B.H. and SKINNER E.M.W. 1984b. Diamondiferous lamproites. Journal of Geology 92, 433-438.

SEARS C.E. and BILBERT M.C. 1973. Petrography of the Mt. Horeb, Virginia kimberlite. Geological Society of America Program with Abstracts 5, 434.

SHEE S.R. 1984. The oxide minerals of the Wesselton Mine kimberlite, Kimberley, South Africa. In: Kornprobst J. ed., Kimberlites I: Kimberlites and related rocks, p59-73. Elsevier.

SHIMIZU N. and RICHARDSON S.H. 1987. Trace element abundance patterns of garnet inclusions in peridotite-suite diamonds. Geochimica et Cosmochimica Acta 51, 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 1: Their composition, occurrence, origin and emplacement. Geological Society of Australia Special Publication 14, 528-544.

SKINNER E.M.W. and CLEMENT C.R. 1979. Mineralogical classification of southern African kimberlites. In: Boyd F.R. and Meyer H.O.A. eds., Kimberlites, Diatremes and Diamonds: Their geology, petrology and geochemistry, p129-139. American Geophysical Union, Washington.

SLODKEVICH V.V. 1983. Graphite paramorphs after diamond. International Geology Review 23, 497-514.

SMITH C.B. 1983. Pb, Sr and Nd isotopic evidence for sources of southern African Cretaceous kimberlites. Nature 304, 51-54.

SMITH C.B., GURNEY J.J., SKINNER E.M.W., CLEMENT C.R. and EBRAHIM N. 1985. Geochemical character of southern African kimberlites: A new approach based on isotopic constraints.

Transactions of the Geological Society of South Africa 88, 267-280.

SMITH C.B., GURNEY J.J., HARRIS J.W., OTTER M.L., KIRKLEY M.B. and JAGOUTZ E. 1989. Nd and Sr isotope systematics of large eclogite and lherzolite paragenesis single diamonds, Finsch and Kimberley Pool. 28th I.G.C., Workshop on Diamonds, Extended Abstracts, 102-104.

SMITH D. 1979. Hydrous minerals and carbonates in peridotitic inclusions from the Green Knobs and Buell Park kimberlite diatremes on the Colorado Plateau. In: Boyd F.R. and Meyer H.O.A. eds., The mantle sample: Inclusions in kimberlites and other volcanics, p345-356. American Geophysical Union, Washington.

SOBOLEV N.V. and LAVRENT'YEV Yu.G. 1971. Isomorphic sodium admixture in garnets formed at high pressures. Contributions to Mineralogy and Petrology 31, 1-12.

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 Geol. Inv. Map I-674.

STEPHENS W.E. and DAWSON J.B. 1977. Statistical comparison between pyroxenes from kimberlites and their associated xenoliths. Journal of Geology 85, 433-449.

TROGER W.E. 1935. Spezialle Petrographie der Eruptivgesteine, Ein Nomenklatur Kompendium. Verlag de Deutschen Mineralogischan Gesellschaft, Berlin.

WADE A. and PRIDER R.T. 1940. THe leucite-bearing rocks of the West Kimberley area, Western Australia. Quarterly Journal of the Geological Society of London 96, 39-98.

WAGNER P.A. 1914. The diamond fields of South Africa. Transvaal Leader, Johannesburg.

WATSON K.D. 1967a. Kimberlites of eastern North America. In: Wyllie P.J. ed., Ultramafic and related rocks, p312-323. Wiley, New York.

WATSON K.D. 1967b. Kimberlite pipes of north-eastern Arizona. In: Wyllie P.J. ed., Ultramafic and related rocks, p261-269. Wiley, New York.

WATSON K.D. 1973. Kimberlites of the Superior Province, Canadian Shield. International Kimberlite Conference, Cape Town, Extended Abstracts, 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: Boyd F.R. and Meyer H.O.A. eds., Kimberlites, Diatremes And Diamonds: Their Geology, Petrology and Geochemistry, p300-312. American Geophysical Union, Washington.

WILDING M.C., HARTE B. and HARRIS J.W. 1989. Evidence of asthenospheric source for diamonds from Brazil. 28th I.G.C., Abstracts Volume 3, 359-360.

WILLIAMS A.F. 1932. The Genesis of Diamond. Ernest Benn Ltd., London. (2 volumes).

WYLLIE P.J. 1989. The genesis of kimberlites and some low-SiO_2, high-alkali magmas. In: Kimberlites and related rocks 1: Their composition, occurrence, origin and emplacement. Geological Society of Australia Special Publication 14, 603-615.

YOUNG R.S and BAILEY R.A. 1955. A mica peridotite dike near Front Royal, Virginia. Virginia Journal of Science 6, 282-283.

