PETROGENESIS OF KIMBERLITES AND
ASSOCIATED POTASSIC LAMPROPHYRES
FROM CENTRAL WEST GREENLAND

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DECLARATION

I hereby declare that all the work presented in this thesis is my own, except where stated within the text, and that the thesis has been composed by myself.

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ABSTRACT

The geology of kimberlites and other potassium-rich magnesian rocks is reviewed.

The post-tectonic Holsteinsborg dykes were formed by numerous injections of magma. The kimberlites have megacrysts of olivine, phlogopite, picroilmenite and rare pyrope-garnet in a groundmass of olivine, phlogopite, perovskite and spinel. The potassic lamprophyres have megacrysts of pseudoleucite, olivine, phlogopite and diopside set in a fine-grained groundmass which may include phlogopite, potassic richterite, diopside and sanidine. All the dykes contain abundant primary carbonate and serpentine.

The whole-rock geochemistry of the Holsteinsborg dykes demonstrates a very wide range of composition, particularly in MgO and K₂O. The kimberlite dykes have all the characteristics of micaceous hypabyssal-facies kimberlites. The lamprophyres are characterised by high K₂O contents (up to 10 wt%) and are distinguished from the kimberlites by higher SiO₂, K₂O, Al₂O₃, Na₂O and P₂O₅ but lower MgO, CaO, MnO and H₂O⁺. All the dykes are rich in volatiles, especially *CO₂. The dykes also have high concentrations of Sr, Rb, Y, Zr and Ba relative to other ultrabasic rock types.

The inclusions found in the kimberlite dykes are dominated by dunites, which is unusual in comparison with inclusion suites from other kimberlites. Lherzolites, wehrlites, harzburgites, garnet-granulites and eclogites are also found.

It is proposed that a kimberlitic magma was formed from a partial melt of a phlogopite-carbonate-peridotite at a depth of over 170km. After olivine fractionation, multiple injections of magma formed the kimberlite dykes. The lamprophyres formed from another portion of

the initial kimberlitic magma by extensive olivine plus spinel fractionation followed by a low pressure fractionation when leucite and the other megacryst phases crystallised. In all the dykes a residual or immiscible carbonatitic fluid was generated during eruption. It is suggested that the carbonatitic fraction of these dykes plays an important role in their genesis.

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CHAPTER 1 A GENERAL DESCRIPTION OF KIMBERLITES AND POTASSIUM-RICH
MAGNESIAN HYPABYSSAL AND EXTRUSIVE ROCKS

Kimberlites and potassic lamprophyres both have extreme and unusual compositions and it has been suggested that they may be genetically related. The first section of this chapter gives a comprehensive description of kimberlites and the subsequent section discusses potassium-rich magnesian rocks, but in less detail.

1.1. KIMBERLITES

1.1.1 Introduction

Kimberlites are of particular interest because of the occurrence of the accessory mineral diamond and the inclusion of ultrabasic nodules which give some direct information about the nature of the mantle. Kimberlite is an ultrabasic rock which occurs in small intrusions which are volumetrically insignificant but geographically widespread.

1.1.2 Literature Review

The discovery of the major South African kimberlite intrusions between about 1870 and 1930 resulted in a large amount of information being produced on kimberlites. Among the earlier reports were those of Lewis (1887,1888) and Du Toit (1906). Much of the accumulated information was collected in two detailed works by Wagner (1914) and Williams (1932).

After this period of activity in kimberlite research, little work was produced until the 1950's. In 1954 the discovery of

the kimberlite province of Yakutia, Russia led to the production of two major volumes, the first being a monograph on Siberian kimberlites (Bobrievich et al. 1957) which was followed in 1959 by the "Diamond deposits of Yakutia" (Bobrievich et al. 1959). This discovery resulted in a revival of interest in kimberlites. It is impossible to briefly review all the recent literature but some of the ideas and more important publications are summarised in the following description of kimberlites. Several useful reviews have also been published by Dawson (1967a, 1967b, 1968 and 1971a) and another good collection of data and discussion is given in Wyllie (1967).

In late 1973 the first International Kimberlite Conference was held in South Africa. The extended abstracts and the proceedings (Physics and Chemistry of the Earth Vol.9, 1975) both provide an excellent and comprehensive outline of current research in this field. Coincident with the kimberlite conference was the publication of a volume on Lesotho Kimberlites (Nixon 1973).

A Kimberlite Symposium was held in Cambridge, England in 1975 (organised by J. B. Hawthorne, De Beers Consolidated Mines Ltd., Kimberley, South Africa) and the abstracts are a summary of the research subsequent to the 1973 kimberlite conference.

1.1.3 Definition

The term kimberlite was first proposed by Lewis (1888) when describing the "matrix of diamond" at its type locality at Kimberley, South Africa.

A number of definitions have been suggested but none has been completely satisfactory because it is difficult, in one simple definition, to encompass the large variety of rock types which are

generally accepted as being kimberlites. This variability is a characteristic of kimberlites.

The best definition to date is probably that proposed by Dawson (1971a) : "kimberlite is a very rare, potassic, ultrabasic, hybrid igneous rock that occurs in small diatremes, or in dykes and sills of limited extent. It has an inequigranular texture, the porphyritic aspect being due to megacrysts of olivine, enstatite, chrome diopside, pyrope, picro-ilmenite and phlogopite, set in a finer-grained matrix of which serpentine, carbonates, phlogopite, magnetite and perovskite form the major part. Many of the megacrysts are derived from fragmentation of mantle-derived garnet lherzolite (blocks of which are embedded in the kimberlite) and are in various stages of reaction with the kimberlite matrix. The matrix may, or may not, contain diamond; even in the most diamondiferous kimberlites, diamond is a very rare and widely dispersed mineral".

1.1.4 Petrography and Mineralogy (largely after Dawson 1967a and Mitchell 1970)

Kimberlite characteristically has an inequigranular texture containing megacrysts (i.e. crystals significantly larger than the groundmass minerals) of olivine, phlogopite, garnet, magnesian ilmenite, enstatite and chrome diopside which are often rounded, corroded and metasomatically altered. The incorporation of xenolithic fragments into kimberlite gives it a complex and hybrid mineralogy.

The finer grained kimberlite matrix is made up of olivine (usually serpentinised), calcite, perovskite, spinel, phlogopite, apatite and ilmenite. A large number of other, less common, minerals have been recorded in kimberlite, for example, richterite (Erlank 1973),

zircon (Kresten 1973), monticellite (Clement, Gurney and Skinner 1975), sulphides (Haggerty, Boyd, Collerson and Gurney 1975). Diamond may occur as a rare accessory mineral.

Kimberlite also contains secondary minerals possibly due to autometamorphism, a function of P_{CO_2} , P_{H_2O} and temperature (Dawson 1971a). These minerals include serpentine, zeolites, amphiboles, hydro-micas, low-temperature sulphates and carbonate.

The characteristics of the common kimberlite minerals are summarised below.

Two generations of olivine, often serpentinitised, are commonly found and have compositions of Fo_{92-88} . The olivines are usually rounded but the smaller second generation olivines which occur in the groundmass are more often euhedral.

Kimberlite micas are usually phlogopite, often rich in titanium, which occur both as megacrysts and in the groundmass. These phlogopites, particularly the larger crystals, show corroded, bleached and rounded margins and are sometimes zoned.

Garnet occurs as megacrysts that usually have the composition of chrome pyrope, a variety of garnet found in only a few rock types and therefore useful as a kimberlite indicator mineral. Other varieties of garnet found in kimberlites are thought to be derived from fragmented inclusions of peridotite, eclogite and granulite (Nixon, von Knorring and Rooke 1963).

Pyroxenes are usually enstatite, En_{92-94} , and chrome diopside which, together with some garnets, are thought to be derived from ultrabasic inclusions.

Ilmenite often occurs as rounded crystals that typically have high magnesia contents. Magnetite occurs both as primary

ehedral crystals and as a product of serpentinisation of olivine. Haggerty (1973, 1975a, 1975b) and Clarke and Mitchell (1975) studied kimberlite opaque minerals in detail and revealed a large variety of types including the first terrestrial occurrence of armalcolite ($(\text{FeMg})\text{Ti}_2\text{O}_5$). The detailed and variable, but systematic, zonation found in the opaque minerals suggested wide and rapid fluctuations of the oxygen fugacity within the kimberlite as well as the existence of late-stage titanium-rich fluids in the majority of kimberlites.

Calcite is a very common groundmass constituent and much of it is regarded as being primary, although it is probable that some is the result of alteration. Dolomitic carbonates are also found.

1.1.5 Geochemistry

Kimberlites are a group of ultrabasic rocks which have a distinct chemistry although they include a wide range of compositions. They have affinities with, or are gradational into, alnoites and carbonatites. Kimberlite compositions show apparent evolutionary trends (e.g. Danchin et al. 1975) despite contamination of the initial kimberlite liquid by xenolithic material from the crust and mantle (as shown by Fesq, Kable and Gurney 1975, for example). Kimberlites are sub-divided petrographically into basaltic and micaceous types and average whole-rock analyses for these types are given in Table 1.1, but there is however a complete gradation in chemistry between them. Some characteristics of kimberlite geochemistry are summarised below (partly after Dawson 1967b).

(a) Major Oxides

SiO_2 : Kimberlites are undersaturated rocks with silica content less

	Basaltic kimberlite	Micaceous kimberlite
SiO ₂	35.2	31.1
TiO ₂	2.32	2.03
Al ₂ O ₃	4.4	4.9
FeO (total)	9.8	10.5
MnO	0.11	0.10
MgO	27.9	23.9
CaO	7.6	10.6
Na ₂ O	0.32	0.31
K ₂ O	0.98	2.1
H ₂ O+	7.4	5.9
P ₂ O ₅	0.72	0.66
CO ₂	3.3	7.1

Table 1.1 Average kimberlite analyses from Dawson (1971b) after
Dawson (1960)

than 40 wt%, the majority being around 30 wt%.

TiO_2 : Titania is present in unusually high amounts for such ultrabasic rocks (up to 4 wt%), the values being more in keeping with alkalic rocks and carbonatites.

Al_2O_3 : Alumina is variable (2 - 7 wt%), but usually occurs in greater amounts than in other ultrabasic rocks.

FeO and Fe_2O_3 : Values for the iron content are similar in amount to those of ultrabasic and basic rocks (total FeO being 5 to 12 wt%), but the oxidation state is different and varies directly with the water content. The $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio reaches values up to 7.5 while it is less than 1.0 in most peridotites, for example.

MgO : Magnesia occurs in variable amounts, commonly about 25 - 30 wt%, but often reaches 35 wt%.

CaO : Lime content is variable, up to 40 wt%, and rises with increasing CO_2 content as Ca is a component of calcite as well as several other kimberlite minerals.

Na_2O and K_2O : The soda and potash content are both usually less than 3 wt%. The average soda content is 0.3 wt% and the average potash content is usually greater, resulting in high $\text{K}_2\text{O}/\text{Na}_2\text{O}$ wt% ratios of between 2 and 5.

CO_2 and H_2O^+ : The carbon dioxide and fixed water contents are unusually

high (up to 15 and 10 wt% respectively), as compared with most other ultrabasic rocks.

P_2O_5 : The P_2O_5 content is often high (up to 1.5 wt%) when compared with other ultrabasic rocks.

(b) Minor Elements

Ni, Cr, Co and Ge contents in kimberlite are similar in amount to those found in other ultrabasic rocks. A second group of minor elements, which includes Li, B, Sc, V, Cu, Ga, Rb, Sr, Y, Zr, Cs, Nb, Ba, La, Ta and Pb, occur in greater amounts than are usual for other ultrabasic rocks. Characteristic minor trace element values for kimberlites are given in Dawson (1967b) and Kable, Fesq and Gurney (1975). Many of these higher concentrations of minor elements may reflect, through substitution, the greater amounts of the major elements Fe, K, Al, Ca and Ti relative to other ultrabasic rocks, for example, Zr for Ti and Sr and Y for Ca. This might also suggest that many of these elements are not truly incompatible as is often thought to be the case.

Kable, Fesq and Gurney (1975) suggest that micaceous kimberlites are characterised by higher concentrations of Nb, Zr, Hf, Sc, P, Sr, Th and U as well as REE, when compared with non-micaceous kimberlites.

(c) Isotope Chemistry

Powell (1966) suggested that the $^{87}Sr/^{86}Sr$ ratio for kimberlites ranged from 0.705 to 0.721 and similar values were suggested by Mitchell and Crockett (1971). In a preliminary study, Berg and Allsopp (1972) suggested a very low ratio for very fresh kimberlites.

Barrett and Berg (1975) confirmed a ratio of about 0.704 for fresh basaltic kimberlites and suggested that the spread to higher values is largely due to the effect of percolating groundwater. The assimilation of xenoliths provides another likely source of contamination.

Hydrogen and oxygen isotope data (Sheppard and Dawson 1975) indicate that meteoric-hydrothermal fluids interacted with the kimberlite during the serpentinisation process. Carbon isotope values for kimberlite (e.g. $^{12}\text{C}/^{13}\text{C}$ of 89.49 to 89.69, Vinogradov, Kroptova and Ustinov 1965) are similar to those of diamond and primary igneous carbonatites.

(d) Rare Earth Elements

Rare earth element (REE) abundance patterns for kimberlite, ^{(see} for example Haskin, Frey, Schmitt and Smith (1966)) show high total REE contents relative to other igneous rocks. There is also a very high concentration of light REE relative to heavy REE, which is distinctive of kimberlites. The major sites for REE are considered to be apatite, perovskite and carbonate (Mitchell and Brunfelt 1975).

These REE concentrations are different from those found in mantle-derived inclusions from kimberlites, and this has led to a debate as to whether kimberlitic magmas are direct partial melts or whether some fractional crystallisation is required to account for REE patterns. Fesq, Kable and Gurney (1975) believe selective formation and transport of volatile-REE complexes (e.g. Schilling and Winchester 1969) to be the dominant factor in controlling both the strong REE enrichment and the light REE / heavy REE fractionation observed in South African kimberlites.

1.1.6 Inclusions

Inclusions are characteristic of kimberlites, their type and concentration being variable. A suite of inclusions in a kimberlite can be considered as representing a composite section through the earth from the point of origin of that kimberlite within the mantle to the surface. Two main groups of inclusions are found:

- (1) Xenoliths consisting not only of angular blocks of high-level country rock but also rounded deeper-level crustal blocks of high grade metamorphic rocks, e.g. granulites, gneisses and schists.
- (2) Rounded ultrabasic blocks (nodules), for example peridotites and eclogites, usually considered to be derived from the mantle.

The origin of group (1) is self-evident. The origin of group (2), however, has been a matter of some dispute, but it is generally accepted that they are derived from the mantle. The two main groups of ultrabasic inclusions are peridotites and eclogites.

Peridotites consist mainly of olivine, enstatite, garnet and clinopyroxene. Textures are variable and the peridotite inclusions have, therefore, been sub-divided into sheared and granular types (Boyd and Nixon 1973a, Nixon and Boyd 1973a and MacGregor 1975) although a gradation between these two extremes has been suggested by Harte, Cox and Gurney (1975). Equilibration conditions of the minerals in sheared nodules seems to reflect higher pressures and temperatures than do those of the granular types. Inclusions from any one intrusion show a wide range of conditions of equilibration which indicates their accidental derivation from the mantle and theoretically allows the determination of palaeogeotherms (e.g. Boyd and Nixon 1975, MacGregor

1975, Dawson, Gurney and Lawless 1975). The principle of the deduction of palaeogeotherms from experimental and ultrabasic inclusion data seems to be agreed upon, but the method and results of such deductions is still a matter of some debate.

Eclogites comprise the other main group of ultrabasic inclusions which are made up largely of garnet and clinopyroxene. Like the peridotites they appear to be derived from a variety of depths, for example diamond-bearing eclogites are probably derived from regions where pressures are greater than 50kb (150km) while Harte and Gurney (1973) deduce a pressure of 35kb (100km) for the origin of eclogite from Roberts Victor Mine, South Africa.

In addition to these two main groups both discrete megacrysts and autoliths can be considered as inclusions in kimberlite.

Discrete megacrysts (or discrete nodules) are also thought to be of mantle origin. They are coarse (greater than 1cm) monomineralic crystals which are said to have a distinct morphology, colour and composition (Boyd and Nixon 1975). They have also been discussed by Nixon and Boyd (1973b), Bloomer and Nixon (1973) and Shimizu (1975), for example. Evidence presented at the Cambridge Kimberlite Symposium 1975 (e.g. Boyd; Danchin and Boyd) confirms that these megacrysts equilibrated at temperatures generally higher than the peridotite nodules. It was also proposed that these discrete megacrysts were igneous in origin and derived from a crystal mush in the upper part of the asthenosphere.

Lastly, the group of inclusions referred to as autoliths comprise nodular bodies which usually consist of a rock or mineral fragment nucleus encased in a fine-grained, frequently concentrically layered kimberlitic material. Their petrochemistry has

been discussed by Ferguson, Danchin and Nixon (1973) and Danchin, Ferguson, McIver and Nixon (1975) who conclude that autoliths represent kimberlite matrix which precipitated around solid nuclei during pipe development and have been erupted from depths greater than 100km.

1.1.7 Diamond

Kimberlite is the main, primary source of diamonds, although they are also found in alluvial deposits derived from the erosion of kimberlites. Diamonds are probably formed only in exceptional conditions of high pressures and temperatures. There must also have been suitable conditions within the kimberlite for the transportation of the diamond to the surface without it reacting or being resorbed.

Diamonds can contain a number of essentially mono-mineralic inclusions (Harris 1968). Many of these are in equilibrium with, and were incorporated in, the host diamond at the time of crystallisation and have subsequently been insulated from re-equilibration with their surroundings because of the relatively inert nature of diamond. As these inclusions are syngenetic with the diamond, their association gives evidence of the possible environment of crystallisation and leads to inferences about the nature of the earth's mantle.

Two suites of syngenetic oxide and silicate inclusions have been recognised - the peridotite and the eclogite suites - which are mineralogically and chemically linked to the equivalent two suites of mantle-derived rocks found in kimberlite (Prinz et al. 1975). Harris and Gurney (in press) consider that many of these inclusions have crystallised together with diamond but in a variety of magmas and under different pressures and temperatures. Evidence also suggests that these processes are common to all sub-continental regions which have been

sampled by kimberlites. There are, however, several chemical distinctions between many of the inclusions in diamonds and minerals from peridotite and eclogite xenoliths (e.g. Meyer and Boyd 1972). Harris and Gurney (in press) suggest that these features, along with the apparent lack of what are considered to be typical kimberlitic minerals (e.g. calcite, ilmenite, magnetite, phlogopite, perovskite) as inclusions in diamond, indicate that kimberlite only acts as a means of sampling both diamonds and xenoliths from different parts of the mantle and then transporting them to the surface.

Fesq, Bibby, Erasmus, Kable and Sellschop (1975) give evidence for sub-microscopic inclusions of parental magma in diamonds which contain variable amounts of H_2O-CO_2 -rich fluids and Fe-Ni-Cu-Co sulphides in addition to a major silicate phase.

1.1.8 Classification

Various schemes have been proposed to classify kimberlites (e.g. Lewis 1887, Wagner 1914). Dawson (1967a) put forward a classification in which he divided kimberlites into massive, intrusive breccias or tuffs and tuff-breccias. The massive kimberlite was subdivided into (i) basaltic - with olivine as the dominant phenocrystal mineral and (ii) micaceous - with mica constituting more than 5% of the phenocryst phases or a large part of the groundmass; a division which is still frequently used although the term 'basaltic' may be somewhat misleading. Dawson (1971a), however, suggested a modified classification which is more useful.

- (1) Diatrema-facies kimberlite - fragmental kimberlite cemented by massive kimberlite with included xenoliths, confined to diatremes.
- (2) Hypabyssal-facies kimberlite - massive kimberlite with no

xenolithic inclusions usually occurring as dykes and sills. Flow textures and magmatic-sedimentary structures are characteristic.

- (3) Sedimentary kimberlites - occur in the upper part of the diatreme in the vicinity of the crater, formed by the re-deposition and reworking of explosively extruded, kimberlite fragments.

1.1.9 Weathering

Kimberlites are susceptible to weathering, particularly in more tropical regions, often resulting in substantial alteration of minerals.

The following characteristic sequence occurs with increasing depth, as found in diamond mines in South Africa where the climate is conducive to weathering.

- (a) Yellow ground - almost completely decomposed kimberlite, usually a yellow or yellowish-brown soft rock with some of the more resistant kimberlite components remaining.
- (b) Blue ground - as (a) but decomposed to a lesser extent, generally a bluish, serpentine-rich matrix with remnant inclusions from the kimberlite.
- (c) Hardebanke - comparatively well preserved kimberlite.

It is possible to include these various types in the classification of kimberlites, but the distribution of these types is controlled only by the depth of surface weathering and percolating groundwater. In areas where the climate is not conducive to chemical decomposition, yellow ground is absent.

1.1.10 Types of intrusion and their field relations

Kimberlites occur not only as small diatremes up to two square kilometres in plan size, but also as sills, dykes and veins. The diatremes tend to occur in clusters, often along elongate zones, which have been suggested to be the surface expressions of a single kimberlite dyke at depth, as for example with the kimberlite vents in Lesotho (Dempster and Richard 1973). Dykes often occur in swarms with preferred strike. Idealised models of kimberlite intrusions have been proposed by Dawson (1971a) and Hawthorne (1975).

Kimberlite intrusions penetrate the surface to form explosion craters and can produce sedimentary kimberlites in the near-surface part of the pipe, as shown at Orapa, Botswana.

Below this crater zone, there is a zone of brecciated or fragmental kimberlite, as in examples from Sierra Leone. There are often concentrations of angular high-level country-rock xenoliths in this part of the pipe. Below this zone, the true, non-brecciated kimberlite occurs, containing the characteristic rounded ultrabasic inclusions with a relatively lower concentration of country rock. The pipe narrows with depth.

At depths of about 2-3 kilometres, the kimberlite pipes grade into dykes. These dykes infill deep fundamental fractures that often cut across the deepest known basement structures. The fractures often form a simple geometric pattern, sometimes intersecting to give areas of intense diatreme formation (Dawson 1970, Arsenyev 1962).

1.1.11 Distribution and tectonic setting

Kimberlite, despite being a rare rock type, has been found in most continental areas of the world. A map of the world

distribution is given by Dawson (1971a). The best known, largely diamondiferous and most concentrated kimberlites are those of South Africa and Russia (Yakutia). Reviews of the geographical distribution of kimberlites are given by Davidson (1967) for Russia and Watson (1967) and Meyer (1976) for North America.

Kimberlites are confined to non-orogenic continental regions, but their intrusion seems to be restricted to certain parts of these continental platform areas. Their occurrence often seems to be related to deep-seated tectonics which can result in groups of kimberlite intrusions having linear trends. A common factor of the structural setting of kimberlites seems to be epeirogenic uplift and the formation of deep-seated fracture systems (Dawson 1970). These areas are also characterised by low thermal gradients.

1.1.12 Age

It is apparent that kimberlite magmatism has occurred at several times during the earth's history, from the Precambrian to at least the Tertiary. Radiometric ages from groundmass phlogopites are generally consistent with the geologic age deduced from field relations. Some K/Ar dates are anomalous, being older than the sediments penetrated, but in some cases these dates were determined using xenolithic or xenocrystal material. Allsopp and Barrett (1975), however, attempted to obtain a more reliable Rb-Sr isochron method of dating using phlogopite, and some more reliable dates for certain South African kimberlites were obtained (80 - 150 my).

1.1.13 Emplacement

Different modes of emplacement, including, for example,

the intrusion of a crystal-mush or gas-bearing magma, have been suggested to account for the variety of types of occurrence of kimberlites. Du Toit (1907), Wagner (1914) and others have postulated the intrusion of kimberlite as a relatively cold breccia, largely to account for the lack of thermal effects on the adjacent country rocks.

Dawson and Hawthorne (1970) showed that the matrix of hypabyssal kimberlites was a hot liquid at the time of emplacement and, therefore, that kimberlite magmas persisted to high levels in the crust. It is now generally accepted that the motive power for diatreme emplacement is the expansion of high temperature gases within the kimberlite at depths of 2-3 km.

A composite picture of kimberlite emplacement was suggested by Dawson (1971a) and is quoted below.

"A composite picture of kimberlite emplacement would be that highly gas-charged kimberlite magma, containing within it xenocrysts and xenoliths, is intruded rapidly up a system of deep-seated fractures. The speed of ascent must have been sufficiently rapid to preclude sedimentation of the high density peridotite and eclogite xenoliths and also prevent total resorption or inversion of diamonds. The rapid ascent concept is also important, since it would rule out the possibility of incorporation of its 'non-peridotite' trace elements by wall rock transfer (Green and Ringwood 1967). Then at preferred points, where access to the surface is easiest, the kimberlites will break through to the surface from depths of 2-3 kilometres. Adiabatic expansion of the gases causes cooling and the explosion vent is enlarged and infilled by fluidised fragmental kimberlite, drilling upwards with a sand blasting effect and taking advantage of jointing; major blocks of country rock subside gently to form "floating reefs". In some diatremes, later gas

surges emplace later distinctive tuff columns or tuffisite dykes, while cavities in the vent may be infilled with quietly upwelling kimberlite that consolidates as massive kimberlite or cements clastic material to form kimberlite breccia. The overall picture is a diatreme rising above the general level of dyke intrusion, the surface expression probably being a crater with a tuff ring of fragmental kimberlite. If the crater contained a lake, tuff ring material washed back into the crater would form kimberlite shales and sandstones. There is also evidence that after the cessation of intrusive activity, the vent material settled and compacted in the diatreme, causing minor faulting or slumping."

Nixon (1973b) points out many features described in the Lesotho kimberlites volume (Nixon 1973a) which support and elaborate on this composite picture.

Clement (1975) suggested that immiscible carbonatitic liquids acted as the primary transporting fluid during the liquid-solid fluidized intrusion and emplacement of diatreme kimberlites. Lorenz (1975) and Woolsey et al. (1975) also suggested similar types of diatreme formation and included a suggestion that diatreme development was initiated by the action of groundwater.

1.1.14 Genesis

Du Toit (1906) suggested that "kimberlite has been produced by the shattering of various holocrystalline basic and ultrabasic rocks and the incorporation of this material in a magma of ultrabasic character".

Williams (1932) assumed "at some unknown depth there existed a reservoir of molten magma....which started to crystallise .. ultrabasic rocks....during which time the composition of the original

magma was undergoing changes until it eventually assumed the composition of a kimberlite magma".

Theories for the origin of kimberlites involving olivine-melilitite (often referred to as melilitite basalt) either by its hydrothermal alteration (Taljaard 1936) or by mixing with ultrabasic xenoliths and volatiles (Holmes 1936) have difficulty in explaining the high alkali contents found in kimberlites.

It is now generally accepted that kimberlites originated in the mantle, because of the occurrence of diamond and from experimental data on various high pressure inclusions found in kimberlite. There are still, however, several modern hypotheses for the genesis of kimberlite which must account for the precise nature of the processes and mutual relations between kimberlite magmas and their ultrabasic inclusions. Some of these ideas are summarised below:-

(i) Residual or fractional crystallisation hypothesis

This hypothesis has been put forward by O'Hara and Yoder (1967), O'Hara (1968), O'Hara, Saunders and Mercy (1975) and MacGregor (1970) for example, and suggests that fractional crystallisation, at high pressures, of the liquid produced by partial melting of garnet peridotite gives rise to bi-mineralic, eclogite accumulates and a series of silica-poor, alkaline, residual liquids, which have the geochemical characteristics of the groundmass of kimberlites. This gives rise to the association of nodules of garnet peridotite (a possible source rock and mantle material) with nodules of eclogite (a possible cumulate) in kimberlite (a possible residual fluid of high pressure fractionation). Garnet harzburgite and harzburgite inclusions are considered to represent residual mantle.

The relative concentration of certain elements, such as K_2O , TiO_2 and P_2O_5 is explained by enrichment through extensive eclogite

and/or olivine fractionating although additional phases in the source rock (e.g. phlogopite) and contamination by xenolithic inclusions may also be significant. Barrett (1975) concluded from strontium isotope data that garnet-peridotites of the type analysed cannot be a recent parent of eclogite.

(ii) Partial melting

Dawson (1971b) suggested that kimberlites may be formed by the partial melting of garnet peridotite. This mantle rock, however, is considered to contain small amounts of phlogopite and/or amphibole in order to account for the K_2O , TiO_2 , H_2O and numerous trace elements that are found to be concentrated in kimberlites. With this hypothesis the peridotite and eclogite nodules are accidental inclusions.

(iii) Zone refining

This mechanism has been suggested by Harris (1957) and Harris and Middlemost (1970) as being important in the evolution of kimberlites and they envisage a body of magma being generated at considerable depth and, being unstable, rising to the surface by 'solution-stoping' or 'zone refining'. The induced pressure gradient allows simultaneous solution of roof material and deposition at the base of the liquid body. Residual elements (those unable to substitute readily in the major mineral phases) will undergo continued enrichment, while the major components remain more or less in equilibrium between liquid and solid phases. The magma undergoes fractionation which increases the concentration of residual elements. There is also concentration of the volatiles H_2O , CO_2 and F.

Turner and Verhoogen (1960) suggest that, if

kimberlites and associated rocks originated by zone refining, they should be more abundant and, therefore, the limited volume of kimberlite is contrary to the expected results from this hypothesis. Carmichael, Turner and Verhoogen (1974) suggest that high $^{87}\text{Sr}/^{86}\text{Sr}$ values in a rock could reflect the previous operation of such a process but without the eruption of the magma. This hypothesis of zone refining, however, does not explain the presence of the ultrabasic inclusions in kimberlite or the suggested high speed of eruption.

(iv) Carbonatite reaction

Kimberlites are often considered to be genetically associated with other rock types, most commonly carbonatite and olivine-melilitite. Dawson (1960, 1967a) suggested that kimberlite may be the end product of interaction between the water-rich ankeritic fraction of a carbonatite magma and granitic crustal rocks. This theory, however, still has to account for the origin of the carbonatite magma and cannot explain the inclusion in kimberlite of diamond and ultrabasic nodules which were derived from regions with much higher pressures and temperatures than are found in the crust. Theories involving olivine-melilitite, for example by mixing with ultrabasic rocks and volatiles (Holmes 1936), cannot explain the high $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios found in kimberlite. The relationship of melilitite-bearing rock with kimberlites is still under discussion (e.g. Yoder 1975). It has also been suggested (e.g. Nixon and Boyd 1973b, Clement 1975) that a kimberlite magma itself might be made up of two components, possibly immiscible silicate and carbonatitic liquids.

None of these hypotheses explains the source of certain elements such as C, S, P and N (the latter found in diamond), although

diamond (Lang 1970) and apatite (Kable, Fesq and Gurney 1975) have been proposed as possible primary phases in the mantle. Studies of fluid inclusions in minerals indicate that CO_2 is an important volatile species associated with magmas. Eggler (1975), Mysen and Boettcher (1975a, 1975b) and Wyllie and Huang (1976) have suggested that magmas produced at depth by the partial melting of a CO_2 - and H_2O -bearing mantle may (i) contain abundant dissolved CO_2 and H_2O (ii) be silica-undersaturated (iii) co-exist with mantle peridotite over a wide range of pressures and temperatures, and (iv) be parental to kimberlites. Wyllie (in press) suggested that the CO_2 may be stored in the mantle as a carbonate (calcic dolomite). The probable presence of H_2O in the mantle is important with respect to the stability of hydrous phases such as phlogopite and amphibole.

1.2 POTASSIUM-RICH MAGNESIAN HYPABYSSAL AND EXTRUSIVE ROCKS

This review section discusses rocks which are not only mafic but also enriched in potassium and includes rocks covered by the rather broad term lamprophyre (e.g. minettes, monchiquites and vogesites) as well as assorted ultrapotassic mafic extrusive and hypabyssal rocks (e.g. orendites and cedricites). The nomenclature of potassium-rich mafic rocks is confused but the problem has been discussed by Métais and Chayes (1963), and Sørensen (1974) includes a useful glossary of alkaline and related rocks. The potassium-rich mafic rocks can broadly be divided into two groups:

- (a) Rocks that are rich in MgO (approximately 10-20 wt%) and generally silica undersaturated but having a high $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio relative to other basic and ultrabasic rocks. The excess potassium is commonly

contained in phlogopite and/or interstitial glass. This group, which includes such rocks as madupites, alnoites, melilitites and many lamprophyres, is characterised by a mineralogy of olivine, phlogopite, perovskite and possibly melilite with an absence of felsic minerals. These rocks are chemically and mineralogically allied to kimberlites and the latter might be considered as the MgO-rich (greater than 20 wt%) extremes of this group.

(b) In contrast, the second group of potassium-rich mafic rocks are slightly silica saturated. They generally have lower MgO and higher K_2O contents than the previous group and also have unusually high K_2O/Na_2O ratios. The potassium is contained largely in leucite, sanidine or phlogopite, and these minerals together with diopside, potassic amphibole, spinel, glass and olivine (with reaction rims of phlogopite) are common constituents of these rocks. This group includes, for example, the rock types cedricite, wyomingite, orendite, wolgidite, fitzroyite and jumillite. The silica saturated nature of these mafic rocks is reflected not only in the occurrence of felsic minerals and often by the presence of sanidine rather than leucite in the groundmass, but also by the occurrence of hy (and sometimes even qtz) in the norm which in the mode is concentrated in the highly siliceous interstitial glass. Examples of rock types from this group have been described from the Leucite Hills, Wyoming (Carmichael 1967b) and West Kimberley, Australia (Wade and Prider 1940).

Sahama (1974) subdivides potassium-rich alkaline rocks into those of (i) orenditic or (ii) kamafugitic affinities, which largely correspond to the above division into silica saturated and silica undersaturated groups. These groups may be gradational in their characteristics and in certain instances rocks from the two groups may have been derived from the same initial magma. Wade and Prider (1940),

for example, suggest that madupite represents an early crystallisation phase (diopside and phlogopite) of a magma where the residual liquid gave rise to wyomingite and orendite.

These potassium-rich magnesian rocks in general occur in localised provinces in similar structural environments to kimberlites. They have remarkable trace element patterns with extreme concentrations of elements characteristic elsewhere of both ultrabasic rocks, e.g. Cr and Ni, and of highly fractionated rocks, e.g. Rb and Zr. The strontium isotope compositions of the potassium-rich mafic rocks also display anomalies and there is little agreement on their genetic implications. Many of the older ideas for the genesis of these rocks (summarised by Turner and Verhoogen 1960) involved the assimilation of granitic crustal material into a basic magma but the hypothesis seems unlikely as such assimilation would dilute the Cr and Ni contents. Recent theories about the genesis of these rocks have been discussed by Sahama (1974) and many of them involve partial melting and differentiation and some relate to a potassium-rich source rock. Simple models of fractional crystallisation (e.g. Cundari and Le Maitre 1970) have been proposed for the origin of some of these rocks but these models often encounter difficulties when considering the trace element chemistry (Carmichael, Turner and Verhoogen 1974). Many of the characteristics of the potassium-rich undersaturated rocks are reminiscent of kimberlites which might indicate that they have some particular petrogenetic processes in common.

Lamprophyres: Lamprophyres are mafic rocks grouped together largely on the basis of their distinctive textures; they are strongly porphyritic with ferromagnesian silicates occurring as crystals of two generations, with feldspar (if present at all) confined to the groundmass (Carmichael, Turner and Verhoogen 1974). Lamprophyres are an ill-defined

group of rocks and, therefore, the term covers a variety of rock types which can include members of both the sub-groups of potassium-rich mafic rocks discussed earlier in this section.

Lamprophyres typically occur as narrow dykes. Chemically, they have low SiO_2 (40-47 wt%), high (MgO+FeO) and high ($\text{Na}_2\text{O}+\text{K}_2\text{O}$) and are also rich in volatiles. Hornblende, biotite and augite commonly occur but some lamprophyres contain abundant mica which is reflected in relatively high K_2O values, i.e. potassic lamprophyres. Many lamprophyres, e.g. camptonites, are relatively soda-rich and therefore not relevant to this discussion. Several modes of origin are required to explain the genesis of these rocks grouped together in rather an arbitrary way and called lamprophyres. The occasional apparent gradation of mica-, or potassic-, lamprophyre and kimberlite (e.g. in the Navajo Butte area of Arizona, Williams 1936) seems to indicate that certain petrogenetic processes might result in the formation of kimberlites and/or potassic lamprophyres.

Lamproites: Lamproite is a term often used to describe some of these potassium-rich mafic rock types. Lamproite was defined by Troger (1935) as a potassium- and magnesium-rich lamprophyric rock including the rock types jumillite, madupite, orendite, verite and wyomingite. In current usage the term is often synonymous with potassic lamprophyre. Wade and Prider (1940) have used the term lamproite (as defined by Troger 1935) to embrace particular rock types found at West Kimberley, all of which are silica saturated.

Nomenclature in potassium-rich mafic rocks is complicated, so for clarity a few relevant terms are defined together with their main source references.

- CEDRICITE a porphyritic rock (lamproite) with diopside and leucite phenocrysts in a fine-grained groundmass in which magnophorite, phlogopite or sanidine may be present. Pseudomorphs after olivine may occur. (Wade and Prider 1940)
- FERGUSITE a pseudoleucite-bearing rock possibly with olivine, biotite, augite, orthoclase, nepheline and apatite. (Pirsson 1905)
- FITZROYITE a porphyritic rock (lamproite) with phenocrysts of phlogopite and leucite. No olivine is present. Leucite or sanidine may occur in the groundmass. (Wade and Prider 1940)
- KERSANTITE a lamprophyre with essential plagioclase and biotite. (Tröger 1935)
- MADUPITE a rock with diopside and phlogopite phenocrysts in a fine-grained groundmass of diopside, leucite and apatite. Olivine is not found. (Cross 1897 and Carmichael 1967b)
- MAMILITE a fine-grained magnophorite-leucite-lamproite with the groundmass including rare diopside and phlogopite and the occasional altered olivine. (Wade and Prider 1940)
- ORENDITE a rock with phenocrysts of phlogopite in a matrix of diopside, apatite and both leucite and sanidine (Cross

1897 and Carmichael 1967b)

WOLGIDITE

a comparatively coarse-grained rock (lamproite) characterised by poikilitic textures. The main constituents are magnophorite, phlogopite, diopside, rutile, sanidine and a serpentinous base. (Wade and Prider 1940)

WYOMINGITE

a rock with phenocrysts of phlogopite in a groundmass of leucite, diopside and apatite. Sanidine does not occur. (Cross 1897 and Carmichael 1967b).

2.1 Introduction

This study was initiated with the co-operation of Dr. J. Watterson (University of Liverpool), whose Liverpool Geological Boundary Programme has recently been concerned with the geology of the basement rocks in the area of Holsteinsborg, Central West Greenland.

The field area is situated in Central West Greenland as shown in Figure 2.1. The main part includes the mainland and islands between Holsteinsborg and Itivdleq, 40km to the south. A few localities were also visited in the region of Sarfartup Nuna, at the northern limit of the Sukkertoppen Iskappe.

Sampling of the dykes was carried out by joining the Liverpool geology programme for part of their field season in 1973.

This study is mainly concerned with the whole-rock geochemistry and mineral chemistry of the kimberlite and lamprophyre dykes from the Holsteinsborg area. It was decided to concentrate on the whole-rock geochemistry of these dykes for four reasons:

(i) No detailed geochemical studies have been completed on the matrices of kimberlites as research has been focused mainly on the diamond and mantle-derived inclusions found within kimberlite. This lack of attention, which was also apparent at the First International Kimberlite Conference 1973, might be attributed to the complex nature of the kimberlite matrix. Other problems in considering the whole-rock geochemistry of kimberlites arise from their

characteristic inhomogeneous nature, possible xenolithic content and the extreme compositions of these rocks.

(ii) The Holsteinsborg dykes are extremely fresh, particularly in contrast to many South African and other kimberlite occurrences.

(iii) A few preliminary whole-rock analyses indicated a very wide range of compositions within the Holsteinsborg dykes. The dykes appeared to include not only kimberlites but also lamprophyres, many with unusually high concentrations of potassium.

(iv) The Holsteinsborg kimberlite and potassic lamprophyre dykes are related in both space and time (although the relationship, with respect to time, is not closely defined). This situation provided an opportunity to study the well-documented, but generally little understood, association of kimberlites with other alkaline mafic rocks. The problem was summarised by Sahama (1974) in the statement "it is tempting to relate ultrapotassic-magnesian rocks with kimberlites but it is as debatable as the kimberlite problem itself."

2.2 Notes on terminology

To avoid ambiguity in this study the use of certain terms are defined.

Kimberlite and potassic lamprophyre

The term 'kimberlite' is used according to the definition in Section 1.1.3 of Chapter 1. The use of the term 'lamprophyre' is fairly general in this study and is based on the description given in Section 1.2 of Chapter 1. Some of the Holsteinsborg dykes contain megacrysts of pseudoleucite and should, therefore, strictly not be called

lamprophyres. All the non-kimberlite Holsteinsborg dykes will, however, be grouped together and called potassic lamprophyres, but it is not suggested that the use of the term lamprophyre should otherwise be extended to include rocks with felsic phenocrysts. The nomenclature of the Holsteinsborg dyke rocks is discussed in more detail in Chapter 6.

Megacryst, phenocryst, xenocryst and aphyric

Megacryst refers to a large crystal which is significantly larger than the matrix. This term can be used for both cognate and accidentally included material. In this study the megacrysts are generally greater than 2mm in size.

Phenocryst is a megacryst which is cognate, usually representing an early stage of crystallisation of a magma.

Xenocryst is a megacryst which is foreign to its host rock, often derived by mechanical breakdown of accidental, i.e. xenolithic, inclusions.

Aphyric is the term applied to a rock with no megacrysts and usually describes a fine-grained equigranular rock.

Inclusion and xenolith

The term 'inclusion' is used to describe solidified material, whether cognate or xenolithic, which has been disrupted and then included in the magma from which the host rock was derived. They may be referred to as blocks, fragments or nodules.

Xenoliths are accidental inclusions in a magma and are foreign to the rock in which they occur.

2.3 Discovery and previous work

Kimberlitic dykes were first found in this region during reconnaissance mapping in 1969 (Escher, Escher and Watterson 1970) and further examples were discovered in 1972 (Escher and Watterson 1973). Some individuals of this group of dykes, however, are probably first reported by Noe-Nygaard and Ramberg (1961) as kersantitic dykes during their reconnaissance mapping of West Greenland.