Plates to accompany Appendix 9.1 (Part III)(On microfiche)

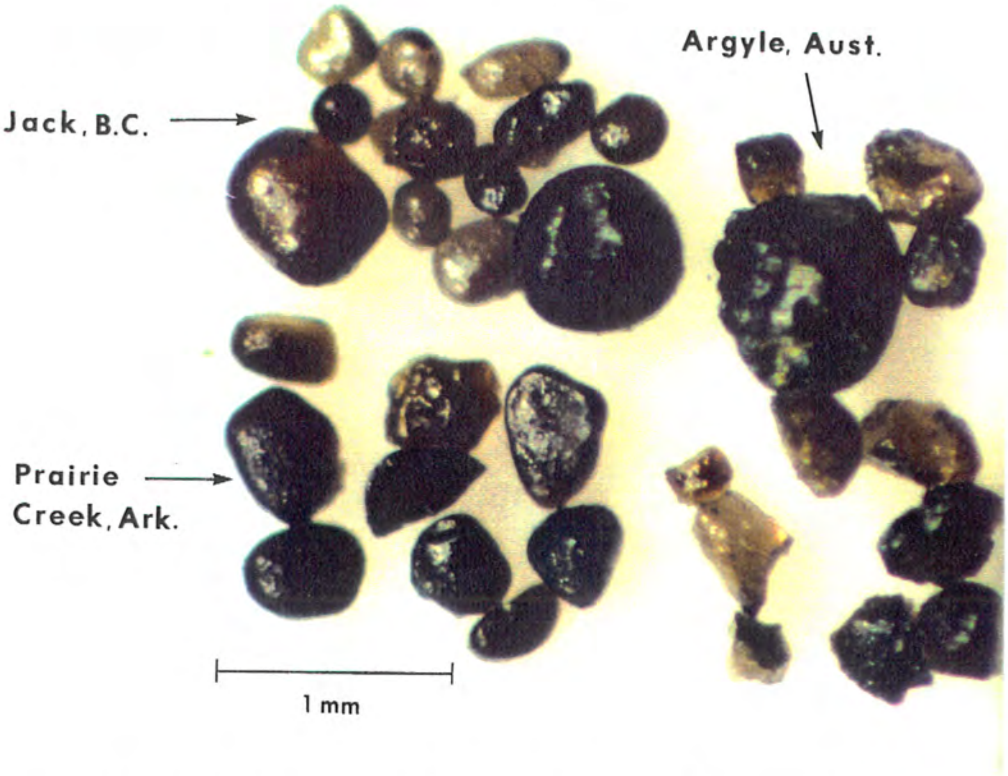


Plate 1 : Typical round to rounded or broken, light-brown translucent to dark nearly opaque tourmalines from Argyle, Aust., Jack, B.C. and Prairie Creek, Ark. lamproites.

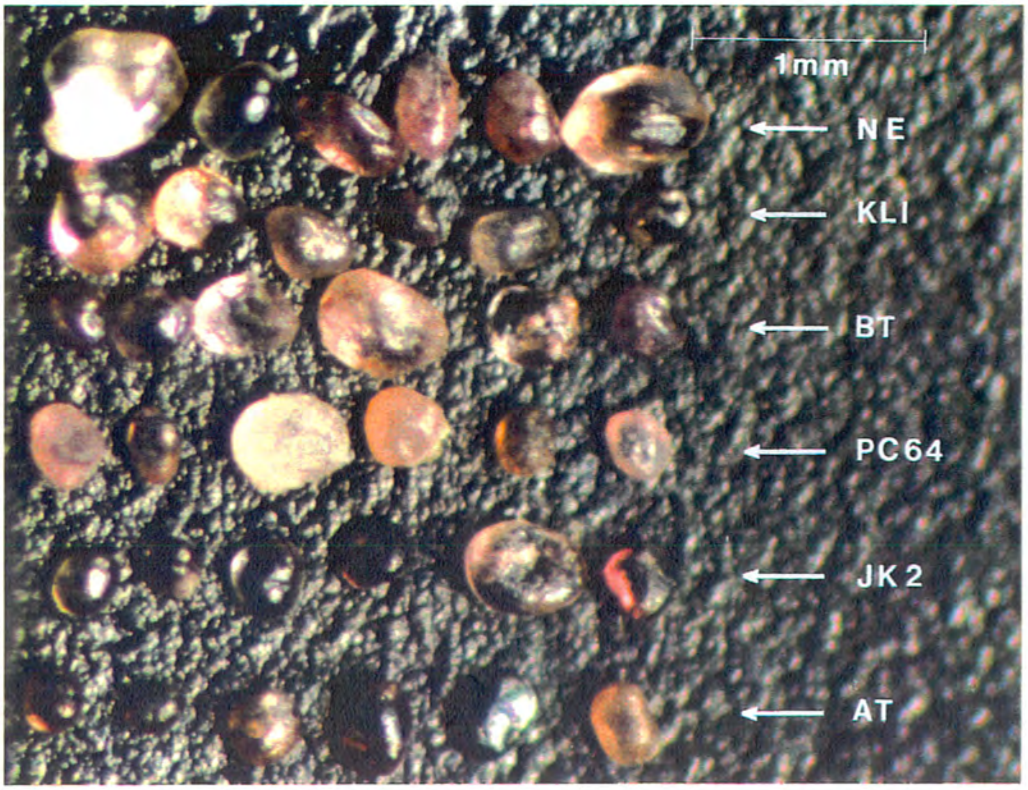


Plate 2: Photomicrographic of typical round to rounded light pink to purple zircons from NE (New Elands, S.A.), KLI (Kirkland Lake Ont.), BT(Baltey, N.W.T.), PC64(Prairie Ck, Ark.) JK2(Jack, B.C.) and AT (Argyle, Aust.).

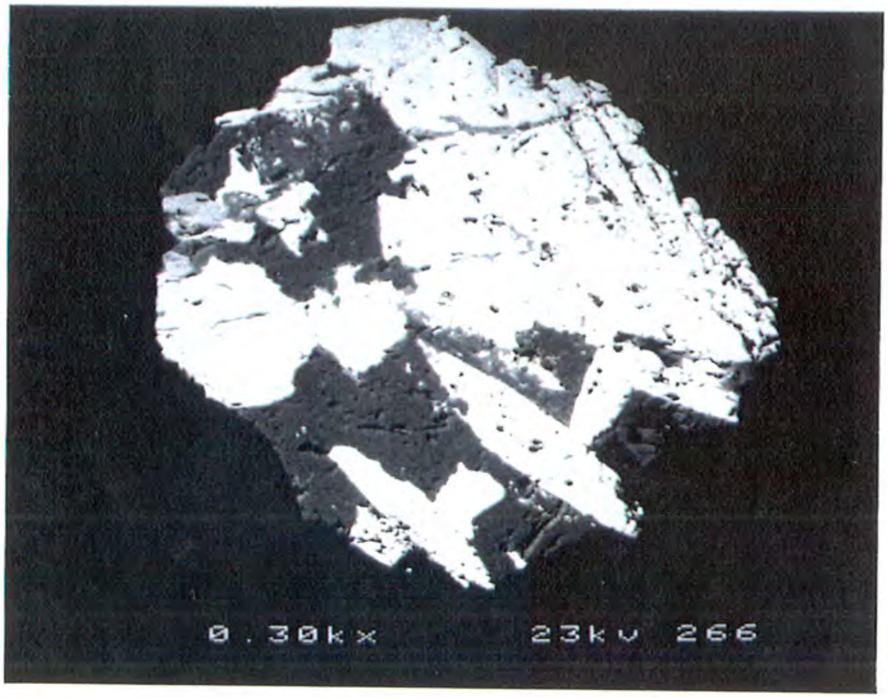


Plate 5: S.E.M. Backscatter photomicrograph (300X) of intergrowth of niobium rutile (light grey) and titanferous dolomite (dark) from Jack B.C. phase 2 lamproites. The rutile contains tiny (whitish) blebs of unidentified Nb-Ti-W-Fe and Zr-Ti-Fe silicate minerals.

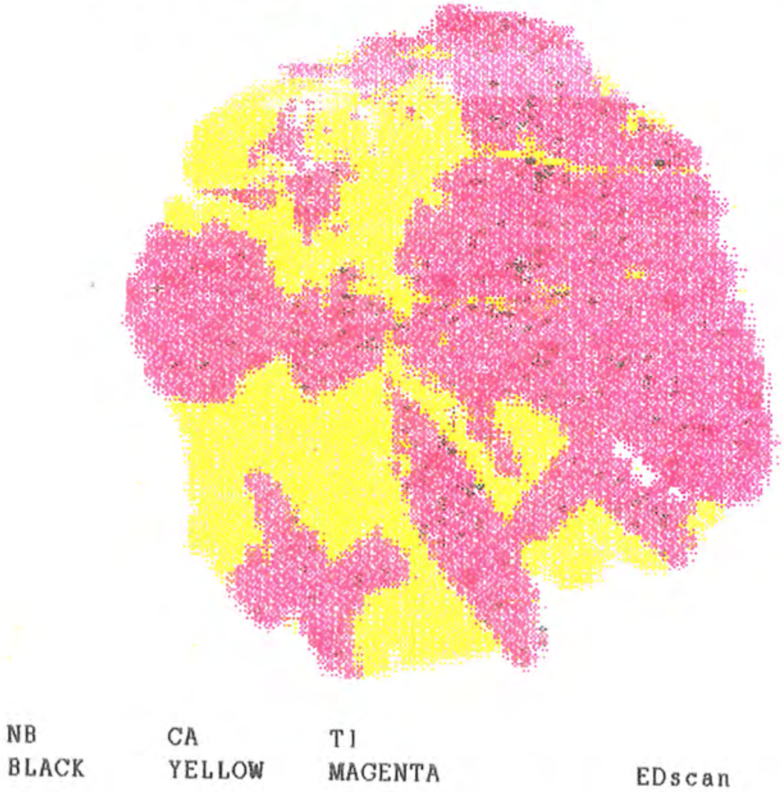


Plate 6: X-ray scan of plate 5 (300X) illustrating distribution of Nb minerals(black) in rutile(red). The compositions of all the mineral phases are given in mineralogic appendix (JK2-4534 results).