Bridgwater, Escher, Nash and Watterson (1973) mentioned the occurrence of kimberlitic dykes which appear to be concentrated in zones of intense Nagssugtoqidian deformation.

Escher and Watterson (1973) provided the only report specifically concerned with this suite of kimberlitic dykes. They report the intrusions as 0.5 - 2m wide and up to 1 - 2km in length, with consistent strike directions of 100-120°. They suggest that a typical dyke contains 20-35% of rounded, ultramafic inclusions, including dunite, harzburgite, wehrlite and lherzolite with eclogites abundant in only one dyke. The groundmass consists of carbonate, olivine, phlogopite, ilmenite, melilite, perovskite and spinel. They also noted the occurrence of carbonatite and mica-peridotite dykes.

2.4 Location of the kimberlite and potassic lamprophyre dykes

Most of the known kimberlite and potassic lamprophyre dykes occur in the coastal area between Holsteinsborg and Itivdleq, but a few dykes have been found north of the Sukkertoppen Iskappe. The main localities sampled are shown in Fig. 2.1 together with additional occurrences of associated dykes reported by Escher and Watterson (1973) but not visited during the course of this study. Particular rock samples are referred to using Liverpool Geological Boundary Programme sample

numbers and they are listed with their locality number in Appendix A. The precise position of each locality is given in Map 1 in the back pocket.

2.5 Geological setting

The known occurrences of the post-tectonic kimberlite and potassic lamprophyre dykes, in the region of Holsteinsborg, are confined to the southern part of the Nagssugtoqidian, which is younger than 2600 my, just north of the boundary with the older Archaean block. The general geology of the area is summarised from the literature; the main publications relevant to the geology of this area include Bridgwater, Escher and Watterson (1973), Bridgwater, Escher, Nash and Watterson (1973), Escher, Escher and Watterson (1970, 1975), Watterson (1974), Bak, Sørensen, Grocott, Korstgård, Nash and Watterson (1975), Escher, Jack and Watterson (1976) and the tectonic/geological map of Greenland (Escher et al. 1970).

The Nagssugtoqidian belt of West Greenland is formed mainly of Archaean basement gneisses which were strongly reworked during the early Proterozoic. Interlayered and folded relics of Archaean and early Proterozoic supracrustals occur locally. The reworked gneisses are of amphibolite and granulite facies and are mostly granodioritic and quartz dioritic, containing biotite, hornblende and garnet. Basic layers and agmatites are common. Most of these rocks have a strong tectonite fabric resulting in a persistent ENE strike direction of the gneissose foliation.

A suite of basic dykes - the Kangamuit dyke swarm - intruded the area around Itivdlek and have strike directions of NNE in the Archaean block south of the Itivdlek fjord and a strike of ENE within the Nagssugtoqidian belt. This change in attitude of the dykes was

thought to indicate a progressive deformation towards the north and was initially used to map the southern boundary of the Nagssugtoqidian belt (Noe-Nygaard and Ramberg 1961).

Watterson (1974), however, proposed a re-interpretation of the geology of this area. Watterson suggested that the Kangerlussuaq dykes within the Nagssugtoqidian north of the Archaean block were intruded with an ENE strike controlled by the pre-dyke tectonic fabric in the country rock because original igneous textures observed within the dykes show that they have not been re-oriented. The pre-dyke deformation (Nag 1) is now thought to have been the main phase of deformation of regional importance responsible for the formation of tectonite fabrics. The change in direction and form of the dykes across the boundary is ascribed to the difference in ductility of the country rock, thought to be at relatively high temperatures during intrusion. The amphibolite rocks were more ductile than the granulite facies rocks at the same temperature and so pinch and swell (boudinage-like) dyke forms were produced in contrast to the normal parallel-sided dykes found in the granulite facies rocks.

According to Bak et al. (1975) and Watterson (1974) the area between the NW coast of Sarfanguaq and Itivdleq fjord represents one of four major shear zones in West Greenland. In the coastal region this zone, the Ikertoq zone, is a strip about 40km wide striking ENE which forms the southern edge of the Nagssugtoqidian belt. It consists of highly deformed amphibolite facies rocks bounded to the north and south by relatively undeformed granulite facies rocks, and in the area of Kingaq includes a large block (maximum width of 12km) of granulite facies gneisses which is thought to be an augen-like structure. The metamorphic facies distribution is shown in Fig. 3 of Bak et al. (1975).

The structural history of the shear zone is complicated. Pseudotachylite veins occur throughout the Ikertoq zone, but are especially concentrated on the northern margin which was the locus of later intense brittle deformation.

North of the boundary of the Ikertoq zone, towards Holsteinsborg, the lithology changes and the granulite facies gneisses include supracrustals such as marbles, garnet-sillimanite schists and siliceous bands believed to be acid volcanics.

The intrusion of the post-tectonic ultrabasic dykes seems to be focused on the Ikertoq shear zone. In the coastal region the potassic lamprophyre dykes are confined to the Ikertoq zone itself. Bak et al. (1975) and Watterson (1975) suggest that some of the pseudotachylites post-date intrusion of the lamprophyre dykes. The kimberlite dykes are found outside the main shear zone in the granulite facies rocks just north of the boundary of the Ikertoq zone.

The dykes which occur in the region of Sarfartup Nuna occur north of the transition zone suggested by Escher, Escher and Watterson (1975), but south of the southern boundary of the Ikertoq shear zone (Bak et al. 1975). The kimberlite dykes from localities 22 to 29 (see Map 1 in back pocket) intrude granulite facies rocks. The dykes found further north in the region of locality 47, which include both kimberlites and lamprophyres, intrude a supracrustal metavolcanic succession of greenschist and low amphibolite facies schists (Diggens and Talbot 1974). It should also be noted that the latter occurrences, in the region of Sarfartup Nuna, are approximately at 1000m above sea level indicating a considerable difference in altitude from the coastal dyke occurrences.

Comparing the distribution of the kimberlite

and potassic lamprophyre dykes (see Fig. 2.1) with the metamorphic facies given in Fig. 3 of Bak et al. (1975) there appears to be some correlation. The kimberlite dykes occur in granulite facies rocks both near Holsteinsborg and in the region of Sarfartup Nuna, just north of the Sukkertoppen Iskappe. The lamprophyre dykes which occur in the coastal area between the Ikertoq and Itivdleq fjords, however, intrude amphibolite facies rocks although some do occur within the suggested granulite augen. In the region of Sarfartup Nuna near locality 47 (see Map 1) both kimberlite and lamprophyre dykes are found intruding the supracrustals.

2.6 Field description

The kimberlite and potassic lamprophyre dykes in the area south of Holsteinsborg are relatively late-stage intrusions, showing no features of subsequent deformation apart from some minor fracturing with virtually no displacement.

The dykes are vertical and have fairly constant strike directions approximately east-west, although a few dykes do locally show slight deflections from the general dip and strike. The dykes, often with apophyses, may occur singly or with several dykes concentrated in a narrow zone with adjacent dykes sometimes separated by only a few centimetres of country rock. Some of the dykes can be followed for several kilometres and are often extremely uniform along their length. The dykes have sharp contacts with the country rock (see Plates 2.1 and 2.2) and are usually transgressive to the gneissose foliation but may be concordant as can be seen in Plate 2.1. The dykes have had little effect on the country rock, although there may be some pink colouration in the immediate vicinity of the contact.

Plate 2.1

Potassic lamprophyre dyke (55cm wide) with sharp contacts which are concordant with the gneissose country rock. The dyke is banded as a result of multiple phases of intrusion. Arrows indicate the continuation, although slightly offset, of the gullies formed by solution of the dyke in the foreground and an adjacent intrusion.

Locality 8 (see Map 1 in back pocket)

Plate 2.2

Potassic lamprophyre dyke with sharp contacts but no apparent banding. The large gneissose xenolith is similar to the country rock.

Locality 8a.

Many of the dykes have internal contacts parallel to the dyke margin indicating multiple phases of intrusion and giving the dykes a zoned appearance which is emphasised on exposed surfaces where the bands show different susceptibilities to weathering. Plates 2.3 and 2.4 show the only observed occurrences of different intrusion phases exhibiting cross-cutting (rather than parallel) contacts.

The matrices of these dykes are rich in carbonate and are, therefore, more susceptible to solution than the country rock and the resulting gullies form distinct topographic features (see Plate 2.1). The dykes are very fresh apart from a narrow zone of weathering.

The dykes can be divided into (i) the kimberlite dykes and (ii) the potassic lamprophyre dykes and their geographic distribution is given in Fig. 2.1. In the region between Holsteinsborg and Itivdleq the kimberlite dykes are confined to the area north of Nipisat (i.e. north of latitude $66^{\circ} 50'$) and the lamprophyre dykes occur only to the south of Nipisat (see Map 1 in back pocket). Both kimberlite and lamprophyre dykes are found at the northern limit of the Sukkertoppen Iskappe.

The field relationships described so far are common to most of the dykes; other features are characteristic of either the kimberlite or the lamprophyre dykes.

(i) Kimberlite dykes

The kimberlite dykes vary in width up to 2 metres and have strike directions between 090° and 120° , except for those at Sarfartup Nuna where the strike is generally 070° . The wider kimberlite dykes (1 - 2m wide) have a large central zone (approximately 0.5m wide) which is thought to be a separate intrusion phase and may contain up to 50% of inclusions, mostly rounded ultrabasic nodules (see Plate 2.5).

Plate 2.3

Part of a 1.5m wide kimberlite dyke with a late injection of magma cutting across the banding parallel to the dyke margins which resulted from earlier multiple phases of intrusion.

(Graduations on hammer shaft at 10cm intervals).

Locality 40.

Plate 2.4

Kimberlite dyke with at least two symmetrical phases of intrusion cut by a later narrow and irregular intrusion.

Locality 36.

The concentration of inclusions is variable and they may in parts be totally absent (see Plate 2.6). The outer parts of these dykes are symmetrical and zoned parallel to their margins (see Plates 2.5 and 2.6) and may contain large megacrysts, but usually no inclusions. The kimberlite matrix is rich in carbonate with megacrysts of olivine up to 4 - 5cm in size, dark mica crystals up to 2cm across, opaque minerals and the occasional purple-red garnet. The ultrabasic inclusions found in the central zone range in size up to 40cm, but 10 - 20cm is more typical and they consist dominantly of olivine with some pyroxene including bright-green chrome diopside and a few of the inclusions contain garnet. A few sub-angular gneissose inclusions are found (e.g. at localities 21 and 27) and some dark-grey inclusions that are similar in appearance to the kimberlite matrix might be autoliths (defined in Part 1.1.6 of Chapter 1).

The narrower kimberlite dykes (usually less than 0.5m wide) are apparently devoid of ultrabasic nodules and garnet megacrysts but are otherwise similar to the matrix of the wider kimberlite dykes (see Plate 2.7 and 2.8). These dykes resemble, and may be equivalent to, the zoned outer parts of the wide kimberlite dykes but in these cases the nodular central zone is absent. Narrow kimberlite dykes have been found only on the island of Umanarssuk and at locality 37 on the island of Manitsorssuaq (see Map 1).

Along many parts of the margins of the kimberlite dykes there are concentrations of calcite forming white 'blebs' (see Plate 2.9). These calcite segregations are irregular in shape, but often elongate and parallel to the dyke margin and will subsequently be referred to as 'ocelli'. These dykes also sometimes have thin discontinuous calcite veins which are usually parallel or perpendicular

Plate 2.5

Wide kimberlite dyke with an extremely high concentration of rounded inclusions confined to a 0.5m central zone. The outer zones are banded parallel to the dyke contacts.

(Graduations on hammer shaft at 10cm intervals).

Locality 40.

Plate 2.6

Kimberlite dyke showing variable concentrations of rounded inclusions. The upper part of the dyke contains abundant inclusions while they are virtually absent in the lower part. The marginal zones of the dyke are banded and the sharp contact with the country rock is also evident.

Locality 41.

Plate 2.7

Vertical section through a kimberlite dyke with a narrow apophysis. This illustrates the occasional deviations from otherwise consistent dip and strike directions. Contacts are sharp and transgressive to the gneissose foliation. Locality 43.

Plate 2.8

Narrow kimberlite dyke with sharp internal contacts parallel to the dyke margins which resulted from multiple phases of intrusion.
(Graduations on hammer shaft at 10cm intervals).
Locality 37.

Plate 2.9

Irregularly shaped calcite-rich ocelli which are often elongated parallel to the kimberlite dyke margin (upper edge of sample).

Locality 43, sample 5502.

Plate 2.10

Discontinuous thin calcite veins cutting across the fabric of the kimberlite dyke matrix.

Locality 25, sample 5908.

5 cm

5 cm

to the dyke contacts and cut across the fabric of the dyke (see Plate 2.10), features which are characteristic of precipitation in cooling fractures.

(ii) Potassic lamprophyre dykes

The potassic lamprophyre dykes are less than 1m wide and usually have consistent strike directions between 075° and 090° . Some of these dykes are probably those referred to as kersantitic dykes by Noe-Nygaard and Ramberg (1961). Several dykes may be concentrated, and possibly anastomosing, within a narrow zone as shown in Plate 2.11. Individual lamprophyre dykes can often be followed for 1 - 2km, although they may be discontinuous, where a dyke decreases in width and terminates, but continues offset by 0.5 - 1m in an en echelon pattern as shown in Plate 2.12.

The lamprophyre dykes have a dark-grey carbonate-rich matrix with megacrysts of mica, olivine and pseudoleucite. The larger megacrysts are often concentrated towards the centre of an individual intrusion phase and the dykes may be zoned as a result of modal variations in megacryst and groundmass constituents between different intrusion phases (as shown in Plate 2.13). Many of the dykes have finer grained, presumably chilled, margins and similar features can occur as internal contacts. Some lamprophyre dykes, however, show no evidence of zoning (Plate 2.2). The only inclusions found in these dykes are xenoliths which are usually angular and similar in appearance to the country rock. Small and often pink xenoliths may be locally abundant as shown in Plate 2.14. Some xenoliths have thin reaction rims but there is no indication of chemical contamination to the dykes. Xenoliths found in marginal zones may be oriented parallel to the contact.

Plate 2.11

A concentration of several potassic lamprophyre intrusions (dykes marked with 'L').

Locality 9.

Plate 2.12

Offset lamprophyre dyke terminations resulting in an en echelon pattern of intrusion.

Locality 9.

Plate 2.13

Symmetrically banded lamprophyre dyke with modal variations in megacryst constituents between different phases of intrusion. The later central zone is rich in olivine (marked 'O') while the earlier intrusion contained abundant megacrysts of phlogopite (marked 'P').

Locality 9.

Plate 2.14

Locally abundant small acid xenoliths in a lamprophyre dyke.

(Graduations on hammer shaft at 10cm intervals).

Locality 15.

Apart from the kimberlite and lamprophyre dykes described so far, a few other relatively late-stage intrusions have been found which are presumably associated with the main post-tectonic dyke intrusion phase in this area, but apparently do not fit into the general pattern. For example, two dykes found on Sagdlerssuaq are not typical of the lamprophyres. The dyke at locality 18 (see Map 1) has variable strike turning from 070° to 324° and has several distinct internal contacts. The dyke at locality 19 is unusually dark and contains abundant euhedral augite crystals. These two dykes are subsequently referred to as the 'anomalous lamprophyre dykes'.

Another peculiar intrusion occurs east of Itivdleg at locality 30 (see Map 1). The outcrop is 30 x 10m in size and although no contacts are exposed appears to be more of a pipe-like intrusion and will be referred to using the field term 'pipe' intrusion. The matrix appears to be almost completely made up of a coarse, dark mica. Part of the outcrop contains a high concentration of rounded inclusions (see Plate 2.15) which vary in size up to 10cm, are usually rounded, weather to an orange colour and appear to consist mainly of olivine. These inclusions appear to be concentrated in a shallow dipping 'bed' about one metre thick. The relationship of this intrusion to the rest of the dykes is not understood except that the intrusion is obviously post-tectonic even though it has a cleavage of 67° 060° . Also the intrusion occurs in an area where all the other post-tectonic intrusions are lamprophyre dykes and it is the only known occurrence of ultrabasic inclusions outside the areas of kimberlite dyke intrusion.

2.7 Age

There is no geological evidence to indicate either

the age of intrusion of the Holsteinsborg dykes or the time relationship between the kimberlite and lamprophyre dykes.

One kimberlite dyke, sample 121510 from near Holsteinsborg (close to locality 1 on Map 1) has been dated and results using both K/Ar ratios in phlogopite (M. MacIntyre, Scottish Universities Research and Reactor Centre, East Kilbride) and Rb/Sr ratios (I. Pringle, Cambridge University) indicate ages of around 570 my. Bridgwater (1971) has determined a similar age of 584 ± 18 my for a kimberlitic dyke (sample 120668) found approximately 100km east of Itivdleg, but also expressed some doubt in the reliability of these results because very different ages were obtained when two different dating methods were used on one kimberlite sample.

2.8 Palaeomagnetism

Several 'kimberlite' dykes were included as part of the sampling programme for a palaeomagnetic study of the area between Holsteinsborg and Itivdleg (G. Morgan, Imperial College London and G. Beckmann, Newcastle University). Beckmann and Mitchell (1976) report palaeomagnetic results for these samples which might reflect different ages all within the Cambrian for 'kimberlite' samples from Sagdlerssuaq and Itivdleg. As defined in this thesis these so-called 'kimberlite' samples would be members of the potassic lamprophyre suite.

3.1 Introduction

The kimberlite and potassic lamprophyre dykes are hard, dark-grey, carbonate-rich rocks which are usually extremely fresh but have a thin deep-brown weathered zone. They are characterised by their inequigranular texture with megacrysts, up to several centimetres in size, of translucent olivine and glittering bronze-coloured mica. These megacryst phases can occur in the narrowest of intrusions, often only a few centimetres wide.

The phlogopite megacrysts are often oriented parallel to the dyke contacts. The olivine megacrysts from the kimberlite dykes are generally rounded and fresh but those from the lamprophyre dykes are more frequently altered and often have conspicuous reaction rims. A pale pink megacryst phase which occurs in the lamprophyre dykes is thought to be pseudoleucite. Garnet is found as rare, red-purple megacrysts in the kimberlite dykes. Small isolated white patches of calcite are common throughout all the dykes, although they tend to be larger in the kimberlite dykes.

The dykes have microscopically sharp contacts with only local and minor brecciation of the country rock and some sericitization of the feldspar in the gneisses.

Examination of thin sections confirms that the apparent zonation observed on exposed surfaces in the field (see Part 2.6 of Chapter 2) is a result of variations in the modal proportions of both megacryst and groundmass phases. Two adjacent zones can sometimes contrast strongly producing a distinct contact, as can be seen in Plate 3.1, and substantiates the suggestion of multiple phases of intrusion.

Plate 3.1

Sharp internal contact between two different phases of kimberlite intrusion, the left hand side with a dark brown turbid groundmass in contrast to the carbonate-rich matrix on the right hand side. Both intrusions contain olivine and phlogopite. Sample 5966, plane polarised light, x 40.

3.2 Kimberlite dykes

The kimberlite dykes have megacrysts of olivine, phlogopite and occasionally garnet and clinopyroxene which are set in a finer-grained groundmass of olivine, phlogopite, calcite, serpentine, perovskite, opaque minerals, apatite and clinopyroxene. The proportions of these groundmass phases vary considerably, and parts of the groundmass may be dark brown and turbid but otherwise indeterminable. Irregular isolated patches of calcite can be up to 1cm in size and the elongate ones tend to parallel the dyke contacts. These segregations, which have irregular outlines and often partly enclose silicate minerals from the surrounding groundmass, as mentioned in Chapter 2, will be referred to as 'ocelli' although this term should strictly be used for rounded or sub-spherical structures (Carmichael, Turner and Verhoogen 1974). The ocelli consist largely of calcite but may envelope a pale-green kernel of serpentine. They can also be rimmed by small phlogopite crystals, and have small clinopyroxene needles growing in from their walls

3.2.1 Olivine

The olivines found in the kimberlite dykes range in size up to 5cm but are usually less than 2cm and their size distribution indicates two generations of olivine. The larger olivine megacrysts (greater than 3mm) are usually irregular or rounded but occasionally euhedral crystals occur. The smaller second generation olivines (less than 2mm) are more commonly euhedral. Most olivines are fresh but there may be some alteration to serpentine and magnetite, particularly in smaller crystals, and a few larger olivines are rimmed by phlogopite crystals. In contrast, many of the kimberlite occurrences in the region of Sarfartup Nuna (see Map 1) contain olivines which are

totally altered to serpentine and abundant opaque minerals. The alteration in the olivines (see Plate 3.2) is concentrated along fractures subparallel to the dyke margins. Sometimes deformation lamellae occur in the fresher olivines and these are also parallel to dyke contacts. These features seem to indicate that some external pressure was being exerted on to the dykes close to their time of intrusion.

Some small fragments which in hand specimen are similar in appearance to the olivine megacrysts are found to be composite and have textures that resemble both the 'coarse' and 'porphyroclastic' larger olivine-rich ultrabasic inclusions which occur in the kimberlite dykes (see Part 3.6 of this chapter). These polycrystalline olivines are, therefore, probably microinclusions or fragments of the larger peridotite nodules, although they are sometimes found in parts of dykes which are devoid of the larger nodules.

3.2.2 Phlogopite

The phlogopites are strongly pleochroic (X = colourless to pale yellow, Y = Z = brown, strong red-brown or greenish brown) and their size distribution indicates two generations. The larger phlogopite megacrysts are typically greater than 1.5mm in size, have irregular corroded margins and are often deformed and broken. The smaller groundmass phlogopites (less than 1mm) are usually well-formed tabular crystals which have occasionally become deformed when squashed between olivine megacrysts. Many phlogopites of both generations have narrow distinct rims with reverse pleochroism relative to the core and an example of this is shown in Plate 3.3. A few phlogopites have cores which are pleochroic from pale brown to dark green. Some of the larger phlogopites enclose small anhedral olivines.

Plate 3.2

Megacryst and groundmass olivines extensively altered to serpentine and oxides along subparallel cracks (parallel to margin of photograph).
Interstitial matrix mostly calcite and oxides.
Sample 5820, plane polarised light, x 30.

Plate 3.3

Groundmass phlogopites with optically distinct rims showing reverse pleochroism.
Sample 5834, plane polarised light, x 120.

3.2.3 Garnet

Garnet megacrysts, although rare, have been found in most of the kimberlite dykes and are up to 5mm in size. They are rounded and a pale pink colour in thin section with narrow alteration rims (see Plate 3.4). One garnet (in sample 5518) has a wide structureless green corona, apparently of serpentine, but one patch of serpentine appears to be pseudomorphing olivine which must have been intergrown with the garnet and this is shown in Plate 3.5.

3.2.4 Clinopyroxene

Clinopyroxene megacrysts have been found in only one sample (5605) which is also unusual in that it appears to be devoid of olivine. The clinopyroxene megacrysts (up to 5mm in size) are very ragged in appearance, usually zoned and sometimes deformed. Clinopyroxene is, however, a common groundmass constituent of many of these dykes where it occurs as pale green needles less than 0.25mm long which are always associated with the interstitial calcite or the calcite-serpentine ocelli (see Plate 3.8). This association suggests that the clinopyroxene needles have crystallised from the late-stage residual liquid just preceeding the crystallisation of the primary calcite.

3.2.5 Oxides

Opaque minerals occur occasionally as large ragged megacrysts but the majority are found in the groundmass. The groundmass phases have a variety of forms including cubic, rhombic, needle-like, polygonal and irregular grains which are all generally less than 0.25mm in size. Perovskite is a common accessory mineral and occurs as small brown, equant grains usually less than 0.1mm in size and many have narrow opaque overgrowths.

Plate 3.4

Garnet megacryst with a narrow reaction rim in a kimberlite matrix of olivine, phlogopite and spinel.

Sample 5603, plane polarised light, x 30.

Plate 3.5

Garnet megacryst with a wide structureless corona.

Note also a white patch of serpentine which appears to pseudomorph olivine and must have been intergrown with the garnet.

Sample 5518, plane polarised light, x 30.

3.2.6 Calcite

Calcite can be very abundant and occurs not only dispersed throughout the groundmass (see Plates 3.6 and 3.7) but also concentrated in ocelli. There is no evidence to suggest that the calcite represents the alteration of other phases, and features such as straight crystal boundaries, triple junctions and ophitic textures within the calcite indicate that it is a primary magmatic constituent and probably represents the crystallisation of a residual liquid. Occasionally calcite constitutes as much as half the volume of a dyke (e.g. Liverpool University sample 120217).

Small late-stage and discontinuous calcite veins up to 5mm wide occur in some of the kimberlite dykes. They are a post-intrusion feature as they cut across the fabric of the dyke, and even through large olivine megacrysts. The calcite is fibrous and has grown perpendicular to the walls of the veins and may have formed while the fracture widened during the cooling of the dyke.

3.2.7 Serpentine

Primary serpentine is another late-stage crystallisation product associated with the calcite. It occurs as pale green or colourless interstitial patches or as cores to the calcite-rich ocelli.

3.2.8 Apatite

Apatite occurs as small euhedral six-sided prismatic or elongate tabular crystals which are exclusively associated with the primary calcite (see Plates 3.6 and 3.7).

Plate 3.6

Kimberlite matrix with interstitial calcite
surrounding euhedral, prismatic apatite crystals
(high relief) and partially enclosing silicate
minerals protruding from the adjacent groundmass.
Sample 5504, plane polarised light, x 120.

Plate 3.7

As Plate 3.6 but with crossed nicols.

Plate 3.8

Needles of clinopyroxene associated with interstitial calcite (white). Ragged opaque oxides also present.
Sample 5985, plane polarised light, x 120.

Plate 3.9

Deformed phlogopite megacrysts in a fine-grained groundmass containing abundant small phlogopite laths.
Sample 5629, plane polarised light, x 30.

3.3 Potassic lamprophyre dykes

The most characteristic feature of the lamprophyre dykes is the ubiquitous phlogopite. Megacrysts of phlogopite, olivine, pseudoleucite and clinopyroxene are set in a finer-grained groundmass of a green amphibole, clinopyroxene, alkali feldspar, calcite, serpentine, opaque minerals and rutile. In some dykes the groundmass can be an extremely fine-grained indeterminable microcrystalline aggregate.

3.3.1 Phlogopite

Phlogopite in these dykes is a distinctive bright-red chestnut brown colour, generally brighter than the phlogopites from the kimberlite dykes, and is strongly pleochroic (X = pale yellow-brown, Y = Z = strong red-brown). Contrasting grain sizes indicate two generations of phlogopite. The large phlogopites (up to 7mm long) are often deformed with bent and broken crystals, kinked cleavage and irregular crystal outlines (see Plate 3.9). A few large phlogopites have growths of calcite along split cleavage planes. The second generation of phlogopites occurs as small (less than 1mm) tabular crystals in the groundmass.

In the lamprophyre dykes phlogopites of both generations may have narrow rims, distinct because of their reverse pleochroism (X = very strong red-brown, Y = Z = pale yellow-brown) and when found they are similar to those shown in Plate 3.3 from a kimberlite dyke. The rims, which have sharp boundaries with the main crystals, can be continuous round a phlogopite even if the crystal is irregular and deformed. The rims, therefore, probably represent a late-stage overgrowth.

3.3.2 Olivine

The modal proportions of olivine vary considerably,

as certain zones have abundant olivine whilst in others it is absent. All the olivines are anhedral and up to 1.5cm in size. There is a gradation of alteration from fresh olivines to completely serpentinised or occasionally carbonated megacrysts. Many of the olivines have conspicuous reaction rims which can be brown, black or grey in colour and an example is shown in Plate 3.10. These reaction rims might suggest that olivine is unstable in the liquid with which it was intruded and, if so, the magma must have been erupted rapidly for any olivine to be preserved. These rims, however, could have resulted from alteration caused by the volatiles which are abundant in these dykes, but no similar feature is observed in the even more volatile-rich kimberlite dykes.

3.3.3 Clinopyroxene

Clinopyroxene occurs as megacrysts in these dykes as fresh, slender subhedral crystals up to 5mm long. Radiating clusters of these clinopyroxene crystals, sometimes together with other megacryst phases, are occasionally found (see Plate 3.11). Clinopyroxene is the least common of the megacryst phases.

3.3.4 Pseudoleucite

Another common megacryst phase which is pale pink in hand specimen is thought to be pseudoleucite. These megacrysts, which can be up to 5mm in diameter, are often euhedral and polygonal as shown in Plate 3.12. They are commonly concentrated in clusters as shown in Plate 3.13. In thin section these megacrysts have a variable number of crystal faces which are consistent with different sections through perfect trapezohedral crystals, the characteristic form of leucite. Each megacryst is made up of a mosaic of feldspar crystals which are transparent in thin section but are usually turbid

Plate 3.10

Part of the reaction rim to a large and partially altered olivine megacryst from a lamprophyre dyke. Sample 5651, plane polarised light, x 30.

Plate 3.11

A radiating cluster of clinopyroxene megacrysts surrounded by small pseudoleucites in a fine-grained lamprophyre groundmass. Sample 5647, plane polarised light, x 30.

Plate 3.12

A six-sided euhedral megacryst of pseudoleucite partially intergrown with a crystal of clinopyroxene.

Sample 5647, plane polarised light, x 30.

Plate 3.13

A cluster of pseudoleucite megacrysts from a potassic lamprophyre dyke.

Sample 5647, plane polarised light, x 30.

as the result of alteration to highly birefringent sericite flakes.

3.3.5 Alkali feldspar

The most abundant groundmass phase is alkali feldspar which can be turbid from alteration. This feldspar may exhibit a poikilitic texture enclosing many of the other phases, but it commonly occurs as interlocking, lath-like crystals which sometimes form poorly developed radiating textures. The majority of the crystals have a small negative 2V (less than 10°) which indicates that the feldspar is sanidine and that the interstitial liquid must have cooled rapidly. Some of the crystals have larger, more variable and positive 2Vs which may be a result of ordering in the feldspar structure to form orthoclase.

3.3.6 Amphibole

A green amphibole occurs in the groundmass as poorly formed tabular crystals, usually less than 0.5mm long, which are pleochroic (X = dark greenish brown or pale green, Z = darkish green).

3.3.7 Oxides

Opaque minerals are not common in these dykes. They occur as tiny irregular, often ragged, crystals. Rutile grains are frequently found in the groundmass.

3.3.8 Calcite and Serpentine

Primary and relatively coarse crystalline calcite occurs as single crystals or in small polycrystalline patches. The calcite together with minor pale green or colourless serpentine is late-stage crystallisation constituent of these dykes. These minerals can also occur as secondary alteration products.

Note : Modal data for thirteen selected rock samples are given in Table 3.1 (in back pocket). The main mineral assemblages found in both the kimberlites and potassic lamprophyres are listed in Table 3.2 (also in back pocket).

3.4 Anomalous lamprophyre dykes

These anomalous dykes differ from the other lamprophyres because clinopyroxene is far more abundant.

The dykes from localities 18 and 19 (see Map 1) have large, up to 4mm, euhedral megacrysts of clinopyroxene which can become extremely abundant, particularly in the central parts of the dykes. Many of these crystals are strongly zoned. Clinopyroxene is also the main constituent of the groundmass of these dykes where it occurs as long slender crystals up to 2mm in length.

Megacrysts of olivine up to 2mm in size occur but are now totally serpentinitised although they still retain their euhedral outline. Similar, but smaller olivines are found in the groundmass.

Phlogopite is found as a megacryst phase in the coarser central parts of the dykes where it is usually found as deformed deep-brown, pleochroic crystals up to 3mm long. Phlogopite is always abundant in the groundmass and is often euhedral. The occasional 2 - 3mm phlogopite crystal exhibits a poikilitic texture enclosing smaller clinopyroxene crystals.

Tiny cubic opaque minerals are common and occur throughout the groundmass and in all parts of the dykes. Sanidine and to a lesser extent calcite are interstitial to the main groundmass phases discussed so far.

The anomalous dyke at locality 47 (see Map 1) is not porphyritic but does contain abundant slender crystals of clinopyroxene up to 2mm long. Deep brown pleochroic crystals of phlogopite are also common, and they show some development of the distinct narrow rims with reverse pleochroism which were often found in the kimberlite and lamprophyre dykes.

Ocelli up to 5mm long occur in all these anomalous dykes and appear to be similar to those found in some of the other dykes. Those found at locality 19, however, are largely formed of radiating fibrous needles of sanidine sometimes enclosing large crystals of clinopyroxene and phlogopite similar to the megacryst phases. The sanidine also partly encloses crystals protruding from the surrounding groundmass. One ocelli was a polycrystalline intergrowth of calcite and sanidine with individual crystals being up to 0.5mm in size.

3.5 The 'pipe' intrusion

The main constituent of this intrusion is large books of mica which are pale brown in thin section and up to 1.5cm long. They are generally deformed with undulose extinction as well as bent cleavage. These micas enclose both small irregular opaque oxides and subhedral olivines which are partly serpentinised and up to 2mm in size. A few subhedral clinopyroxenes are also found as crystals up to 1mm in size which have darkish brown turbid areas formed as the result of alteration. (This 'pipe' intrusion has not been included in the mineralogical and geochemical studies discussed in subsequent chapters of this thesis).

3.6 Inclusions

In parts of some of the Holsteinsborg kimberlite dykes there is a high concentration of rounded inclusions which are predominantly peridotites*. Escher and Watterson (1973) examined some inclusions from these dykes and reported finding 16 dunites, 10 harzburgites, 2 wehrlites and 1 lherzolite and also mentioned the occurrence of some small eclogite inclusions.

* see addendum on page 56.

In this study thin sections of 75 inclusions were examined. These included some of those discussed by Escher and Watterson (1973) and others from the Liverpool University collection (referred to using 6 figure G.G.U. specimen numbers). Although the majority of inclusions were found to be peridotites two eclogites and two granulites were identified.

3.6.1 Peridotites

From the examination of thin sections 44 dunites, 10 lherzolites, 9 wehrlites and 8 harzburgite inclusions were identified. Olivine is particularly abundant in these peridotites in comparison with inclusion suites found in other kimberlites, and as a result the chance occurrence of the scarce pyroxene in any thin section makes the nomenclature of the Holsteinsborg peridotites somewhat arbitrary.

As a result of recent research on peridotite inclusions in kimberlites (and in basalts) a variety of textures have been recognised. Boyd and Nixon (1972) made a general textural distinction between 'granular' (relatively little deformed) and 'sheared' (relatively strongly deformed) inclusions in kimberlites. Since then other authors have described more detailed textural types (Boullier and Nicolas 1973, 1975; Cox, Gurney and Harte 1973; Harte, Cox and Gurney 1975). The various terms used by these authors have created some confusion in the descriptive terminology of these textures and in order to overcome this problem Harte (in press) has proposed a set of consistent textural terms and rock names (which is correlated with previous terminology) for olivine-bearing xenoliths found in kimberlites and basalts. Harte's classification will be used in this study.

(A copy of Harte's Table 1 - Summary of Rock Classification - is provided in the back pocket).

The peridotite inclusions from the Holsteinsborg kimberlite dykes largely have either coarse or porphyroclastic textures but a few mosaic-porphyroclastic and granuloblastic inclusions were found.

The coarse inclusions are fairly equigranular with relatively large olivine grains usually greater than 2mm in size but ranging up to 8mm. The grain boundaries are often serrated but can be straight or smoothly curved and many of the olivine grains have undulose extinction. An example of a coarse inclusion is shown in Plate 3.14. A few inclusions show a tendency for grains to be elongated with approximate parallel orientation and are referred to by Harte (in press) as coarse-tabular inclusions. Both clinopyroxene, orthopyroxene and more rarely garnet are found in the coarse inclusions as irregular or globular grains approximately 2mm in size. The garnet is usually substantially altered along grain boundaries obscuring textural relations. Opaque oxides are not common but occur as small irregular grains (less than 0.25mm) which are sometimes included within a large olivine crystal.

Porphyroclastic inclusions form the other major textural category of the Holsteinsborg peridotites. These rocks have relatively large (2 - 7mm) and often strained porphyroclasts of olivine which are surrounded by distinctly smaller olivine grains (less than 1mm) with straight or sometimes curved grain boundaries (see Plate 3.15). These small and relatively little strained grains (neoblasts) are believed to result from the recrystallisation of coarse inclusions where the porphyroclasts are relict grains. Scarce pyroxene usually occurs as porphyroclasts but very occasionally is found as a recrystallised mosaic. Opaque oxides are more abundant in the recrystallised parts of the peridotites and appear to be similar in size to, and in equilibrium

Plate 3.15

Porphyroclastic lherzolite inclusion. Relatively large porphyroclasts are surrounded by smaller neoblasts which have smooth grain boundaries. Sample 5698(1), plane polarised light, x 7.

with, the other silicate neoblasts.

A few examples of mosaic-porphyroclastic and granuloblastic inclusions also occur, and these, together with variable proportions of porphyroclast to neoblast in the porphyroclastic inclusions seem to indicate a continuous transition in texture from coarse to granuloblastic.

Two of the peridotite inclusions examined were layered and relatively rich in pyroxene. Sample 5952, a lherzolite, has a layer, at least 1cm wide, consisting of approximately 90% pyroxene and there is a gradual transition to an olivine-rich layer. The pyroxenes (approximately 2mm in size) include both clinopyroxene and orthopyroxene. Sample 5967 is essentially a coarse harzburgite. The orthopyroxene occurs in the occasional stringer or band of single crystals (2mm) as well as being a minor constituent throughout the inclusion. The significance of banding in ultrabasic xenoliths from Matsoku, Lesotho has been discussed by Harte, Cox and Gurney (1975) and in comparison it seems that the banded lherzolite 5952 which has diffuse contacts between bands and no sign of deformation is likely to have a cumulate igneous origin. There is not sufficient evidence to suggest an origin for the banding in sample 5967.

Although a large number of the peridotite inclusions examined are extremely fresh, many inclusions show evidence of metasomatism and late-secondary alteration (terminology after Harte, Cox and Gurney 1975). In the Holsteinsborg suite of peridotites the occurrence and textural relations of phlogopite and ilmenite are the main indicators of primary metasomatism and late-secondary alteration.

Late-secondary alteration is comparatively easy to identify and occurs along grain boundaries, as small isolated patches

or as a network of thin veins. The secondary minerals serpentine, phlogopite, ilmenite and sometimes carbonate occur usually as aggregates or as small crystals which are not in textural equilibrium with the primary peridotite minerals. The veins which penetrate through the inclusion often widen towards the inclusion/matrix interface and there is apparent injection of the host kimberlite matrix into the vein. This might suggest that the late-secondary alteration may have resulted from reaction with the host kimberlitic fluids, perhaps close to the time of eruption. Very occasionally late-secondary phlogopites with irregular grain boundaries show distinct rims with reverse pleochroism relative to the core, which is a feature often found in the phlogopites of the kimberlite matrix. The late-secondary alteration may be very extensive and is often concentrated along numerous irregular but subparallel planes.

Harte, Cox and Gurney (1975) identify several features in peridotite inclusions which they suggest are indicative of infiltration metasomatism of material derived from the kimberlite magma at depth leading to the introduction of primary metasomatic phlogopite and ore minerals. The metasomatism occurred only in the finer-grained and recrystallised parts of the inclusions which lead Harte, Cox and Gurney (1975) to suggest that the recrystallisation and metasomatism may have occurred together. Some similar features have been observed in the Holsteinsborg peridotite inclusions, namely

(a) the occurrence of phlogopite (brown and pleochroic) and sometimes ilmenite in recrystallised parts of inclusions where they are of similar grain size to the other silicate minerals and in textural equilibrium

(b) the occasional metasomatic 'vein' enriched in

phlogopite and olivine

- (c) clouded pyroxenes, particularly orthopyroxene
- (d) the absence of phlogopite and ilmenite in most of the coarse-grained inclusions.

As mentioned above many of the ilmenite-bearing Holsteinsborg inclusions are either late-secondary or primary metasomatic in origin. A few inclusions, however, have relatively large patches or vein networks of polycrystalline ilmenite (see Plate 3.16). From textural relations this ilmenite does not appear to be a cumulate phase and it is thought to be metasomatic in origin as it occurs only in strongly recrystallised inclusions.

Occasionally relatively large crystals of ilmenite and phlogopite with serrated or smooth boundaries occur in coarse inclusions. They are not associated with other metasomatic or late-secondary minerals and, therefore, may constitute additional primary phases to the olivine and pyroxene.

3.6.2 Eclogites

The two eclogites are rounded, small (approximately 2cm in diameter) inclusions with reaction rims against the kimberlite matrix. Clinopyroxene and garnet occur in approximately similar amounts but the garnet tends to occur in larger grains (up to 5mm). Along grain boundaries and fractures there is abundant alteration to a dark turbid or colourless serpentine-bearing material. This alteration tends to obliterate evidence for the textural relations of the primary minerals, but the grain boundaries appear to be smooth and curved. These inclusions also contain some carbonate.

3.6.3 Granulites

Two garnet-granulite inclusions were identified. They are small (less than 3cm) and somewhat angular inclusions. They have an inequigranular texture with garnets (up to 4mm) occurring in a finer-grained mosaic of plagioclase, green clinopyroxene, amphibole and minor rutile. Grain boundaries tend to be straight or curved. One of these inclusions (5518) is crudely layered and the other (5519) is extensively altered to an opaque brown material. These inclusions also contain some carbonate.

Addendum

In the sampling of the inclusion suite from the kimberlite dykes it was attempted not only to include all the types present but also to make the collection as representative as possible.

4.1 Introduction

The mineral chemistry of the Holsteinsborg dykes is discussed in three parts, firstly the minerals from the matrices of the kimberlite and potassic lamprophyre dykes, secondly those from an anomalous lamprophyre dyke and finally minerals from the rounded inclusions found in the kimberlite dykes. Analyses of these minerals were determined using the Edinburgh Microscan 5 and further details of the methods are given in Appendix F (Part F.2). The analyses of the minerals from the dyke matrices are given in Appendix B and those from the inclusions in Appendix C.

4.2 Kimberlite and potassic lamprophyre dykes4.2.1 Olivine

Analyses of olivines from the kimberlite and lamprophyre dykes are given in Tables B.1(a) and B.1(b) respectively. The variation in olivine compositions in terms of $Mg/Mg+Fe$ atomic per cent ratios is illustrated in Fig. 4.1.

The groundmass and megacryst olivines found in the matrices of the kimberlite dykes have a compositional range of $Mg_{78-92.5}$ (see Fig. 4.1). The NiO contents of these olivines vary widely but tend to show a positive correlation with the MgO values. The size of the olivines analysed ranges from 0.25 to 20mm but there appears to be no relationship between size and composition. The olivines are usually not zoned although occasionally both normal and reverse zoning occur.