Plates to accompany Appendix 9.1 (Part III)(on microfiche)

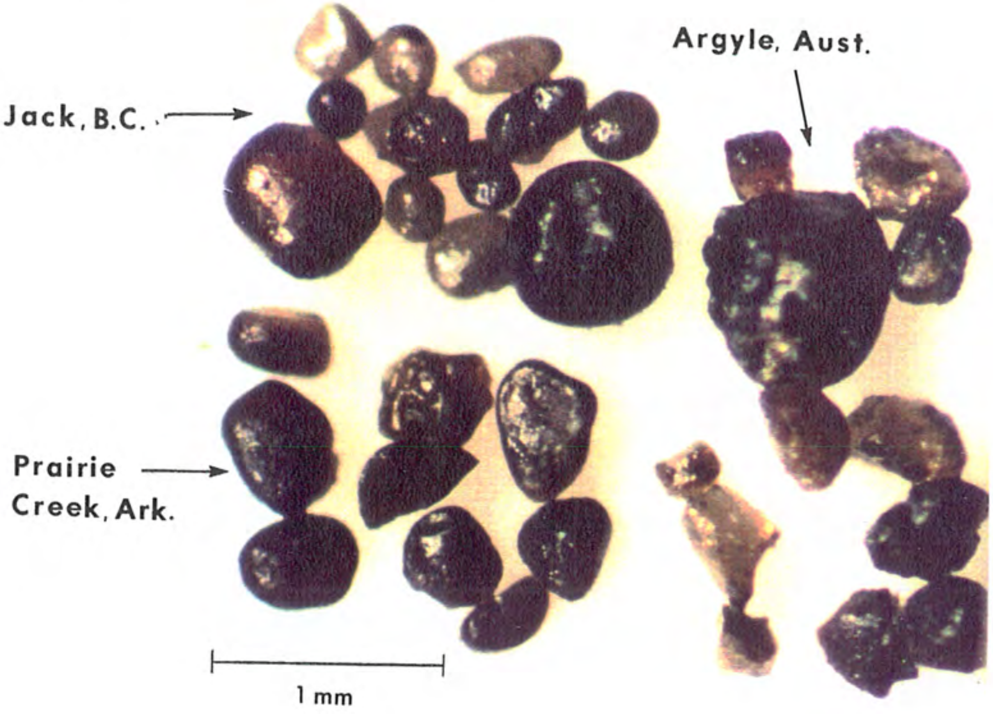


Plate 1 : Typical round to rounded or broken, light-brown translucent to dark nearly opaque tourmalines from Argyle, Aust., Jack, B.C. and Prairie Creek, Ark. lamproites.