All the euhedral olivines form a group characterised by having sizes less than 2mm and compositions of Mg_{85} ($\pm 1\%$).

Olivine analyses from two different phases of intrusion of a narrow kimberlite dyke (sample 5966(1) = central zone and 5966(2) = marginal zone) show that those in the later (central) intrusion are richer in Fe which suggests some differentiation between the two intrusion phases.

Many of the olivines from the Holsteinsborg kimberlite dykes are more Fe-rich than compositions thought typical of kimberlites (i.e. Mg_{88-92} , Dawson 1967a). Other Fe-rich kimberlite olivines have been reported from the Frank Smith and Monastery Mines, South Africa (Boyd 1974) and Liquobong, Lesotho (Boyd and Nixon 1975). Some of those found at Monastery which are euhedral have similar compositions to the euhedral crystals found in the Holsteinsborg kimberlites.

A single crystal (found in sample 5914), which is 3.5cm in maximum dimension and has broken rather than the usual rounded margins, has a composition of Mg_{75} with high MnO and low NiO contents (analysis numbers 338, 339 and 350). This crystal is the most Fe-rich olivine found in these dykes (see Fig. 4.1). The difference in composition seems to suggest that this crystal is not related to the other megacryst or groundmass olivines or to the ultrabasic nodules from other dykes in this suite.

The analysed olivines from the lamprophyre dykes fall within the compositional range $Mg_{87.5-93}$ (see Fig. 4.1). The NiO content of these olivines, which is generally high (0.32 - 0.5 wt%), does not seem to correlate with the MgO content. Zoning is not usually apparent but is normal when it does occur. The olivines from the

Holsteinsborg lamprophyre dykes tend to be somewhat more Mg-rich than those found in other potassium-rich mafic rocks (e.g. Fo_{85-90.6} from Carmichael 1967b or Fo_{82.5-88.5} from Borley 1967) but do have similarly high NiO contents.

It has been suggested that the CaO content of olivines may be an indicator of pressure (although relatively insensitive); Simkin and Smith (1970) show that olivines from extrusive and hypabyssal rocks contain more than 0.1 wt% CaO whereas those from plutonic rocks and ultrabasic xenoliths contain less. The olivines from the Holsteinsborg kimberlite dykes and their ultrabasic inclusions seem to follow this pattern with CaO contents of more than 0.1 wt% occurring only in smaller (less than 0.5mm) crystals and in rims of larger olivines both of which are likely to have crystallised later and under lower pressure conditions. The olivines from the lamprophyre dykes, however, show a range of CaO contents but those greater than 0.1 wt% occur mainly in the more Fe-rich olivines (less than Mg₉₀).

4.2.2 Phlogopite

Analyses of phlogopites from the kimberlite and lamprophyre dykes are given in Tables B.2(a) and B.2(b) respectively. The phlogopites from the matrices of these dykes are unusual because of their high TiO₂ contents (up to 8 wt%) which gives them their distinctive deep-red brown colour. They are extremely variable in composition but it can be seen from the (Fe+Mg)-Ti-Al plot (Fig. 4.2) that the phlogopites from the kimberlite dykes tend to have lower Ti and Al contents than those of the lamprophyre dykes. Otherwise there seems to be no systematic compositional variation with respect to their

Fig. 4.2 (Fe+Mg)-Ti-Al atomic proportions plot for phlogopites from the Holsteinsborg dykes (after Velde 1975, p. 571).

open squares = kimberlites

solid circles = potassic lamprophyres

solid diamonds = peridotite inclusions

Line A is the substitution studied experimentally by Robert (1973).

Line B is the substitution studied by Forbes and Flower (1974).

host rock type or to the two generations of phlogopites suggested by their size distribution.

Phlogopites from the Holsteinsborg kimberlite dykes have higher TiO_2 contents than are typical of phlogopites from other kimberlites. Those from the Holsteinsborg lamprophyre dykes are even more enriched in TiO_2 and such titaniferous phlogopites are largely restricted to potassium-rich mafic rocks such as jumillites and wyomingites, although they are occasionally found in other rocks, for example, as phenocrysts in alkali-rich basaltic lavas (Flower 1969) or in a mica-garnet-lherzolite (Dawson, Powell and Reid 1970). The phlogopites from the Holsteinsborg lamprophyre dykes compare best in composition with phlogopites from the lamproites of West Kimberley, Australia (Carmichael 1967b) and the jumillites from Spain (Borley 1967). Phlogopites from other potassium-rich rocks such as the Leucite Hills, Wyoming (Carmichael 1967b) and Smoky Butte, Montana (Velde 1975) have different TiO_2 contents. Velde (1975) suggested that the Ti-content of these phlogopites was related to the Ti-content of the host whole-rock but by comparing the TiO_2 contents for the phlogopites and whole-rock for some of these rock types, as shown in Table 4.1, this does not seem to be the case.

The Ti-rich nature of the phlogopites found in the kimberlite dykes from Holsteinsborg can be explained by the substitutions $2\text{Si}^{\text{IV}}, \text{Mg}^{\text{VI}} = 2\text{Al}^{\text{IV}}, \text{Ti}^{\text{VI}}$ and $2\text{Mg}^{\text{VI}} = \text{Ti}^{\text{VI}}$ studied by Robert (1973, 1976b) and Forbes and Flower (1974). The phlogopites from the lamprophyre dykes, however, which are richer in Ti and poorer in Al, cannot be explained by these substitutions. Comparing Fig. 4.2 with Fig. 6 of Velde (1975, p. 571) the Holsteinsborg lamprophyre phlogopites are similar in composition to those from the lamproites described by Carmichael (1967b)

	whole rock	phlogopite
Holsteinsborg kimberlite dykes	2-5	2-6
Holsteinsborg potassic lamprophyre dykes	2-4	5-8
Kimberlites in general	0-4	0-4
Leucite Hills, Wyoming	1-2	2
Jumillites, Spain	2	6-8
West Kimberley, Australia	5-7	5-7
Smoky Butte, Montana	5	12
Narssaq - Tugtutoq, South Greenland	3-8	6-9

Table 4.1 A comparison of the TiO_2 wt% contents from phlogopites and whole-rock analyses of certain potassic mafic rocks

and all these phlogopites are generally Al-deficient with less than two ions per structural formula and Velde (1975) suggests that Fe might substitute for Al, and Ti for Si.

Forbes and Flower (1974) and Robert (1976b) indicate that the Ti substitutions are probably favoured by high temperatures and possibly high pressures and it has also been suggested that the incorporation of F (rather than OH) stabilises micas at high temperatures. As Ti and F are both abundant in many of the phlogopites from the Holsteinsborg dykes, in particular the lamprophyres, it suggests that some of these phlogopites may have crystallised at depth. Robert (1976a) suggests that the Al_2O_3 content of phlogopite decreases with increasing temperature and as the Holsteinsborg phlogopites are poor in Al_2O_3 this may indicate that they crystallised at high temperatures.

Smith and Dawson (in press) have classified micas from kimberlites and associated ultrabasic inclusions using mineral chemistry to identify several categories. Plotting the Holsteinsborg dyke phlogopites on diagrams used by Smith and Dawson revealed no correlation with their classification, although with $Mg/Mg+Fe$ atomic ratios (mg) between 0.78 and 0.87 they are most similar to the MARID-group. The Holsteinsborg kimberlite dyke phlogopites do not coincide with either the kimberlite groundmass or megacryst phlogopite groups of Smith and Dawson, the former having more TiO_2 and Na_2O and lower $Mg/Mg+Fe$ atomic ratios. The phlogopites from all the Holsteinsborg dykes have higher Na_2O/Na_2O+K_2O wt% ratios than most of the phlogopites considered by Smith and Dawson and a plot of this ratio against TiO_2 wt% shows some systematic variation between the kimberlite and lamprophyre dyke phlogopites from the Holsteinsborg suite (see Fig. 4.3); the kimberlitic phlogopites have higher Na_2O/Na_2O+K_2O wt% ratios and lower TiO_2 values.

The optically distinct rims to many of the Holsteinsborg dyke phlogopites (discussed in Parts 3.2.2 and 3.3.1 of Chapter 3) can also be distinguished chemically as can be seen by comparing analyses of the rims (analyses 73, 103, 150, 151, 154, 176, 185 and 368 from Table B.2(a) and 29, 31, 36 and 140 from Table B.2(b)) with the main cores of the phlogopites which otherwise show little or no zoning. The rims show varying degrees of enrichment in Fe and depletion in Al and are similar to those studied by Rinskaya-Korsokova and Sokolova (1966) who referred to them as tetraferriphlogopites. The rims of the Holsteinsborg phlogopites also tend to be depleted in Na and enriched in Ca relative to the cores and appear to be late-stage overgrowths from an Al-depleted and Fe-enriched liquid. Such rims are

known to occur in alkali ultrabasic rocks and carbonatites (e.g. Emeleus and Andrews 1975, Velde 1975).

4.2.3 Clinopyroxene

Analyses of the clinopyroxenes from the two types of Holsteinsborg dykes are given in Tables B.3(a) and B.3(b). All the clinopyroxenes found in the matrices of these dykes are diopsides and their compositions are illustrated in Fig. 4.4 in terms of their Ca-Mg-Fe atomic proportions.

The clinopyroxenes found in kimberlite dykes occur as small slender needles within the carbonate-rich matrix. Clinopyroxene is not a common constituent of kimberlites in general but diopsides, usually chrome-rich, have been reported as megacrysts from some kimberlites (e.g. Boyd and Nixon 1970, Dawson and Hawthorne 1973). These megacrysts, however, are often considered to be derived by the disaggregation of ultrabasic nodules. The clinopyroxenes from the Holsteinsborg kimberlites are not xenocrystal and are generally richer in Ca and Ti and poorer in Na and Cr than most of the analysed diopsides from kimberlites. They are more similar in composition to a recently analysed diopside from Roberts Victor Mine, South Africa (J. B. Dawson, personal communication) where (in wt%) $\text{SiO}_2 = 54.4$, $\text{TiO}_2 = 0.69$, $\text{Al}_2\text{O}_3 = 0.15$, $\text{Cr}_2\text{O}_3 = 0.18$, $\text{FeO} = 3.50$, $\text{MgO} = 17.41$, $\text{CaO} = 23.90$ and $\text{Na}_2\text{O} = 0.31$ and to the euhedral diopside analysed from a kimberlite in South West Greenland by Emeleus and Andrews (1975), and in both these cases the diopsides were considered not to be xenocrystal.

The Holsteinsborg kimberlite clinopyroxene needles must have crystallised, together with calcite and serpentine, from late-stage interstitial fluids which were dispersed through the matrix or

Fig 4.4 Ca-Mg-Fe atomic variation in pyroxenes.

open squares = kimberlites
shaded area = potassic lamprophyres
open triangles = anomalous lamprophyres
open diamonds = peridotite inclusions
solid inverted triangles = granulite inclusions
R = Roberts Victor diopside (see text)

concentrated in ocelli. This fluid must have been rich in volatiles and it seems likely that the partial pressure of CO_2 was sufficient to prevent the early crystallisation, from the residual fluid, of a hydrous phase such as amphibole, so allowing clinopyroxene to form.

The clinopyroxenes from the lamprophyre dykes, which occur as megacrysts, are mostly diopsides and similar in composition to those from the kimberlite dykes but have lower Ca and Al and higher Cr, Mg and Na contents (compare Tables B.3(a) and B.3(b)). The Cr_2O_3 contents are variable but generally high with values up to 1.2 wt%. These pyroxenes are similar in composition to the diopside megacrysts which occur in lamproites from West Kimberley, Australia (Carmichael 1967b) whereas in other potassium-rich mafic rocks diopside is usually confined to the groundmass (e.g. Velde 1975).

4.2.4 Amphibole

The only analysis of an amphibole (see Table B.4(a)) from a kimberlite dyke showed it to be a soda-rich richterite with only 0.42 wt% K_2O and depleted in Ca.

Amphibole is, however, a common groundmass constituent of the lamprophyre dykes and it can be seen from Table B.4(b) that they are potassic richterites (using the classification of Leake 1968). Potassic richterite is the amphibole usually found in potassium-rich mafic rocks such as lamproites and they typically have K in excess of Na (in atomic proportions) and have been referred to as magnophorites by Prider (1939). The richterites found in the Holsteinsborg lamprophyre dykes are richer in Fe and Na and poorer in Ti and Ca and as Na is in excess of K in the unit formula they are not magnophorites. Richterites similar in composition to those from Holsteinsborg have, however, been

reported from a jumillite (analysis S.1 from Carmichael 1967b), a minette (Velde 1967) and also from a diopside-phlogopite nodule (Aoki 1975). The Holsteinsborg richterites are much richer in total alkalis (12 wt% oxides) and Fe and are extremely depleted in Ca relative to most other potassic richterites. They also seem to have an excess of Si^{4+} in the tetrahedral site of the unit formula. Analysis 310 from Table B.4(b) of an amphibole which is colourless in contrast to the usual green colour is somewhat different in composition to the rest and is similar to the amphibole described by Erlank (1973) from a kimberlite-like ultramafic rock.

4.2.5 Alkali feldspar

Potassium feldspar has been analysed from both the kimberlite and lamprophyre dykes and the results are given in Tables B.5(a) and B.5(b).

In the kimberlite dykes one 0.5mm megacryst, which is partly altered and has angular broken margins, was shown to be potassium feldspar. This megacryst is thought to be xenocrystal and probably derived from some feldspar-bearing crustal xenoliths which occur in the same sample.

The lamprophyre dykes often have feldspar as a groundmass constituent and they were found to be fairly pure potassium feldspar with high FeO contents (up to 3.84 wt%).

4.2.6 Pseudoleucite

Analyses from points within the now polycrystalline pseudoleucite megacrysts found only in the lamprophyre dykes are given in Table B.6. All these analyses indicate an alkali feldspar approximating

pure KAlSi_3O_8 some with considerable BaO . Potassium feldspar, a usual constituent of pseudoleucite, is more commonly intergrown with nepheline (Fudali 1963) but there is no evidence to suggest the presence of nepheline in any of the Holsteinsborg pseudoleucites. The original megacrysts may have crystallised as almost pure leucite, with little or no sodium in solid solution, from a magma with a high K/Na ratio and they might have resembled unaltered leucites found in other potassium-rich mafic rocks (e.g. Carmichael 1967b). The breakdown of pure leucite to potassium feldspar has been suggested by experimental work (Goranson 1938, Seki and Kennedy 1964). The compositions of the pseudoleucites from the Holsteinsborg lamprophyre dykes have lower FeO contents but are otherwise very similar in composition to the groundmass feldspar of these dykes.

4.2.7 Garnet

Two garnet megacrysts were analysed from the kimberlite dykes and the results, which are given in Table B.7, show them to be pyropes. Their compositions are illustrated in Fig. 4.5 (atomic proportion ternary plots) and they mostly coincide with the field of kimberlitic garnets suggested by Boyd (1970). The Holsteinsborg megacrysts are similar, in certain respects, to the garnets analysed from the rounded ultrabasic nodules (see Table C.5(a) in Appendix C) perhaps suggesting their derivation from these nodules, but the megacrysts do have lower TiO_2 and Cr_2O_3 contents.

Using the classification of garnets from kimberlites and associated xenoliths put forward by Dawson and Stephens (1975, 1976) these garnet megacrysts fall into the titanian pyrope group (group 1). This group includes mostly garnets from kimberlites with a few from

Fig. 4.5 Atomic proportion ternary plots for garnet compositions.

a. Fe^{2+} - Mg - Ca

b. Cr - Fe^{3+} - Al

open squares = kimberlites

open triangles = peridotite inclusions

solid diamonds = granulite inclusions

kimberlite and lherzolite fields after Boyd (1970)

sheared garnet-lherzolite xenoliths. The Holsteinsborg megacrysts are more Cr-rich than most of the garnets that fall within this group.

4.2.8 Perovskite

Analyses of perovskites, which occur only in the kimberlite dykes, are given in Table B.8. The low totals may be attributable to the lack of analyses for rare earths and strontium. They are very similar in composition to perovskites found in the groundmass of other kimberlites (e.g. Mitchell 1972) which further supports Mitchell's suggestion that there is little variation in their composition within or between kimberlites. A few perovskites from the Holsteinsborg kimberlites, particularly in sample 5914(2), have narrow and more opaque overgrowths which, from analysis 387, appear to be rich in Fe and some Mg but low in Ca.

4.2.9 Fe-Ti-Cr Oxides

Opaque oxides are ubiquitous in the matrices of the kimberlite dykes and are largely a variety of Fe-Ti-Cr oxides and their analyses are given in Table B.9(a). Even after recalculation of some FeO to Fe_2O_3 some of the totals of these oxides are still poor and this may be attributable to the problem of the precise relocation of an analysis point in an opaque mineral which may be inhomogeneous or polycrystalline. The complexity of the oxides found in kimberlites has been shown by Haggerty (1973, 1975a) but this study of oxide minerals is not so detailed. The compositions of the Holsteinsborg kimberlitic oxides are illustrated in a $\text{RO}-\text{RO}_2-\text{R}_2\text{O}_3$ plot which is shown in Fig. 4.6.

Magnesian ilmenite (picroilmenite) is common in these kimberlite dykes and has low Fe_2O_3 values which are characteristic

of picroilmenites. The Holsteinsborg ilmenites have two modes of occurrence, firstly as medium-sized (1mm) ragged crystals and secondly as small (0.1mm) euhedral needle-like crystals. From Table B.9(a) it can be seen that the late euhedral crystals (analyses 70, 95, 182, 193 and 366) have lower MgO values of 0.85 - 8.62 wt% as compared with 9.44 - 11.06 wt% MgO in the larger picroilmenites. The smaller needles have high MnO contents whilst the larger crystals are richer in Cr_2O_3 . Al_2O_3 is not detectable in the small needles but is relatively high (0.2 - 0.7 wt%) in the larger crystals which is more typical of kimberlitic ilmenites. The variation in MgO contents between the ilmenites might suggest some differentiation but the difference in MgO may be very dependent on cooling rates. It has been shown (O'Hara, Biggar, Hill, Jefferies and Humphries 1974 and O'Hara, personal communication) that fast-quenched experimental runs contain ilmenite with much higher MgO contents than found in any equivalent natural rocks.

It has been suggested that picroilmenite, possibly together with diamond, is xenocrystal and uniquely sampled by kimberlites. The larger ilmenites found in the Holsteinsborg kimberlites are similar to other kimberlitic ilmenites and using the criteria suggested by Haggerty (1973) they would be considered as primary igneous minerals. The smaller less kimberlite-like ilmenites, because of their mode of occurrence, must also be primary. Mitchell (1973) considers picroilmenite in kimberlites to be phenocrystal in origin, even preceeding diamond in crystallising from an early partial melt.

Several chrome-spinels (35 - 53 wt% Cr_2O_3) have been analysed from the Holsteinsborg kimberlite dykes and they differ in composition from typical kimberlitic chrome-spinels having much lower Al_2O_3 and higher total FeO contents compared with those reported for

example by Frantsesson (1970) and Clarke and Mitchell (1975). The five chrome-spinels analysed fall into two groups; the first comprises medium-sized (up to 1mm) ragged crystals (analyses 66, 272 and 273 from Table B.9(a)) and the second is made up of smaller (less than 0.25mm) euhedral hexagonal crystals.

The larger anhedral chrome-spinels, which could be xenocrysts as is often suggested for chrome-spinels in other kimberlites, are not similar in composition to the spinels which occur in ultrabasic nodules from either Holsteinsborg or other localities. They have not, therefore, been derived from the associated nodules. These chrome-spinels, however, do have similar Cr/Cr+Al and $Mg/Mg+Fe^{2+}$ atomic ratios to chromites found as inclusions in diamond (see Fig. 5B of Meyer and Boyd 1972) although the latter chromites are much richer in Cr_2O_3 (greater than 60 wt%). This might suggest that the larger Holsteinsborg chrome-spinels could have been a very early crystallisation phase. These spinels are particularly depleted in Al_2O_3 , but if they crystallised together with garnet the Al would go into the garnet and the Cr into the spinel. Relative to these spinels the smaller euhedral chrome-spinels are not so poor in Al_2O_3 , but are richer in MgO which is the reverse of what might be expected if both crystallised from a fractionating magma.

The magnetites, which are euhedral or subhedral crystals from the kimberlite matrix, are fairly pure (see Table B.9(a)). They have probably crystallised from a late-stage liquid in association with the calcite, as is found in the Benfontein Sills, South Africa (Dawson and Hawthorne 1973).

The most common opaque oxides, found as small often euhedral crystals in the matrix of the kimberlite dykes, are spinels rich in Fe and Ti. These titanomagnetites are similar in composition

to others reported from kimberlites (e.g. Dawson and Hawthorne 1973, Clarke and Mitchell 1975, Emeleus and Andrews 1975). The Holsteinsborg titanomagnetites represent variable solid solution between magnetite and ulvospinel, which can be seen in Fig. 4.6. The variation in composition could reflect changes in either the fO_2 (Haggerty 1973) or the bulk composition of the magma. These spinels seem to form two groups (see Table B.9(a)), the first with greater than 69 wt% total FeO and some Al_2O_3 and MgO. The second group has less total FeO, up to 13.5 wt% Cr_2O_3 and generally higher Al_2O_3 . The Fe-rich group could have crystallised from a more fractionated liquid, and if that was the case it would agree with the suggestion of depletion of Cr_2O_3 and Al_2O_3 in titanomagnetites with fractionation (Carmichael, Turner and Verhoogen 1974).

Oxide minerals are far less common in the lamprophyre dykes than in the kimberlites and when they do occur they are generally too small for microprobe analysis. Rutile is the only oxide phase analysed from the lamprophyre dykes and the results are presented in Table B.9(b).

4.2.10 Sulphides

Sulphides are consistently present as small grains in the matrices of both the kimberlite and lamprophyre dykes. The partial analyses given in Table B.10 show them to be fairly pure pyrite.

4.2.11 Carbonate

Carbonate is abundant in both the lamprophyre and kimberlite dykes. Scans of the carbonates from kimberlite dykes indicate that they are calcite with very minor Fe and Mg contents. Scans of

lamprophyre dyke carbonates, however, reveal a significant magnesium content and a partial analysis is given in Table B.11.

4.2.12 Apatite

Apatite is a common accessory mineral in both the kimberlite and lamprophyre dykes. Three crystals enclosed by calcite in the matrix of one of the kimberlite dykes were analysed and the results are given in Table B.12. They have lower P_2O_5 contents than most apatites but contain unusually high amounts of SiO_2 (up to 2.26 wt%) presumably as the result of the substitution of Si^{4+} for P^{5+} which is known in apatites (Cruft 1966, Deer, Howie and Zussman 1962), but does not generally result in such high concentrations of Si.

4.2.13 Serpentine

Some analyses of the green cores of the calcite-rich vug-like structures, or ocelli, from the kimberlite dykes are given in Table B.13. These serpentines are distinctive because of their unusually high iron contents (up to 12.2 wt% as FeO), a feature which seems to be restricted to kimberlites. These serpentines from Holsteinsborg are extremely similar in composition and have a similar mode of occurrence to the one reported by Emeleus and Andrews (1975) from a kimberlite in South West Greenland and all these serpentines are thought to be primary crystallisation phases from a very late-stage liquid. No analyses of serpentine from the lamprophyres were completed.

4.3 Anomalous lamprophyre dykes

Analyses of minerals from one sample (5669) from the anomalous dykes are given in Table B.14.

Clinopyroxene megacrysts are very abundant in the anomalous dykes and those analysed are variable in composition (salite and one endiopside) and generally richer in Fe than those from the other Holsteinsborg dykes.

The phlogopites from this anomalous dyke are Ti-rich like those from the other dykes but have higher Na_2O and FeO contents giving an $\text{Mg}/\text{Mg}+\text{Fe}$ ratio of about 0.78 and a $\text{Na}_2\text{O}/\text{Na}_2\text{O}+\text{K}_2\text{O}$ wt% ratio of 0.10 - 0.15.

The amphiboles are very different from those found in the lamprophyre dykes. They are richer in Ti, Al and Ca and are kaersutites which are characteristic of other alkaline rocks such as camptonites.

The alkali feldspar which occurs as a late-stage groundmass mineral has variable K/Na ratios.

Analyses of the opaque oxides show them to include two titanomagnetites and a chrome-spinel. The titanomagnetite occurred as a tiny (0.1mm) cubic grain and also as a narrow but distinct rim or overgrowth (analysis 337) on the larger chrome-spinel.

4.4 Inclusions

Minerals from a variety of the rounded inclusions found in the Holsteinsborg kimberlite dykes have been analysed and the results are given in Appendix C (Tables C.2 to C.8). Table C.1 of Appendix C lists for each inclusion the sample number, the type of inclusion and the minerals analysed, together with the appropriate analysis number. The inclusions considered in this part of the study comprise 16 peridotites and 2 granulites.

4.4.1 Peridotites

The peridotite inclusions examined comprise dunites, lherzolites and wehrlites, many of which have coarse textures but some are porphyroclastic or granuloblastic. The minerals analysed include olivine, clinopyroxene, orthopyroxene, garnet, chrome-spinel, ilmenite, phlogopite and amphibole.

(a) Olivine

The analyses of the peridotite olivines are given in Table C.2 and as can be seen from Fig. 4.1 their compositions are mostly in the range $Mg_{86-92.5}$ but for a particular inclusion the variation in Mg is usually more restricted to less than 2.5%. Some of the olivines from these inclusions are richer in Fe than those from many other peridotites found in kimberlites where compositions of Mg_{90-93} are perhaps more typical. The NiO content of the Holsteinsborg peridotite olivines is high, varying from 0.25 to 0.39 wt% and this NiO variation shows a poorly defined positive correlation with the MgO content. These olivines also have consistently low CaO values (less than 0.1 wt%).

(b) Clinopyroxene

Analyses of clinopyroxene, the next most abundant phase, are given in Table C.3(a). Their compositions are illustrated in terms of their Ca-Mg-Fe atomic proportions in Fig. 4.4 which show them to be diopsides or endiopsides (terminology after Deer, Howie and Zussman 1962). The Mg/Mg+Fe atomic ratio of these clinopyroxenes varies from 0.87 to 0.93. The diopsides are rich in chrome ($Cr_2O_3=1-2$ wt%) and are otherwise restricted in composition with 2-3 wt% FeO, 16-18 wt% MgO and 19-22 wt% CaO and are similar to clinopyroxenes from other

peridotite inclusions (for example Boyd 1970). The calcium-poor endiopsides (only analysed from sample 5524B) are poorer in chrome and richer in FeO compared with the diopsides.

(c) Orthopyroxene

All the orthopyroxenes analysed from the Holsteinsborg peridotite inclusions (see Table C.4) are enstatites with a restricted range of compositions, $\text{En}_{89.7-92.7}$, which can be seen from Fig. 4.4. They have low Al_2O_3 contents of 0.09 - 2.54 wt% but are otherwise similar to orthopyroxenes from other inclusion suites found in kimberlites (for example compare with Reid et al. 1975, Fig. 2).

(d) Garnet

Garnet has been analysed from two peridotite inclusions and the results are given in Table C.5(a). The garnets are rich in pyrope and have Mg/Mg+Fe atomic ratios of 0.81. The garnets from sample 5524B show little zoning or variation in composition but the garnet from 5984a is comparatively rich in Cr_2O_3 (4.28 wt%) but poorer in Al_2O_3 . The difference in Cr_2O_3 contents of the garnets is also reflected in the associated clinopyroxenes which agrees with the suggestion of Gurney, Harte and Cox (1975) that garnets typically have twice the Cr_2O_3 content of the coexisting clinopyroxene. Their compositions are illustrated in terms of certain atomic proportions in Figs. 4.5a and 4.5b.

The garnets from sample 5524B fall in the titanian pyrope group (group 1) of the garnet classification put forward by Dawson and Stephens (1975, 1976) but the garnet from 5984a falls in the chrome pyrope group (group 9). Both these groups (1 and 9) are largely made up from garnet occurrences in kimberlite matrices and from garnet-lherzolites.

(e) Fe-Ti-Cr Oxides

There are two main modes of occurrence of oxide minerals in the inclusions studied, (a) as minor and probably primary constituents which were found to be chrome spinels and (b) ilmenite which, from its textural relations, is thought not to be primary but is considered to be of metasomatic origin. Analyses of all these oxides are given in Table C.6.

The spinels are mostly chromites with 57.08 - 62.18 wt% Cr_2O_3 and 9.82 - 11.23 wt% MgO and low Al_2O_3 contents of between 0.99 and 3.88 wt% and they would plot close to the $\text{RO}_2\text{-R}_2\text{O}_3$ point in a $\text{RO-R}_2\text{O}_3$ plot (as used in Fig. 4.6) but showing some solid solution to ulvospinel. Although most of these chromites are considered to be primary constituents of the inclusions, those analysed from sample 55180L are small crystals which are associated with patches of late secondary green phlogopites. Analysis 263 (Table C.6) is similar to the other chromites, but analyses 259 and 260 (Table C.6) are very different and are chrome-spinels with approximately 32 wt% Al_2O_3 , 32 wt% Cr_2O_3 and 15 wt% MgO. It is suggested that this difference in composition is the result of secondary alteration. The oxide analysed from sample 5925 (an inclusion from the so-called 'pipe intrusion') is a relatively Fe-rich chromite.

The two ilmenite analyses (Table C.6) are from the ilmenite-olivine inclusion 5988 (see Plate 3.16 of Chapter 3). They are microilmenites (approximately 10.7 wt% Mg) and are extremely similar in composition to the microilmenite megacrysts found in the matrix of the Holsteinsborg kimberlite dykes. Ilmenite-silicate inclusions from other kimberlites have been discussed by Boyd and Nixon (1973a) and Harte and Gurney (1975) but these authors reach very different

conclusions about the origin of such inclusions.. Boyd and Nixon (1973a) suggest that ilmenite crystallised in equilibrium with the primary assemblage garnet-diopside-enstatite. Harte and Gurney (1975), however, suggest that the ilmenite crystallised as the result of primary metasomatic infiltration which probably occurred at the time of recrystallisation of the silicate minerals. The ilmenite-bearing inclusions are similar to those from Matsoku, Lesotho (Harte and Gurney 1975) and it is considered that they are mostly of primary metasomatic origin.

(f) Phlogopite

A variety of phlogopites have been analysed from the peridotite inclusions and the results are given in Table C.7. Their compositions are illustrated in the (Fe+Mg)-Ti-Al plot of Fig. 4.2. Several phlogopites (e.g. analyses 22, 23, 24, 257 and 261 in Table C.7), which are often green in colour, are associated with serpentine and other minerals in patches or veins of late secondary alteration. Other phlogopites which are brown in colour (e.g. analyses 56, 57, 110 and 111 in Table C.7) occur in equilibrium in recrystallised parts of the peridotite inclusions and are considered to be of primary metasomatic origin (after Harte and Gurney 1975; Harte, Cox and Gurney 1975). As can be seen from Fig. 4.2 all the phlogopites have somewhat restricted compositions but some of those thought to be of metasomatic origin plot away from the main cluster of peridotite phlogopites and closer to the main field of kimberlite phlogopites. The main chemical distinction between primary metasomatic and late secondary phlogopites in the Matsoku peridotites is their Cr_2O_3 content (Harte and Gurney 1975) but this does not hold for those from the Holsteinsborg peridotites. The Holsteinsborg phlogopites, however, can be distinguished using their

TiO₂ and NiO contents, the metasomatic phlogopites having greater than 1 wt% TiO₂ but no detectable NiO, while the secondary phlogopites have lower TiO₂ contents and greater than 0.15 wt% NiO. These phlogopite compositions do not correlate with those proposed by Smith and Dawson (in press) for peridotite phlogopites in their classification of micas from kimberlites and their inclusions.

(g) Amphibole

Four analyses of amphiboles are given in Table C.8 and include both tremolite and richterite (after Leake 1968). The tremolite occurs in the inclusion 5925 as fibrous patches apparently representing the recrystallisation of clinopyroxene while the rest of the inclusion is very fresh and coarse in texture. The richterite analyses from 55180L resulted from the analyses of what was thought to be "rather altered clinopyroxene". Although it seems that these amphiboles have formed as the result of alteration of clinopyroxene it is not clear when this alteration took place.

4.4.2 Granulites

Both the inclusions examined were garnet-granulites and analysed minerals include garnet, omphacite, plagioclase, potassium feldspar, rutile and calcite. The garnet and clinopyroxene from these granulites are much richer in Fe than those from the peridotite inclusions.

(a) Garnet

The garnets from the two granulites studied (see Table C.5(b)) are similar in composition, both having approximately 47% of the almandine and 30-35% of the pyrope molecules. Their compositions are illustrated in terms of atomic proportion plots in Fig. 4.5 and the relatively Fe-rich nature of these garnets is

particularly evident in Fig. 4.5a. These garnets are similar in composition to those reported from granulites found in other kimberlites, for example in Lesotho at Matsoku (Cox, Gurney and Harte 1973), and at Kao and Liquobong (Nixon and Boyd 1973c and 1973d).

(b) Clinopyroxene

The clinopyroxenes which have only been analysed from one granulite inclusion, 55180L (see Table C.3(b)), are rich in sodium and are omphacites, the clinopyroxene often found associated with pyrope-almandine garnets. Pyroxene compositions from inclusion 55180L are illustrated in the Ca-Mg-Fe atomic proportions plot shown in Fig. 4.4.

(c) Other minerals

Analyses of other minerals from the granulite inclusions are given in Table C.9. A potassium feldspar occurs in the granulite 5519 whereas the feldspar found in 5518G is a sodic plagioclase. Rutile and calcite are accessory minerals in the granulite 5518G.

5.1 Introduction

The kimberlite and potassic lamprophyre dykes from the Holsteinsborg region are particularly suitable for a whole-rock geochemical study because the rocks are extremely fresh, except for a clearly defined thin weathered zone on exposed surfaces. This lack of alteration contrasts markedly with the situation of many otherwise similar rocks from South Africa and elsewhere.

Eighty seven whole-rock analyses have been made using largely X-ray fluorescence techniques; details of these results are given in Appendix D and sample localities are listed in Appendix A and given in Map 1 (in back pocket). The major element contents of the samples were determined using fused rock powders, while pressed powders were used for the trace elements. FeO , Na_2O , H_2O^+ and CO_2 for all samples, and Sr and Zr for selected samples, were determined using standard wet-chemical techniques. Details of all the analytical techniques used are given in Appendix F. The accuracy and precision, which were satisfactory for all major elements and most trace elements, are also discussed in Appendix F.

Generally the kimberlite analyses give totals close to 100% but the major oxide totals for the lamprophyre samples (see Appendix D) tend to be low, usually in the range 96 - 98%. This discrepancy is partly accounted for by the "minor" element concentrations, in particular Ba and Sr. F, Cl, S and B were analysed in selected samples to see whether any of these elements were significant components of the lamprophyres.

In addition to the eighty seven whole-rock analyses, a further

six full wet-chemical analyses (analysts M. J. Saunders and A. C. S. Smith) of samples from the Holsteinsborg dykes were carried out. These analysed rocks were subsequently used as standards and their analyses are presented in Table F.4 of Appendix F.

5.2 MAJOR ELEMENT GEOCHEMISTRY

5.2.1 Introduction

In general, the Holsteinsborg dykes are ultrabasic (see Appendix D) but contain more TiO_2 , CaO and K_2O than 'average' ultrabasic analyses as given in Wyllie (1967). There is, however, considerable variation in chemical composition between the dykes. These variations define two chemically distinct groups consistent with the division on field, petrographical and mineralogical evidence suggested in Chapters 2, 3 and 4, where the dykes were divided into kimberlitic and lamprophyric types.

The average chemical compositions of the kimberlite and potassic lamprophyre groups are given in Table 5.1. Whilst average analyses are not a good method of representing geochemical data, in this instance they do illustrate the principal chemical differences between the two groups of Holsteinsborg dykes and are also used for reference later in this chapter.

In the following sections the major element geochemistry is presented in several different ways to illustrate the chemical variation within the Holsteinsborg dykes, and used to discuss the petrogenesis of these dykes.

	average kimberlite	average potassic lamprophyre
SiO ₂	30.18	41.76
TiO ₂	3.39	3.12
Al ₂ O ₃	2.48	7.17
Cr ₂ O ₃	0.22	0.08
Fe ₂ O ₃	3.92	1.85
FeO	8.68	5.85
MnO	0.19	0.10
MgO	27.53	11.84
CaO	9.65	7.85
Na ₂ O	0.25	1.42
K ₂ O	1.82	7.05
H ₂ O ⁺	3.70	2.49
P ₂ O ₅	0.51	1.14
CO ₂	7.39	5.72

Table 5.1

The average major oxide compositions of the
Holsteinsborg kimberlite and potassic
lamprophyre dykes (calculated using the 41
kimberlite and 52 lamprophyre analyses given
in Appendix D)

5.2.2 Frequency distribution

Histograms showing the frequency distribution of the major oxide compositions of the Holsteinsborg dykes are shown in Fig. 5.1 and several important features are apparent:-

- (1) the distinctive differences in chemistry of the kimberlites and potassic lamprophyres as well as the overall extremely wide range of compositions shown by most of the major oxides
- (2) the very ultrabasic nature of the kimberlites which is shown by low SiO_2 and high $(\text{MgO} + \text{FeO})$
- (3) the very potassic nature of the lamprophyres, with K_2O contents up to 10 wt%
- (4) the extremely high volatile content of both groups with $(\text{H}_2\text{O} + \text{CO}_2)$ values up to 26 wt%.

Apart from these features, kimberlites with SiO_2 values less than 30 wt % have higher CO_2 values (greater than 10 wt%), which is consistent with their calcite content. These are referred to as carbonate-rich kimberlites. Concentrations of Al_2O_3 , K_2O and TiO_2 in the kimberlites are related to the presence of phlogopite, ilmenite and perovskite. These kimberlite analyses lie within the compositional range of kimberlites suggested by Dawson (1967b) although one deviation of the Holsteinsborg kimberlites from the 'average' kimberlite is the lower fixed water content of 3.7 wt% as compared to the average of 7.7 wt%.

The average Mg/Fe ratio for the Holsteinsborg kimberlites is 1.75 which is low for ultrabasic rocks, and the average K/Na ratio of 8.4 is high. These values, however, compare well with values suggested by Dawson (1967b) of 1.8 and 7.4 respectively for

micaceous kimberlites.

The lamprophyre dykes are characterised by high K_2O contents and should, therefore, be referred to as potassic lamprophyres. The high K_2O content, along with high Al_2O_3 , reflects not only the abundant phlogopite in these rocks but also the groundmass potassium feldspar and the pseudoleucite megacrysts. The lamprophyres are chemically distinguished from the kimberlites by higher SiO_2 , K_2O , Al_2O_3 , Na_2O and P_2O_5 and lower MgO , CaO , MnO and H_2O^+ contents (see Fig. 5.1). The lower MgO values reflect the generally lower olivine content of the lamprophyre dykes. These dykes have an average Mg/Fe ratio of 1.2, a high average K/Na ratio of 6.0 and a K_2O/Na_2O wt% ratio of greater than 3, values characteristic of potassic magnesian rocks (Carmichael, Turner and Verhoogen 1974).

The Fe^{+++}/Fe^{++} ratios for all the Holsteinsborg dykes lie within the range 0.3 - 0.4 and vary sympathetically with the H_2O^+ content. Values of less than 1 for this ratio are usual for peridotites and dunites, but Dawson (1967b) suggests a much higher value of 7.5 for kimberlites. It has already been noted that the Holsteinsborg dykes contain considerably less H_2O^+ than other kimberlites and show significantly less alteration than, say, many South African kimberlites. It appears, therefore, that the Fe^{+++}/Fe^{++} ratio varies with the H_2O^+ content and generally reflects the degree to which these rock types have been altered, particularly through serpentinisation.

5.2.3 'SAL-FEM-VOL' diagram

The SAL ($SiO_2 + Al_2O_3 + K_2O + Na_2O$) - FEM ($CaO + MgO + FeO + Fe_2O_3 + TiO_2$) - VOL ($CO_2 + H_2O + P_2O_5$) triangular weight per cent plot (after Dawson 1967b) is a useful method of

illustrating the compositional fields and relationships of kimberlites to carbonatites and related rock types. In this case the plot distinguishes between the kimberlite and potassic lamprophyre dykes of the Holsteinsborg swarm. The SAL-FEM-VOL diagram is shown in Fig. 5.2 in which it is seen that the Holsteinsborg kimberlites are confined to the FEM-rich part of the general kimberlite field. Specific kimberlites which plot in the same area as the Holsteinsborg dykes are the Nigerdlikasik kimberlites, south-west Greenland (Emeleus and Andrews 1975), the Benfontein kimberlite (Dawson and Hawthorne 1973) and a kimberlite from Yakutia (Zhabin 1968, cited in Goff 1973). Three of the Holsteinsborg dyke samples which are carbonate-rich kimberlites (samples 5518, 5905 and 5907 from Appendix D) form a spread from the main field towards the carbonatite field. These samples are similar to the Søndre Isortoq dyke from south-west Greenland (Goff 1973), the Marakabei dyke, Lesotho (Dawson and Hawthorne 1970) and the Jagersfontein dyke and the carbonated kimberlite dyke from Premier Mine, South Africa (Williams 1932, p.137 and 143 respectively).

The Holsteinsborg lamprophyre dykes form a distinct field which overlaps slightly with the SAL-rich part of the general kimberlite field. They lie adjacent to the field of other lamprophyres and potassic magnesian rocks because of their higher volatile content.

The general compositional fields of the kimberlites, carbonatites, lamprophyres and other related rocks were based on analyses from the literature. These analyses were taken from the volumes Carmichael, Turner and Verhoogen (1974), Nixon (1973a), Tuttle and Gittins (1966), Wyllie (1967) and the Physics and Chemistry of the Earth Volume 9 (1975) as well as Allens and Deans (1965), Carmichael (1967b), K. Collerson (personal communication), Cundari (1973),

Holsteinsborg dykes

kimberlites

carbonate-rich kimberlites

potassic lamprophyres

Analyses from the literature

lamprophyres and other
potassium-rich magnesian rocks

kimberlites

carbonatites

Cundari and le Maitre (1970), Dawson (1960, 1962), Dawson and Hawthorne (1970 and 1973), Eckermann (1948), Goff (1973), Hawthorne (1968), Holmes (1950), Holmes and Harwood (1937), Métais, Ravier and Duong (1962), Nockolds (1954), Prider (1960), Rivalenti and Sighinolfi (1971), Sahama (1974), Strong and Harris (1974), Sukeswala and Avasia (1971), Sutherland (1965), Upton (1965), Velde (1967), Wade and Prider (1940), Walton and Arnold (1970) and Williams (1932).

5.2.4 C.I.P.W. Norms

C.I.P.W. norms for the Holsteinsborg dykes are given in Appendix D. The undersaturated nature of the kimberlite dykes is reflected in the high normative percentage of ol, the occurrence of ne and lc and occasionally cs (Ca_2SiO_4). These features, together with the occurrence of ab, an, ac and c are characteristic of kimberlites in general. Dawson (1967b) has suggested that ac occurs only in the norms of soda-rich kimberlites (e.g. a kimberlite from Dutoitspan with 2.7 wt% Na_2O), but minor ac occurs in about 25% of the analysed Holsteinsborg kimberlite samples. The Holsteinsborg samples have lower Na_2O contents with values up to 1.30 wt% and an average of 0.25 wt%.

In contrast, the potassic lamprophyre dykes are silica saturated being mostly hy normative. The more salic rocks mineralogically have sanidine rather than leucite in the groundmass and those which are qtz normative are aphyric and contain abundant sanidine. The high normative percentage of or in part reflects the usually abundant phlogopite. The occurrence of ks and ns (K_2SiO_3 and Na_2SiO_3 respectively), which are rarely found in norms, reflects the peralkaline nature of these rocks and can be reflected mineralogically by ubiquitous potassic richterite in the groundmass. The combination

of both the hy normative and peralkaline nature of these is unusual but has been found in similar rock types including wyomingites and orendites from the Leucite Hills (Carmichael 1967b), and wolgidites, cedricites, fitzroyites and mamilites from West Kimberley (Wade and Prider 1940).

Variable amounts of or, ol, cr, il, ct, ap and H_2O^+ are common to both groups of rocks. There are also samples which have norms intermediate between the two groups. The anomalous lamprophyre dykes 5667, 5668 and 5672 are ne normative with a high percentage of di (20 - 40%). Their norms appear most similar to the kimberlite dykes but the enrichment in normative di reflects a possible clinopyroxene accumulation which is discussed later in this chapter. The one other anomalous dyke, 5688, shows the same high di values but has a norm more similar to those of the potassic lamprophyre dykes.

The differentiation indices (DI, after Thornton and Tuttle 1960) are a further indication of the ultrabasic to basic nature of all these dykes. The DI for the kimberlites fall between 1 and 22 and those of the lamprophyre dykes between 32 and 53.

5.2.5 Harker Variation Diagrams

The use of variation diagrams has been questioned, for example by Pearce (1968); nevertheless they are useful for illustrating compositional relations within a group of rocks, and in particular for discriminating between rival hypotheses of crystal-liquid fractionation.

When using variation diagrams to indicate lines of liquid descent, glassy or fine-grained rocks are likely to have been derived from a liquid of essentially the same composition as the

rock. However, when considering porphyritic rocks, the composition of the rock could be similar to, or very different from, the original liquid, depending on the degree of accumulation of the phenocryst phase. Many of the Holsteinsborg dyke samples are porphyritic (with crystals up to 3cm in size) but plots based on the aphyric samples have trends on variation diagrams not markedly different from those obtained by plotting the group as a whole.

Standard variation diagrams for the Holsteinsborg dykes are shown in Fig. 5.3. With decreasing MgO:-

- (1) the kimberlite dykes show
 - (a) scatter for SiO_2 , TiO_2 , total FeO, MnO, Na_2O and CO_2
 - (b) poorly defined increases of K_2O , CaO and P_2O_5
 - (c) increase of Al_2O_3
- (2) the potassic lamprophyre dykes show
 - (a) increase of SiO_2 , TiO_2 , K_2O and Al_2O_3
 - (b) poorly defined increases of Na_2O and P_2O_5
 - (c) poorly defined decrease of total FeO
 - (d) scatter for MnO, CaO and CO_2 .

There is a general scatter of the kimberlite compositions on the variation diagrams which could be the result of the inclusion of xenolithic material although all obvious xenolithic material was removed during sample preparation. In contrast the lamprophyre dykes lie on better defined trends.

Among the whole-rock analyses are several groups of two to four samples representing different parts of a single intrusion which generally comprise the aphyric marginal zone and the phlogopite and/or olivine megacryst-rich central zones. The central zones are

Fig. 5.3

(2 pages, overleaf)

Major oxide (wt%) variation diagrams of the Holsteinsborg dykes, plotted with MgO as the abscissa.

open squares = kimberlites

solid circles = potassic lamprophyres

open triangles = anomalous lamprophyres

more magnesian while the marginal zones are richer in K_2O and Al_2O_3 reflecting the abundance of the megacryst phases possibly as a result of flow differentiation.

It can be seen from most of these variation diagrams (Fig. 5.3) that the kimberlite dykes tend to plot on the continuation of the lamprophyre trends, implying a genetic connection between the two groups possibly as the result of crystal fractionation. It would, therefore, seem likely that these two rock groups evolved from a common parental magma.

Harker variation diagrams are rarely used for the interpretation of the petrogenesis of kimberlites and related rock types, presumably because of the problems caused by the high carbonate and xenolith contents characteristic of these rock types. In an attempt to overcome the problem of the high and variable carbonate contents found in the Holsteinsborg dykes the whole-rock analyses were replotted having removed the H_2O^+ and CO_2 as $Ca(Mg)CO_3$ and recalculating to 100% and the results are given in Appendix E. The details of the method of removal of the $Ca(Mg)CO_3$ are given in Section 5.2.10a. Although the carbonate and water are considered to be primary constituents in the Holsteinsborg dykes, it is often suggested that the volatile-rich and silicate fractions of kimberlites and other alkaline ultrabasic rocks are immiscible (Ferguson and Currie 1971, Clement 1975) and evolve independently. Considerations of the fractionation of silicate minerals, therefore, would not directly involve the volatile-rich fluid. It is also thought that the amount of carbonate and associated minerals (apatite and serpentine) included in the rock sample after solidification is not governed by the evolution of the magma but by the conditions controlling the movement or escape of the more fluid volatile-rich

liquid, particularly if the system is open with respect to volatiles. For these reasons, therefore, it was thought to be meaningful to remove the CO_2 and H_2O^+ and consider the petrogenesis of the remaining silicate fraction.

These H_2O^+ and $\text{Ca}(\text{Mg})\text{CO}_3$ -free analyses (Appendix E) were found to be more useful than the complete analyses for the interpretation of the petrogenesis of the Holsteinsborg dykes, and are used in the majority of the following sections of this chapter. Fig. 5.4 shows these analyses plotted on similar Harker variation diagrams to those of Fig. 5.3. The recalculation of the analyses in this way was further justified because much better defined trends were produced through the reduction in scatter and the slight shift of the points, and these trends were found to be consistent with a simple hypothesis for their evolution. Also the fact that these trends were produced illustrated that the chemical variation of the kimberlite and lamprophyre rocks had not been overwhelmed by the inclusion of xenolithic material.

It can be seen from the variation diagrams in Fig. 5.4 that with decreasing MgO :-

- (1) the kimberlite dykes show
 - (a) increase of Al_2O_3 and K_2O
 - (b) poorly defined decrease of total FeO and MnO
 - (c) little change of SiO_2 and Na_2O
 - (d) scatter for P_2O_5
 - (e) poorly defined increase of TiO_2
- (2) the potassic lamprophyre dykes show
 - (a) increase of SiO_2 , TiO_2 , Al_2O_3 , K_2O and P_2O_5
 - (b) poorly defined increase of Na_2O
 - (c) poorly defined decrease of total FeO and MnO .

Fig. 5.4 Major oxide (wt%) variation diagrams, as Fig. 5.3,
but plotting recalculated Ca(Mg)CO_3 - and H_2O^+ -free
whole-rock analyses (see Appendix E).

open squares = kimberlites

solid circles = potassic lamprophyres

open triangles = anomalous lamprophyres

Other points which are shown in these diagrams are:-

- (1) P_2O_5 and Na_2O show little change between Figs. 5.3 and 5.4. In the case of P_2O_5 the oxide should perhaps have been considered as a volatile, particularly as the apatite in the rocks is generally found associated with the calcite, and their co-crystallisation in carbonatitic-like fluids has been suggested by Biggar (1969)
- (2) the anomalous nature of the samples 5667, 5668, 5672 and to a lesser extent 5688, can be explained by clinopyroxene enrichment.

It has been shown from the variation diagrams that the kimberlites and the lamprophyres are chemically distinct but there are apparent trends within, and in some cases between, each of the groups. These trends could result from a process of crystal fractionation. Fig. 5.5 shows the fields of kimberlite and lamprophyre compositions on the oxide:oxide variation diagrams (largely from Fig. 5.4) together with the plots of likely fractionating phases, principally megacryst phases found within the dykes.

The variation in chemistry within each group of dykes can be explained largely by olivine fractionation or enrichment. The kimberlite trend leads away from olivine with an average composition Mg_{85} (Fig. 5.5), the composition of euhedral crystals in the kimberlite dykes. The lamprophyre trend likewise leads away from olivine but with an average composition $Mg_{91.5}$ which is also the mean composition of the olivines found in the lamprophyre dykes. The kimberlites are very much richer in olivine, and thus in MgO , than the lamprophyres and the olivines in the kimberlites have a wide range of compositions with a mean about Mg_{85} . It is proposed in subsequent parts of this chapter that the lamprophyres have evolved from a kimberlitic parent by substantial extraction of not only olivine but also titanomagnetite, which may have maintained the Mg/Fe ratio in the liquids at levels consistent with Mg_{90+} olivine crystallisation while depleting the liquid in total $MgO+FeO$. The conditions, therefore, were never

suitable for the crystallisation of the more Fe-rich olivine in the lamprophyric liquids.

It can be seen from Fig. 5.5 that in detail the lamprophyre trend might be more accurately explained by extracting a relatively minor amount of clinopyroxene and phlogopite in addition to the olivine. The control point for the lamprophyre trend would, therefore, lie within the triangle joining olivine, clinopyroxene and phlogopite, but close to the olivine apex. The position of this point is difficult to define because of the uncertainty in the composition of the fractionating phlogopite (the analysed megacrysts show such variable chemistry (see Table B.2)).

As most of the rocks considered in this study are porphyritic it is difficult to distinguish between the part of the trend due to liquid evolution and that part which might be the result of phenocryst and/or xenocryst accumulation in the liquid. In these rocks it is virtually impossible to differentiate between xenocrysts and phenocrysts. The few composite olivines which are found in the kimberlite dykes might be considered to be xenocrysts, but would have little effect on the whole-rock chemistry of the dykes as they represent such a small proportion of the total olivine present. The MgO content of the rocks analysed does correlate with the modal content of olivine in these samples (see Table 3.1 in back pocket). Different phases of intrusion, therefore, must have carried different amounts of olivine crystals. The occurrence of relatively large rounded ultrabasic nodules suggests that during eruption the kimberlites did not undergo any significant modification of the megacryst content by crystal settling. The local concentration of megacrysts within one intrusion may have been modified by flow differentiation.

Both the kimberlite and lamprophyre dykes, therefore, may have resulted from the pulsatory eruption from magma systems in which olivine was able to fractionate. Each eruption of magma contained different concentrations of megacrysts.

Fig. 5.5 Compositional fields of the kimberlites and
lamprophyres plotted with some possible fractionating
phases on oxide:oxide (wt%) variation diagrams using
 $\text{Ca}(\text{Mg})\text{CO}_3$ - and H_2O^+ -free analyses (largely from
Fig. 5.4).

average chemical compositions of the kimberlite and potassic lamprophyre dykes (from Table 5.1)
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* The most magnesian aphyric rock analysed lies close to the average lamprophyre

It was suggested on page 88 that the variation diagrams may also indicate that all the dykes are genetically related. A discussion of this possibility requires an estimate of the composition of the liquid parental to each group of dykes. For the kimberlite dykes, and indeed kimberlites in general, it is impossible to be certain of the composition of a kimberlitic liquid. If each injection of magma was derived from a fractionating body of magma, it might be reasonable to suppose that eruptions sampled parts which had either lost or accumulated olivine and hence an average composition might be a suitable approximation. This average (see Table 5.1) lies close to the midway point between the most extreme samples analysed. This average composition also lies just to the MgO-rich side of the main cluster of kimberlite analyses. Similar arguments can be put forward for the use of the average lamprophyre composition (see Table 5.1) to represent the parental lamprophyre liquid. In the case of the lamprophyre dykes, however, a few of the samples analysed are aphyric and so represent true liquid compositions. The most magnesian aphyric rock analysed is sample 5653 (see Table D.2, MgO = 12.53 wt%) and this approximates closely to the average lamprophyre composition.

It is suggested that, within each group of dykes, rocks which are more magnesian than the proposed parental fluids represent magmas which have accumulated olivine. Conversely the MgO-poor rocks represent olivine depleted magmas.

For subsequent discussion it was decided, therefore, to use the average compositions given in Table 5.1 to represent the parental liquids for each group (calculated $\text{Ca}(\text{Mg})\text{CO}_3$ - and H_2O^+ -free when appropriate). It should also be noted (from Fig. 5.5) that some modification to the proposed parental fluid compositions within the ranges of observed compositions does not alter the principal conclusions of the following discussion.

Considering the Holsteinsborg dykes as one group some of the trends observed in Fig. 5.5 lie close to an overall olivine control line.

Olivine is a megacryst phase in most of the dykes, hence it should be considered whether the relationship between the kimberlites and lamprophyres is one of simple olivine fractionation. It is clear, however, that the chemistry of the group as a whole cannot be controlled solely by olivine fractionation. In the plot MgO vs. TiO_2 (see Fig. 5.4 or 5.5), for example, the evolution from a kimberlitic parental magma to a lamprophyric magma with a similar TiO_2 content cannot be explained by the fractionation of a phase containing essentially no TiO_2 , such as olivine. To explain this and other deviations from an olivine control line requires the crystallisation of a Fe-Ti-rich phase together with olivine. The most abundant Ti-rich mineral, apart from perovskite, in the kimberlite dykes is spinel, essentially titanomagnetite of fairly constant composition. The titanomagnetite analysis 192 (see Table B.9 (a) in Appendix B) and an olivine of composition Mg_{92} were used for reference in the following discussions. The suggested olivine plus spinel fractionation trends are illustrated in Fig. 5.5. It can be seen from Fig. 5.5 that the evolution of the initial lamprophyre liquid from the parental kimberlitic magma is consistent with the fractionation of approximately 75% olivine of composition Mg_{92} and 25% spinel with a composition similar to analysis 192.

It can be seen that both the Ni variation (see Fig. 5.5 and 5.15) and the Rb vs. K_2O variation (see Fig. 5.16) appear inconsistent with this hypothesis in its simple form. These points are dealt with in section 5.3.3, where it is shown that there is no necessary inconsistency provided that the variation in the distribution coefficient for Ni is considered and a small amount of phlogopite is removed along with the olivine and spinel. The amount of phlogopite fractionation required to explain some of these trace element variations would not significantly affect the major oxide considerations of this hypothesis.

The proposed olivine plus spinel (plus phlogopite) fractionation process must have occurred at depth to allow the formation of a lamprophyric liquid from the parental kimberlitic magma. The parental

kimberlite and lamprophyre magmas then evolved independently by a second stage of fractionation which is shown by the different and non-parallel trends for the two groups of dykes on the Harker variation diagrams (Fig. 5.4).

In summary, considerations of these variation diagrams seem to indicate a possible genetic relationship between the Holsteinsborg kimberlite and potassic lamprophyre dykes by a two stage fractionation process involving phases found in the dykes. In total, therefore, the proposed model involves three separate fractionation processes:- (a) the evolution of part of the kimberlitic magma by olivine fractionation, (b) the evolution of the lamprophyric magma from a kimberlitic magma by the fractionation of olivine, titanomagnetite and minor phlogopite, and (c) further evolution of the lamprophyric magma by olivine plus clinopyroxene plus phlogopite ($\pm$ pseudoleucite) fractionation.

In subsequent parts of this chapter the major oxide and trace element chemistry of the Holsteinsborg dykes is presented in a variety of ways which support the proposed fractionation model.

5.2.6 'FMA' diagram

Fig. 5.6 shows the 'FMA' plot for the Holsteinsborg kimberlite and potassic lamprophyre dykes; where $F = \text{FeO} + \text{Fe}_2\text{O}_3$ and $M = \text{MgO}$ and $A = \text{Na}_2\text{O} + \text{K}_2\text{O}$, all in weight per cent. The two groups of rocks lie on different trends reflecting the separate evolution of the initial lamprophyre and kimberlite magmas by a second stage fractionation controlled largely by olivine. The scatter amongst the MgO-poor lamprophyre samples can be explained by pseudoleucite (or leucite) fractionation.

The proposed evolution of the initial lamprophyre magma from the parental kimberlite magma by olivine plus spinel fractionation is again illustrated.

Fig. 5.6 - a 'FMA' diagram for the Holsteinsborg dykes.

ol = olivine

sp = spinel

open squares = kimberlites

solid circles = potassic lamprophyres

open triangles = anomalous lamprophyres

Fig. 5.7 - b $\text{K}_2\text{O}-\text{Al}_2\text{O}_3-\text{TiO}_2$ ternary (wt%) variation diagram for the Holsteinsborg dykes.

k-feld = potassium feldspar

other symbols as for Fig. 5.6

5.2.7 K₂O-Al₂O₃-TiO₂ ternary variation diagram

The K₂O-Al₂O₃-TiO₂ (wt%) ternary variation diagram for the Holsteinsborg dykes is given in Fig. 5.7. These three components are essentially independent of any variation caused by olivine fractionation and it would be expected that no trends would be evident if the control was purely a result of olivine fractionation. The observed trend away from spinel (using analysis 192) supports the suggestion of spinel being an important fractionating phase.

The spinels in the kimberlite dykes including analysis 192 contain some Al₂O₃ (see Table B.9(a) in Appendix B) so during olivine plus spinel fractionation some Al₂O₃ is abstracted from the magma while K₂O is not involved (see Fig. 5.7) and this could account for the development of the peralkaline nature of the lamprophyre dykes.

5.2.8 Molar ratio comparisons

It is sometimes difficult to discriminate between rival hypotheses of magmatic evolution using Harker variation diagrams and ternary weight per cent plots. To overcome this problem and to determine possible extract compositions Pearce (1968, 1970) suggested the use of molar ratio comparisons, where molar ratios of the oxides are calculated using one specific oxide as the constant divisor and these values are used to plot variation diagrams.

Examination of the Harker variation diagrams (Fig. 5.4) suggests that K₂O and Al₂O₃ which lie on good and fairly continuous trends and might almost be considered as incompatible elements, would be suitable for use as the constant divisor for Pearce's method. K₂O is independent of the suggested important fractionating phases and can be used to essentially normalise the other components. Plotting

MgO/K₂O vs. SiO₂/K₂O (moles) gives a good linear trend as shown in Fig. 5.8a. The gradient of the trend suggests an olivine composition of Mg₉₁ for the fractionating phase.

The slope of the MgO/Al₂O₃ vs. SiO₂/Al₂O₃ plot (Fig. 5.8b) is greater than two. This is, however, consistent with approximately 25% spinel fractionating along with olivine. Al₂O₃ is, therefore, not an independent component, so this plot cannot be used for predicting the composition of any one fractionating phase.

The anomalous dykes appear to define a trend with a less steep gradient, more indicative of clinopyroxene fractionation.

5.2.9 Extract calculations

The evolution of the initial lamprophyre magma suggested in earlier parts of this chapter can be represented by the equation

$$\begin{array}{ccccccc} \text{kimberlite} & & & \text{lamprophyre} & & & \\ \text{magma} & = & & \text{magma} & + & \text{olivine} & + & \text{spinel.} \end{array}$$

Extract calculations, using a modification of the least-square-fit computer programme of Wright and Doherty (1970), were performed in an attempt to solve the above equation and to see if any solution was consistent with the suggested hypothesis. The average kimberlite and potassic lamprophyre compositions from Table 5.1 (calculated free of Ca(Mg)CO₃ and H₂O⁺) were used to represent the parental and evolved magmas. Using spinel 192 and pure forsterite and fayalite as possible precipitating phases the equation gives the solution

$$\begin{array}{ccccccc} \text{kimberlite} & & & \text{lamprophyre} & & & \\ \text{magma} & = & 28.96\% & \text{magma} & + & 55.66\% \text{ olivine} & + & 15.38\% \text{ spinel} \\ & & & & & (\text{Mg}_{91.5}) & & 192 \end{array}$$

This solution gives the sum of the residuals as 0.24 and, as values of less than one are generally considered to be meaningful, it strongly supports the proposed magmatic evolution. The formation of a precipitate of 22% spinel and 78% olivine is also in good agreement with the suggested first stage fractionation.

5.2.10 C-M-A-S

(a) Introduction

O'Hara (1968) devised a scheme for representing analytical data for basic and ultrabasic rocks in terms of a pseudo-quaternary system C-M-A-S. The definition of the four components is summarised in Fig. 5.9. This system is the natural analogue of the synthetic quaternary system $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$. Projections within the C-M-A-S system, together with experimentally determined phase relations, can be used to predict crystallisation paths for some magmas. The method of projection and the location of phase boundaries are given by O'Hara (1968) and Jamieson (1969, 1970).

The Holsteinsborg dykes are plotted in C-M-A-S using two different planes of projection which are illustrated in Fig. 5.9 (all projections in this study are plotted in weight per cent). Depending on the position of the points within the tetrahedron some of the projection planes are prone to distortion. These possible distortion effects become apparent if the position of the points within the tetrahedron can be studied stereoscopically. A stereo pair of the Holsteinsborg dyke compositions in the C-M-A-S tetrahedron was plotted using the computer programme PLUTO (a molecular plotting programme written by S. Motherwell at the University Chemistry Laboratory, Cambridge and adapted for the Edinburgh Multi-Access System by Dr. M. Barrow, Department of Chemistry,

Fig. 5.9

The C-M-A-S tetrahedron showing the projection
planes C_3A -M-S and $CS-M_2S$ -AS.

$$\text{wt\% C} = (\text{molar proportions } CaO - \frac{1}{3}P_2O_5 + 2Na_2O + 2K_2O) \times 56.08$$

$$\text{wt\% M} = (\text{molar proportions } MgO + FeO + MnO + NiO - TiO_2) \times 40.311$$

$$\text{wt\% A} = (\text{molar proportions } Al_2O_3 + Cr_2O_3 + Fe_2O_3 + TiO_2 + Na_2O + K_2O) \times 101.961$$

$$\text{wt\% S} = (\text{molar proportions } SiO_2 - 2Na_2O - 2K_2O) \times 60.085$$

University of Edinburgh). The stereo pair is given in Fig. 5.10 (kept in the back pocket to facilitate use with a stereoscope) from which it can be seen that the Holsteinsborg dykes lie close to a plane parallel to C-A-M (at S = 40%). The points also fall close to a line trending away from olivine.

In considering kimberlites and related rock types in terms of the C-M-A-S system a number of problems arise. Firstly, CO_2 is an oxide not accounted for in this scheme and kimberlitic rocks contain high and variable amounts of CO_2 , carbonate being an important constituent of these rocks. Kimberlites have been interpreted using the C-M-A-S system by Ferguson *et al.* (1975) where the analyses were used both complete and CO_2 -free, removing the CO_2 as dolomite. In this study the analyses were also used complete and CO_2 -free. However, as the main carbonate phase in the Holsteinsborg dykes is calcite, sometimes with minor magnesium contents, the CO_2 -free analyses were calculated by the removal of CaCO_3 . For some analyses, however, this gave a small negative CaO content and this was compensated for by removing an equivalent amount of MgO. The adjusted analyses, recalculated to 100%, are given in Appendix E. As with the Harker variation diagrams (see Section 5.2.5) the Ca(Mg)CO_3 analyses showed considerably less scatter than the complete analyses on all plots in C-M-A-S, and this can be illustrated by comparing Fig. 5.12 with Fig. 5.13, for example.

Another problem with kimberlitic rocks in the C-M-A-S tetrahedron is their relationship to experimentally determined phase boundaries. Jamieson (1969) has suggested that differences in content of some 'minor' elements (Ti, K, P) may cause shifts in the position of phase boundaries in the C-M-A-S system and the Holsteinsborg dykes do show extreme and variable concentrations of these elements.

Also Eggler (1975) has suggested that the presence of CO_2 in a melt, again likely to be present in the Holsteinsborg parental magma, will enhance the undersaturated character of the magma by movement of phase boundaries.

The kimberlite dykes show a greater degree of scatter than the lamprophyre dykes which is attributable to the inhomogeneous and more carbonate-rich nature of the kimberlites and the possible inclusion of xenolithic material.

Bearing in mind these possible modifying factors, the C-M-A-S system can be used to interpret the petrogenesis of the Holsteinsborg dykes by considering the analyses in terms of different projections.

(b) Clinopyroxene (CMS_2) into $\text{C}_3\text{A-M-S}$

The plot of the $\text{Ca}(\text{Mg})\text{CO}_3$ -free Holsteinsborg dyke analyses on the clinopyroxene into $\text{C}_3\text{A-M-S}$ projection is illustrated in Fig. 5.11. There is a clear evolutionary trend linking the kimberlite and the lamprophyre dykes, and this trend essentially follows an olivine control line.

The kimberlite dykes all lie within the primary phase volume of olivine at 30kb. The extreme picritic nature of these dykes is clearly displayed by their position closer to the olivine point. In the region of 47% S, 30% M and 23% C_3A on this projection there appears to be a cluster of kimberlite dyke compositions, including the average composition. It is tempting to suggest that the kimberlite magma was formed by a small degree of partial melting at a pressure greater than 30kb, which has its pseudo-invariant point plotting in the region of this

cluster. There appears to be little evidence to support some of the other hypotheses for the origin of kimberlites, for example by the mixing of an ultrabasic magma with crustal or carbonatitic material, or deriving kimberlitic magmas by eclogite fractionation of a primary magma (O'Hara, Saunders and Mercy (1975) since the few eclogite inclusions found in the Holsteinsborg dykes seem to be related to the granulite xenoliths rather than representing igneous cumulates.

The inclusion of ultrabasic nodules in parts of the kimberlite dykes suggests that the kimberlite magmas have undergone rapid ascent towards the surface and that any modification of that magma by crystal settling would be negligible. If these dykes were derived from a single partial melting event they would produce such a clustering of points around the suggested invariant point as can be seen in Fig. 5.11. The equilibrium at this depth is presumably between olivine, orthopyroxene, garnet and liquid and might explain the inclusion of garnet megacrysts in the kimberlite matrix. The observed cluster, in this projection, however, does not indicate a control by the projecting mineral, clinopyroxene.

There is also some evidence for olivine fractionation subsequent to the formation of the initial partial melt, as the spread of some of the kimberlite compositions from the suggested high pressure pseudo-invariant point defines a line towards and away from the olivine point. This fractionation must have occurred prior to or between the successive injections of magma.

The lamprophyre dykes lie on a continuation of the kimberlite trend, away from olivine. This trend is consistent with the derivation of a lamprophyre magma from a parental, kimberlitic partial melt by olivine plus spinel fractionation.

The lamprophyre dykes also fall between the 10 and 30kb pseudo-invariant points, where the equilibrium is between olivine, spinel, orthopyroxene and a liquid which might indicate their last depth of equilibration with the mantle. The magma was then erupted rapidly to prevent further equilibration at shallower depths.

The observed overall trend for both groups of the Holsteinsborg dykes could also be explained by the rapid eruption of a series of separate partial melts formed at pressures between 15 and, say, 40kb. Evoking such an origin, however, would ignore the clear evolutionary trend.

(c) Silica into CS-M₂S-AS

Silica projections into the plane CS-M₂S-AS have also been found to be useful for examining these rock types. The projection plane is oblique to the C₃A-M-S plane just discussed and is close to the plane cutting the C-M-A-S tetrahedron in which the Holsteinsborg dykes plot. This projection plane is also advantageous in that it passes through the olivine point and close to clinopyroxene and feldspar, all of which are potential fractionating phases in these dykes.

As before Ca(Mg)CO₃-free analyses were plotted for the Holsteinsborg dykes and the diagram is presented in Fig. 5.12. The dykes define a good trend which is slightly displaced from an olivine control line towards spinel and, with the less magnesian compositions trending towards the feldspar point. The observed offset from an olivine control line for the kimberlite dykes is a trend similar to that found for the ultramafic extrusives of the Onveracht Group, South Africa (McIver and Lenthall 1974) which were considered to be the parental

Fig. 5.12

A projection of silica into the plane CS-M₂S-AS of the Holsteinsborg Ca(Mg)CO₃- and H₂O⁺-free analyses.

ol = olivine

sp = spinel (analysis 192)

cpx = clinopyroxene

k-feld = potassium feldspar

open squares = kimberlites

solid circles = potassic lamprophyres

open triangles = anomalous lamprophyres

sample 5907 = most carbonate-rich kimberlite

magma of the less magnesian extrusives in that area and were derived by partial melting at depth.

This plot as shown in Fig. 5.12 is again consistent with the derivation of a lamprophyre magma from a parental kimberlite magma by olivine plus spinel fractionation. The clinopyroxene enrichment of the anomalous dykes is again illustrated.

Plotting the Holsteinsborg dykes using complete analyses in the same projection (shown in Fig. 5.13), the amount of scatter increases but the points lie closer to a good olivine control line and also show an essentially continuous trend among all the dykes. Simple olivine fractionation, however, cannot account for all aspects of the geochemistry of these rocks (e.g. as shown by Harker variation diagrams). This trend might be considered to result from a coincidence of the olivine control lines of two independent magmas, namely the initial lamprophyre and parental kimberlite magmas. Such a conclusion would agree with the proposed second stage fractionation.

The CS-M₂S-AS projection is also the most suitable one to relate the dyke compositions in C-M-A-S to their petrography.

The samples forming the main cluster of the kimberlite dykes are rich in olivine and spinel (titanomagnetite) and all the euhedral olivines are found amongst these samples. The M₂S-rich kimberlite samples have very minor amounts of matrix which is composed principally of carbonate. The M₂S-poor kimberlites have more matrix which consists of phlogopite, perovskite, carbonate and opaque minerals.

The lamprophyre samples show a more obvious change in petrography in relation to their composition. The M₂S-rich samples contain abundant olivine megacrysts which are observed to be in reaction with the liquid. In samples away from M₂S the concentration of olivine

megacrysts decreases, and is eventually eliminated. The samples closest to the CS-AS joint contain no megacrysts but are rich in groundmass phlogopite and potassium feldspar.

5.3 TRACE ELEMENT GEOCHEMISTRY

5.3.1 Introduction

The concentration of trace elements is sensitive to fractionation processes having certain distribution patterns between the liquid and mineral phases during the cooling of a magma. Elements accommodated with difficulty in the common mineral phases behave as 'incompatible elements' and become concentrated in the liquid. These elements should retain linear relations to one another during such processes as fractionation or partial melting. Other elements preferentially concentrate in the crystalline phase and are termed 'compatible elements'.

The trace-element chemistry of potassic-magnesian rocks and kimberlites in general are as remarkable as their mineralogy and general chemistry. For these rock types simple models of fractionation are often consistent with their major element chemistry, but often encounter difficulties when considering their trace element concentrations.

The trace element concentrations for the Holsteinsborg dykes are presented in Appendix D.

5.3.2 Frequency distribution diagrams

The trace element concentrations of the Holsteinsborg dykes are presented in the form of histograms in Fig. 5.14.

The main characteristic of the trace element contents

is their often extremely high concentrations, particularly in comparison with the trace element abundances in 'average' ultrabasic rocks (e.g. Wyllie 1967, p.354). This includes elements which are discussed in this study as major elements, for example potassium, which would normally be considered as minor elements in most ultrabasic rocks. This enrichment of trace elements is, however, characteristic of kimberlites and potassic-magnesian rocks. This enrichment holds for all the trace elements determined except for Cr and Ni, which are apparently similar in concentrations to average ultrabasic rocks.

The occurrence of two such contrasting groups of trace elements in kimberlites has been established by Dawson (1962, 1967a). One suite of trace elements, including Cr and Ni, occur in amounts characteristic of ultrabasic rocks and the second suite occur in greater amounts than is usual for ultrabasic rocks. It is well known that potassic lamprophyres show similar trace-element patterns to kimberlites, and that many of these unusual characteristics are further intensified in carbonatites.

In addition to the main trace elements determined F, Cl, S and B were determined for selected samples but are not presented in the frequency distribution diagrams. These additional trace elements were determined to see if their concentrations could account for the discrepancy found in the major oxide totals mentioned in Section 5.1 and the results are given in Table 5.2. The lamprophyre dykes did in fact contain significant fluorine but the other concentrations found did not help in accounting for the discrepancy.

	sample number	F	Cl	S**	B
lamprophyre dykes	5620	0.44	nd	0.25	nd
	5630			0.30	
	5692	0.27	nd	0.25	nd
	5938			0.20	
kimberlite dykes	5907	0.21	0.05	0.40	nd
	5915	0.10	0.14	0.20	nd

** determinations by M. J. Saunders

nd = not detected

Table 5.2 Results of F, Cl, S and B determinations for selected
samples of the Holsteinsborg dykes (in wt%)

5.3.3 Harker Variation Diagrams

Harker variation diagrams for the trace element abundances, plotted against MgO, are given in Fig. 5.15. They generally show a high degree of scatter, but Cr and Ni are again the exceptions.

Ni^{++} tends to substitute for Mg^{++} and concentrates in olivine. From the variation diagrams given in Fig. 5.5 it appears that the suggested high pressure fractionating phases, Ni-bearing olivine (Mg_{92}) and spinel 192, cannot explain the NiO vs. MgO variation. The distribution coefficient for Ni between olivine and silicate liquids, however, is sensitive not only to pressure but also to composition of the liquid (O'Hara, Saunders and Mercy 1975; Hart et al. 1976). Hart et al. (1976) suggest that D_{Ni} varies inversely with MgO. The olivine involved in the proposed first stage high pressure fractionation may, therefore, have had a very low nickel content since the olivine was crystallising from a very magnesian liquid. If this was the case the slope of the olivine-spinel tie line given in Fig. 5.5 would be reversed and could then be consistent with the proposed fractionation model. If some change in the physical conditions, such as $P_{\text{H}_2\text{O}}$, then occurred resulting in a higher D_{Ni} , nickeliferous olivine would have crystallised during the later second stage fractionation. Using the conclusions of Hart et al. (1976) the olivines crystallising from the lamprophyric magma would be expected to be richer in Ni than the olivines crystallising from the more magnesian kimberlitic liquids, and this is seen to be the case.

The good trend obtained for Cr vs. MgO (Fig. 5.15) is consistent with approximately 25% spinel plus olivine fractionation (Fig. 5.5). The expected smear of points towards olivine reflecting the proposed second stage fractionation, however, is not present.

The remaining trace elements, especially Ba, Ce, La, V and Sr, have a fairly random distribution relative to MgO as shown in the Harker variation diagrams. This may reflect the mineral content of individual hand-specimens rather than the evolution of the magma, as many of these trace

Fig. 5.15 (2 pages, overleaf)

Trace element variation in the Hclsteinsborg
dykes (ppm) with MgO (wt%) as the abscissa.

open squares = kimberlites

solid circles = potassic lamprophyres

open triangles = anomalous lamprophyres

elements concentrate in one particular mineral, e.g. Rb in phlogopite; a variation in content of that mineral could have a considerable effect on the trace element abundances of individual specimens, and kimberlites in particular are characteristically inhomogeneous. There is also the possibility of a random loss of some of the elements along with the volatile-rich fraction of the intruding magma. The carbonate-rich kimberlites (5518, 5905 and 5907) do show a relative enrichment of Ba, Sr, Ce, La and P (see Table D.1 in Appendix D). It is difficult to discuss the precise relationships of the trace elements since neither the concentration nor the appropriate distribution coefficients for many of these trace elements in the possible fractionating phases is known. The Harker variation diagrams shown in Fig. 5.15, however, do not appear to be inconsistent with the proposed fractionation hypothesis. Examining the Cu vs. MgO diagram, for example, shows the kimberlites and lamprophyres to have different trends. Both trend away from olivine, however, and so could be reflecting the separate evolution of the two groups by the proposed second stages of fractionation (of predominantly olivine). As Cu is likely to substitute in spinel the fractionation of a relatively Cu-rich spinel and a Cu-poor olivine could account for the evolution of a lamprophyric magma containing less Cu than its parental kimberlitic magma.

There seems to be no simple correlation of trace elements with concentrations of major elements for which they commonly substitute, e.g. Ba and K, Ca and Sr, Li and Mg, V and Ti. There is, however, a good correlation of K and Rb, but only for the kimberlites (Fig. 5.16). As phlogopite is the only host for potassium in the kimberlites this might suggest a systematic substitution of Rb for K in phlogopite. The potassium in the lamprophyre dykes, however, has several hosts - two generations of phlogopite, potassium feldspar, pseudoleucite and potassic richterite - which would obscure any systematic substitution of Rb for K in any individual mineral. From Fig. 5.16 it can be seen that the K/Rb ratio of the kimberlites is fairly constant and consistent with the fractionation of any phases containing no K or Rb such as olivine or spinel. The lamprophyres, however,

have higher K/Rb ratios than the kimberlites and so could not have been derived from a kimberlitic fluid solely by the suggested olivine plus spinel fractionation. This apparent anomaly could be explained by invoking the additional fractionation of some phlogopite, a phase found as megacrysts in both types of dykes. Kimberlitic phlogopites contain significant Rb; Allsopp and Barrett (1975), for example, give values which fall between 200 and 950 ppm. If the fractionating phlogopite contained 500 ppm of Rb the difference in K/Rb can be explained by the addition of 5% phlogopite to the fractionating phases. This amount, or even less if the phlogopite contains more than 500 ppm Rb, would not have a significant effect on the major oxide chemistry. Cundari (1973) has also suggested that Rb has a selective preference for leucite, increasing the K/Rb ratios with differentiation. This factor may be significant if the pseudoleucites in the lamprophyres were originally leucite and were also able to fractionate or become sorted.

From the plot of K_2O vs. Ba (Fig. 5.16) it can be seen that there may be some systematic variation for the kimberlites and so the Ba in the kimberlites could be associated with phlogopite, as well as the carbonate phase.

The Sr vs. Rb plot (Fig. 5.16) appears to give a random distribution. There is, however, a possible positive correlation of Ca with Sr for the kimberlites which suggests that Sr is substituting in the carbonate phase. Calcic plagioclase is commonly the host for Sr in igneous rocks, but it probably resides in the potassium feldspar, amphibole and carbonate of the lamprophyre dykes.

Few trace elements appear to behave as incompatible elements except for possibly Y, Zr and Zn. The gradient of the plot of Y vs. Zr (Fig. 5.16), however, suggests that these elements cannot both be behaving as incompatible elements. Y may substitute for Ca and Zr for Ti. Zr has also been shown to be relatively enriched in kimberlitic ilmenites relative to other terrestrial ilmenites.

5.4 Summary

The chemistry of the Holsteinsborg dykes provides a definite distinction between the kimberlite and potassic lamprophyre dykes. The kimberlite dykes are compositionally similar to micaceous kimberlites (Dawson 1967b). The lamprophyres are characterised by their extreme concentrations of potassium.

Considerations in terms of C-M-A-S suggest that a magma with a composition similar to the average Holsteinsborg kimberlite (from Table 5.1) was generated at a pressure greater than 30kb. The magma may have been produced by the partial melting of the mantle.

The major element geochemistry, supported in part by the trace element chemistry, suggests a genetic relationship between the kimberlite and the potassic lamprophyre dykes, particularly considering their close association in the field. It has been proposed in this chapter that the two groups of rocks are related by a simple process of crystal fractionation. It is suggested that the parental lamprophyric magma could have formed by the fractionation of 70% of a mixture consisting of approximately 75% olivine and 25% spinel from a part of the primary kimberlitic magma. To account for some of the trace element abundances a small amount of phlogopite may also have to be extracted.

In this study the hypothesis proposed for the relationship of the Holsteinsborg kimberlites and lamprophyres involved a simple fractionation process. This hypothesis, however, is based on one major assumption, namely that there was a random loss or relative movement of a carbonatitic fluid fraction during the eruption of the kimberlitic and lamprophyric magmas. The presence of ocelli and the nature of intrusion of the dykes strongly supports this argument. It was considered, therefore, more appropriate to interpret the chemistry of these rocks using the $\text{Ca}(\text{Mg})\text{CO}_3$ - and H_2O -free analyses. If complete whole-rock analyses had been used many of the trends in Fig. 5.3 would still suggest some olivine fractionation. The CaO vs. MgO diagram (Fig. 5.3), however, would require

the abstraction of substantial amounts of a Ca-bearing phase to keep the CaO content essentially constant with decreasing MgO. Diopside is the most likely Ca-rich phase to fractionate and, although it is a minor constituent of some of the rounded inclusions within the kimberlite dykes, there is no other evidence for it being a major fractionating phase. Olivine plus diopside fractionation could not, for example, explain the TiO_2 vs. MgO plot (Fig. 5.3).

The suggestion that the initial kimberlite liquid may have been derived by partial melting of the mantle is discussed in more detail in section 6.2.8 (Chapter 6). As an alternative to the proposed fractionation model it should also perhaps be considered whether or not the lamprophyres may also have been derived by partial melting of a phlogopite-bearing mantle but under a different volatile regime. Mysen and Boettcher (1975a, 1975b) and Wyllie (in press) indicate the important control that the volatiles have on partial melting within the mantle. Any suggested compositions of direct partial melts of a phlogopite-bearing mantle do not resemble even the least potassic (5 wt%) Holsteinsborg lamprophyre analysed. To derive the Holsteinsborg potassic lamprophyres would, therefore, still require an additional process such as crystal fractionation or crustal contamination to produce the compositions observed. Even if a lamprophyric magma could be derived by a very small degree of partial melting it would be difficult to explain the REE enrichment because it would involve some unreasonable distribution coefficients. It is also difficult to envisage a process by which any liquid produced by such a small degree of partial melting could be extracted from the mantle to form a fractionating body of magma.

Independent of the origin of the parental kimberlite and lamprophyre magmas, each group appears to have undergone a separate late stage crystal fractionation. Part of the kimberlite magma underwent olivine (average composition Mg_{85}) fractionation before being rapidly erupted to the

6.1 Introduction

The kimberlite and potassic lamprophyre dykes from the Holsteinsborg region have many features in common. There are, however, several criteria which can be used to distinguish between the different types of dykes and these are summarised in Table 6.1.