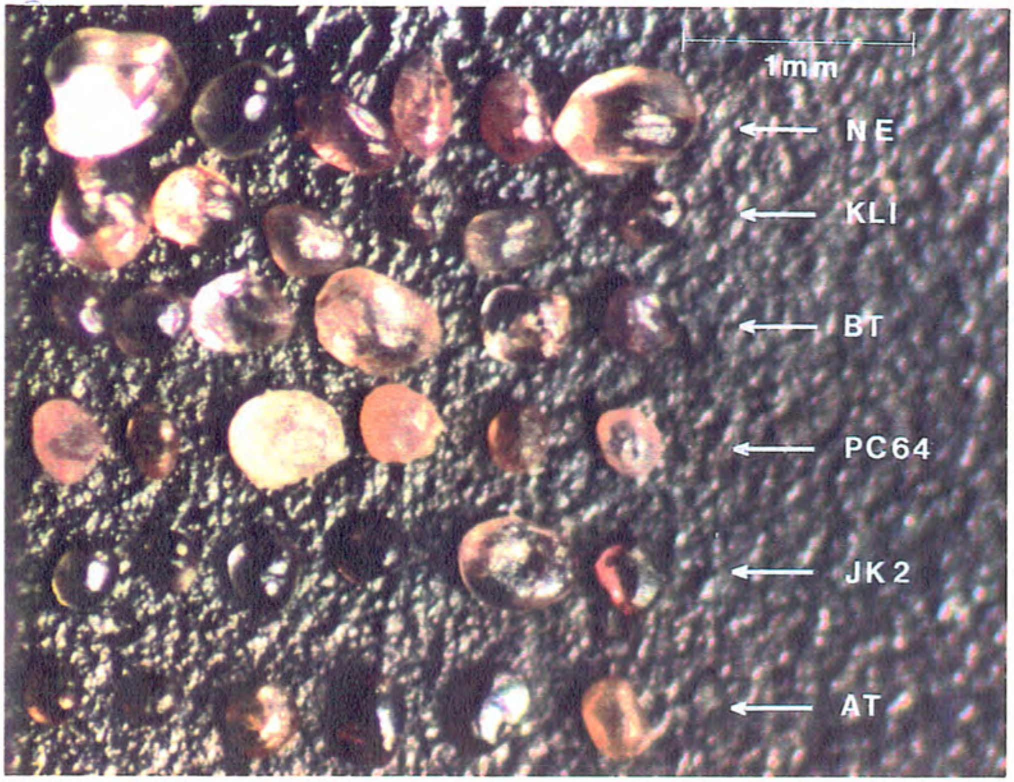


Plate 2: Photomicrographic of typical round to rounded light pink to purple zircons from NE (New Elands, S.A.), KLI (Kirkland Lake Ont.), BT(Baltey, N.W.T.), PC64(Prairie Ck. Ark.) JK2(Jack, B.C.) and AT (Argyle, Aust.).

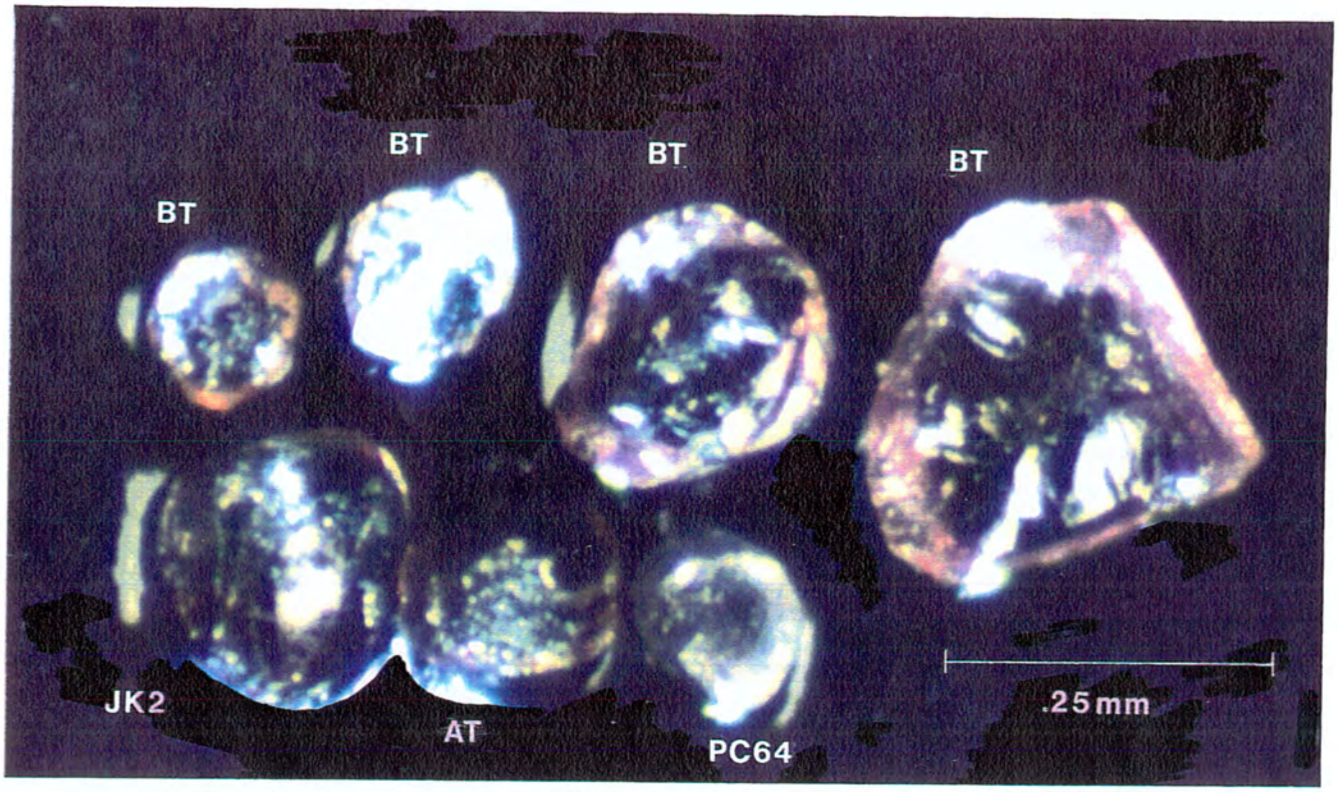


Plate 3: Photomicrograph (173X) of zircons with light pink to purple overgrowth on round to rounded clear to light pink zircon cores-from BT(Battey, N.W.T), PC64 (Prairie Creek, Ark.), AT Argyle, Aust. and JK2(Jack, B.C.).

Plate 4: Amber colored, rounded zircon macrocrysts with whitish alteration rims from the (SK) Saskatchewan Sturgeon Lake, kimberlite. Although such zircons are frequently present in Southern African kimberlites, zircon macrocrysts were only present in the SK kimberlite sample.