This chapter presents a discussion of the significance of various aspects of these dykes drawing information from all the preceeding chapters. As a summary of all the available information, a petrogenetic model for the Holsteinsborg kimberlites and potassic lamprophyre dykes is then proposed. The chapter closes with a brief discussion of the general conclusions which can be made from this study.

6.2 Discussion

6.2.1 Nomenclature

(a) The kimberlite dykes

The Holsteinsborg kimberlite dykes have the mineralogical and chemical characteristics of true kimberlites (cf. Section 1.1 of Chapter 1). The Holsteinsborg kimberlite dykes are massive as opposed to fragmental and belong to the hypabyssal-facies type of kimberlite. Strictly speaking this implies that no xenoliths are present (see Part 1.1.8), but rounded inclusions are common, not only in the Holsteinsborg kimberlite dykes, but also in other kimberlite dykes and sills, for example at Lipelaneng, Lesotho (Nixon and Kresten 1973) and in south west Greenland (Emeleus and Andrews 1975). The Holsteinsborg

	KIMBERLITES	POTASSIC LAMPROPHYRES
FIELD ASPECTS		
(a) megacrysts	rare red-purple garnets	may contain abundant pale pink pseudoleucite
(b) inclusions	often abundant rounded peridotites	scarce angular gneissose xenoliths
MINERALOGY		
(a) megacrysts	pyrope-garnet and picroilmenite	diopside, pseudoleucite
(b) groundmass	olivine, Fe-Ti oxides and the association of diopside with calcite and serpentine	sanidine, pseudoleucite, diopside and potassic richterite
WHOLE-ROCK GEOCHEMISTRY		
(a) silica saturation	mostly undersaturated	mostly saturated
(b) oxides		
SiO ₂	<34 wt%	>38 wt%
Al ₂ O ₃	<5 wt%	>5 wt%
K ₂ O	<3 wt%	>5 wt%
MgO	>22 wt%	<23 wt%
FeO	>5 wt%	<5 wt%
Fe ₂ O ₃	>2 wt%	<4 wt%
(c) CIPW norm constituents	<u>lc</u> , <u>ne</u> (a few with <u>hy</u>)	<u>hy</u> (a few with <u>lc</u>) <u>ac</u> , <u>ks</u> , <u>ns</u>

Table 6.1 The main features which can be used to discriminate between the Holsteinsborg kimberlite and potassic lamprophyre dykes

kimberlites contain abundant phlogopite reflected in the high average K_2O content of 1.82 wt% and therefore may be classified as micaceous as opposed to basaltic (see Part 1.1.8).

(b) The potassic lamprophyre dykes

Defining the Holsteinsborg potassic lamprophyre dykes is not so straightforward as there is confusion regarding existing nomenclature for these rock types (see Part 1.2). All the rock names used in this discussion have been defined in Part 1.2 of Chapter 1. The non-kimberlitic Holsteinsborg dykes can be considered as lamprophyres. If, however, the term lamprophyre is confined to hypabyssal intrusives which contain only ferromagnesian phenocrysts, then the pseudoleucite-bearing Holsteinsborg dykes should not strictly be called lamprophyres. The high K/Na ratio of these rocks indicates their very potassic nature.

Noe-Nygaard and Ramberg (1961), when describing some members of the lamprophyre suite, mis-used the term kersantite because the dykes do not contain biotite or plagioclase.

The term fergusite refers to rocks containing pseudoleucite rather than leucite but the associated minerals mentioned in the definition (Pirsson 1905) are not found in the Holsteinsborg dykes so the term is not relevant to this discussion.

Using the term lamproite to describe the Holsteinsborg lamprophyres would emphasise their potassic nature, and with contents of 5-10 wt% K_2O they are comparable with other lamproites (e.g. Cross 1897, Carmichael 1967b, Wade and Prider 1940). Many sub-divisions of lamproites have been proposed and, using the silicate mineral assemblages of the Holsteinsborg dykes, cedricites, fitzroyites and mamilites, for example, can be identified. The mineral assemblages observed in the Holsteinsborg lamprophyres, however, are far more varied than the terminology caters for.

Two common megacryst assemblages are (a) solely olivine and (b) phlogopite + pseudoleucite + diopside + olivine, but at least ten additional permutations or combinations of these megacrysts have been observed. Furthermore some members of the suite are aphyric. Although olivine does occur in some lamproites it is not abundant, nor is it found as the only megacryst phase.

The mineral chemistry of the Holsteinsborg dykes also indicates a similarity to described lamproites although the amphibole is potassic richterite rather than magnophorite.

The Holsteinsborg lamprophyres, however, are very different from described lamproites because of their high volatile content. This is partly reflected in lower SiO_2 values but the norms still show their predominantly saturated nature. The Holsteinsborg dykes would be included in the saturated group (group (b)) of the potassic magnesian rocks as described in Section 1.2 (Chapter 1) or in the group of orenditic affinity defined by Sahama (1974). If the Holsteinsborg dykes are recalculated on a volatile-free basis (as given in Appendix E) the lamprophyre compositions compare well with the rocks from the Leucite Hills and West Kimberley (Carmichael 1967b). Definitions of the term lamproite in the literature, however, do not specifically exclude volatile-rich rocks.

It was decided, therefore, to call the non-kimberlitic potassic magnesian Holsteinsborg dykes "potassic lamprophyres" to account for their high volatile content, and the common occurrence of olivine megacrysts, despite the fact that felsic megacrysts (pseudoleucites) may occur.

6.2.2 Emplacement of the dykes

All the Holsteinsborg dykes are long narrow intrusions with chilled margins and parallel or cross-cutting internal contacts resulting from multiple phases of intrusion. The evidence supports the suggestion of Dawson and Hawthorne (1973) that hypabyssal kimberlites were formed by the injection of relatively hot magmas in contrast to the cold, fragmental intrusion of kimberlite often proposed to account for the lack of thermal effects in adjacent country rocks. The Holsteinsborg dykes also have minimal contact effects probably because the gneisses are less susceptible to alteration than the sediments in which thermal effects have been observed (e.g. Dawson and Hawthorne 1973).

It has been suggested that the liquidus temperatures of certain potassic magnesian rocks are high, approximately 1100°C at 1 kbar $\text{P}_{\text{H}_2\text{O}}$ (Barton 1976) or up to 1360°C at one atmosphere dry (Carmichael 1967b, Cundari and O'Hara 1976). The presence of CO_2 in the vapour phase may, however, reduce the suggested liquidus temperatures. Franz and Wyllie (1967) have shown that forsterite can exist in equilibrium with a carbonate-rich fluid at temperatures as low as 600°C . Biggar (1969) also suggested that calcite and apatite can precipitate over a range of at least 300°C and can co-exist with a liquid to temperatures below 600°C . In many of the dykes the last primary phase to crystallise was serpentine which has an upper stability limit of 400 to 500°C over a wide range of pressures (Scarfe and Wyllie 1967). It appears, therefore, that the Holsteinsborg dykes may have been intruded at a temperature below the suggested liquidus temperatures. Many of the dykes, in particular the kimberlites, can be considered as being erupted to the surface as a suspension of silicate crystals in a carbonate-rich fluid with relatively low temperatures, possibly as low as 500 to 600°C . Many of the dykes

which have a fine-grained silicate groundmass must have been intruded as a predominantly silicate magma and presumably at higher temperatures.

The vapour-rich nature of the dykes can help to explain why solidification did not prevent the formation of such narrow sheet-like intrusions. The dykes must have been intruded rapidly to prevent the re-equilibration of high pressure minerals. The viscosity of the magma is reduced by the presence of abundant volatiles and make rapid intrusion more likely. From observations of intrusions at Callander Bay, Ontario, which in many respects are similar to the Holsteinsborg dykes, Currie and Ferguson (1970) envisage a magma initially saturated with volatiles (CO_2 and H_2O) which boil off as the result of a reduction in pressure and so provide a very low viscosity volatile-rich precursor to the main magma. The volatile-rich fluids rapidly follow and open fissures allowing the main injection of magma to occur.

The volatile-rich fluids may have forced open brittle fractures which had formed in the country rock under the prevailing stress field. The occurrence of thin screens of country rock between adjacent dykes may indicate that dilation of the basement rocks occurred during intrusion of the dykes. A relaxation of the stress field might have produced external pressures on the dykes, and may have been responsible for the post-crystallisation features including deformation lamellae and serpentinisation cracks, all of which are parallel to the dyke margins.

The main banding in the Holsteinsborg dykes is the result of multiple or pulsatory injections of magma. Within an individual band formed from one injection of magma there is sometimes a concentration of megacrysts towards the centre which is probably the result of the process flow differentiation as described by Simkin (1967) and Bhattacharji (1967). Flow differentiation cannot account for the major zonation within the

dykes because features such as sharp internal contacts and alternating porphyritic and aphyric layers would not be produced. It is also unlikely that the Holsteinsborg dykes resulted from a gas-solid fluidisation process of intrusion because the characteristic brecciation of the solid fragments is not evident.

6.2.3 Tectonic setting

Kimberlites are generally confined to non-orogenic continental platform areas and the Holsteinsborg kimberlites are no exception. The Holsteinsborg dykes, having a likely age of 570my (see Sections 2.7 and 2.8 in Chapter 2), may be associated with other alkaline magmatism in the west Greenland - Labrador area. Reports of similar ages have been given for a lamprophyre in the Umanak area, west Greenland (Larsen and Møller 1968), a carbonatite from Aillik Bay, Labrador (Leech et al. 1963) and other carbonatites in eastern Canada (Doig 1970). Doig (1970) suggests that widespread alkaline intrusion occurred at 565my in North America and Europe which might be associated with remarkably synchronous events along fracture systems including the St. Lawrence graben and the Davis Strait lineament. Later, the continents separated away from some of these fracture systems. Many other younger, but less widespread, intrusions occur in this area and Doig (1970) suggested subsequent periodic intrusions from 520 to 110my.

The Mesozoic kimberlites from south west Greenland (Andrews and Emeleus 1976) have been related to the development of rifting in the Davis Strait prior to the breakup of the continents.

On a smaller scale in central and south west Greenland there appears to be some correlation between the distribution of post-tectonic kimberlite and other associated intrusions with the PreCambrian

shear belts proposed by Bak et al. (1975). The Holsteinsborg kimberlite and lamprophyre dykes appear to be focused on the Ikertoq shear belt, the Søndre Isortoq kimberlite and lamprophyres (Goff 1973) are associated with the Evighedsfjord shear belt and, kimberlites, lamprophyres and carbonatites described by Larsen and Møller (1968), Walton and Arnold (1970) and Andrews and Emeleus (1971) appear to be related to the Vesterland shear belt. Although the complete distribution of kimberlites and associated rocks is not known in west Greenland and Bak et al. (1975) suggest it is likely that other shear belts might be recognised in this area, the correlation seems to be significant. Watterson (1975) suggested that mechanical weakening through a reduction in grain size may account for longevity of major tectonic lineaments including the Nagssugtoqidian boundary. The PreCambrian shear belts, therefore, might provide planes of weakness within the crust which can be taken advantage of during certain tectonic regimes (and when conditions are suitable for the formation of kimberlitic magmas) to allow intrusion of the magmas into the upper crust. The tectonic conditions suitable for the formation of fissures in the crust might well be the suggested uplift and large-scale fracturing in the Davis Strait, although there is no direct evidence for the existence of such a fracture system in the Cambrian.

6.2.4 Ocelli - Liquid immiscibility?

Globular ocelli with sharp boundaries have often been interpreted as resulting from two immiscible liquids (e.g. Ferguson and Currie 1971). Ocelli are commonly found in kimberlites and lamprophyres (e.g. Ramsay 1955, Philpotts and Hodgson 1968, Clarke and Mitchell 1975), and they are often rich in carbonate as found in the Holsteinsborg dykes. The main alternative explanation for ocelli is the

suggestion that they are "segregation vesicles" (e.g. Smith 1967). MacKenzie and White (1970) also suggest that the phonolite globules in a basanite did not result from liquid-liquid immiscibility but by flow of late-stage residual fluids into vesicles formed by earlier separation of an immiscible gas phase. Dawson and Hawthorne (1973), however, interpret the carbonate structures in the Benfontein kimberlite as crystallising from a carbonatitic transporting fluid with possible immiscibility.

In the Holsteinsborg dykes carbonate-rich ocelli are abundant, particularly in the kimberlites. Although some of the ocelli may be spherical and lined with phlogopite laths many are elongate with irregular boundaries (see Plate 2.10). Many of these irregular ocelli superficially resemble the felsic ocelli described by Philpotts (1972, see Fig. 2) who suggested that they resulted from liquid immiscibility rather than the filling of gas cavities with residual magma. If the Holsteinsborg ocelli were also formed from two immiscible liquids - a silicate and a carbonate liquid - it would further justify the discussions on the whole-rock geochemistry of these dykes using mainly analyses recalculated free of Ca(Mg)CO_3 and H_2O (see Chapter 5). The existence of immiscible carbonatitic liquids associated with kimberlites has frequently been proposed (e.g. Clement 1975, Ferguson et al. 1975).

In the Holsteinsborg dykes carbonate in both the ocelli and the groundmass may partially enclose silicate minerals protruding from the surrounding groundmass (see Plate 3.6 for example) resulting in a poikilitic-like texture. This texture and the occurrence of carbonate, sometimes as single crystals, dispersed throughout the groundmass might suggest that not all the carbonate crystallised from

an immiscible liquid.

Another explanation for the formation of the Holsteinsborg ocelli might be that the crystallisation of largely silicate minerals from the magma produced a carbonate-rich residual liquid, which would be dispersed throughout the solidifying matrices of the dykes. The residual liquid might concentrate in ocelli by coalescence, possibly encouraged by flow within the dyke, or by flow into gas vesicles and form the so-called segregation vesicles. It is also possible that the ocelli resulted from the crystallisation of a vapour phase which, at pressure, may contain dissolved silicate material to allow the formation of the clinopyroxene, phlogopite, apatite and serpentine as well as carbonate.

In summary, the evidence from the Holsteinsborg dykes does not conclusively indicate the origin of the carbonate-rich ocelli or the carbonate matrix, but it is clear that the silicate and carbonate fractions of these dykes must have been in mutual equilibrium. It seems likely, however, that at the time of intrusion there was an immiscible carbonate-rich liquid or vapour co-existing with a silicate magma.

6.2.5 Significance of the pseudoleucite megacrysts and the crystallisation of the lamprophyres

It is assumed that the pseudoleucite megacrysts which are found in many of the Holsteinsborg lamprophyres represent the initial crystallisation of leucite which had little or no sodium in solid solution (see Section 4.2.6 of Chapter 4). Leucite is known to be unstable at high pressures and is usually found only in volcanic or sub-volcanic rocks. Lindsley (1966) showed that in dry conditions leucite is stable only at pressures less than 20kb. The stability field of leucite is

considerably reduced with increasing P_{H_2O} . Goranson (1938) has shown that leucite is stable only to a pressure of 3kb in the presence of a hydrous vapour. The effect of CO_2 on the stability of leucite is not known.

To form the large leucite crystals found in the Holsteinsborg dykes from a H_2O -rich lamprophyric magma requires prolonged crystallisation at a pressure in the lower part of the range 3 to 20kb. Assuming the lamprophyric magma originated in the mantle, the crystallisation must have occurred either during ascent or at a point where the ascent of the magma was arrested for a time, both at depths considerably less than 70km.

This period of leucite crystallisation may have also been the time of formation of some of the other megacryst phases, namely phlogopite, clinopyroxene and possibly olivine. This is consistent with the phase relations (to 30kb) of a similar ultrapotassic rock (orendite LHL2 from Carmichael 1967b) proposed by Barton (1976) for P_{H_2O} less than P_{total} . The large variety of megacryst assemblages observed in the Holsteinsborg dykes can be explained from these phase relations by invoking only small changes in pressure and temperature (below 8kb and $1200^{\circ}C$). Forsterite is stable on the liquidus over a wide pressure interval and may have crystallised at higher pressures before leucite.

The effect of CO_2 on these phase relations is not known so it should be noted that the orendite studied is not directly analagous to the Holsteinsborg lamprophyres as it contains only 0.20 wt% CO_2 .

Luth (1967) used his studies in the system $KAlSiO_4$ - Mg_2SiO_4 - SiO_2 - H_2O (to 3kb) to explain the mineral assemblages found in the potassic rock types from West Kimberley, Leucite Hills and

Shonkin Sag, many of which also occur in the Holsteinsborg lamprophyres.

In the Holsteinsborg dykes the leucite megacrysts have been pseudomorphed by orthoclase and/or sanidine. Pseudoleucite forms by the reaction of the leucite with the silica from the magma. The siliceous nature of the groundmass of saturated ultrapotassic rocks has already been commented on (Part 1.2(b) of Chapter 1) so the interstitial liquid could have provided the silica necessary for the reaction.

6.2.6 Derivation of the rounded inclusions found in the kimberlite dykes

Various approaches have been taken to estimate the temperature and pressure of a mineralogical assemblage using experimental evidence and/or thermodynamical calculations. Although the principle of these determinations is established, in some cases there are large discrepancies in the results obtained (see for example Figs. 1 and 2 of Howells 1975). Despite these uncertainties, some estimates of equilibration temperatures and pressures for the Holsteinsborg peridotites were made since such estimates should give a minimum depth of origin of the host kimberlite magma.

Equilibration temperatures calculated from the Ca/Ca+Mg atomic ratio of clinopyroxene after Davis and Boyd (1966) gives 1000 to 1100°C for the inclusions 5698(1), 5698(2), 5961 and 5984a, and 1290°C for 5524B. The calculation methods of Wood and Banno (1973) for co-existing clinopyroxene and orthopyroxene gives 1090°C for 5698(2) and 1056°C for 5984a. The Ca/Ca+Mg atomic ratio of enstatite co-existing with garnet and clinopyroxene (Boyd and Nixon 1973) gives a temperature of 1030°C for 5984a. The Al_2O_3 content of enstatite is known to be pressure sensitive and the low alumina contents found in the orthopyroxene from the Holsteinsborg peridotites is a general indication that they must

have been derived from regions with high pressures. Although there are no experimental data on orthopyroxenes containing less than 2 wt% Al_2O_3 , extrapolating data presented by Akella (1974) and MacGregor (1974) and using the temperatures calculated above, pressures of approximately 50kb are indicated for 5984a. Using a garnet-clinopyroxene geothermometer (Råheim and Green 1974) the garnet granulite 5518G with a K_D of approximately 4 could have equilibrated at 800°C and 10kb.

It might be tentatively concluded, therefore, that many of the peridotites found in the Holsteinsborg kimberlites originated in regions with a temperature between 1000 and 1100°C and pressures greater than 40kb. The garnet wehrlite, 5524B, may have been derived from an area with higher pressures with a temperature close to 1300°C. The garnet granulites are probably derived from much lower pressures and temperatures.

These conclusions, which are in keeping with those for inclusions from other kimberlites, suggest that the host kimberlitic magma of the Holsteinsborg dykes originated from depths greater than 170km and at a temperature above 1100°C and so come from a point within the diamond stability field.

Although a full study of the inclusions found in the Holsteinsborg dykes has not been made, the available data are the only source of information about the nature of the crust and mantle below Holsteinsborg at the time of intrusion of the dykes. Suites of inclusions are characteristic of kimberlites and are considered to be a sampling of the parts of the crust and mantle through which the kimberlite magma passed during eruption.

The granulite inclusions are considered to be xenoliths of the high-grade metamorphic lower crust, a conclusion put forward by other authors for similar inclusions (e.g. Cox, Gurney and

Harte 1973). The small eclogite inclusions may represent an associated, but different, mineral facies of the lower crust.

Lherzolites, harzburgites and wehrlites, all found in the Holsteinsborg dykes, as well as in other kimberlites, are thought to be high pressure inclusions representing the source mantle, depleted mantle after various stages of partial melting or cumulates from the liquid (see Section 1.1.6 of Chapter 1). The Holsteinsborg peridotites, however, are dominated by dunites (comprising over 50% of those described in Section 3.4.1). Dunites have been described from other kimberlites, for example from Thaba Putsoa, Lesotho and Frank Smith Mine, South Africa (Boyd and Nixon 1975) and from Matsoku, Lesotho (Gurney, Harte and Cox 1975), but they are rarely very abundant. Dunites can be considered as the residuum after extreme partial melting, i.e. depleted mantle, or as cumulates from mantle liquids crystallising only olivine. The olivine compositions expected in depleted mantle xenoliths would be approximately Mg_{95} and since the Holsteinsborg dunites are made up of more Fe-rich olivines it is inferred that they are cumulitic in origin. The Holsteinsborg dunites also have a wide range of compositions, $Mg_{82-92.5}$, a greater range than found in the other peridotite inclusions.

The occurrence of cumulate dunite inclusions in the Holsteinsborg kimberlites strongly supports the ideas put forward in Chapter 5 that olivine fractionation was the main control in the evolution of the kimberlitic magma. Arguments for the derivation of the lamprophyres from a kimberlitic magma by the fractionation of olivine and a Fe-Ti-rich phase (titanomagnetite) are weakened by the lack of any evidence of corresponding cumulates. Titanomagnetite is not commonly found in peridotite inclusions. It is likely that the suggested fractionation occurred in a separate portion of the initial kimberlitic

magma at some level in the mantle shallower than the point from which the magma erupted to form the kimberlite dykes. If this was the case, the olivine-spinel cumulates would not be included in the magma forming the kimberlite dykes. Also the mode of eruption of the lamprophyric magma was not conducive to carrying relatively large inclusions to the surface.

Dawson and Hawthorne (1973), however, have reported both olivine and olivine+spinel+perovskite cumulate layers in the Benfontein kimberlites. The Benfontein spinels are similar in composition to the Holsteinsborg titanomagnetites. Dawson and Hawthorne (1973) suggest that the layering in the Benfontein Sills was formed by multiple injections of magma, which prior to eruption have different concentrations of olivine, spinel and/or perovskite resulting from some type of differentiation. Olivine-spinel fractionation, therefore, seems to be a possible process. Clarke and Mitchell (1975) find similar spinels as epitaxial zones on chrome-spinels but suggest that they are a post-fluidisation crystallisation phase.

An alternative suggestion might be that the Fe-Ti-rich phase crystallising together with olivine to form the lamprophyric magma was ilmenite which is sometimes considered to be a stable mantle phase (Boyd and Nixon 1973, Goff 1973). Using ilmenite rather than titanomagnetite, however, does not give such consistent results from the interpretation of the whole-rock geochemistry of the Holsteinsborg dykes as given in Chapter 5.

The Holsteinsborg peridotites also have a variety of textures from coarse to granuloblastic (see Section 3.6.1). The relationship of these textures to geotherms has been discussed. Boyd and Nixon (1975), for example, have related undeformed (coarse) inclusions

with the lower pressure part of the geotherm they proposed for Lesotho. They also suggest that the deformation progressively increases with depth and so recrystallised inclusions are related to deeper parts of the geotherm. Dawson, Gurney and Lawless (1975), however, using data from lherzolites found in the Bultfontein kimberlite, show that increased deformation cannot always be correlated with significant increases in temperature and pressure. Also Gurney, Harte and Cox (1975) show that inclusions from Matsoku, which have a variety of textures (see Harte, Cox and Gurney 1975), equilibrated within a limited range of pressures and temperatures.

The information available from the Holsteinsborg inclusions does not allow the determination of a geotherm or examination of the depth relations of textures since few inclusions have mineralogical assemblages suitable for pressure and temperature estimations. It is clear, however, that there is evidence for some major deformation within the mantle.

6.2.7 Rare earth element geochemistry

Crude chondrite normalised rare earth element (REE) abundance patterns for the Holsteinsborg dykes are shown in Fig. 6.1 using the concentrations of La, Ce and Y given in Appendix D. The kimberlite dykes have high total REE contents and a high concentration of light relative to heavy REE, both features characteristic of kimberlites in general (see Section 1.1.5(d)). The potassic lamprophyres have very similar REE patterns to the kimberlites but with slightly higher average values. This similarity in form of the REE patterns between the two types of dykes supports the suggestion of a genetic relationship between the lamprophyres and the kimberlites. The higher concentrations of La, Ce

and Y in the lamprophyres (see also Fig. 5.14) agrees with the lamprophyric magma being derived from a kimberlitic magma by the fractionation of phases poor in REE.

From Fesq, Kable and Gurney (1975, see Fig. 5) and Mitchell and Brunfelt (1975) it is thought that the major hosts of REE are apatite, perovskite and carbonate. Perovskite occurs only in the kimberlites, but P_2O_5 and presumably apatite is more abundant in the lamprophyres and carbonate is common in all the dykes. These REE patterns again show the affinity of these rock types to carbonatites. Fesq, Kable and Gurney (1975) consider that the REE enrichment and fractionation in kimberlitic magmas is dominantly controlled by the selective formation and removal of mobile REE-carbonate complexes into carbonatitic fluids which separate from the complementary "kimberlite" magma during emplacement. If a similar process occurred in the evolution of the Holsteinsborg dykes it again supports the interpretation of the whole-rock geochemistry of these dykes in terms of $Ca(Mg)CO_3$ -free analyses (see Chapter 5).

6.2.8 The unusual enrichment of certain elements in the kimberlites and potassic lamprophyres

The Holsteinsborg kimberlites and potassic lamprophyres have high concentrations of K_2O and CO_2 as well as many trace elements, for example Ba, Sr and Zr, and probably also the rare earth elements (see Section 6.2.7). Many of these concentrations are high when compared with other ultrabasic rocks but are characteristic of kimberlites and some potassic magnesian rocks and so put constraints on the petrogenesis of these rock types.

There is no evidence in the Holsteinsborg dykes to

indicate that crustal contamination or assimilation were important processes in the formation of these dykes.

Many of these high concentrations are intensified not only in the carbonate-rich Holsteinsborg dykes but in carbonatites in general and so the enrichments appear to be related to the carbonate content of these rock types. The reaction of a carbonatitic magma with granitic crustal rocks has been used to explain the trace element concentrations in potassic magnesian rocks (Higazy 1954) but with this hypothesis the origin of the carbonatitic magma still has to be explained as well as the high Cr and Ni contents.

It has been shown that the Holsteinsborg kimberlites originated in the mantle (see Sections 5.2.10 and 6.2.6). If the mantle is considered to be garnet-lherzolite, as is often suggested, the assemblage is virtually barren with respect to many of the elements concentrated in kimberlites and potassic lamprophyres. Even invoking small degrees of partial melting followed by extreme crystal fractionation it is difficult to explain many of the concentrations reported (see for example Table 9 of O'Hara, Saunders and Mercy 1975).

In recent years, however, several other phases have been proposed as being part of the stable mantle assemblage and include phlogopite (Dawson 1971b, Boettcher et al. 1975, Carswell 1975 and Beswick 1976), rutile and apatite (Kable, Fesq and Gurney 1975), amphibole (Oxburgh 1964, Millhollen et al. 1974) and carbonate (Wyllie in press). Small degrees of partial melting of a mantle containing such phases might produce ultrabasic magmas with significant concentrations of many elements which have been difficult to explain using other petrogenetic models.

Phlogopite in the mantle would provide a source not only of K but probably also of Ti, Al, Rb, Ba and F. Bravo and O'Hara

(1975) have shown experimentally that at 1080°C and 30kb a liquid with 3.6 wt% K_2O is in equilibrium with a phlogopite-garnet-lherzolite. They also suggest that at pressures greater than 30kb the initial partial melt of a phlogopite-garnet-lherzolite may be rich in K_2O and resemble a kimberlite. Boettcher et al. (1975) formed liquids by the partial melting of phlogopite-spiked peridotites (1 wt% K_2O) with 0.6 wt% K_2O . It appears, therefore, that a primary kimberlitic magma can contain 1 - 2 wt% K_2O . The assumption that the magma parental to all the Holsteinsborg dykes contained 1.82 wt% K_2O (see Section 5.2.5 and Table 5.1) seems realistic and the derivation of the more potassic dykes by crystal fractionation therefore becomes feasible.

There is now convincing evidence that both CO_2 and H_2O do exist in the upper mantle and Wyllie (in press) suggests that at upper mantle pressures carbonate (calcic dolomite) is stable. Wyllie also suggests that the distribution of carbonate, together with phlogopite and amphibole, strongly influences the composition of mantle-derived magmas. Amphibole is not thought to be stable at the pressures and temperatures required for the formation of kimberlitic magmas. Recent experimental data (e.g. Wyllie and Huang 1975a and 1975b, Mysen and Boettcher 1975a and 1975b, Eggler 1976) led Wyllie (in press) to suggest that for high $\text{CO}_2/\text{H}_2\text{O}$ ratios the interstitial fluid at the top of the low velocity zone is carbonatitic and probably enriched in alkalis and a host of trace elements. At deeper levels the liquid becomes more siliceous but still undersaturated to give kimberlitic compositions. It seems that the presence of carbonate and phlogopite in the mantle is important in explaining many of the unusual characteristics of potassic magnesian rocks, kimberlites and carbonatites.

6.2.9 Diamonds

Diamonds have been found associated with other kimberlites in west Greenland. Renzy Mines Ltd. have found eight microscopic diamonds in four kimberlite samples found by Andrews and Emeleus (1971) from the area between Ivigtut and Frederikshåb (Prast 1973, Nielsen 1976 p. 483). Nielsen also mentioned that Platinomino A/S have found ten microscopic diamonds in heavy concentrates from stream sediment samples found in the Fiskenaesset area.

No diamonds have yet been reported from the Holsteinsborg kimberlites. The Holsteinsborg kimberlites are very similar to those reported by Andrews and Emeleus (1971) and contain the typical indicator minerals but they are probably different in age. As the Holsteinsborg kimberlites are thought to have originated from a region in the mantle within the diamond stability field (see Section 6.2.6), they may also be diamondiferous.

6.3 Petrogenetic model

From all the data on the Holsteinsborg kimberlite and potassic lamprophyre dykes the following model is proposed for their petrogenesis.

- (1) A magma with a kimberlitic composition was generated in the mantle at a depth greater than 170km.
- (2) Substantial olivine fractionation of this magma occurred and many of the dunite inclusions found in the kimberlite dykes represent cumulates from this period of crystallisation. Many of these inclusions were extensively deformed prior to eruption.
- (3) Brittle fracture occurred, taking advantage of an old shear belt in the gneissose crustal rocks.

(4) A reduction of pressure in the magma chamber released a low viscosity volatile-rich fluid which moved towards the surface and opened the fractures.

(5) At different stages of differentiation a series of small amounts of magma were intruded along the opened fractures to form narrow banded dykes in the near surface parts of the crust.

(6) The kimberlitic magma carried megacrysts of olivine, phlogopite, microilmenite and garnet and continued to crystallise olivine, phlogopite and oxides at low pressures. Diopside, apatite, calcite and serpentine crystallised from residual fluids at low pressure.

(7) The phases of kimberlite intrusion carrying high pressure inclusions or megacrysts must have been erupted rapidly to the surface from the mantle without interruption, so not only preventing re-equilibration but also the gravitational settling of the peridotite inclusions.

(8) A separate portion of the initial kimberlitic magma was either erupted slowly to near surface regions or its ascent was arrested at least twice.

(9) During an early part of the magma's ascent extensive fractionation of olivine and spinel occurred. This crystallisation resulted in the relative enrichment in the magma of many elements, for example K. The crystallisation of an Fe-Ti spinel accounts for the formation of a silica-saturated magma. The composition of this magma was then lamprophyric in character.

(10) At a higher level, probably less than 40km, the magma underwent a period of crystallisation of leucite, phlogopite and diopside. Olivine may have crystallised at all stages during the ascent of the magma and remained stable until during the final eruption to the surface.

Fractionation of these phenocryst phases can account for the variation

in compositions of the dykes relative to the parental lamprophyre magma.

(11) As with the kimberlite dykes, a volatile-rich fluid probably opened fractures and allowed multiple injections of magma to form banded potassic lamprophyre dykes.

(12) Before reaching the surface, the leucite megacrysts became unstable and formed pseudoleucite and olivine also became unstable and started to react with the liquid.

(13) The interstitial liquid crystallised to form a fine-grained groundmass which included phlogopite, potassic richterite, diopside, sanidine, carbonate, apatite and serpentine.

(14) In all the dykes a carbonate-rich fluid formed either as the result of the separation of an immiscible liquid during eruption or as a residual fluid after the main crystallisation. From this fluid apatite, carbonate and serpentine crystallised. Diopside crystallised prior to the carbonate in the kimberlite dykes only. The optically and chemically distinct rims found on many phlogopites from both the kimberlite and the potassic lamprophyres may have been an early crystallisation phase from this fluid.

(15) The anomalous lamprophyre dykes probably represent a part of the initial lamprophyric magma which has accumulated abundant clinopyroxene.

6.4 Conclusions

(1) The geochemical trends in the Holsteinsborg dykes indicate that the whole-rock compositions have not been overwhelmed by the assimilation of xenolithic material.

(2) The main chemical variation within the kimberlite dykes is the result of olivine fractionation.

(3) The Holsteinsborg kimberlites and potassic lamprophyres are genetically related. This evidence strongly supports the derivation of certain potassium-rich magnesian rocks from a kimberlitic magma of mantle origin; a hypothesis often proposed (e.g. Wade and Prider 1940) to explain the similarities and/or geographic association of these two rock types.

(4) For the Holsteinsborg dykes, it is proposed that the parental magma to the lamprophyre dykes was formed by extensive olivine plus spinel fractionation of a portion of the mantle-derived kimberlitic magma.

(5) Evidence from all the Holsteinsborg dykes emphasises the association of these rock types with carbonate-rich fluids.

(6) The unusually abundant dunite inclusions found in the kimberlite dykes represent cumulates from the olivine fractionation referred to in conclusion (2).

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APPENDICES

APPENDIX ATHE LOCATION OF ROCK SPECIMENS COLLECTED FROM THE
HOLSTEINSBORG AREA

The precise position of each locality number is given on Map 1 (in the back pocket).

rock specimen	locality number	region	type of intrusion
5501	42	Sarfanguaqland	lamprophyre
5502 - 5506	43	Umanarssuk	kimberlite
5507 - 5511	44	Umanarssuk	kimberlite
5512	45	Umanarssuk	kimberlite
5513	44	Umanarssuk	kimberlite
5514 - 5517	43	Umanarssuk	kimberlite
5518	46	Manitsorssuaq	kimberlite
5519 - 5522	by 2	Holsteinsborg	kimberlite
5601	1	Holsteinsborg	kimberlite
5603 - 5604	2	Holsteinsborg	kimberlite
5605	3	Holsteinsborg	kimberlite
5606	1	Holsteinsborg	kimberlite
5607	3	Holsteinsborg	kimberlite
5608 - 5614	8	Sagdlerssuaq	lamprophyre
5615 - 5621	8a	Sagdlerssuaq	lamprophyre
5622 - 5629	9	Sagdlerssuaq	lamprophyre
5630	10	Kingap timerdlia	lamprophyre
5631 - 5633	11	Kingap timerdlia	lamprophyre
5634	12	Kingap timerdlia	lamprophyre
5635 - 5637	13	Kingap timerdlia	lamprophyre
5638 - 5645	14	Sagdlerssuaq	lamprophyre
5646 - 5652	15	Sagdlerssuaq	lamprophyre
5653 - 5665	16	Sagdlerssuaq	lamprophyre
5666	17	Sagdlerssuaq	lamprophyre
5667 - 5671	18	Sagdlerssuaq	anomalous lamprophyre
5672 - 5687	19	Sagdlerssuaq	anomalous lamprophyre
5688 - 5691	47	Itivdleq	lamprophyre
5692 - 5693	20	Sarfanguaqland	lamprophyre
5694 - 5699	21	Sarfanguaqland	lamprophyre

rock specimen	locality number	region	type of intrusion
5820	31	Sarfartup Nuna	kimberlite
5834	31	Sarfartup Nuna	kimberlite
5890 - 5891	31	Sarfartup Nuna	lamprophyre
5901	21	Sarfanguaqland	lamprophyre
5902 - 5903	22	Sarfartup Nuna	kimberlite
5904 - 5905	23	Sarfartup Nuna	kimberlite
5906 - 5907	24	Sarfartup Nuna	kimberlite
5908 - 5910	25	Sarfartup Nuna	kimberlite
5911	26	Sarfartup Nuna	kimberlite
5912 - 5916	28	Sarfartup Nuna	kimberlite
5917	29	Sarfartup Nuna	kimberlite
5918 - 5931	30	Itivdleq	'pipe' intrusion
5932	31	Sarfartup Nuna	kimberlite
5933 - 5935	32	Itivdleq	lamprophyre
5936	33	Itivdleq	lamprophyre
5937 - 5939	34	Itivdleq	lamprophyre
5940 - 5946	35	Itivdleq	lamprophyre
5947 - 5963	36	Manitsorssuaq	kimberlite
5964 - 5966	37	Manitsorssuaq	kimberlite
5967 - 5975	40	Manitsorssuaq	kimberlite
5976 - 5983	41	Manitsorssuaq	kimberlite
5984 - 5997	38a	Manitsorssuaq	kimberlite
5998 - 5999	38b	Manitsorssuaq	kimberlite

APPENDIX BANALYSES OF MINERALS FROM THE MATRICES OF THE
HOLSTEINSBORG KIMBERLITE AND POTASSIC LAMPROPHYRE DYKESContents

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Notes

- (a) All analyses were determined using the electron microprobe at Edinburgh University (for methods see part F.2 of Appendix F).
- (b) Oxides are given in weight per cent.
- (c) Iron was calculated as total FeO.
- (d) Abbreviations nd = not detected (less than 0.01 wt%).
 - = not determined
 C = centre of grain
 R = rim of grain
 E = euhedral crystal
- (e) Formulae were calculated using a departmental computer programme written by D.J. Humphries.
- (f) Garnet end-member calculations were performed using the computer programme GAREND from Dalhousie University (D.B. Clarke). The method is similar to that of Rickwood (1968).
- (g) For Fe-oxides, ferric iron was calculated by the method of Carmichael (1967a).