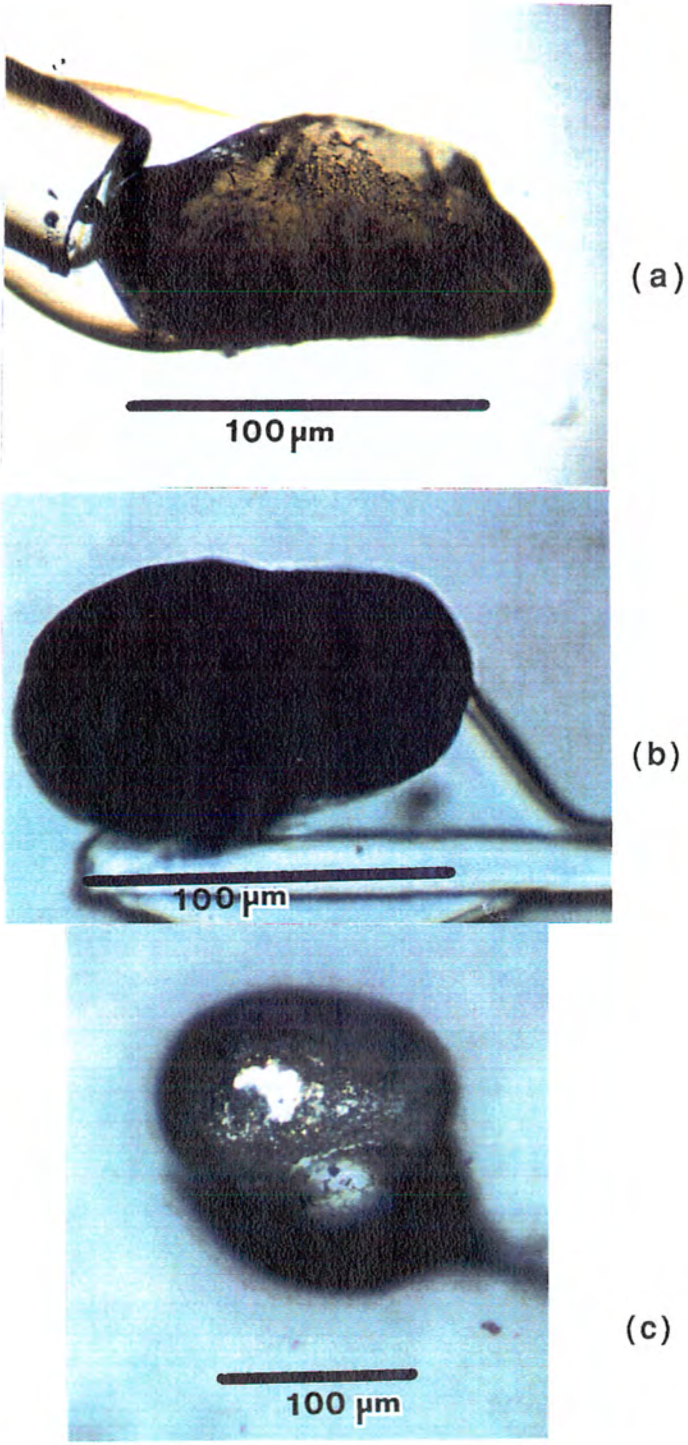


Figure 1. Optical micrographs: (a) natural transmitted light of yellow dravite grain. (b) transmitted light of opaque rutile grain. (c) reflected light rutile grain show in (b) and in fig. 4a All three grains are mounted on glass fibers which were used to support them in the Gandolfi x-ray camera.