(h)	Size - in millimetres
	- or M = megacryst
	G = groundmass
	P = polycrystalline

Table B.1 OLIVINES (a) KIMBERLITE DYKES

Analysis number	1	2	3	4	5	9	10	58	59	68
Sample number	5519	5519	5519	5519	5519	5698(3)	5698(3)	5966(1)	5966(1)	5502
	C - R									
SiO ₂	40.98	41.06	41.53	40.97	40.75	41.18	40.33	39.59	39.64	40.54
TiO ₂	nd	nd	nd	nd	nd	nd	0.03	nd	0.04	nd
Al ₂ O ₃	-	-	-	-	-	-	-	0.04	nd	0.07
Cr ₂ O ₃	-	-	-	-	-	-	-	nd	nd	0.07
FeO	9.25	9.88	7.74	9.69	10.33	10.11	14.85	17.42	15.90	7.82
MnO	0.14	nd	0.10	nd	0.35	nd	0.21	0.16	0.21	0.11
NiO	0.35	0.38	0.40	0.38	nd	0.34	0.25	-	-	-
MgO	49.56	49.46	51.09	49.57	49.09	48.98	45.58	43.01	44.32	49.87
CaO	nd	nd	0.08	nd	nd	nd	0.03	0.04	0.04	0.08
Na ₂ O	-	-	-	-	-	-	-	nd	nd	0.05
K ₂ O	-	-	-	-	-	-	-	nd	nd	nd
Total	100.28	100.78	100.94	100.61	100.52	100.61	101.28	100.26	100.15	98.61
Formula based on 4 oxygens										
Si	1.000	0.999	1.000	0.998	0.996	1.013	0.999	1.002	0.998	0.999
Ti	-	-	-	-	-	-	0.001	-	0.001	-
Al	-	-	-	-	-	-	-	0.001	-	0.002
Cr	-	-	-	-	-	-	-	-	-	0.001
Fe	0.189	0.201	0.156	0.197	0.211	0.204	0.308	0.369	0.335	0.161
Mn	0.003	-	0.002	-	0.007	-	0.004	0.003	0.004	0.002
Ni	0.007	0.007	0.008	0.007	-	0.007	0.005	-	-	-
Mg	1.802	1.794	1.833	1.800	1.789	1.762	1.683	1.622	1.663	1.831
Ca	-	-	0.002	-	-	-	0.001	0.001	0.001	0.002
Na	-	-	-	-	-	-	-	-	-	0.002
K	-	-	-	-	-	-	-	-	-	-
Atomic ratio										
Fe	9.5	10.1	7.8	9.9	10.5	10.4	15.5	18.5	16.8	8.1
Mg	90.5	89.9	92.2	90.1	89.5	89.6	84.5	81.5	83.2	91.9
Size										
	M	M	M	G	M	G	G	M	G	M

Table B.1 O L I V I N E S (a) KIMBERLITE DYKES (continued)

Analysis number	69	76	79	81	82	91	92	97	98	99
Sample number	5502	5502	5603	5603	5603	5603	5698(4)	5698(4)	5698(4)	5698(4)
						E				E
SiO ₂	40.36	40.49	39.72	40.62	40.23	40.73	40.10	40.21	40.14	40.45
TiO ₂	0.04	nd	0.01	nd	nd	nd	nd	nd	0.05	nd
Al ₂ O ₃	0.07	0.06	0.03	0.09	0.08	nd	nd	nd	nd	0.04
Cr ₂ O ₃	0.09	nd	0.01	0.07	0.05	nd	0.03	0.02	0.03	0.02
FeO	9.42	10.26	16.18	11.77	13.55	14.18	18.39	13.75	14.45	13.52
MnO	0.11	0.14	0.15	0.15	0.15	0.16	0.22	0.22	0.16	0.18
NiO	-	-	-	-	-	-	-	-	-	-
MgO	48.77	47.68	45.03	47.67	46.26	46.41	42.96	46.31	45.74	46.46
CaO	0.12	0.05	0.03	0.13	0.10	0.09	0.05	0.02	0.07	0.07
Na ₂ O	0.05	nd	0.03	0.08	nd	nd	nd	0.03	0.05	nd
K ₂ O	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.02
Total	99.03	98.54	101.21	100.58	100.42	101.57	101.75	100.56	100.69	100.76
Formula based on 4 oxygens										
Si	0.997	1.007	0.991	0.999	0.998	1.001	1.003	0.998	0.998	1.000
Ti	0.001	-	-	-	-	-	-	-	0.001	-
Al	0.002	0.002	0.001	0.003	0.002	-	-	-	-	0.001
Cr	0.002	-	-	0.001	0.001	-	0.001	-	0.001	-
Fe	0.195	0.213	0.338	0.242	0.281	0.292	0.385	0.285	0.300	0.280
Mn	0.001	0.003	0.003	0.003	0.003	0.003	0.005	0.005	0.003	0.004
Ni	-	-	-	-	-	-	-	-	-	-
Mg	1.797	1.767	1.674	1.747	1.711	1.700	1.602	1.713	1.695	1.712
Ca	0.003	0.001	0.001	0.003	0.003	0.002	0.001	0.001	0.002	0.002
Na	0.002	-	0.001	0.004	-	-	-	0.001	0.002	-
K	-	-	-	-	-	-	-	-	-	0.001
Atomic ratio										
Fe	9.8	10.8	16.8	12.2	14.1	14.7	19.4	14.3	15.0	16.4
Mg	90.2	89.2	83.2	87.8	85.9	85.3	80.6	85.7	85.0	85.9
Size										
	G	M	M	M	G	G	P	M	G	G

Table B.1 O L I V I N E S (a) KIMBERLITE DYKES (continued)

Analysis number	123	124	125	126	172	173	177	181	186	190
Sample number	5966(2)	5966(2)	5966(2)	5966(2)	5512	5512	5512	5512	5518G	5518G
				E	E					
SiO ₂	39.51	40.83	40.81	41.33	39.85	40.98	39.78	41.59	40.74	41.15
TiO ₂	0.01	nd	nd	nd	0.05	nd	0.05	0.02	nd	0.05
Al ₂ O ₃	0.05	nd	nd	nd	0.03	nd	0.04	0.06	0.03	0.03
Cr ₂ O ₃	nd	0.07	0.07	0.08	0.06	0.11	0.09	0.03	0.09	0.04
FeO	12.29	10.88	11.28	10.63	14.09	8.03	13.16	10.23	13.25	10.05
MnO	0.12	0.09	0.13	0.09	0.20	0.18	0.14	0.11	0.17	0.12
NiO	-	-	-	-	0.25	0.40	0.19	0.43	0.30	0.33
MgO	47.68	48.69	48.11	48.57	46.47	50.93	47.25	49.06	46.44	48.81
CaO	0.09	0.09	0.13	0.08	0.07	0.08	0.12	0.09	0.08	0.04
Na ₂ O	0.04	nd	nd	nd	nd	0.05	0.03	0.03	0.02	0.03
K ₂ O	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Total	99.79	100.65	100.53	100.78	101.07	100.76	100.85	101.65	101.12	100.65
Formula based on 4 oxygens										
Si	0.983	0.998	1.001	1.007	0.988	0.991	0.985	1.005	1.003	1.003
Ti	-	-	-	-	0.001	-	0.001	-	-	0.001
Al	0.001	-	-	-	0.001	-	0.001	0.002	0.001	0.001
Cr	-	0.001	0.001	0.002	0.001	0.002	0.002	0.001	0.002	0.001
Fe	0.256	0.222	0.231	0.217	0.292	0.162	0.273	0.207	0.273	0.205
Mn	0.003	0.002	0.003	0.002	0.004	0.004	0.003	0.002	0.004	0.002
Ni	-	-	-	-	0.005	0.008	0.004	0.008	0.006	0.006
Mg	1.769	1.775	1.759	1.764	1.717	1.837	1.744	1.766	1.705	1.774
Ca	0.002	0.002	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.001
Na	0.002	-	-	-	-	0.002	0.001	0.001	0.001	0.001
K	-	-	-	-	-	-	-	-	-	-
Atomic ratio										
Fe	12.6	11.1	11.6	10.9	14.5	8.1	13.5	10.5	13.8	10.4
Mg	87.4	88.9	88.4	89.1	85.5	91.9	86.5	89.5	86.2	89.6
Size										
	M	G	G	G	1	3	0.25	4	0.75	2

Table B.1 O L I V I N E S (a) KIMBERLITE DYKES (continued)

Analysis number	215	231	236	238	245	246	254	266	267	270
Sample number	5518G	5518G	5987	5987	5987	5987	5987	5518OL	5518OL	5518OL
								E	E	
SiO ₂	41.83	39.78	40.50	40.13	40.76	40.63	40.84	40.11	40.18	40.98
TiO ₂	nd	0.02	0.03	0.02	0.04	0.05	0.06	0.05	0.03	0.05
Al ₂ O ₃	nd	0.04	0.06	0.03	0.01	0.05	0.06	0.04	0.04	0.03
Cr ₂ O ₃	0.02	-	-	0.04	0.03	0.01	0.03	0.05	0.03	nd
FeO	7.52	18.38	13.81	14.63	11.93	14.03	12.50	15.41	14.07	10.82
MnO	0.11	0.23	0.13	0.21	0.12	0.19	0.12	0.16	0.14	0.19
NiO	0.28	0.10	0.16	0.25	0.31	0.29	0.28	0.24	0.25	0.24
MgO	51.57	42.88	46.72	46.27	48.34	46.55	47.30	45.25	46.26	48.57
CaO	nd	0.05	0.09	0.07	0.12	0.10	0.07	0.08	0.08	0.02
Na ₂ O	0.01	0.02	0.03	0.04	0.02	0.03	0.05	0.03	0.02	0.03
K ₂ O	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Total	101.34	101.50	101.53	101.69	101.68	101.93	101.31	101.42	101.08	100.93
Formula based on 4 oxygens										
Si	1.001	0.999	0.996	0.990	0.993	0.997	1.000	0.995	0.994	1.000
Ti	-	-	0.001	-	0.001	0.001	0.001	0.001	0.001	0.001
Al	-	0.001	0.002	0.001	-	-	0.002	0.001	0.001	0.001
Cr	-	-	-	-	0.001	-	0.001	0.001	0.001	-
Fe	0.150	0.386	0.284	0.302	0.243	0.288	0.256	0.320	0.291	0.221
Mn	0.002	0.005	0.003	0.004	0.002	0.004	0.002	0.003	0.003	0.004
Ni	0.005	0.002	0.003	0.005	0.006	0.006	0.006	0.005	0.005	0.005
Mg	1.839	1.605	1.712	1.702	1.756	1.703	1.727	1.674	1.706	1.766
Ca	-	0.001	0.002	0.002	0.003	0.003	0.002	0.002	0.002	0.001
Na	-	0.001	0.001	0.002	0.001	0.001	0.002	0.001	0.001	0.001
K	-	-	-	-	-	-	-	-	-	-
Atomic ratio										
Fe	7.5	19.4	14.3	15.1	12.2	14.5	12.9	16.1	14.6	11.1
Mg	92.5	80.6	85.7	84.9	87.8	85.5	87.9	83.9	85.4	88.9
Size										
	0.5	4	1	P	1	2	2	1	0.5	2.5

Table B.1 O L I V I N E S (a) KIMBERLITE DYKES (continued)

Analysis number	279	282	283	338	339	342	343	350	353	354
Sample number	5518OL	5518OL	5518OL	5914(4)	5914(4)	5914(4)	5914(4)	5914(4)	5914(1)	5914(1)
	E				C - R					
SiO ₂	40.48	40.68	39.66	38.52	38.87	41.25	40.97	38.40	41.17	40.77
TiO ₂	0.05	0.06	nd	0.04	0.03	0.05	0.03	0.01	0.02	0.02
Al ₂ O ₃	0.03	0.06	0.02	0.04	0.03	0.06	0.06	0.04	0.07	0.12
Cr ₂ O ₃	0.02	0.07	nd	nd	nd	0.06	0.09	0.01	0.07	0.07
FeO	11.98	14.38	19.95	22.44	22.96	9.52	9.65	22.46	9.54	9.50
MnO	0.11	0.09	0.27	0.30	0.35	0.12	0.09	0.39	0.13	0.09
NiO	0.32	0.28	0.08	0.11	0.12	0.33	0.48	0.06	0.39	0.34
MgO	47.48	46.08	42.12	39.67	39.52	49.49	49.38	39.49	49.53	49.48
CaO	0.13	0.08	0.07	0.04	0.02	0.13	0.13	0.03	0.12	0.11
Na ₂ O	0.06	0.06	0.01	0.03	0.04	0.05	0.06	0.02	0.04	0.05
K ₂ O	nd	nd	nd	nd	nd	nd	0.02	nd	0.02	nd
Total	100.66	101.84	102.18	101.19	101.94	101.06	100.96	100.91	101.10	100.55
Formula based on 4 oxygens										
Si	0.997	1.000	0.996	0.991	0.994	1.000	0.996	0.991	0.998	0.994
Ti	0.001	0.001	-	0.001	0.001	0.001	0.001	-	-	-
Al	0.001	0.002	0.001	0.001	0.001	0.002	0.002	0.001	0.002	0.003
Cr	-	0.001	-	-	-	0.001	0.002	-	0.001	0.001
Fe	0.247	0.295	0.419	0.483	0.491	0.193	0.196	0.485	0.193	0.194
Mn	0.002	0.002	0.006	0.007	0.008	0.002	0.002	0.009	0.003	0.002
Ni	0.006	0.006	0.002	0.002	0.002	0.006	0.009	0.001	0.008	0.007
Mg	1.743	1.688	1.577	1.521	1.506	1.788	1.789	1.519	1.790	1.798
Ca	0.003	0.002	0.002	0.001	0.001	0.003	0.003	0.001	0.003	0.003
Na	0.003	0.003	-	0.001	0.002	0.002	0.003	0.001	0.002	0.002
K	-	-	-	-	-	-	0.001	-	0.001	-
Atomic ratio										
Fe	12.4	14.9	21.0	24.1	24.6	9.7	9.9	24.2	9.7	9.7
Mg	87.6	85.1	79.0	75.9	75.4	90.3	90.1	75.8	90.3	90.3
Size										
	0.3	1	3	350	350	0.75	0.3	350	2	3

Table B.1 O L I V I N E S (a) KIMBERLITE DYKES (continued)

Analysis number	355	361	362	363	375	388	389	390	391	392		
Sample number	5914(1)	5975	5975	5975	5975	5696	5696	5696	5696	5696		
					E	C	-	R	C	-	R	E
SiO ₂	40.59	39.57	39.74	40.65	39.92	40.64	39.87	40.07	39.84	40.05		
TiO ₂	0.02	0.05	0.05	0.02	0.05	0.04	0.07	0.04	0.08	0.04		
Al ₂ O ₃	0.06	0.03	0.03	0.04	0.03	0.04	0.05	nd	nd	0.02		
Cr ₂ O ₃	0.11	0.08	nd	nd	0.09	0.04	0.04	0.03	nd	nd		
FeO	10.67	13.78	15.09	8.51	14.28	10.00	14.35	13.82	13.85	13.93		
MnO	0.12	0.12	0.19	0.14	0.14	0.13	0.18	0.18	0.22	0.05		
NiO	0.33	0.34	0.22	0.32	0.29	0.39	0.18	0.29	0.12	0.35		
MgO	48.45	46.53	46.00	50.82	45.79	49.31	45.75	45.99	46.30	45.51		
CaO	0.13	0.11	0.02	0.05	0.12	0.07	0.15	0.03	0.15	0.65		
Na ₂ O	0.03	0.05	0.04	0.04	nd	0.03	nd	0.02	nd	nd		
K ₂ O	nd	nd	nd	0.02	0.03	nd	0.03	nd	nd	0.02		
Total	100.51	100.60	101.38	100.61	100.74	100.69	100.67	100.47	100.56	100.62		
Formula based on 4 oxygens												
Si	0.955	0.985	0.986	0.987	0.993	0.992	0.990	0.997	0.991	0.997		
Ti	-	0.001	0.001	-	0.001	0.001	0.001	0.001	0.001	0.001		
Al	0.002	0.001	0.001	0.001	0.001	0.001	0.001	-	-	0.001		
Cr	0.002	-	-	-	0.002	0.001	0.001	0.001	-	-		
Fe	0.219	0.287	0.313	0.173	0.297	0.204	0.308	0.288	0.288	0.290		
Mn	0.002	0.003	0.004	0.003	0.003	0.003	0.004	0.004	0.005	0.001		
Ni	0.007	0.007	0.004	0.006	0.006	0.008	0.004	0.006	0.002	0.007		
Mg	1.771	1.726	1.701	1.839	1.698	1.794	1.693	1.705	1.716	1.688		
Ca	0.003	0.003	0.001	0.001	0.003	0.002	0.004	0.001	0.004	0.017		
Na	0.001	0.002	0.002	0.002	-	0.001	-	0.001	-	-		
K	-	-	-	0.001	0.001	-	0.001	-	-	0.001		
Atomic ratio												
Fe	11.0	14.3	15.5	8.6	14.9	10.2	15.4	14.5	14.4	14.7		
Mg	89.0	85.7	84.5	91.4	85.1	89.8	84.6	85.5	85.6	85.3		
Size												
	0.3	2	3	0.3	0.5	3	3	3	3	0.5		

Table B.1 OLIVINES (a) KIMBERLITE DYKES (continued)

Analysis number	393	471	474	476	477
Sample number	5696	5524	5524	5524	5524
				R - C	
SiO ₂	40.91	40.10	40.75	40.30	40.02
TiO ₂	0.01	0.06	0.05	0.05	0.05
Al ₂ O ₃	0.07	0.04	0.15	0.02	0.04
Cr ₂ O ₃	0.03	nd	0.06	0.02	0.01
FeO	10.11	14.17	10.59	12.30	13.55
MnO	0.15	0.20	0.16	0.15	0.19
NiO	0.34	0.30	0.33	0.37	0.26
MgO	48.98	46.11	48.34	46.27	45.47
CaO	0.09	0.06	0.16	0.13	0.07
Na ₂ O	0.04	-	-	-	-
K ₂ O	0.05	-	-	-	-
Total	100.78	101.04	100.59	99.61	99.66

Formula based on 4 oxygens

Si	0.998	0.994	0.998	1.004	1.002
Ti	-	0.001	0.001	0.001	0.001
Al	0.002	0.001	0.004	0.001	0.001
Cr	0.001	-	0.001	-	-
Fe	0.206	0.294	0.217	0.256	0.284
Mn	0.003	0.004	0.003	0.003	0.004
Ni	0.007	0.006	0.006	0.007	0.005
Mg	1.781	1.703	1.764	1.718	1.697
Ca	0.002	0.002	0.004	0.003	0.002
Na	0.002	-	-	-	-
K	0.002	-	-	-	-

Atomic ratio

Fe	10.4	14.7	10.9	13.0	14.3
Mg	89.6	85.3	89.1	87.0	85.7

Size

0.5	M	G	M	M
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Table B.1 O L I V I N E S (b) LAMPROPHYRE DYKES[illegible]

Table B.1 OLIVINES (b) LAMPROPHYRE DYKES (continued)

Analysis number	418	419	420	421	422	423	424	425	426	427			
Sample number	5612	5612	5612	5612	5612	5612	5612	5612	5612	5631			
	C	-	R	C	-	R	C	-	R				
SiO ₂	41.18		41.63	41.30		41.40	41.18		40.94	41.20	41.11	41.35	41.12
TiO ₂	nd		nd	nd		nd	nd		nd	nd	nd	nd	nd
Al ₂ O ₃	-		-	-		-	-		-	-	-	-	-
Cr ₂ O ₃	0.02		0.05	0.09		0.07	0.07		0.05	0.05	0.11	0.01	nd
FeO	7.19		7.87	6.86		7.04	7.57		7.59	8.10	7.52	7.05	7.55
MnO	0.08		0.09	0.06		0.09	0.12		0.15	0.12	0.12	0.13	0.11
NiO	0.44		0.39	0.44		0.44	0.43		0.45	0.37	0.39	0.41	0.41
MgO	50.25		49.87	50.52		50.01	50.02		49.80	49.63	49.89	50.60	50.07
CaO	0.02		nd	0.02		0.04	nd		0.03	0.06	0.02	nd	nd
Na ₂ O	-		-	-		-	-		-	-	-	-	-
K ₂ O	-		-	-		-	-		-	-	-	-	-
Total	99.45		99.70	99.29		99.09	99.39		99.01	99.53	99.16	99.55	99.26
Formula based on 4 oxygens													
Si	1.006		1.012	1.006		1.011	1.006		1.004	1.007	1.006	1.010	1.005
Ti	-		-	-		-	-		-	-	-	-	-
Al	-		-	-		-	-		-	-	-	-	-
Cr	-		0.001	0.002		0.003	0.001		0.001	0.001	0.002	-	-
Fe	0.147		0.160	0.140		0.144	0.155		0.156	0.165	0.154	0.144	0.154
Mn	0.002		0.002	0.001		0.002	0.002		0.003	0.002	0.002	0.003	0.002
Ni	0.009		0.008	0.009		0.009	0.008		0.009	0.007	0.008	0.008	0.008
Mg	1.830		1.806	1.835		1.820	1.821		1.821	1.808	1.820	1.824	1.824
Ca	-		-	-		0.001	-		0.001	0.002	-	-	-
Na	-		-	-		-	-		-	-	-	-	-
K	-		-	-		-	-		-	-	-	-	-
Atomic ratio													
Fe	7.4		8.1	7.1		7.3	7.8		7.9	8.4	7.8	7.3	7.8
Mg	92.6		91.9	92.9		92.7	92.2		92.1	91.6	92.2	92.7	92.2
Size													
	1.5		1.5	4			3			3	1.5	1	1

Table B.1 OLIVINES (b) LAMPROPHYRE DYKES (continued)

Analysis number	428	429	430	432	433	434	435	436	437
Sample number	5631	5631	5631	5631	5631	5631	5631	5631	5631
	C	-	R	C	-	R			
SiO ₂	41.28	41.06	40.53	41.10	40.52	40.21	41.41	40.76	40.72
TiO ₂	nd	nd	nd	0.02	0.08	nd	nd	nd	nd
Al ₂ O ₃	-	-	-	-	-	-	-	-	-
Cr ₂ O ₃	0.05	0.05	0.06	0.11	0.05	0.05	0.04	0.05	0.10
FeO	7.71	7.69	10.94	6.03	11.15	11.63	7.81	7.77	9.89
MnO	0.09	0.11	0.13	0.10	0.14	0.19	0.24	0.09	0.15
NiO	0.44	0.33	0.41	0.36	0.40	0.46	0.46	0.43	0.44
MgO	49.93	49.99	47.27	51.16	47.06	46.59	49.92	50.04	48.34
CaO	0.03	0.02	0.13	nd	0.13	0.13	0.02	nd	0.12
Na ₂ O	-	-	-	-	-	-	-	-	-
K ₂ O	-	-	-	-	-	-	-	-	-
Total	99.53	99.25	99.47	98.88	99.53	99.26	99.90	99.14	99.76
Formula based on 4 oxygens									
Si	1.007	1.005	1.005	1.002	1.005	1.003	1.008	1.000	1.002
Ti	-	-	-	-	0.002	-	-	-	-
Al	-	-	-	-	-	-	-	-	-
Cr	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.002
Fe	0.157	0.157	0.227	0.123	0.231	0.243	0.159	0.159	0.204
Mn	0.002	0.002	0.003	0.002	0.003	0.004	0.005	0.002	0.003
Ni	0.009	0.006	0.008	0.007	0.008	0.009	0.009	0.009	0.009
Mg	1.816	1.823	1.747	1.860	1.740	1.733	1.810	1.830	1.774
Ca	0.001	-	0.003	-	0.003	0.003	-	-	0.003
Na	-	-	-	-	-	-	-	-	-
K	-	-	-	-	-	-	-	-	-
Atomic ratio									
Fe	8.0	7.9	11.5	6.2	11.7	12.3	8.1	8.0	10.3
Mg	92.0	92.1	88.5	93.8	88.3	87.7	91.9	92.0	89.7
Size									
	5		0.2	2		0.3	P	P	0.5

Table B.1 OLIVINES (b) LAMPROPHYRE DYKES (continued)

Analysis number	438	439	440	441	442	444	445	446	447
Sample number	5631	5631	5665	5665	5665	5665	5665	5934	5934
	C - R			C - R					
SiO ₂	41.19	41.20	40.46	41.26	40.73	41.11	40.55	39.98	40.49
TiO ₂	nd	0.03	nd	0.05	nd	nd	nd	0.02	nd
Al ₂ O ₃	-	-	-	-	-	-	-	-	-
Cr ₂ O ₃	0.02	0.09	0.09	0.04	0.09	0.07	0.08	0.08	0.04
FeO	8.12	8.12	10.08	7.92	10.22	7.98	10.28	10.97	10.35
MnO	0.13	0.15	0.13	0.12	0.10	0.10	0.12	0.14	0.13
NiO	0.39	0.43	0.44	0.39	0.41	0.46	0.41	0.41	0.46
MgO	49.77	49.79	47.90	49.59	47.72	49.51	47.59	46.87	47.17
CaO	nd	nd	0.10	0.01	0.10	0.02	0.13	0.15	0.15
Na ₂ O	-	-	-	-	-	-	-	-	-
K ₂ O	-	-	-	-	-	-	-	-	-
Total	99.62	99.81	99.20	99.38	99.37	99.25	99.16	98.62	98.79

Formula based on 4 oxygens

Si	1.006	1.005	1.003	1.009	1.007	1.007	1.005	1.001	1.008
Ti	-	0.001	-	0.001	-	-	-	-	-
Al	-	-	-	-	-	-	-	-	-
Cr	-	0.002	0.002	0.001	0.003	0.001	0.002	0.002	0.001
Fe	0.166	0.166	0.209	0.162	0.211	0.164	0.231	0.230	0.215
Mn	0.003	0.003	0.003	0.002	0.002	0.002	0.002	0.003	0.003
Ni	0.008	0.008	0.009	0.008	0.008	0.009	0.008	0.008	0.009
Mg	1.811	1.810	1.769	1.807	1.759	1.808	1.759	1.750	1.751
Ca	-	-	0.002	-	0.003	0.001	0.004	0.004	0.004
Na	-	-	-	-	-	-	-	-	-
K	-	-	-	-	-	-	-	-	-

Atomic ratio

Fe	8.4	8.4	10.6	8.2	10.7	8.3	10.8	11.6	10.9
Mg	91.6	91.6	89.4	91.8	89.3	91.7	89.2	88.4	89.1

Size

1	0.25	4	3	3	0.3	1	4
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Table B.1 O L I V I N E S (b) LAMPROPHYRE DYKES (continued)

Analysis number	448	449	450	451	452	453	454	455	
Sample number	5934	5934	5934	5637	5637	5637	5637	5637	
	C	-	R	C	-	R			
SiO ₂	40.21		41.46	40.60	40.72	40.57	40.55	40.81	40.87
TiO ₂	0.01		nd	0.04	0.02	nd	nd	0.02	nd
Al ₂ O ₃	-		-	-	-	-	-	-	-
Cr ₂ O ₃	0.04		0.04	0.06	0.06	0.09	0.07	0.06	0.05
FeO	10.79		10.32	10.92	10.47	10.63	10.29	10.37	10.52
MnO	0.12		0.12	0.18	0.13	0.10	0.15	0.14	0.12
NiO	0.48		0.45	0.41	0.45	0.32	0.41	0.41	0.45
MgO	47.43		44.60	47.54	47.58	47.34	47.43	47.39	47.62
CaO	0.15		0.17	0.15	0.14	0.18	0.18	0.20	0.21
Na ₂ O	-		-	-	-	-	-	-	-
K ₂ O	-		-	-	-	-	-	-	-
Total	99.23		96.96	99.90	99.57	99.23	99.08	99.40	99.84
Formula based on 4 oxygens									
Si	1.000		1.045	1.003	1.006	1.006	1.007	1.010	1.008
Ti	-		-	0.001	-	-	-	-	-
Al	-		-	-	-	-	-	-	-
Cr	0.001		0.001	0.001	0.001	0.002	0.001	0.001	0.001
Fe	0.224		0.217	0.225	0.216	0.220	0.214	0.215	0.217
Mn	0.003		0.003	0.004	0.003	0.002	0.003	0.003	0.003
Ni	0.010		0.009	0.008	0.009	0.006	0.008	0.008	0.009
Mg	1.758		1.658	1.750	1.753	1.750	1.755	1.748	1.750
Ca	0.004		0.005	0.004	0.004	0.005	0.005	0.005	0.005
Na	-		-	-	-	-	-	-	-
K	-		-	-	-	-	-	-	-
Atomic ratios.									
Fe	11.3		11.6	11.4	11.0	11.2	10.9	10.9	11.0
Mg	88.7		88.4	88.6	89.0	88.8	89.1	89.1	89.0
Size									
	1			1			1.5	0.2	0.5

Table B.2 P H L O G O P I T E S (a) KIMBERLITE DYKES

Analysis number	11	12	13	14	15	25	60	61	62		
Sample number	5519	5519	5519	5519	5519	5698(3)	5966(1)	5966(1)	5966(1)		
	C	-	R	C	-	R		C	-	R	
SiO ₂	36.77		37.64	36.29		36.60	36.99	36.17	37.05	38.77	38.87
TiO ₂	6.20		6.35	6.14		5.88	5.97	3.90	3.29	4.80	4.65
Al ₂ O ₃	14.21		14.35	14.62		14.17	14.54	15.42	15.46	13.18	13.07
Cr ₂ O ₃	0.87		1.04	0.24		nd	nd	0.03	0.04	0.19	0.21
FeO	7.40		7.29	8.08		7.03	7.64	6.66	6.57	7.57	7.23
MnO	0.08		0.07	0.08		nd	nd	0.06	0.04	0.02	0.03
NiO	0.04		0.09	0.02		0.03	nd	0.05	-	-	-
MgO	20.46		19.01	19.15		19.68	19.41	21.05	21.67	20.07	20.51
CaO	0.06		0.05	0.03		0.03	0.04	0.03	nd	nd	nd
Na ₂ O	0.36		0.33	0.29		0.31	0.36	0.16	0.27	0.28	0.28
K ₂ O	9.59		9.66	9.45		9.23	9.60	9.77	9.61	10.00	9.79
Total	96.04		95.88	94.39		92.96	94.55	93.30	94.00	94.88	94.64
Formula based on 22 oxygens											
Si	5.310		5.429	5.334		5.420	5.407	5.342	5.411	5.641	5.654
Ti	0.673		0.689	0.679		0.655	0.656	0.433	0.361	0.525	0.509
Al	2.419		2.439	2.533		2.473	2.505	2.684	2.661	2.260	2.241
Cr	0.099		0.119	0.028		-	-	0.004	0.005	0.022	0.024
Fe	0.894		0.879	0.993		0.871	0.934	0.823	0.802	0.921	0.880
Mn	0.010		0.009	0.010		-	-	0.008	0.005	0.002	0.004
Ni	0.005		0.010	0.002		0.004	-	0.006	-	-	-
Mg	4.404		4.087	4.196		4.344	4.229	4.634	4.717	4.353	4.447
Ca	0.009		0.008	0.005		0.005	0.006	0.005	-	-	-
Na	0.101		0.092	0.083		0.087	0.102	0.046	0.076	0.079	0.079
K	1.767		1.777	1.772		1.744	1.790	1.841	1.790	1.856	1.817
Weight per cent oxide ratio											
$\frac{\text{Na}_2\text{O}}{\text{Na}_2\text{O}+\text{K}_2\text{O}}$	0.036		0.033	0.030		0.032	0.036	0.016	0.027	0.027	0.028
Atomic ratio											
$\frac{\text{Mg}}{\text{Mg}+\text{Fe}}$	0.83		0.82	0.81		0.83	0.82	0.85	0.85	0.82	0.83
Size											
							G	G	M	M	

Table B.2 P H L O G O P I T E S (a) KIMBERLITE DYKES (continued)

Analysis number	63	64	72	73	74	77	78	83	84	85	
Sample number	5966(1)	5966(1)	5502	5502	5502	5502	5502	5603	5603	5603	
	C	-	R	C	-	R	C	-	R		
SiO ₂	40.64		37.57	36.18	41.19	37.46	37.18	36.07	37.99	36.17	36.43
TiO ₂	1.99		5.51	3.27	nd	4.69	4.83	3.15	6.58	3.68	5.96
Al ₂ O ₃	10.54		14.48	16.27	1.10	13.92	14.00	15.70	14.91	14.72	16.12
Cr ₂ O ₃	0.14		1.07	0.08	nd	0.07	1.46	0.04	0.62	0.12	0.32
FeO	10.16		6.69	6.41	15.30	6.24	5.52	6.67	6.74	6.60	7.84
MnO	0.06		0.02	0.03	0.19	0.06	0.06	0.08	0.07	0.04	0.06
NiO	-		-	-	-	-	-	-	-	-	-
MgO	20.92		19.51	21.06	24.04	20.51	20.08	21.07	19.00	20.23	18.37
CaO	nd		nd	nd	nd	nd	nd	nd	nd	0.06	0.03
Na ₂ O	0.20		0.27	0.29	nd	0.34	0.34	0.33	0.29	0.30	0.53
K ₂ O	9.79		9.94	9.60	9.42	9.41	9.51	9.56	9.41	8.83	9.09
Total	94.44		95.06	93.16	91.24	92.70	92.98	92.67	95.61	90.75	94.75
Formula based on 22 oxygens											
Si	5.991		5.453	5.331	6.514	5.537	5.486	5.356	5.453	5.460	5.306
Ti	0.221		0.601	0.362	-	0.521	0.536	0.352	0.710	0.418	0.653
Al	1.831		2.477	2.825	0.205	2.425	2.435	2.748	2.522	2.619	2.767
Cr	0.016		0.123	0.009	-	0.008	0.170	0.005	0.070	0.014	0.037
Fe	1.253		0.812	0.790	2.023	0.771	0.681	0.828	0.809	0.833	0.955
Mn	0.007		0.002	0.004	0.025	0.008	0.007	0.010	0.009	0.005	0.007
Ni	-		-	-	-	-	-	-	-	-	-
Mg	4.597		4.220	4.625	5.666	4.519	4.416	4.664	4.065	4.552	3.988
Ca	-		-	-	-	-	-	-	0.000	0.010	0.005
Na	0.057		0.076	0.083	-	0.097	0.097	0.095	0.081	0.088	0.150
K	1.841		1.840	1.804	1.900	1.774	1.790	1.811	1.723	1.700	1.639
Weight per cent oxide ratio											
$\frac{\text{Na}_2\text{O}}{\text{Na}_2\text{O}+\text{K}_2\text{O}}$	0.020		0.026	0.031	-	0.035	0.035	0.033	0.030	0.033	0.055
Atomic ratio											
$\frac{\text{Mg}}{\text{Mg}+\text{Fe}}$	0.79		0.84	0.85	0.74	0.85	0.87	0.85	0.83	0.84	0.81
Size	M		M			G					

Table B.2 P H L O G O P I T E S (a) KIMBERLITE DYKES (continued)

Analysis number	86	100	102	103	127	128	129	146	147
Sample number	5603	5698(4)	5698(4)	5698(4)	5966(2)	5966(2)	5966(2)	5605	5605
			C - R	C - R	C - R	C - R	C - R	C - R	C - R
SiO ₂	36.56	36.65	36.95	41.11	39.45	36.60	37.49	37.85	36.18
TiO ₂	6.04	2.86	3.73	0.32	0.92	3.52	4.44	4.47	4.19
Al ₂ O ₃	15.14	14.05	15.41	2.35	13.57	15.17	15.36	14.28	11.65
Cr ₂ O ₃	0.79	0.08	nd	0.02	0.05	0.04	0.21	0.04	nd
FeO	7.09	7.02	6.79	14.87	8.95	9.27	7.26	8.11	8.66
MnO	0.16	0.13	0.04	0.08	0.07	0.06	0.05	0.03	0.48
NiO	-	-	-	-	-	-	-	0.04	0.04
MgO	18.85	20.93	21.24	24.86	21.66	21.00	19.64	19.96	20.68
CaO	0.12	0.07	0.02	0.11	nd	0.12	nd	0.05	0.09
Na ₂ O	0.34	0.27	0.19	0.29	0.37	0.21	0.32	0.36	0.56
K ₂ O	9.44	9.70	9.71	9.69	10.03	9.65	9.59	9.73	5.86
Total	94.53	91.76	94.08	93.70	95.07	95.64	94.36	94.92	88.39
Formula based on 22 oxygens									
Si	5.343	5.514	5.400	6.234	5.751	5.334	5.467	5.529	5.600
Ti	0.664	0.324	0.410	0.037	0.101	0.386	0.487	0.488	0.488
Al	2.608	2.491	2.655	0.426	2.331	2.606	2.640	2.429	2.125
Cr	0.091	0.010	-	0.002	0.006	0.005	0.024	0.005	-
Fe	0.866	0.883	0.830	1.913	1.091	1.130	0.885	0.991	1.121
Mn	0.020	0.017	0.005	0.010	0.009	0.007	0.006	0.004	0.063
Ni	-	-	-	-	-	-	-	0.005	0.005
Mg	4.106	4.693	4.627	5.700	4.706	4.562	4.269	4.350	4.771
Ca	0.019	0.011	0.003	0.018	-	0.019	-	0.003	0.015
Na	0.096	0.079	0.054	0.086	0.105	0.059	0.090	0.102	0.168
K	1.760	1.862	1.810	1.901	1.865	1.794	1.784	1.814	1.157
Weight per cent oxide ratio									
$\frac{\text{Na}_2\text{O}}{\text{Na}_2\text{O}+\text{K}_2\text{O}}$	0.035	0.027	0.019	0.029	0.036	0.021	0.032	0.036	0.087
Atomic ratio									
$\frac{\text{Mg}}{\text{Mg}+\text{Fe}}$	0.93	0.84	0.85	0.75	0.81	0.80	0.83	0.81	0.81
Size		G	G	G	M	M	G	M	M

Table B.2 P H L O G O P I T E S (a) KIMBERLITE DYKES (continued)

Analysis number	149	150	151	154	175	176	179	180	184	185
Sample number	5605	5605	5605	5605	5512	5512	5512	5512	5512	5512
	C	-	R		C	-	R	C	-	R
SiO ₂	37.37	31.58	34.82	35.90	35.57	40.77	38.10	37.21	37.78	40.98
TiO ₂	4.66	3.31	5.38	5.63	3.24	0.46	4.72	2.89	4.68	0.55
Al ₂ O ₃	14.03	9.08	10.07	10.53	16.71	1.59	14.33	15.43	14.45	1.60
Cr ₂ O ₃	0.05	0.02	nd	0.03	0.14	0.05	1.03	0.07	1.32	nd
FeO	10.16	25.43	30.37	27.48	6.17	15.51	6.09	6.94	6.19	14.28
MnO	0.04	0.76	0.75	0.83	0.06	0.19	0.06	0.06	0.06	0.06
NiO	nd	0.03	nd	0.03	0.04	0.05	0.05	0.04	0.02	0.01
MgO	19.10	17.21	4.43	6.69	21.59	24.45	20.52	21.71	20.35	24.52
CaO	0.08	0.71	0.44	0.10	0.04	0.23	0.03	0.09	0.05	0.28
Na ₂ O	0.62	0.15	0.38	0.24	0.22	0.39	0.37	0.32	0.32	0.29
K ₂ O	9.18	5.58	8.89	9.14	9.04	8.96	9.67	9.62	9.85	9.59
Total	95.29	93.86	95.53	96.60	92.82	92.62	94.97	94.43	95.07	92.16
Formula based on 22 oxygens										
Si	5.492	5.132	5.613	5.691	5.246	6.359	5.508	5.422	5.471	6.400
Ti	0.514	0.358	0.643	0.671	0.359	0.054	0.513	0.317	0.510	0.065
Al	2.406	1.698	2.173	1.968	2.905	0.292	2.442	2.658	2.466	0.295
Cr	0.006	0.003	-	0.004	0.016	0.006	0.118	0.008	0.151	-
Fe	1.247	3.459	4.073	3.643	0.761	2.023	0.736	0.845	0.750	1.865
Mn	0.005	0.105	0.102	0.111	0.007	0.025	0.007	0.007	0.007	0.008
Ni	-	0.004	-	0.004	0.005	0.006	0.006	0.005	0.002	0.001
Mg	4.178	4.174	1.055	1.581	4.746	5.684	4.422	4.714	4.392	5.708
Ca	0.013	0.124	0.076	0.017	0.006	0.038	0.005	0.014	0.008	0.047
Na	0.176	0.047	0.118	0.074	0.063	0.113	0.104	0.090	0.090	0.088
K	1.718	1.158	1.704	1.848	1.701	1.783	1.783	1.788	1.819	1.911
Weight per cent oxide ratio										
$\frac{\text{Na}_2\text{O}}{\text{Na}_2\text{O}+\text{K}_2\text{O}}$	0.063	0.027	0.041	0.026	0.024	0.042	0.037	0.032	0.031	0.027
Atomic ratio										
$\frac{\text{Mg}}{\text{Mg}+\text{Fe}}$	0.77	0.55	0.21	0.30	0.86	0.74	0.86	0.85	0.85	0.75
Size	G	G	G	G	M	M	M	M	G	G

Table B.2 P H L O G O P I T E S (a) KIMBERLITE DYKES (continued)

Analysis number	191	200	201	207	223	229	230	233	234	242
Sample number	5518G	5518G	5518G	5518G	5518G	5518G	5518G	5518G	5518G	5987
	C - R						C - R		C - R	
SiO ₂	41.43	40.76	40.61	40.30	37.29	41.24	39.50	41.71	39.15	37.63
TiO ₂	0.17	0.44	0.46	1.86	2.76	0.46	2.82	0.20	3.67	3.01
Al ₂ O ₃	7.06	11.52	11.55	13.08	15.09	11.61	12.70	10.96	13.16	14.16
Cr ₂ O ₃	0.03	nd	nd	nd	0.29	0.06	0.31	0.11	0.82	nd
FeO	10.69	10.21	9.68	13.18	10.37	7.58	6.39	6.09	6.09	7.89
MnO	0.05	0.09	0.12	0.02	0.06	nd	0.06	0.04	0.04	0.06
NiO	0.04	0.03	nd	nd	0.08	0.04	0.03	0.07	0.15	0.04
MgO	24.47	21.99	22.00	15.95	18.84	23.56	22.69	25.31	21.85	21.40
CaO	0.13	0.01	0.14	nd	0.14	nd	0.08	0.05	0.07	0.09
Na ₂ O	0.12	0.04	0.05	0.37	0.51	0.09	0.31	0.11	0.36	0.26
K ₂ O	10.00	10.17	10.08	9.53	9.31	10.12	9.57	9.72	9.73	9.73
Total	94.19	95.26	94.69	94.29	94.74	94.76	94.96	94.37	95.09	94.27
Formula based on 22 oxygens										
Si	6.169	5.958	5.958	6.000	5.498	5.977	5.709	6.017	5.648	5.521
Ti	0.019	0.048	0.051	0.208	0.306	0.050	0.307	0.022	0.398	0.332
Al	1.239	1.985	1.997	2.295	2.622	1.983	2.163	1.864	2.237	2.448
Cr	0.004	-	-	-	0.034	0.007	0.035	0.013	0.094	-
Fe	1.331	1.248	1.188	1.641	1.279	0.919	0.833	0.735	0.735	0.968
Mn	0.006	0.011	0.015	0.003	0.007	-	0.007	0.005	0.005	0.007
Ni	0.005	0.004	-	-	0.009	0.005	0.003	0.008	0.017	0.005
Mg	5.431	4.791	4.811	3.539	4.141	5.089	4.888	5.443	4.698	4.680
Ca	0.021	0.002	0.022	-	0.022	-	0.012	0.008	0.011	0.014
Na	0.035	0.011	0.014	0.107	0.146	0.025	0.087	0.031	0.101	0.074
K	1.899	1.896	1.887	1.810	1.751	1.871	1.765	1.789	1.791	1.821
Weight per cent oxide ratio										
$\frac{\text{Na}_2\text{O}}{\text{Na}_2\text{O}+\text{K}_2\text{O}}$	0.012	0.004	0.005	0.037	0.052	0.009	0.031	0.011	0.036	0.026
Atomic ratio										
$\frac{\text{Mg}}{\text{Mg}+\text{Fe}}$	0.80	0.79	0.80	0.68	0.76	0.85	0.85	0.88	0.86	0.83
Size	G	M	M		G	M	M			G

Table B.2 P H L O G O P I T E S (a) KIMBERLITE DYKES (continued)

Analysis number	243	247	250	271	275	276	277	278	281
Sample number	5987	5987	5987	5518OL	5518OL	5518OL	5518OL	5518OL	5518OL
	C - R					C - R			
SiO ₂	38.30	41.51	37.23	41.03	38.73	40.44	39.97	39.40	39.03
TiO ₂	0.98	1.43	3.64	3.26	2.62	3.45	4.08	2.59	2.83
Al ₂ O ₃	10.91	10.17	15.10	11.98	13.51	11.77	11.89	12.99	13.61
Cr ₂ O ₃	nd	0.12	0.02	0.28	0.12	0.10	0.24	0.78	0.52
FeO	7.59	7.68	7.32	6.79	6.78	7.18	6.96	6.39	6.25
MnO	0.07	0.04	0.06	0.02	0.04	nd	0.04	0.02	0.05
NiO	0.01	0.11	nd	0.11	0.10	0.11	0.06	0.11	0.10
MgO	22.45	23.79	21.53	21.75	22.64	21.72	21.42	22.67	22.49
CaO	0.07	nd	0.06	0.15	0.23	0.05	0.29	0.20	0.14
Na ₂ O	0.25	0.18	0.22	0.32	0.31	0.24	0.27	0.31	0.21
K ₂ O	9.85	10.12	9.86	9.74	9.66	9.92	9.74	9.34	9.57
Total	90.48	95.15	95.04	95.43	94.74	94.98	94.96	94.80	94.80
Formula based on 22 oxygens									
Si	5.858	6.011	5.405	5.886	5.618	5.854	5.785	5.692	5.637
Ti	0.113	0.156	0.367	0.352	0.286	0.376	0.444	0.281	0.307
Al	1.967	1.736	2.584	2.025	2.310	2.008	2.028	2.212	2.317
Cr	-	0.014	0.002	0.032	0.014	0.011	0.027	0.089	0.059
Fe	0.971	0.930	0.889	0.815	0.822	0.869	0.842	0.772	0.755
Mn	0.009	0.005	0.007	0.002	0.005	-	0.005	0.002	0.006
Ni	0.001	0.013	0.007	0.013	0.012	0.013	0.007	0.013	0.012
Mg	5.118	5.135	4.659	4.651	4.895	4.686	4.621	4.881	4.842
Ca	0.011	-	0.009	0.023	0.036	0.008	0.045	0.031	0.022
Na	0.074	0.051	0.062	0.089	0.087	0.067	0.076	0.087	0.059
K	1.922	1.869	1.826	1.782	1.787	1.832	1.798	1.721	1.763
Weight per cent oxide ratio									
$\frac{\text{Na}_2\text{O}}{\text{Na}_2\text{O}+\text{K}_2\text{O}}$	0.025	0.017	0.021	0.032	0.031	0.024	0.027	0.032	0.021
Atomic ratio									
$\frac{\text{Mg}}{\text{Mg}+\text{Fe}}$	0.84	0.85	0.84	0.85	0.86	0.84	0.84	0.86	0.87
Size	M	M	M	G	C			G	G