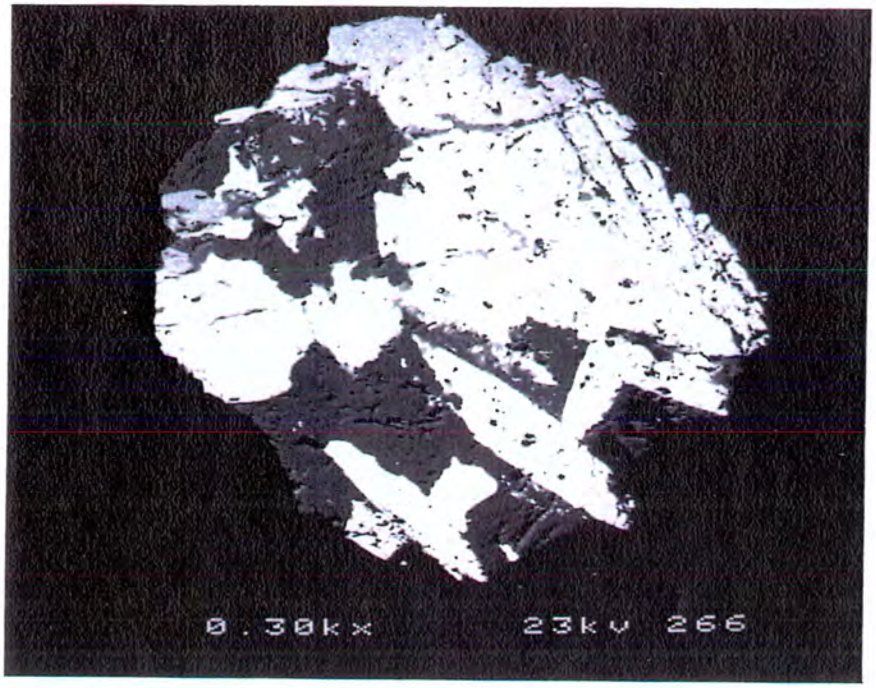


Plate 5: S.E.M. Backscatter photomicrograph (300X) of intergrowth of niobium rutile (light grey) and titanferous dolomite (dark) from Jack B.C. phase 2 lamproites. The rutile contains tiny (whitish) blebs of unidentified Nb-Ti-W-Fe and Zr-Ti-Fe silicate minerals.

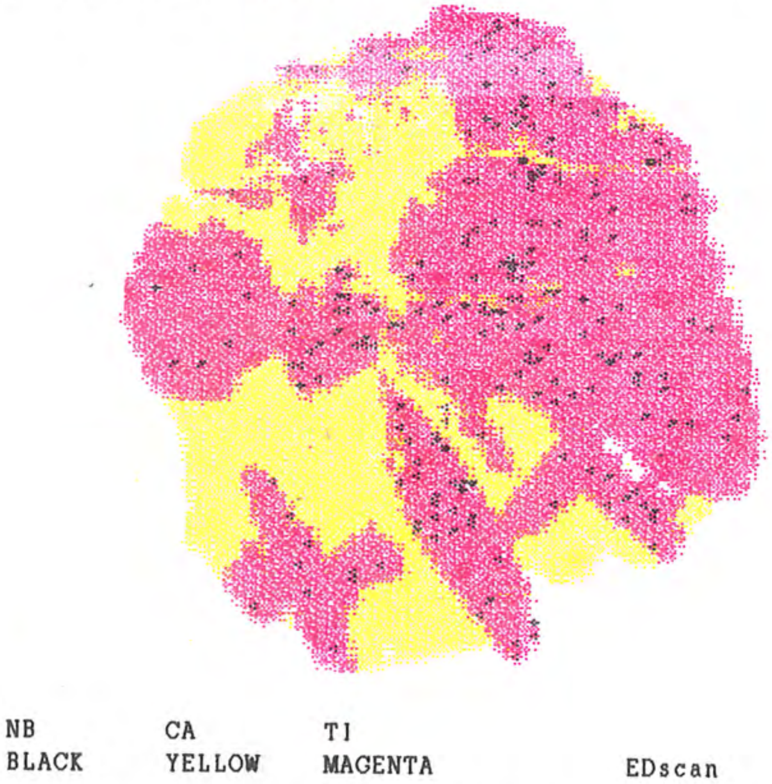


Plate 6: X-ray scan of plate 5 (300X) illustrating distribution of Nb minerals(black) in rutile(red). The compositions of all the mineral phases are given in mineralogic appendix (JK2-4534 results).

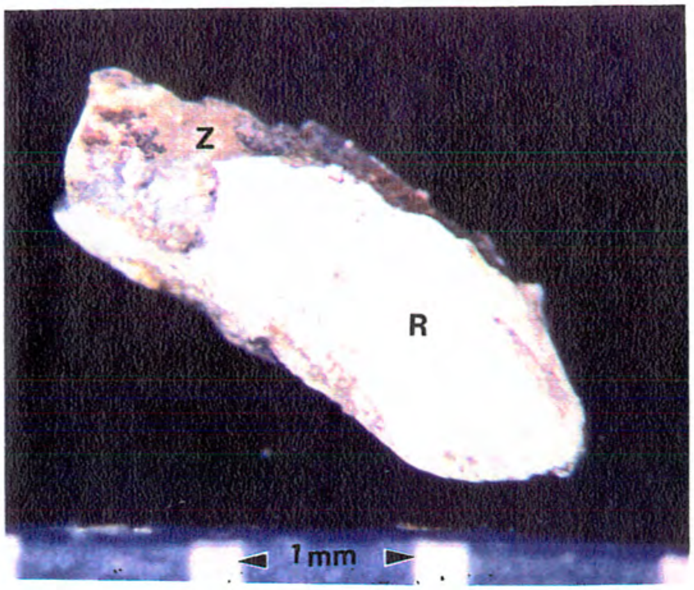


Figure 4a.

Optical micrograph of zircon grain #2 (Z) from dike 170, Leshotho, showing kelyphitic rim (R).