Table B.2 PHLOGOPITES (a) KIMBERLITE DYKES (continued)

Analysis number	344	349	351	357	358	364	365
Sample number	5914(4)	5914(4)	5914(4)	5914(1)	5914(1)	5975	5975
						C - R	
SiO ₂	36.97	36.58	37.73	35.75	35.13	36.61	36.85
TiO ₂	3.25	3.28	3.09	2.11	3.83	4.26	4.25
Al ₂ O ₃	15.34	15.48	15.19	12.08	16.00	14.77	14.80
Cr ₂ O ₃	nd	nd	0.01	nd	0.01	0.06	0.09
FeO	7.46	7.00	7.56	7.08	7.41	7.39	7.31
MnO	0.10	0.11	0.08	0.08	0.09	0.03	0.05
NiO	0.02	0.01	0.02	0.06	nd	0.13	0.06
MgO	21.25	21.29	26.26	21.23	20.76	20.87	21.10
CaO	0.06	0.05	0.20	0.08	0.07	0.02	0.03
Na ₂ O	0.21	0.22	0.26	0.31	0.22	0.20	0.28
K ₂ O	10.20	9.89	9.98	9.00	9.44	10.63	10.63
BaO	0.38	0.46	0.04	0.24	1.30	0.59	0.56
F	0.18	0.32	0.17	0.18	0.15	0.36	0.60
	95.42	94.69	100.59	88.20	94.41	95.92	96.61
O = F	0.08	0.13	0.07	0.08	0.06	0.15	0.25
Total	95.34	94.56	100.52	88.12	94.35	95.77	96.36
Formula based on 22 oxygens							
Si	5.390	5.369	5.208	5.621	5.210	5.353	5.357
Ti	0.356	0.362	0.321	0.249	0.427	0.468	0.465
Al	2.636	2.678	2.471	2.238	2.796	2.545	2.536
Cr	-	-	0.001	-	0.001	0.007	0.010
Fe	0.910	0.859	0.873	0.931	0.919	0.904	0.889
Mn	0.012	0.014	0.009	0.011	0.011	0.004	0.006
Ni	0.002	0.001	0.002	0.008	-	0.015	0.007
Mg	4.618	4.657	5.403	4.975	4.589	4.549	4.572
Ca	0.009	0.008	0.030	0.013	0.011	0.003	0.005
Na	0.059	0.063	0.070	0.094	0.063	0.057	0.079
K	1.899	1.852	1.757	1.805	1.786	1.983	1.971
Ba	0.022	0.026	0.002	0.015	0.076	0.034	0.032
Weight per cent oxide ratio							
$\frac{\text{Na}_2\text{O}}{\text{Na}_2\text{O}+\text{K}_2\text{O}}$	0.021	0.022	0.026	0.034	0.023	0.018	0.026
Atomic ratio							
$\frac{\text{Mg}}{\text{Mg}+\text{Fe}}$	0.83	0.84	0.86	0.84	0.83	0.83	0.84
Size							
				G	G		

Table B.2 P H L O G O P I T E S (a) KIMBERLITE DYKES (continued)

Analysis number	367	368	394	395	396	397	398
Sample number	5975	5975	5696	5696	5696	5696	5696
	R - C					R - C	
SiO ₂	38.27	40.50	36.44	36.50	36.50	36.76	37.49
TiO ₂	3.24	0.13	3.47	3.23	3.69	3.39	0.33
Al ₂ O ₃	14.14	1.96	15.31	15.05	15.65	15.23	15.67
Cr ₂ O ₃	nd	0.03	nd	0.04	0.04	0.11	nd
FeO	7.32	16.13	6.68	6.54	6.37	6.51	12.24
MnO	0.07	0.09	0.41	0.06	0.05	0.02	0.13
NiO	0.05	0.01	nd	0.06	0.03	0.03	nd
MgO	21.61	24.85	21.22	21.40	21.19	21.57	18.54
CaO	0.03	0.09	0.11	0.04	0.05	0.02	0.04
Na ₂ O	0.31	0.12	0.30	0.31	0.24	0.29	0.41
K ₂ O	10.70	10.80	9.86	9.92	9.77	9.67	9.70
BaO	0.28	0.03	0.02	0.61	0.69	0.86	0.26
F	0.29	0.11	0.13	0.20	0.28	0.14	0.18
	96.31	94.85	93.95	93.60	94.55	94.60	94.91
O = F	0.12	0.05	0.05	0.08	0.12	0.06	0.08
Total	96.19	94.80	93.90	93.52	94.43	94.54	94.99
Formula based on 22 oxygens							
Si	5.535	6.256	6.030	5.393	5.352	5.387	5.577
Ti	0.352	0.015	0.339	0.359	0.407	0.374	0.037
Al	2.410	0.357	2.343	2.621	2.705	2.631	2.747
Cr	-	0.004	-	0.005	0.005	0.013	-
Fe	0.885	2.084	0.725	0.808	0.781	0.798	1.523
Mn	0.009	0.012	0.045	0.008	0.006	0.002	0.016
Ni	0.006	0.001	-	0.007	0.004	0.004	-
Mg	4.659	5.722	4.107	4.713	4.631	4.712	4.111
Ca	0.005	0.015	0.015	0.006	0.008	0.003	0.006
Na	0.087	0.036	0.076	0.089	0.068	0.082	0.118
K	1.974	2.128	1.633	1.870	1.828	1.808	1.841
Ba	0.016	0.002	0.001	0.035	0.040	0.049	0.015
Weight per cent oxide ratio							
$\frac{\text{Na}_2\text{O}}{\text{Na}_2\text{O}+\text{K}_2\text{O}}$	0.028	0.011	0.029	0.030	0.024	0.029	0.040
Atomic ratio							
$\frac{\text{Mg}}{\text{Mg}+\text{Fe}}$	0.84	0.73	0.85	0.85	0.86	0.85	0.77
Size					G	G	G

Table B.2

PHLOGOPITES

(b) LAMPROPHYRE DYKES

[illegible]

Table B.2 P H L O G O P I T E S (b) LAMPROPHYRE DYKES (continued)

Analysis number	137	139	140	144	145	163	165	166	167	169
Sample number	5693	5693	5693	5693	5693	5646	5646	5646	5646	5646
	C - R			C - R			C - R			
SiO ₂	39.81	40.12	40.21	39.45	39.28	39.61	39.58	39.16	39.77	40.51
TiO ₂	6.65	7.96	7.54	6.92	7.51	7.12	7.32	7.42	7.30	7.62
Al ₂ O ₃	9.70	9.43	8.72	10.21	10.49	11.67	11.65	11.79	11.45	9.19
Cr ₂ O ₃	nd	0.02	0.05	nd	nd	0.40	0.62	0.69	0.36	0.04
FeO	7.61	9.09	12.17	7.72	8.25	5.66	5.64	5.79	5.83	8.79
MnO	nd	0.05	0.04	0.04	0.07	0.02	0.02	0.03	0.03	0.04
NiO	0.12	0.13	0.05	0.11	0.04	0.15	0.14	0.09	0.09	0.10
MgO	20.49	18.67	16.93	20.45	19.38	21.09	20.80	20.41	20.96	19.51
CaO	0.03	nd	nd	0.05	0.05	nd	0.07	0.02	0.05	nd
Na ₂ O	0.09	0.15	0.14	0.13	0.13	0.09	0.11	0.12	0.07	0.12
K ₂ O	9.61	10.00	9.82	9.79	9.88	9.98	9.96	9.91	9.98	9.89
Total	94.11	95.62	95.66	94.87	95.08	95.79	96.91	95.43	95.89	95.81
Formula based on 22 oxygens										
Si	5.838	5.845	5.933	5.754	5.732	5.666	5.659	5.632	5.685	5.872
Ti	0.733	0.872	0.837	0.759	0.824	0.766	0.787	0.803	0.785	0.831
Al	1.677	1.619	1.516	1.755	1.804	1.968	1.963	1.999	1.929	1.570
Cr	-	0.002	0.006	-	-	0.045	0.070	0.078	0.041	0.005
Fe	0.933	1.108	1.502	0.942	1.007	0.677	0.674	0.696	0.697	1.066
Mn	-	0.006	0.005	0.005	0.009	0.002	0.002	0.004	0.004	0.005
Ni	0.014	0.015	0.006	0.013	0.005	0.017	0.016	0.010	0.010	0.012
Mg	4.479	4.054	3.724	4.446	4.215	4.497	4.432	4.375	4.466	4.215
Ca	0.005	-	-	0.008	0.008	-	0.011	0.003	0.008	0.005
Na	0.026	0.042	0.040	0.037	0.037	0.025	0.030	0.033	0.019	0.034
K	1.798	1.858	1.841	1.821	1.839	1.821	1.816	1.818	1.820	1.829
Weight per cent oxide ratio										
$\frac{\text{Na}_2\text{O}}{\text{Na}_2\text{O}+\text{K}_2\text{O}}$	0.009	0.015	0.014	0.013	0.013	0.009	0.011	0.012	0.007	0.012
Atomic ratio										
$\frac{\text{Mg}}{\text{Mg}+\text{Fe}}$	0.83	0.79	0.71	0.82	0.81	0.87	0.87	0.86	0.87	0.80
Size	G	G	G	G	G	M	M	M	M	G

Table B.2 P H L O G O P I T E S (b) LAMPROPHYRE DYKES (continued)

Analysis number	170	300	301	302	303	316	317	318	321
Sample number	5646	5640	5640	5640	5640	5641	5641	5641	5641
	C - R				Q				
SiO ₂	40.08	38.71	38.91	38.95	38.86	38.82	39.32	40.35	39.65
TiO ₂	7.00	7.51	7.08	7.09	7.16	7.26	7.39	7.18	6.92
Al ₂ O ₃	9.77	10.75	10.27	10.47	10.10	11.28	11.11	9.43	10.29
Cr ₂ O ₃	nd	0.06	0.02	0.02	nd	0.24	0.15	nd	0.04
FeO	7.86	6.20	8.66	6.71	6.70	5.68	5.89	7.90	8.02
MnO	0.09	0.04	0.02	0.04	0.03	0.06	0.04	0.07	0.06
NiO	0.09	nd	0.09	0.14	0.07	0.14	0.12	0.14	0.18
MgO	20.60	20.31	19.32	20.30	20.44	20.33	20.39	19.67	19.73
CaO	0.05	0.01	0.02	0.02	nd	0.01	0.03	0.07	0.11
Na ₂ O	0.09	0.14	0.09	0.11	0.10	0.07	0.11	0.13	0.12
K ₂ O	9.76	10.14	10.16	10.17	10.16	10.01	10.09	9.89	9.99
BaO	-	0.19	0.63	0.54	0.60	0.80	0.86	0.66	0.60
F	-	0.74	0.56	0.20	0.66	0.50	0.79	0.32	nd
	-	94.80	95.83	94.76	94.89	95.20	96.29	95.81	-
O ≡ F	-	0.31	0.24	0.08	0.28	0.21	0.33	0.13	-
Total	95.39	94.49	95.59	94.68	94.61	99.99	95.96	95.68	95.71
Formula based on 22 oxygens									
Si	5.810	5.681	5.731	5.715	5.726	5.664	5.694	5.877	5.773
Ti	0.763	0.829	0.784	0.782	0.793	0.797	0.805	0.786	0.758
Al	1.669	1.860	1.783	1.811	1.754	1.940	1.896	1.619	1.766
Cr	-	0.007	0.002	0.002	-	0.028	0.017	-	0.005
Fe	0.953	0.761	1.067	0.823	0.826	0.693	0.713	0.962	0.977
Mn	0.011	0.005	0.002	0.005	0.004	0.007	0.005	0.009	0.007
Ni	0.010	-	0.011	0.017	0.008	0.016	0.014	0.016	0.021
Mg	4.451	4.443	4.242	4.440	4.489	4.421	4.401	4.271	4.282
Ca	0.008	0.002	0.003	0.003	-	0.002	0.005	0.011	0.017
Na	0.025	0.040	0.026	0.031	0.029	0.020	0.031	0.037	0.034
K	1.805	1.898	1.909	1.904	1.910	1.863	1.864	1.838	1.855
Ba	-	0.011	0.036	0.031	0.035	0.046	0.049	0.038	0.034
Weight per cent oxide ratio									
$\frac{\text{Na}_2\text{O}}{\text{Na}_2\text{O}+\text{K}_2\text{O}}$	0.009	0.014	0.009	0.011	0.010	0.007	0.011	0.013	0.012
Atomic ratio									
$\frac{\text{Mg}}{\text{Mg}+\text{Fe}}$	0.82	0.85	0.80	0.84	0.84	0.86	0.86	0.82	0.82
Size	G	M	M	G	G	M	M	G	G

Table B.3 C L I N O P Y R O X E N E S (a) KIMBERLITE DYKES

Analysis number	101	253	456	457	460
Sample number	5698(4)	5987	5983	5983	5983
SiO ₂	52.46	50.84	50.96	49.65	51.35
TiO ₂	0.98	1.34	1.21	2.75	1.68
Al ₂ O ₃	0.97	1.67	1.65	4.52	2.42
Cr ₂ O ₃	0.02	0.02	nd	0.03	nd
FeO	3.93	5.22	4.67	6.13	5.56
MnO	0.10	0.18	0.06	0.07	0.10
NiO	-	0.03	0.01	nd	0.05
MgO	15.74	14.80	15.24	14.28	14.80
CaO	25.73	24.71	24.51	24.22	24.84
Na ₂ O	0.21	0.27	0.23	0.26	0.21
K ₂ O	nd	0.02	0.02	0.14	0.03
Total	100.19	99.10	98.56	101.05	101.04

Formula based on 6 oxygens

Si	1.930	1.906	1.913	1.799	1.888
Ti	0.033	0.038	0.034	0.076	0.046
Al	0.042	0.074	0.073	0.197	0.105
Cr	0.001	0.001	-	0.001	-
Fe	0.122	0.164	0.147	0.190	0.171
Mn	0.003	0.006	0.002	0.002	0.003
Ni	-	0.001	-	-	0.001
Mg	0.863	0.827	0.853	0.787	0.811
Ca	1.014	0.993	0.986	0.960	0.979
Na	0.015	0.020	0.017	0.019	0.015
K	-	0.001	0.001	0.007	0.001

Atomic ratio

Fe	6.1	8.3	7.4	9.8	8.7
Mg	43.2	41.7	42.9	40.6	41.4
Ca	50.7	50.0	49.7	49.6	49.9

Table B.3 C L I N O P Y R O X E N E S (b) LAMPROPHYRE DYKES

Analysis number	133	134	136	141	143	158	159
Sample number	5693	5693	5693	5693	5693	5646	5646
SiO ₂	53.77	53.38	53.21	53.72	53.35	53.18	52.65
TiO ₂	0.92	1.13	1.11	0.80	1.11	1.10	1.20
Al ₂ O ₃	0.41	0.56	0.50	0.49	0.51	0.46	0.69
Cr ₂ O ₃	0.76	0.85	0.81	0.72	0.67	0.78	1.07
FeO	3.08	3.21	3.48	3.00	2.95	3.01	3.14
MnO	0.06	0.08	0.10	0.07	0.04	0.09	0.06
NiO	0.09	0.02	nd	0.02	nd	0.05	0.05
MgO	17.29	16.98	16.64	17.41	16.97	16.76	16.70
CaO	23.50	23.22	22.00	22.81	23.29	23.20	23.27
Na ₂ O	0.37	0.48	0.62	0.39	0.47	0.49	0.53
K ₂ O	0.02	0.02	0.04	nd	0.02	0.02	nd
Total	100.27	99.93	98.51	99.43	99.38	99.14	99.36

Formula based on 6 oxygens

Si	1.960	1.954	1.972	1.969	1.960	1.961	1.942
Ti	0.025	0.031	0.031	0.022	0.031	0.031	0.033
Al	0.018	0.024	0.022	0.021	0.022	0.020	0.030
Cr	0.022	0.025	0.024	0.021	0.019	0.023	0.031
Fe	0.094	0.098	0.108	0.092	0.091	0.093	0.097
Mn	0.002	0.002	0.003	0.002	0.001	0.003	0.002
Ni	0.003	0.001	-	0.001	-	0.001	0.001
Mg	0.940	0.927	0.919	0.951	0.929	0.921	0.918
Ca	0.918	0.911	0.873	0.896	0.917	0.917	0.920
Na	0.026	0.034	0.045	0.028	0.033	0.035	0.038
K	0.001	0.001	0.002	-	0.001	0.001	-

Atomic ratio

Fe	4.8	5.1	5.7	4.7	4.7	4.8	5.0
Mg	48.2	47.9	48.4	49.1	48.0	47.7	47.4
Ca	47.0	47.0	45.9	46.2	47.3	47.5	47.9

Table B.3 C L I N O P Y R O X E N E S (b) LAMPROPHYRE DYKES
(continued)

Analysis number	164	307	309	314	315	319	320
Sample number	5646	5640	5640	5641	5641	5641	5641
SiO ₂	53.74	53.09	52.69	53.88	53.68	53.43	53.48
TiO ₂	1.07	0.99	1.22	0.99	0.97	0.96	0.90
Al ₂ O ₃	0.55	0.48	0.44	0.35	0.34	0.31	0.22
Cr ₂ O ₃	0.08	0.76	0.02	0.39	0.37	0.65	0.18
FeO	3.27	3.03	4.88	3.15	3.17	3.30	3.82
MnO	0.09	0.04	0.14	0.08	0.04	0.09	0.10
NiO	0.03	0.10	0.02	0.10	0.07	0.04	0.10
MgO	17.31	17.11	16.07	17.00	17.05	16.89	16.73
CaO	23.43	23.27	22.60	23.60	23.67	23.40	23.13
Na ₂ O	0.48	0.40	0.60	0.34	0.34	0.37	0.40
K ₂ O	nd	0.02	0.09	nd	0.01	0.01	0.02
Total	100.05	99.29	98.77	99.88	99.71	99.45	99.08

Formula based on 6 oxygens

Si	1.962	1.955	1.963	1.970	1.959	1.965	1.976
Ti	0.029	0.027	0.034	0.027	0.027	0.027	0.025
Al	0.024	0.021	0.019	0.015	0.015	0.013	0.010
Cr	0.002	0.022	0.001	0.011	0.028	0.019	0.005
Fe	0.100	0.093	0.152	0.096	0.097	0.102	0.118
Mn	0.003	0.001	0.004	0.002	0.001	0.003	0.003
Ni	0.001	0.003	0.001	0.003	0.002	0.001	0.003
Mg	0.942	0.939	0.892	0.927	0.927	0.920	0.921
Ca	0.916	0.918	0.902	0.925	0.925	0.922	0.916
Na	0.034	0.029	0.043	0.024	0.024	0.026	0.029
K	-	0.001	0.004	-	-	-	0.001

Atomic ratio

Fe	5.1	4.8	7.8	4.9	5.0	5.3	6.0
Mg	48.1	48.1	45.8	47.6	47.5	47.3	47.1
Ca	46.8	47.1	46.4	47.5	47.5	47.4	46.9

Table B.4 A M P H I B O L E S

(a) KIMBERLITE DYKES

Analysis number	183
Sample number	5512
SiO ₂	55.06
TiO ₂	1.19
Al ₂ O ₃	0.15
Cr ₂ O ₃	0.09
FeO	6.92
MnO	0.15
NiO	0.05
MgO	21.48
CaO	2.94
Na ₂ O	7.72
K ₂ O	0.42
Total	96.17

(b) LAMPROPHYRE DYKES

41	42	160	171	304	310
5622	5622	5646	5646	5640	5640
55.80	55.24	54.52	54.44	53.21	54.35
1.06	0.51	1.52	1.07	2.67	1.41
0.16	0.16	0.07	0.17	0.12	0.13
0.48	0.11	0.05	0.05	nd	0.02
7.76	8.33	12.05	11.86	10.58	7.03
0.06	0.10	0.18	0.11	0.13	0.09
-	-	-	-	0.02	0.04
17.78	18.01	15.69	16.50	15.92	19.19
1.77	1.99	0.49	0.46	2.88	5.02
6.15	5.67	6.00	6.98	5.71	4.05
5.31	5.12	5.09	5.12	5.14	5.08
96.33	95.24	95.66	96.72	96.38	96.41

Formula based on 23 oxygens

Si	7.858	8.106	8.121	8.105	8.027	7.883	7.901
Ti	0.128	0.116	0.056	0.170	0.119	0.297	0.154
Al	0.025	0.027	0.028	0.012	0.030	0.021	0.022
Cr	0.010	0.055	0.013	0.006	0.006	-	0.002
Fe	0.826	0.943	1.024	1.498	1.463	1.311	0.855
Mn	0.018	0.007	0.012	0.023	0.014	0.016	0.011
Ni	0.006	-	-	-	-	0.002	0.005
Mg	4.569	3.850	3.946	3.477	3.626	3.515	4.158
Ca	0.450	0.275	0.313	0.078	0.073	0.457	0.782
Na	2.136	1.732	1.616	1.729	1.996	1.640	1.142
K	0.076	0.984	0.960	0.965	0.963	0.971	0.942

Table B.5 P O T A S S I U M F E L D S P A R S

(a) KIMBERLITE DYKES

(b) LAMPROPHYRE DYKES

Analysis number	232	513	514	515	518	519
Sample number	5518G	5652	5652	5652	5632	5632
SiO ₂	63.72	63.52	62.64	63.47	63.30	63.30
TiO ₂	0.10	0.09	0.04	0.12	0.30	0.30
Al ₂ O ₃	18.47	16.57	19.06	16.10	15.42	15.94
Cr ₂ O ₃	nd	nd	nd	nd	nd	nd
FeO	0.11	2.25	0.05	2.45	3.84	2.85
MnO	0.02	nd	nd	nd	nd	nd
NiO	0.04	nd	nd	nd	nd	nd
MgO	0.04	0.01	nd	0.03	0.04	0.03
CaO	0.04	nd	0.02	0.02	0.09	0.03
Na ₂ O	0.31	0.04	nd	0.02	0.08	0.40
K ₂ O	15.96	15.94	16.15	16.28	15.41	15.73
Total	98.71	98.42	97.96	98.49	98.48	98.58

Formula based on 32 oxygens

Si	11.922	12.058	11.833	12.082	12.087	12.049
Ti	0.014	0.013	0.006	0.017	0.043	0.043
Al	4.079	3.707	4.243	3.612	3.470	3.576
Cr	-	-	-	-	-	-
Fe	0.017	0.357	0.008	0.390	0.613	0.454
Mn	0.003	-	-	-	-	-
Ni	0.006	-	-	-	-	-
Mg	0.011	0.003	-	0.009	0.011	0.009
Ca	0.008	-	0.004	0.004	0.018	0.006
Na	0.113	0.015	-	0.007	0.030	0.148
K	3.815	3.860	3.892	3.953	3.754	3.820

Table B.6 PSEUDOLEUCITES FROM LAMPROPHYRE DYKES

Analysis number	43	46	47	138	155	156
Sample number	5622	5622	5622	5693	5646	5646
SiO ₂	63.37	63.59	64.25	64.37	63.18	62.90
TiO ₂	0.03	nd	nd	0.01	nd	0.02
Al ₂ O ₃	18.47	18.89	18.48	18.25	18.64	19.28
Cr ₂ O ₃	0.02	nd	nd	nd	nd	nd
FeO	0.11	0.16	0.16	0.13	0.05	0.04
MnO	0.03	nd	nd	nd	nd	nd
NiO	-	-	-	nd	nd	nd
MgO	0.07	0.05	0.17	nd	0.03	0.02
CaO	nd	nd	nd	0.02	0.02	nd
Na ₂ O	0.02	nd	0.04	0.03	0.01	0.01
K ₂ O	16.63	16.60	16.53	16.58	16.52	16.26
BaO	-	-	-	-	-	-
Total	98.75	99.28	99.63	99.39	98.45	98.53

Formula based on 32 oxygens

Si	11.907	11.875	11.944	11.993	11.895	11.581
Ti	0.004	-	-	0.001	-	0.003
Al	4.093	4.158	4.049	4.007	4.136	4.268
Cr	0.003	-	-	-	-	-
Fe	0.017	0.022	0.025	0.020	0.008	0.006
Mn	0.005	-	-	-	-	-
Ni	-	-	-	-	-	-
Mg	0.020	0.014	0.047	-	0.008	0.006
Ca	-	-	-	0.004	0.004	-
Na	0.007	-	0.014	0.011	0.004	0.004
K	3.986	3.955	3.920	3.941	3.968	3.896
Ba	-	-	-	-	-	-

Table B.6 PSEUDOLEUCITES FROM LAMPROPHYRE DYKES (continued)

Analysis number	157	168	305	306	308
Sample number	5646	5646	5640	5640	5640
SiO ₂	62.74	63.75	64.08	63.32	62.66
TiO ₂	0.03	nd	0.18	nd	0.04
Al ₂ O ₃	18.99	19.27	17.45	16.75	17.48
Cr ₂ O ₃	nd	nd	nd	nd	nd
FeO	0.05	0.19	0.06	0.03	0.09
MnO	0.01	nd	nd	nd	nd
NiO	nd	nd	nd	nd	0.02
MgO	0.03	0.04	0.03	0.01	0.02
CaO	nd	0.13	0.03	0.02	nd
Na ₂ O	0.01	0.02	0.06	0.03	0.05
K ₂ O	16.60	14.64	16.25	16.70	16.99
BaO	-	-	1.69	0.11	0.07
Total	98.46	98.04	99.83	96.97	97.42

Formula based on 32 oxygens

Si	11.825	11.910	12.027	12.130	11.984
Ti	0.004	-	0.025	-	0.006
Al	4.218	4.243	3.860	3.782	3.940
Cr	-	-	-	-	-
Fe	0.008	0.030	0.009	0.005	0.014
Mn	0.002	-	-	-	-
Ni	-	-	-	-	0.003
Mg	0.008	0.011	0.008	0.003	0.006
Ca	-	0.026	0.006	0.004	-
Na	0.004	0.007	0.002	0.011	0.019
K	3.991	3.489	3.891	4.081	4.145
Ba	-	-	0.124	0.008	0.005

Table B.7 GARNETS FROM KIMBERLITE DYKES

Analysis number	-	-	80
Sample number	UCL(1)	UCL(2)	5603
	C	R	
SiO ₂	42.37*	41.11*	42.92
TiO ₂	0.61	0.68	0.51
Al ₂ O ₃	21.09	21.17	20.66
Cr ₂ O ₃	3.42	3.20	3.38
FeO	6.38	6.98	6.57
MnO	0.16	0.21	0.30
NiO	-	-	-
MgO	21.01	21.80	21.80
CaO	4.96	4.85	4.77
Na ₂ O	-	-	0.07
K ₂ O	-	-	nd
Total	100.00	100.00	100.98

* SiO₂ values adjusted to give 100 weight per cent total.

Formula based on 24 oxygens

Si	6.013	5.868	6.039
Ti	0.065	0.073	0.054
Al	3.528	3.560	3.426
Cr	0.384	0.361	0.376
Fe	0.757	0.823	0.773
Mn	0.019	0.025	0.036
Ni	-	-	-
Mg	4.445	4.637	4.572
Ca	0.754	0.742	0.719
Na	-	-	0.019
K	-	-	-

Garnet molecules

Andradite	-	6.70	-
Ti-garnet*	1.66	1.84	1.42
Spessartine	0.32	0.42	0.63
Uvarovite	9.82	3.94	9.89
Grossular	1.37	-	1.30
Knorringite	-	5.17	-
Pyrope	75.75	72.88	80.17
Almandine	11.08	9.04	6.59
Per cent cations used	98.02	98.46	95.08

* Ti-garnet = Ca₃Ti₂Al₂SiO₁₂

Table B.8

PEROVSKITES FROM KIMBERLITE DYKES

Analysis number	16	27	88	93	96	130
Sample number	5519	5698(3)	5603	5698(4)	5698(4)	5966(2)
SiO ₂	0.03	0.05	nd	0.02	0.03	0.07
TiO ₂	56.61	56.77	56.96	57.14	56.95	55.80
Al ₂ O ₃	1.62	0.18	0.24	0.13	0.20	0.18
Cr ₂ O ₃	nd	0.02	nd	0.03	nd	0.04
FeO	1.13	0.99	1.02	1.06	0.93	1.12
MnO	0.04	0.04	0.08	0.03	nd	0.05
NiO	-	-	0.05	nd	nd	nd
MgO	0.07	0.09	nd	0.07	0.08	0.07
CaO	37.50	38.03	39.14	39.44	39.21	38.93
Na ₂ O	0.46	0.21	0.24	0.23	0.24	0.25
K ₂ O	nd	0.02	0.01	nd	0.04	0.02
BaO	-	-	-	-	-	-
Total	97.46	96.27	97.74	98.15	97.68	96.53

Formula based on 24 oxygens

Si	0.006	0.009	-	0.004	0.006	0.013
Ti	7.873	8.018	7.955	7.949	7.953	7.900
Al	0.353	0.040	0.053	0.028	0.044	0.040
Cr	-	0.003	-	0.004	-	0.006
Fe	0.175	0.156	0.158	0.164	0.144	0.176
Mn	0.006	0.006	0.013	0.005	-	0.008
Ni	-	-	0.007	-	-	-
Mg	0.019	0.025	-	0.019	0.022	0.020
Ca	7.430	7.653	7.788	7.817	7.802	7.853
Na	0.165	0.076	0.086	0.082	0.086	0.091
K	-	0.005	0.002	-	0.009	0.005
Ba	-	-	-	-	-	-

Table B.8 PEROVSKITES FROM KIMBERLITE DYKES (continued)

Analysis number	178	237	345	385	387	399
Sample number	5512	5987	5914(4)	5914(2)	5914(2)	5696
				C	- R	
SiO ₂	nd	nd	nd	nd	0.10	nd
TiO ₂	55.45	56.13	56.45	57.44	55.06	56.50
Al ₂ O ₃	0.23	0.19	0.21	0.18	0.03	0.17
Cr ₂ O ₃	0.08	0.02	nd	nd	nd	nd
FeO	1.22	1.17	1.25	1.22	18.51	1.10
MnO	nd	0.03	nd	nd	0.06	0.01
NiO	nd	nd	nd	nd	0.01	nd
MgO	0.05	0.11	0.08	0.08	2.52	0.11
CaO	38.76	39.99	39.76	38.99	26.49	39.04
Na ₂ O	0.39	0.33	0.10	0.19	0.04	0.32
K ₂ O	0.02	0.02	0.04	nd	nd	0.02
BaO	-	-	0.03	0.10	nd	0.11
Total	96.20	97.99	97.92	98.20	102.83	97.42
Formula based on 24 oxygens						
Si	-	-	-	-	0.018	-
Ti	7.885	7.845	7.887	7.984	7.599	7.932
Al	0.051	0.042	0.046	0.039	0.006	0.037
Cr	0.012	0.003	-	-	-	-
Fe	0.193	0.182	0.194	0.189	2.841	0.172
Mn	-	0.005	-	-	0.009	0.002
Ni	-	-	-	-	0.001	-
Mg	0.014	0.030	0.022	0.022	0.639	0.031
Ca	7.853	7.964	7.915	7.721	5.209	7.808
Na	0.143	0.119	0.035	0.068	0.014	0.116
K	0.005	0.005	0.009	-	-	0.005
Ba	-	-	0.002	0.007	-	0.008

Table B.9 Fe-Ti-Cr O X I D E/S (a) KIMBERLITE DYKESILMENITES

Analysis number	-	70	89	90	95	182	193	214	366	475
Sample number	UCL(3)	5502	5603	5603	5698(4)	5512	5518(G)	5518(G)	5975	5524
C - R										
SiO ₂	nd	0.27	0.07	0.03	0.04	0.06	nd	0.04	nd	0.02
TiO ₂	44.45	51.21	50.19	50.54	52.96	52.03	44.87	52.12	52.85	54.58
Al ₂ O ₃	0.27	nd	0.30	0.49	nd	nd	0.03	0.99	nd	0.69
Cr ₂ O ₃	1.31	0.57	0.27	1.12	0.18	0.28	0.01	1.87	0.14	0.44
FeO	47.03	42.78	37.95	37.02	35.64	36.82	44.22	33.00	40.63	34.18
MnO	0.45	1.21	0.26	0.52	1.49	1.62	0.59	0.28	1.07	0.49
NiO	-	-	-	-	-	nd	nd	0.12	0.07	0.10
MgO	4.66	0.85	9.44	9.68	8.62	6.92	5.91	11.06	4.39	10.46
CaO	-	0.53	0.05	0.06	0.34	0.67	0.39	0.03	0.54	0.03
Na ₂ O	-	0.10	nd	0.05	0.04	0.03	nd	nd	0.03	nd
K ₂ O	-	0.06	nd	0.02	nd	nd	nd	nd	nd	0.02
Total	98.17	97.58	98.53	99.53	99.31	98.43	96.02	99.51	99.72	101.01
Recalculated analysis										
Fe ₂ O ₃	17.6	0.0	10.0	10.4	5.9	5.3	17.2	6.8	3.0	4.7
FeO	31.2	42.78	29.0	27.6	30.4	32.0	28.7	26.9	37.9	29.9
New Total	99.93	97.58	99.58	100.51	99.97	98.91	97.70	100.21	99.99	101.43
Formula based on 6 oxygens										
Si	-	0.014	0.003	0.001	0.002	0.003	-	0.002	-	0.001
Ti	1.642	1.975	1.792	1.780	1.888	1.895	1.677	1.817	1.941	1.908
Al	0.016	-	0.017	0.027	-	-	0.002	0.005	-	-
Cr	0.051	0.023	0.010	0.041	0.007	0.011	-	0.069	0.005	0.016
Fe ³⁺	0.650	-	0.357	0.367	0.211	0.193	0.643	0.237	0.110	0.164
Fe ²⁺	1.281	1.835	1.152	1.081	1.205	1.296	1.193	1.043	1.548	1.162
Mn	0.019	0.053	0.010	0.021	0.060	0.066	0.025	0.011	0.044	0.019
Ni	-	-	-	-	-	-	-	0.004	0.320	0.004
Mg	0.341	0.065	0.668	0.676	0.609	0.500	0.438	0.764	0.028	0.725
Ca	-	0.029	0.003	0.003	0.017	0.035	0.021	0.001	0.028	0.001
Na	-	0.010	-	0.005	0.004	0.003	-	-	0.003	-
K	-	0.004	-	0.001	-	-	-	-	-	0.001

Table B.9 Fe-Ti-Cr O X I D E S (a) KIMBERLITE DYKESCHROME-SPINELS

Analysis number	66	148	272	273	402
Sample number	5966(1)	5605	5518OL	5518OL	5696
SiO ₂	0.04	0.89	nd	0.02	0.10
TiO ₂	2.71	6.38	4.10	6.90	6.31
Al ₂ O ₃	0.42	7.16	0.34	5.69	7.09
Cr ₂ O ₃	53.07	33.77	42.21	38.44	36.70
FeO	34.87	36.22	43.62	39.86	31.02
MnO	0.93	nd	0.45	0.62	0.57
NiO	-	nd	0.27	0.15	0.08
MgO	6.58	13.69	6.56	8.69	11.32
CaO	0.29	0.03	0.01	0.13	0.03
Na ₂ O	nd	0.05	nd	nd	nd
K ₂ O	0.43	nd	0.02	nd	0.03
Total	99.34	98.19	97.58	100.50	93.25

Recalculated analysis

Fe ₂ O ₃	13.0	19.3	20.9	15.9	13.2
FeO	23.2	18.9	24.8	25.5	19.1
New Total	100.67	100.17	99.66	102.04	94.53

Formula based on 4 oxygens

Si	0.001	0.029	-	0.001	0.004
Ti	0.072	0.157	0.111	0.174	0.166
Al	0.018	0.276	0.014	0.225	0.293
Cr	1.483	0.874	1.197	1.021	1.017
Fe ³⁺	0.346	0.476	0.564	0.402	0.348
Fe ²⁺	0.686	0.518	0.744	0.716	0.560
Mn	0.028	-	0.014	0.018	0.017
Ni	-	-	0.008	0.004	0.002
Mg	0.347	0.668	0.351	0.435	0.592
Ca	0.011	0.001	-	0.005	0.001
Na	-	0.003	0.001	-	-
K	0.019	-	-	-	0.001

Table B.9 Fe-Ti-Cr O X I D E S

(a) KIMBERLITE DYKES

MAGNETITES

Analysis number	199	224
Sample number	5518G	5518G
SiO ₂	0.02	nd
TiO ₂	1.63	nd
Al ₂ O ₃	0.04	0.05
Cr ₂ O ₃	0.04	nd
FeO	89.78	76.46
MnO	0.30	0.02
NiO	nd	4.20
MgO	1.03	0.07
CaO	0.01	nd
Na ₂ O	0.03	nd
K ₂ O	nd	nd
Total	92.88	80.80

Recalculated analysis

Fe ₂ O ₃	65.9	56.7
FeO	30.5	25.4
New Total	99.50	86.44

Formula based on 4 oxygens

Si	0.001	-
Ti	0.047	-
Al	0.002	0.003
Cr	0.001	-
Fe ³⁺	1.901	1.921
Fe ²⁺	0.978	0.957
Mn	0.010	0.001
Ni	-	0.152
Mg	0.059	0.005
Ca	-	-
Na	0.002	-
K	-	-

Table B.9 Fe-Ti-Cr O X I D E S (a) KIMBERLITE DYKESTITANOMAGNETITES

Analysis number	26	71	87	94	131	153	174	192	195	240
Sample number	5698(3)	5502	5603	5698(4)	5966(2)	5605	5512	5518G	5518G	5987
SiO ₂	0.30	0.26	0.64	0.48	0.14	0.12	0.06	0.30	nd	0.41
TiO ₂	16.57	11.56	13.49	17.62	16.41	16.73	18.99	20.87	19.97	16.71
Al ₂ O ₃	5.58	3.60	5.87	4.48	4.91	5.01	4.29	1.86	1.75	4.14
Cr ₂ O ₃	6.59	0.34	7.79	2.18	9.89	8.34	1.75	0.93	0.99	1.67
FeO	58.05	75.64	55.51	60.10	62.12	57.48	59.95	61.13	62.02	62.77
MnO	0.69	0.59	0.68	0.79	0.54	0.29	0.68	0.77	0.79	1.18
NiO	0.15	-	-	-	-	0.13	0.08	0.10	0.19	0.08
MgO	11.01	2.71	10.29	9.65	2.83	9.47	10.37	10.19	10.25	7.64
CaO	0.23	0.16	0.19	0.22	0.11	0.03	0.07	0.72	0.37	0.20
Na ₂ O	0.03	0.05	nd	0.05	0.02	nd	0.03	0.03	0.07	0.01
K ₂ O	0.01	0.40	0.02	nd	0.02	nd	nd	nd	nd	nd
Total	99.21	95.31	94.48	95.57	96.72	97.60	96.27	96.90	96.30	94.81

Recalculated analysis

Fe ₂ O ₃	30.3	42.3	30.5	30.6	22.1	27.3	30.4	30.4	32.6	31.9
FeO	30.8	37.5	28.1	32.5	42.2	32.9	32.6	33.8	32.7	34.0
New Total	102.26	99.47	97.57	98.57	98.90	100.32	99.32	99.97	99.58	97.94

Formula based on 4 oxygens

Si	0.010	0.010	0.022	0.017	0.005	0.004	0.002	0.010	-	0.015
Ti	0.413	0.320	0.352	0.461	0.447	0.430	0.492	0.543	0.523	0.447
Al	0.218	0.156	0.240	0.184	0.210	0.202	0.174	0.076	0.072	0.174
Cr	0.173	0.010	0.214	0.060	0.283	0.225	0.048	0.025	0.027	0.047
Fe ³⁺	0.757	1.170	0.797	0.801	0.602	0.702	0.788	0.791	0.854	0.855
Fe ²⁺	0.855	1.153	0.816	0.945	1.278	0.941	0.939	0.977	0.952	1.012
Mn	0.019	0.018	0.020	0.023	0.017	0.008	0.020	0.023	0.023	0.036
Ni	0.004	-	-	-	-	0.004	0.002	-	0.003	0.002
Mg	0.544	0.149	0.532	0.500	0.153	0.483	0.532	0.525	0.532	0.405
Ca	0.008	0.006	0.007	0.008	0.004	0.001	0.003	0.027	0.014	0.008
Na	0.002	0.004	-	0.003	0.001	-	0.002	0.002	0.005	0.001
K	-	0.019	0.001	-	0.001	-	-	-	-	-

Table B.9 Fe-Ti-Cr O X I D E S (a) KIMBERLITE DYKESTITANOMAGNETITES (continued)

Analysis number	244	268	269	346	376	380	381	332	386	400
Sample number	5987	55180L	55180L	5914(4)	5975	5975	5975	5975	5914(2)	5696
SiO ₂	0.03	0.05	1.19	3.50	0.05	0.05	0.20	0.05	0.04	nd
TiO ₂	10.39	16.81	15.46	6.61	16.16	7.23	10.64	8.43	8.83	10.05
Al ₂ O ₃	1.26	1.23	0.34	2.47	3.16	0.18	1.15	0.22	7.09	6.33
Cr ₂ O ₃	0.05	0.12	0.15	0.05	3.28	0.05	nd	0.09	17.59	13.55
FeO	78.83	69.37	69.90	63.69	64.97	82.44	82.61	79.13	46.35	52.81
MnO	0.96	0.71	0.75	0.85	0.58	0.18	0.32	0.26	0.61	0.64
NiO	0.07	0.15	0.08	0.02	3.28	0.04	0.11	0.14	0.11	0.11
MgO	4.14	7.19	7.19	9.46	7.17	2.17	4.39	4.17	10.97	9.20
CaO	0.88	0.22	0.22	0.40	0.06	0.03	0.03	0.04	0.18	0.15
Na ₂ O	0.03	nd	0.02	0.17	0.04	nd	nd	0.03	0.04	0.01
K ₂ O	nd	nd	nd	0.06	nd	nd	nd	nd	0.01	0.01
Total	96.64	95.85	95.30	87.28	98.75	92.37	99.45	92.56	91.82	92.95
Recalculated analysis										
Fe ₂ O ₃	50.9	38.5	39.1	44.4	33.7	54.3	52.1	52.9	27.8	30.5
FeO	33.1	34.8	34.7	23.8	34.7	33.6	35.7	31.5	21.4	25.4
New Total	101.81	99.78	99.20	91.79	102.18	97.83	104.64	97.83	94.67	95.91
Formula based on 4 oxygens										
Si	0.001	0.002	0.043	0.131	0.002	0.002	0.007	0.002	0.001	-
Ti	0.284	0.452	0.418	0.186	0.423	0.209	0.281	0.239	0.235	0.269
Al	0.053	0.052	0.014	0.109	0.130	0.008	0.048	0.010	0.295	0.265
Cr	0.001	0.003	0.004	0.001	0.090	0.002	-	0.003	0.491	0.381
Fe ³⁺	1.379	1.036	1.058	1.251	0.883	1.569	1.375	1.503	0.739	0.816
Fe ²⁺	0.996	1.041	1.044	0.745	1.011	1.079	1.047	0.995	0.632	0.755
Mn	0.029	0.022	0.023	0.027	0.017	0.006	0.010	0.008	0.018	0.019
Ni	0.002	0.003	0.002	0.001	0.092	0.001	0.003	0.004	0.003	0.003
Mg	0.222	0.383	0.385	0.528	0.372	0.124	0.230	0.235	0.578	0.487
Ca	0.034	0.008	0.008	0.016	0.002	0.001	0.001	0.002	0.007	0.006
Na	0.002	-	0.001	0.012	0.003	-	-	0.002	0.003	0.001
K	-	-	-	0.003	-	-	-	-	-	-