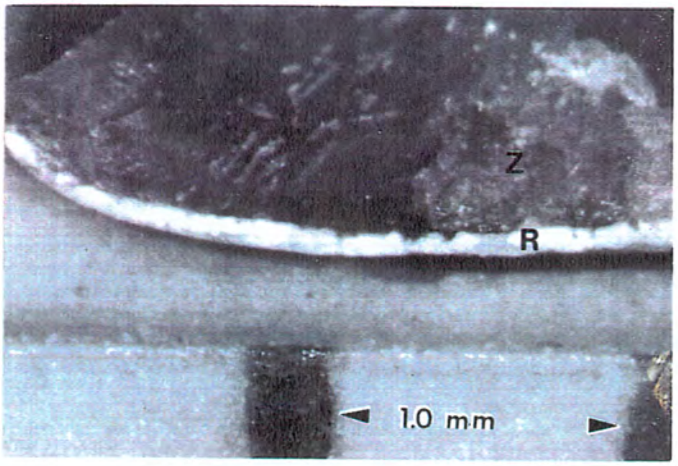


Figure 4b.

Optical micrograph of cross-section of zircon (z) showing the thickness of the kelyphitic rim (R).

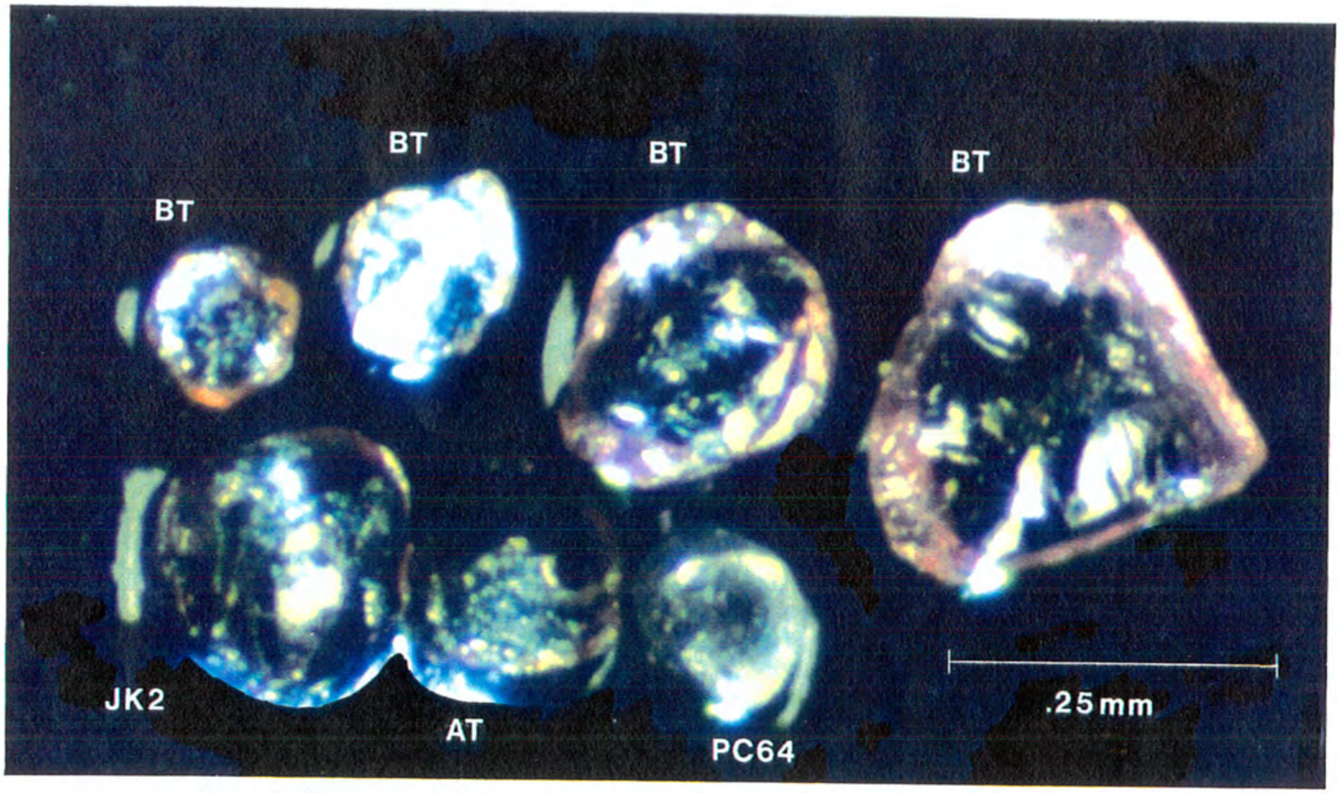


Plate 3: Photomicrograph (173X) of zircons with light pink to purple overgrowth on round to rounded clear to light pink zircon cores–from BT(Battey, N.W.T), PC64 (Prairie Creek, Ark.), AT Argyle, Aust. and JK2(Jack, B.C.).

Plate 4: Amber colored, rounded zircon macrocrysts with whitish alteration rims from the (SK) Saskatchewan Sturgeon Lake, kimberlite. Although such zircons are frequently present in Southern African kimberlites, zircon macrocrysts were only present in the SK kimberlite sample.