Table B.9 Ti - O X I D E S
(b) LAMPROPHYRE DYKES
RUTILES

Analysis number	516	517
Sample number	5652	5652
SiO ₂	0.01	nd
TiO ₂	97.86	98.43
Al ₂ O ₃	0.02	0.04
Cr ₂ O ₃	0.27	0.16
FeO	0.11	0.38
MnO	nd	0.01
NiO	nd	nd
MgO	0.03	0.03
CaO	0.29	0.20
Na ₂ O	0.02	nd
K ₂ O	0.07	0.03
Total	98.68	99.28

Table B.10 Fe - S U L P H I D E S
(a) KIMBERLITE DYKES

Analysis number	132
Sample number	5966(2)
SiO ₂	0.79
TiO ₂	0.08
Al ₂ O ₃	0.02
Cr ₂ O ₃	nd
FeO	59.89
MnO	nd
NiO	nd
MgO	0.41
CaO	0.15
Na ₂ O	0.23
K ₂ O	nd
Total	61.57

Table B.10 Fe - S U L P H I D E S
(b) LAMPROPHYRE DYKES

Analysis number	44	312
Sample number	5622	5640
SiO ₂	0.08	nd
TiO ₂	nd	0.06
Al ₂ O ₃	0.02	0.02
Cr ₂ O ₃	nd	nd
FeO	59.34	62.29
MnO	nd	0.03
NiO	nd	0.63
MgO	0.03	0.06
CaO	nd	nd
Na ₂ O	0.07	0.04
K ₂ O	nd	nd
Total	59.54	63.13

Table B.11

CALCITE FROM LAMPROPHYRE DYKES

Analysis number	161
Sample number	5646
SiO ₂	0.06
TiO ₂	0.02
Al ₂ O ₃	0.03
Cr ₂ O ₃	0.04
FeO	4.47
MnO	0.53
NiO	0.01
MgO	22.41
CaO	28.34
Na ₂ O	0.02
K ₂ O	0.02
Total	55.95

Table B.12

APATITES FROM KIMBERLITE DYKES

Analysis number	248	249	251
Sample number	5987	5987	5987
SiO ₂	2.26	2.16	1.66
TiO ₂	nd	0.01	nd
Al ₂ O ₃	0.01	0.02	nd
Cr ₂ O ₃	0.02	nd	0.03
FeO	0.09	0.11	0.11
MnO	0.05	0.07	nd
NiO	nd	nd	nd
MgO	0.14	0.13	0.09
CaO	54.52	54.26	54.92
Na ₂ O	0.06	0.07	0.04
K ₂ O	nd	0.02	0.01
P ₂ O ₅	37.58	36.83	37.30
Total	94.73	93.68	94.16

Formula based on 24 oxygens

Si	0.380	0.368	0.282
Ti	-	0.001	-
Al	0.002	0.004	-
Cr	0.003	-	0.004
Fe	0.013	0.016	0.016
Mn	0.007	0.010	-
Ni	-	-	-
Mg	0.035	0.033	0.023
Ca	9.811	9.904	9.986
Na	0.020	0.023	0.013
K	-	0.004	-
P	5.343	5.312	5.359

Table B.13 SERPENTINES FROM KIMBERLITE DYKES

Analysis number	75	241	341	347	356	370
Sample number	5502	5987	5914(4)	5914(1)	5914(1)	5975
SiO ₂	39.29	38.87	39.01	38.72	38.82	41.03
TiO ₂	0.60	0.03	0.15	0.16	0.06	0.17
Al ₂ O ₃	1.97	0.67	0.62	0.97	0.36	0.26
Cr ₂ O ₃	0.09	0.02	0.03	nd	0.02	nd
FeO	6.79	8.44	12.20	11.55	11.62	9.96
MnO	0.02	0.07	0.09	0.06	0.08	0.04
NiO	-	nd	0.02	0.04	nd	0.69
MgO	35.31	37.88	33.29	33.65	33.60	32.22
CaO	0.07	0.06	0.20	0.23	0.30	0.09
Na ₂ O	0.09	0.02	0.08	0.06	0.03	0.09
K ₂ O	0.04	0.47	0.05	0.20	0.04	0.10
Total	84.27	86.53	85.74	85.64	84.93	84.65

Formula based on 9 oxygens

Si	2.497	2.447	2.515	2.494	2.520	2.638
Ti	0.029	0.001	0.007	0.008	0.003	0.008
Al	0.148	0.050	0.047	0.074	0.028	0.020
Cr	0.005	0.001	0.002	-	0.001	-
Fe	0.361	0.444	0.658	0.622	0.631	0.536
Mn	0.001	0.004	0.005	0.003	0.004	0.002
Ni	-	-	0.001	0.002	-	0.036
Mg	3.346	3.555	3.199	3.231	3.251	3.008
Ca	0.005	0.004	0.014	0.016	0.021	0.006
Na	0.011	0.002	0.010	0.007	0.004	0.011
K	0.003	0.038	0.004	0.016	0.003	0.008

Table B.14 MINERALS FROM ANOMALOUS LAMPROPHYRE DYKES

Sample 5669

CLINOPYROXENES

Analysis number	322	323	325	333
SiO ₂	53.87	48.55	46.80	49.02
TiO ₂	0.24	1.43	1.63	1.86
Al ₂ O ₃	1.22	3.71	3.36	3.54
Cr ₂ O ₃	1.19	nd	nd	nd
FeO	3.98	8.08	7.18	7.49
MnO	0.11	0.34	0.16	0.18
NiO	0.10	nd	0.04	0.04
MgO	18.86	12.42	13.31	14.07
CaO	19.58	23.03	23.22	22.81
Na ₂ O	0.50	0.65	0.32	0.29
K ₂ O	nd	nd	nd	0.03
Total	99.65	98.21	96.02	99.33

Formula based on 6 oxygens

Si	1.962	1.859	1.833	1.847
Ti	0.007	0.041	0.048	0.053
Al	0.052	0.167	0.155	0.157
Cr	0.034	-	-	-
Fe	0.121	0.259	0.235	0.236
Mn	0.003	0.011	0.005	0.006
Ni	0.003	-	0.001	0.001
Mg	1.024	0.709	0.777	0.790
Ca	0.764	0.945	0.974	0.921
Na	0.035	0.048	0.024	0.021
K	-	-	-	0.001

Atomic ratio

Fe	6.34	13.54	11.82	12.12
Mg	53.64	37.06	39.12	40.58
Ca	40.02	49.40	49.04	47.30

AMPHIBOLES

Analysis number	329	334
SiO ₂	40.13	39.89
TiO ₂	4.02	3.98
Al ₂ O ₃	12.19	13.11
Cr ₂ O ₃	0.01	nd
FeO	11.47	10.37
MnO	0.31	0.24
NiO	nd	nd
MgO	13.36	14.13
CaO	11.79	11.71
Na ₂ O	2.96	2.87
K ₂ O	0.99	0.98
BaO	0.04	0.06
Total	97.27	97.34

Formula based on 23 oxygens

Si	5.741	5.667
Ti	0.432	0.425
Al	2.055	2.195
Cr	0.001	-
Fe	1.372	1.232
Mn	0.038	0.029
Ni	-	-
Mg	2.849	2.992
Ca	1.807	1.782
Na	0.821	0.791
K	0.181	0.178
Ba	0.002	0.003

Table B.14 MINERALS FROM ANOMALOUS LAMPROPHYRE DYKES

Sample 5669

PHLOGOPITES

Analysis number	327	331	332
		C	R
SiO ₂	36.12	36.56	37.05
TiO ₂	4.48	4.89	4.55
Al ₂ O ₃	15.24	15.18	15.24
Cr ₂ O ₃	nd	0.05	nd
FeO	9.02	9.12	9.31
MnO	0.11	0.07	0.07
NiO	0.03	nd	0.05
MgO	19.09	18.80	18.80
CaO	0.08	0.06	0.08
Na ₂ O	1.26	0.93	1.25
K ₂ O	8.51	8.87	8.41
BaO	0.67	0.90	0.70
F	0.15	0.13	0.19
	94.76	95.56	95.70
O = F	0.06	0.05	0.08
Total	94.70	95.51	95.62
Formula based on 22 oxygens			
Si	5.332	5.360	5.408
Ti	0.477	0.539	0.499
Al	2.651	2.623	2.622
Cr	-	0.006	-
Fe	1.114	1.118	1.136
Mn	0.014	0.009	0.009
Ni	0.004	-	0.006
Mg	4.200	4.108	4.090
Ca	0.013	0.009	0.013
Na	0.361	0.264	0.354
K	1.603	1.659	1.566
Ba	0.039	0.052	0.040
Weight per cent oxide ratio			
$\frac{\text{Na}_2\text{O}}{\text{Na}_2\text{O}+\text{K}_2\text{O}}$	0.129	0.105	0.149
Atomic ratios			
$\frac{\text{Mg}}{\text{Mg}+\text{Fe}}$	0.790	0.785	0.783

Table B.14 MINERALS FROM ANOMALOUS LAMPROPHYRE DYKES

Sample 5669

FELDSPARS

Analysis number	326	335
SiO ₂	63.40	65.03
TiO ₂	0.07	0.03
Al ₂ O ₃	21.22	19.27
Cr ₂ O ₃	nd	nd
FeO	0.68	0.25
MnO	nd	nd
NiO	nd	0.02
MgO	0.16	0.02
CaO	1.89	0.37
Na ₂ O	8.75	5.30
K ₂ O	1.59	8.40
BaO	0.26	0.30
Total	98.02	98.99

Formula based on 32 oxygens

Si	11.472	11.862
Ti	0.010	0.004
Al	4.525	4.143
Cr	-	-
Fe	0.103	0.038
Mn	-	-
Ni	-	0.003
Mg	0.043	0.005
Ca	0.366	0.072
Na	3.070	1.874
K	0.367	1.955
Ba	0.018	0.021

Table B.14 MINERALS FROM ANOMALOUS LAMPROPHYRE DYKES

Sample 5669

CHROME-SPINEL

Analysis number	336
SiO ₂	0.08
TiO ₂	1.78
Al ₂ O ₃	8.09
Cr ₂ O ₃	51.17
FeO	25.90
MnO	0.37
NiO	0.22
MgO	12.02
CaO	0.03
Na ₂ O	nd
K ₂ O	nd
Total	99.66

Recalculated analysis

Fe ₂ O ₃	10.6
FeO	16.4
New Total	100.76

Formula based on 6 oxygens

Si	0.003
Ti	0.044
Al	0.313
Cr	1.327
Fe ³⁺	0.262
Fe ²⁺	0.450
Mn	0.010
Ni	0.006
Mg	0.588
Ca	0.001
Na	-
K	-

TITANOMAGNETITES

Analysis number	324	337
SiO ₂	3.30	3.47
TiO ₂	15.28	8.55
Al ₂ O ₃	1.04	1.86
Cr ₂ O ₃	0.36	0.74
FeO	67.42	69.49
MnO	0.22	0.34
NiO	0.03	0.04
MgO	1.29	1.05
CaO	0.20	0.24
Na ₂ O	0.12	0.08
K ₂ O	nd	0.02
Total	89.26	85.88

Recalculated analysis

Fe ₂ O ₃	25.1	34.6
FeO	44.8	38.4
New Total	91.74	89.39

Formula based on 6 oxygens

Si	0.132	0.143
Ti	0.459	0.264
Al	0.049	0.090
Cr	0.011	0.024
Fe ³⁺	0.755	1.070
Fe ²⁺	1.497	1.319
Mn	0.007	0.012
Ni	0.001	0.001
Mg	0.077	0.064
Ca	0.009	0.011
Na	0.009	0.006
K	-	0.001

APPENDIX C ANALYSES OF MINERALS FROM THE INCLUSIONS FOUND
WITHIN THE KIMBERLITE DYKES

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* Notes as for Appendix B

Table C.1 MINERAL ASSEMBLAGES OF THE ANALYSED INCLUSIONS

(a) PERIDOTITES

<u>Sample number</u>	<u>Type of inclusion</u>	<u>Minerals analysed</u>	<u>Analysis numbers</u>
5518G (a)	coarse dunite	olivine phlogopite	187, 188, 198, 202 189, 194, 196, 197
55180L	coarse lherzolite	olivine orthopyroxene spinel phlogopite amphibole	256, 265 255, 264, 501, 502 259, 260, 263 257, 261 262, 503
5524	granuloblastic dunite	olivine	473
5524 B	coarse garnet- wehrlite	olivine garnet clinopyroxene	490, 492 484, 485, 486, 487 488, 489, 491
5698(1)	porphyroclastic lherzolite	olivine clinopyroxene spinel phlogopite	49, 50, 51 52, 53, 54, 55 48 56, 57
5698(2)	porphyroclastic lherzolite	olivine clinopyroxene orthopyroxene spinel phlogopite	105, 106, 107, 109 505, 508 104, 504, 506, 507 108, 112, 113 110, 111
5698(3)	coarse dunite	olivine phlogopite	6, 7, 8 22, 23, 24
5914(2)	coarse dunite	olivine	383, 384
5914(3)	coarse dunite	olivine	403, 404, 405, 406
5925	coarse wehrlite	olivine spinel amphibole	479, 480, 482 483 478, 481
5951	coarse dunite	olivine spinel phlogopite	114, 115, 116, 122 117, 119, 120 118
5961	coarse wehrlite	olivine clinopyroxene	499, 500 497, 498
5983	coarse dunite	olivine	458, 459

Table C.1 MINERAL ASSEMBLAGES OF THE ANALYSED INCLUSIONS (continued)

(a) PERIDOTITES (continued)

<u>Sample number</u>	<u>Type of inclusion</u>	<u>Minerals analysed</u>	<u>Analysis numbers</u>
5984(a)	coarse garnet- lherzolite	olivine garnet clinopyroxene orthopyroxene	461 462 466, 467 493
(b)	granuloblastic dunite	olivine	469, 496
5988	granuloblastic ilmenite-bearing dunite	olivine ilmenite	509, 510 511, 512

(b) GRANULITES

<u>Sample number</u>	<u>Type of inclusion</u>	<u>Minerals analysed</u>	<u>Analysis numbers</u>
5518G (b)	garnet-granulite	garnet plagioclase clinopyroxene rutile calcite	203, 225, 235 205, 212, 216 204, 209, 218, 227 213, 228 206, 210
5519	garnet-granulite	garnet feldspar	18, 20, 21 19

Table C.2 OLIVINES FROM PERIDOTITE INCLUSIONS

Analysis number	6	7	8	49	50	51	105	106	107	109
Sample number	5698(3)	5698(3)	5698(3)	5698(1)	5698(1)	5698(1)	5698(2)	5698(2)	5698(2)	5698(2)
SiO ₂	40.94	41.38	40.52	41.01	40.88	40.99	41.69	40.69	40.95	40.71
TiO ₂	nd	nd	nd	0.04	nd	nd	0.02	nd	nd	nd
Al ₂ O ₃	-	-	-	0.06	0.04	nd	0.05	0.04	0.03	nd
Cr ₂ O ₃	-	-	-	nd	nd	nd	0.05	0.02	0.01	0.08
FeO	8.47	8.38	8.42	9.61	9.64	9.57	10.19	10.69	9.33	10.69
MnO	0.11	0.13	nd	0.16	0.18	0.18	0.16	0.16	0.19	0.17
NiO	0.38	0.36	0.34	-	-	-	-	-	-	-
MgO	50.61	50.82	50.70	49.10	49.28	49.11	48.67	48.48	49.34	48.38
CaO	0.02	nd	nd	0.09	0.04	0.03	0.04	0.08	0.03	0.09
Na ₂ O	-	-	-	0.05	nd	nd	nd	nd	nd	nd
K ₂ O	-	-	-	0.02	nd	nd	0.04	nd	nd	nd
Total	100.53	101.07	99.98	100.14	100.06	99.88	100.91	100.16	99.88	100.12

Formula based on 4 oxygens

Si	0.994	0.998	0.989	1.002	1.000	1.004	1.012	0.999	1.002	1.000
Ti	-	-	-	0.001	-	-	-	-	-	-
Al	-	-	-	0.002	0.001	-	0.001	0.001	0.001	-
Cr	-	-	-	-	-	-	-	-	-	0.002
Fe	0.172	0.169	0.172	0.196	0.197	0.196	0.207	0.220	0.191	0.220
Mn	0.002	0.003	-	0.003	0.004	0.004	0.003	0.003	0.004	0.004
Ni	0.007	0.007	0.007	-	-	-	-	-	-	-
Mg	1.831	1.826	1.844	1.788	1.797	1.792	1.760	1.774	1.799	1.772
Ca	0.001	-	-	0.002	0.001	0.001	0.001	0.002	0.001	0.002
Na	-	-	-	0.002	-	-	-	-	-	-
K	-	-	-	0.001	-	-	0.001	-	-	-

Atomic ratio

Fe	8.59	8.47	8.53	9.88	9.88	9.86	10.52	11.03	9.60	11.04
Mg	91.41	91.53	91.47	90.12	90.12	90.14	89.48	88.97	90.40	88.96

Table C.2 OLIVINES FROM PERIDOTITE INCLUSIONS (continued)

Analysis number	114	115	116	122	187	188	198	202	256	265
Sample number	5951	5951	5951	5951	5518G	5518G	5518G	5518G	5578OL	5578OL
C - R										
SiO ₂	41.54	41.37	41.39	41.24	41.78	41.06	40.76	40.96	41.94	41.64
TiO ₂	nd	nd	nd	nd	0.01	nd	0.02	nd	0.02	nd
Al ₂ O ₃	0.03	nd	nd	nd	0.03	0.03	0.02	0.03	nd	nd
Cr ₂ O ₃	0.03	nd	nd	0.05	nd	nd	0.02	nd	nd	nd
FeO	8.97	10.54	9.56	9.44	8.06	9.86	9.55	10.66	7.54	7.51
MnO	0.16	0.22	0.20	0.21	0.18	0.20	0.16	0.22	0.10	0.10
NiO	-	-	-	-	0.34	0.32	0.25	0.28	0.38	0.35
MgO	50.28	49.46	49.85	50.01	50.56	48.96	49.32	49.40	51.75	51.24
CaO	0.04	0.04	0.03	0.03	nd	0.01	0.02	nd	0.02	nd
Na ₂ O	nd	nd	nd	nd	0.02	0.01	0.03	0.01	nd	0.03
K ₂ O	nd	nd	nd	nd	nd	nd	0.02	nd	nd	nd
Total	101.05	101.63	101.03	100.98	100.97	100.45	100.17	101.56	101.75	100.87

Formula based on 4 oxygens

Si	1.002	1.000	1.002	0.999	1.006	1.002	0.995	0.993	1.000	1.001
Ti	-	-	-	-	-	-	-	-	-	-
Al	0.001	-	-	-	0.001	0.001	0.001	0.001	-	-
Cr	0.001	-	-	0.001	-	-	-	-	-	-
Fe	0.181	0.213	0.193	0.191	0.162	0.201	0.196	0.216	0.150	0.151
Mn	0.003	0.005	0.004	0.004	0.004	0.004	0.003	0.005	0.002	0.002
Ni	-	-	-	-	0.007	0.006	0.005	0.005	0.007	0.007
Mg	1.808	1.782	1.798	1.805	1.814	1.782	1.801	1.786	1.839	1.837
Ca	0.001	0.001	0.001	0.001	-	-	0.001	-	0.001	-
Na	-	-	-	-	0.001	-	0.001	-	-	0.001
K	-	-	-	-	-	-	0.001	-	-	-

Atomic ratio

Fe	9.10	10.68	9.69	9.57	8.20	10.14	9.81	10.79	7.54	7.60
Mg	90.90	89.32	90.31	90.43	91.80	89.86	90.19	89.21	92.46	92.40

Table C.2 OLIVINES FROM PERIDOTITE INCLUSIONS (continued)

Analysis number	383	384	403	404	405	406	458	459	461	469
Sample number	5914(2)	5914(2)	5914(3)	5914(3)	5914(3)	5914(3)	5983	5983	5984a	5984b
SiO ₂	39.80	39.82	39.55	39.84	40.27	39.93	41.75	41.61	40.35	40.48
TiO ₂	0.03	0.03	-	-	-	-	0.04	0.03	0.07	0.04
Al ₂ O ₃	0.03	0.03	-	-	-	-	0.02	0.01	0.04	0.05
Cr ₂ O ₃	nd	nd	0.03	0.04	0.03	0.06	nd	nd	0.02	nd
FeO	16.69	16.86	12.12	12.01	10.64	12.17	7.85	7.79	9.18	13.07
MnO	0.22	0.22	0.16	0.16	0.12	0.13	0.15	0.15	0.12	0.22
NiO	0.27	0.27	0.30	0.26	0.30	0.28	0.39	0.37	0.36	0.36
MgO	44.38	44.47	46.45	46.73	47.69	46.62	51.23	51.23	49.57	46.25
CaO	0.02	0.02	0.07	0.04	0.08	0.06	0.01	0.04	0.03	0.11
Na ₂ O	0.05	0.05	-	-	-	-	-	-	-	-
K ₂ O	0.01	0.01	-	-	-	-	-	-	-	-
Total	101.50	101.78	98.68	99.08	99.13	99.25	101.44	101.23	99.74	100.58

Formula based on 4 oxygens

Si	0.993	0.992	0.995	0.997	1.001	0.998	1.000	0.999	0.991	1.002
Ti	0.001	0.001	-	-	-	-	0.001	0.001	0.001	0.001
Al	0.001	0.001	-	-	-	-	0.001	-	0.001	0.001
Cr	-	-	0.001	0.001	0.001	0.001	-	-	-	-
Fe	0.348	0.351	0.255	0.251	0.221	0.254	0.157	0.156	0.189	0.271
Mn	0.005	0.005	0.003	0.003	0.003	0.003	0.003	0.003	0.002	0.005
Ni	0.005	0.005	0.006	0.005	0.006	0.006	0.008	0.007	0.007	0.007
Mg	1.651	1.651	1.742	1.743	1.766	1.737	1.829	1.833	1.814	1.707
Ca	0.001	0.001	0.002	0.001	0.002	0.002	-	0.001	0.001	0.003
Na	0.002	0.002	-	-	-	-	-	-	-	-
K	-	-	-	-	-	-	-	-	-	-

Atomic ratio

Fe	17.41	17.53	12.77	12.59	11.12	12.76	7.91	7.84	9.44	13.70
Mg	82.59	82.47	87.23	87.41	88.88	87.24	92.09	92.16	90.56	86.30

Table C.2 OLIVINES FROM PERIDOTITE INCLUSIONS (continued)

Analysis number	473	479	480	482	490	492	496	499	500
Sample number	5524	5925	5925	5925	5524B	5524B	5984b	5961	5961
SiO ₂	40.56	40.74	39.91	40.31	40.28	40.39	40.19	41.03	40.64
TiO ₂	0.08	0.02	0.01	0.02	nd	0.01	0.03	0.04	0.04
Al ₂ O ₃	0.06	0.02	0.01	0.02	0.05	0.02	0.05	0.03	0.04
Cr ₂ O ₃	0.02	nd	nd	nd	nd	nd	0.05	0.03	0.02
FeO	13.47	9.48	12.88	11.94	11.74	11.48	12.51	11.57	11.41
MnO	0.15	0.21	0.20	0.20	0.14	0.09	0.21	0.20	0.19
NiO	0.25	0.39	0.25	0.27	0.35	0.43	0.24	0.34	0.38
MgO	46.21	48.63	45.95	46.63	47.09	47.06	46.02	46.86	46.66
CaO	0.09	nd	0.17	0.01	0.06	0.08	0.12	0.03	0.04
Na ₂ O	-	-	-	-	-	-	-	-	-
K ₂ O	-	-	-	-	-	-	-	-	-
Total	100.89	99.49	99.38	99.40	99.71	99.56	99.42	100.13	99.42

Formula based on 4 oxygens

Si	1.002	1.003	1.000	1.004	1.000	1.003	1.004	1.012	1.009
Ti	0.001	-	-	-	-	-	0.001	0.001	0.001
Al	0.002	0.001	-	0.001	0.001	0.001	0.001	0.001	0.001
Cr	-	-	-	-	-	-	0.001	0.001	-
Fe	0.278	0.195	0.270	0.249	0.244	0.238	0.261	0.239	0.237
Mn	0.003	0.004	0.004	0.004	0.003	0.002	0.004	0.004	0.004
Ni	0.005	0.008	0.005	0.005	0.007	0.009	0.005	0.007	0.008
Mg	1.701	1.785	1.716	1.731	1.743	1.742	1.713	1.722	1.728
Ca	0.002	-	0.005	-	0.002	0.002	0.003	0.001	0.001
Na	-	-	-	-	-	-	-	-	-
K	-	-	-	-	-	-	-	-	-

Atomic ratio

Fe	14.05	9.85	13.60	12.58	12.28	12.02	13.22	12.19	12.06
Mg	85.95	90.15	86.40	87.42	87.72	87.98	86.78	87.81	87.94

Table C.2 OLIVINES FROM PERIDOTITE INCLUSIONS (continued)

Analysis number	509	510
Sample number	5988	5988
SiO ₂	39.74	40.14
TiO ₂	0.06	0.08
Al ₂ O ₃	0.04	0.03
Cr ₂ O ₃	nd	nd
FeO	16.22	16.44
MnO	0.19	0.24
NiO	0.22	0.14
MgO	44.76	44.32
CaO	0.10	0.11
Na ₂ O	0.04	0.05
K ₂ O	0.02	0.03
Total	101.39	101.58

Formula based on 4 oxygens

Si	0.991	0.999
Ti	0.001	0.001
Al	0.001	0.001
Cr	-	-
Fe	0.338	0.342
Mn	0.003	0.005
Ni	0.004	0.003
Mg	1.664	1.644
Ca	0.003	0.003
Na	0.002	0.002
K	0.001	0.001

Atomic ratio

Fe	16.88	17.22
Mg	83.12	82.78

Table C.3

C L I N O P Y R O X E N E S

(a) PERIDOTITE INCLUSIONS

Analysis number	52	53	54	55	466	467	488	489	491	497
Sample number	5698(1)	5698(1)	5698(1)	5698(1)	5984a	5984a	5524B	5524B	5524B	5961
SiO ₂	54.22	54.71	54.61	54.70	54.93	55.19	55.19	55.23	54.91	54.34
TiO ₂	nd	0.18	0.21	0.17	0.11	0.15	0.52	0.54	0.52	0.19
Al ₂ O ₃	nd	0.11	0.14	0.14	2.24	2.30	2.90	2.88	2.89	1.12
Cr ₂ O ₃	1.37	1.32	1.32	1.20	1.54	1.91	0.38	0.38	0.37	1.61
FeO	2.49	2.33	2.68	2.42	2.64	2.61	4.62	4.43	4.53	2.93
MnO	0.13	0.12	0.15	0.13	0.08	0.05	0.14	0.11	0.10	0.12
NiO	-	-	-	-	0.04	0.07	0.06	0.08	0.08	nd
MgO	17.39	17.39	17.67	17.38	16.41	16.29	18.06	18.08	17.94	16.44
CaO	22.45	22.29	22.02	22.37	19.62	19.84	16.17	16.35	16.29	21.47
Na ₂ O	nd	0.79	0.80	0.72	1.96	2.01	1.91	1.90	1.95	1.37
K ₂ O	nd	nd	nd	nd	0.01	0.02	0.04	0.03	0.03	0.03
Total	98.05	99.24	99.60	99.23	99.58	100.44	99.99	100.01	99.61	99.62

Formula based on 6 oxygens

Si	2.005	2.001	1.993	2.001	1.991	1.986	1.984	1.984	2.004	1.985
Ti	-	0.005	0.006	0.005	0.003	0.004	0.014	0.015	0.014	0.005
Al	-	0.005	0.003	0.006	0.096	0.098	0.123	0.122	0.081	0.048
Cr	0.040	0.038	0.038	0.035	0.044	0.054	0.011	0.011	0.011	0.046
Fe	0.077	0.071	0.082	0.074	0.080	0.079	0.139	0.133	0.138	0.090
Mn	0.004	0.004	0.005	0.004	0.002	0.002	0.004	0.003	0.003	0.004
Ni	-	-	-	-	0.001	0.002	0.002	0.002	0.002	-
Mg	0.959	0.948	0.961	0.948	0.887	0.874	0.968	0.968	0.967	0.895
Ca	0.890	0.873	0.861	0.877	0.762	0.765	0.623	0.629	0.637	0.840
Na	-	0.056	0.057	0.051	0.138	0.140	0.133	0.132	0.138	0.097
K	-	-	-	-	-	0.001	0.002	0.001	0.001	0.001

Atomic ratio

Fe	4.0	3.8	4.3	3.9	4.6	4.6	8.0	7.7	7.9	4.9
Mg	49.8	50.1	50.5	49.9	51.3	50.9	56.0	55.9	55.5	49.1
Ca	46.2	46.1	45.2	46.2	44.1	44.5	36.0	36.4	36.8	46.0

Table C.3 CLINOPYROXENES

(a) PERIDOTITE INCLUSIONS (continued)

Analysis number	498	505	508
Sample number	5961	5698(2)	5698(2)
SiO ₂	54.58	54.06	54.37
TiO ₂	0.15	0.25	0.10
Al ₂ O ₃	1.13	0.55	0.24
Cr ₂ O ₃	1.51	1.04	1.21
FeO	3.09	3.20	2.78
MnO	0.11	0.12	0.13
NiO	0.05	0.06	0.06
MgO	16.46	18.23	17.96
CaO	21.31	20.98	21.62
Na ₂ O	1.40	0.75	0.66
K ₂ O	0.03	0.04	0.02
Total	99.82	99.28	99.15

Formula based on 6 oxygens

Si	1.989	1.979	1.991
Ti	0.004	0.007	0.003
Al	0.049	0.024	0.010
Cr	0.044	0.030	0.035
Fe	0.094	0.098	0.085
Mn	0.003	0.004	0.004
Ni	0.001	0.002	0.002
Mg	0.894	0.995	0.980
Ca	0.832	0.823	0.848
Na	0.099	0.053	0.047
K	0.001	0.002	0.001

Atomic ratio

Fe	5.2	5.1	4.5
Mg	49.1	51.9	51.2
Ca	45.7	43.0	44.3

(b) GRANULITE INCLUSIONS

204	209	218	227
5518G	5518G	5518G	5518G
53.25	52.55	52.75	54.35
0.49	0.52	0.53	0.44
7.40	7.92	7.36	7.54
0.05	0.05	0.04	0.05
6.15	6.75	6.64	5.86
nd	0.06	0.04	0.04
0.02	0.02	nd	0.04
10.53	10.25	10.46	10.56
17.63	17.12	17.76	17.36
4.10	4.35	4.04	4.21
nd	0.01	nd	nd
99.62	99.60	99.62	100.45

1.947	1.928	1.936	1.963
0.013	0.014	0.015	0.012
0.319	0.343	0.318	0.321
0.001	0.001	0.001	0.001
0.188	0.207	0.204	0.177
-	0.002	0.001	0.001
0.001	0.001	-	0.001
0.574	0.561	0.572	0.568
0.691	0.673	0.698	0.672
0.291	0.310	0.287	0.295
-	-	-	-

Table C.4 ORTHOPYROXENE FROM PERIDOTITE INCLUSIONS

Analysis number	104	255	264	493	501	502	504	506	507
Sample number	5698(2)	5518OL	5518OL	5984a	5518OL	5518OL	5698(2)	5698(2)	5698(2)
SiO ₂	57.63	57.39	57.62	55.36	56.61	56.74	57.29	57.55	58.21
TiO ₂	0.09	0.02	nd	0.08	0.02	0.01	0.10	0.13	0.09
Al ₂ O ₃	0.10	2.54	2.02	0.85	2.49	2.08	0.11	0.09	0.03
Cr ₂ O ₃	0.07	0.51	0.38	0.21	0.56	0.51	0.22	0.15	0.18
FeO	6.30	4.95	5.16	5.49	4.99	4.98	6.93	7.27	5.19
MnO	0.22	0.15	0.12	0.10	0.11	0.12	0.18	0.15	0.16
NiO	-	0.10	0.08	0.10	0.04	0.04	0.13	0.12	0.09
MgO	34.78	35.23	35.30	35.70	34.73	34.81	33.89	33.99	35.60
CaO	0.56	0.34	0.20	0.47	0.39	0.62	0.61	0.83	0.56
Na ₂ O	0.06	0.07	0.03	0.09	0.09	0.19	0.09	0.07	0.05
K ₂ O	nd	0.01	nd	0.01	0.01	0.03	0.02	0.01	0.02
Total	99.81	101.31	100.91	98.46	100.04	100.13	99.57	100.36	100.18

Formula based on 6 oxygens

Si	1.992	1.943	1.958	1.941	1.942	1.947	1.993	1.989	1.995
Ti	0.002	0.001	-	0.002	0.001	-	0.003	0.003	0.002
Al	0.003	0.101	0.081	0.035	0.101	0.084	0.005	0.004	0.001
Cr	0.002	0.014	0.010	0.006	0.015	0.014	0.006	0.004	0.005
Fe	0.182	0.140	0.147	0.161	0.143	0.143	0.202	0.210	0.149
Mn	0.006	0.004	0.003	0.003	0.003	0.003	0.005	0.004	0.005
Ni	-	0.003	0.002	0.003	0.001	0.001	0.004	0.003	0.002
Mg	1.792	1.778	1.788	1.865	1.766	1.781	1.757	1.751	1.818
Ca	0.021	0.012	0.007	0.018	0.014	0.023	0.023	0.031	0.021
Na	0.004	0.005	0.002	0.006	0.006	0.013	0.006	0.005	0.003
K	-	-	-	-	-	0.001	0.001	-	0.001

Atomic ratio

Fe	9.12	7.25	7.57	7.88	7.44	7.34	10.19	10.52	7.49
Mg	89.82	92.13	92.07	91.24	91.84	91.48	88.65	87.90	91.45
Ca	1.06	0.62	0.36	0.88	0.72	1.18	1.16	1.56	1.06

Table C.5 G A R N E T S (a) PERIDOTITE INCLUSIONS

Analysis number	462	484	485	486	487
Sample number	5984a	5524B	5524B	5524B	5524B
				R	C
SiO ₂	42.92	42.18	42.51	42.62	42.28
TiO ₂	0.20	0.67	0.69	0.68	0.67
Al ₂ O ₃	19.87	21.54	21.63	21.77	21.76
Cr ₂ O ₃	4.28	0.87	0.90	0.91	0.93
FeO	8.45	8.87	9.08	8.93	9.03
MnO	0.47	0.29	0.29	0.29	0.25
NiO	nd	0.01	0.04	0.04	0.03
MgO	19.77	20.75	20.86	20.79	20.60
CaO	5.27	4.41	4.44	4.45	4.52
Na ₂ O	0.04	0.08	0.05	0.09	0.05
K ₂ O	0.02	nd	nd	nd	nd
Total	101.29	99.67	100.49	100.57	100.12
Formula based on 24 oxygens					
Si	6.096	6.030	6.032	6.038	6.021
Ti	0.021	0.072	0.074	0.072	0.072
Al	3.326	3.629	3.617	3.635	3.652
Cr	0.481	0.098	0.101	0.102	0.105
Fe	1.004	1.060	1.078	1.058	1.075
Mn	0.057	0.035	0.035	0.035	0.030
Ni	-	0.001	0.005	0.005	0.003
Mg	4.185	4.421	4.412	4.390	4.373
Ca	0.802	0.675	0.675	0.675	0.690
Na	0.011	0.022	0.014	0.025	0.014
K	0.004	-	-	-	-
Garnet molecules					
Andradite	-	1.58	1.90	0.40	1.42
Ti-garnet*	0.55	1.90	1.95	1.92	1.89
Spessartine	1.00	0.62	0.62	0.62	0.52
Uvarovite	12.63	2.59	2.67	2.72	2.76
Grossular	0.86	5.81	5.36	6.96	6.01
Knorringite	-	-	-	-	-
Pyrope	73.29	77.83	77.61	78.00	76.50
Almandine	11.67	9.67	9.90	9.38	10.91
Per cent cations used	95.35	94.55	94.60	93.77	95.16

* Ti-garnet = Ca₃Ti₂Al₂SiO₁₂

Table C.5 G A R N E T S (b) GRANULITE INCLUSIONS

Analysis number	18	20	21	203	225	235
Sample number	5519	5519	5519	5518G	5518G	5518G
	C - R					
SiO ₂	39.16	39.24	39.18	39.57	40.08	39.62
TiO ₂	0.07	0.12	0.14	0.11	0.11	0.13
Al ₂ O ₃	21.69	21.40	21.55	21.71	21.76	21.74
Cr ₂ O ₃	0.09	0.08	nd	0.04	0.04	0.05
FeO	23.51	23.51	23.11	23.30	23.31	23.11
MnO	0.47	0.46	nd	0.39	0.45	0.41
NiO	-	-	-	nd	nd	nd
MgO	7.63	8.22	7.97	9.07	9.14	8.54
CaO	8.09	7.58	8.12	7.02	6.54	7.07
Na ₂ O	0.08	0.06	0.06	0.06	0.05	0.03
K ₂ O	nd	nd	nd	nd	nd	nd
Total	100.79	100.67	100.13	101.27	101.48	100.70
Formula based on 24 oxygens						
Si	5.984	5.996	6.003	5.986	6.035	6.021
Ti	0.008	0.014	0.016	0.013	0.012	0.015
Al	3.906	3.854	3.892	3.871	3.861	3.894
Cr	0.011	0.010	-	0.005	0.005	0.006
Fe	3.005	3.004	2.961	2.948	2.935	2.937
Mn	0.061	0.060	-	0.050	0.057	0.053
Ni	-	-	-	-	-	-
Mg	1.738	1.872	1.820	2.045	2.051	1.934
Ca	1.325	1.241	1.333	1.138	1.055	1.151
Na	0.024	0.018	0.018	0.018	0.015	0.009
K	-	-	-	-	-	-
Garnet molecules						
Andradite	2.03	3.08	1.89	4.18	0.84	0.84
Ti-garnet*	0.20	0.35	0.40	0.33	0.31	0.38
Spessartine	1.02	1.01	-	0.83	0.97	0.90
Uvarovite	-	-	-	0.13	0.13	0.15
Grossular	19.93	17.37	20.11	14.34	16.76	18.14
Knorringite	-	-	-	-	-	-
Pyrope	29.06	31.38	30.59	34.09	35.07	32.78
Almandine	47.76	46.81	47.01	46.11	45.92	46.81
Per cent cations used	99.50	99.16	99.01	99.63	97.40	98.26

* Ti-garnet = Ca₃Ti₂Al₂SiO₁₂

Table C.6

Fe-Ti-Cr OXIDES FROM PERIDOTITE INCLUSIONS

(a) CHROME-SPINELS

Analysis number	48	108	112	113	117	119	120	259	260	263
Sample number	5698(1)	5698(2)	5698(2)	5698(2)	5951	5951	5951	5518OL	5518OL	5518OL
			C	-	R		C	-	R	
SiO ₂	0.09	0.03	0.04	0.07	nd	0.09	0.06	nd	0.02	0.95
TiO ₂	2.54	1.88	2.59	1.20	2.58	0.05	2.01	0.02	0.02	0.11
Al ₂ O ₃	1.95	0.99	2.52	2.58	3.77	3.18	3.88	32.05	32.75	3.31
Cr ₂ O ₃	59.49	60.80	57.27	62.18	59.06	61.71	57.08	31.78	32.38	57.78
FeO	24.08	25.01	25.87	22.69	23.18	24.09	24.18	19.94	20.66	24.94
MnO	0.89	0.85	0.81	0.85	0.93	0.91	0.91	0.32	0.35	0.56
NiO	-	-	-	-	-	-	-	0.19	0.16	0.05
MgO	11.23	9.54	10.09	10.15	10.75	10.16	10.68	15.10	14.85	9.83
CaO	0.09	nd	0.02	0.01	0.03	nd	0.03	nd	nd	0.03
Na ₂ O	nd	nd	nd	nd	0.02	nd	nd	nd	nd	0.03
K ₂ O	nd	nd	0.01	0.02	nd	nd	nd	nd	nd	0.11
Total	100.36	99.10	99.22	99.75	100.32	100.19	98.83	99.40	101.19	97.70
Recalculated analysis										
Fe ₂ O ₃	8.0	7.4	8.2	6.0	6.0	8.4	7.9	7.1	6.7	8.1
FeO	16.9	18.4	18.5	17.3	17.8	16.5	17.0	13.6	14.7	17.6
New total	101.18	99.89	100.05	100.36	100.94	101.00	99.55	100.16	101.93	98.46
Formula based on 4 oxygens										
Si	0.003	0.001	0.001	0.002	-	0.003	0.002	-	0.001	0.033
Ti	0.064	0.049	0.087	0.031	0.066	0.001	0.051	-	-	0.003
Al	0.077	0.040	0.102	0.104	0.111	0.127	0.156	1.105	1.112	0.135
Cr	1.584	1.666	1.550	1.676	1.592	1.645	1.536	0.735	0.738	1.581
Fe ³⁺	0.203	0.193	0.211	0.154	0.154	0.215	0.202	0.156	0.145	0.211
Fe ²⁺	0.476	0.533	0.530	0.493	0.507	0.469	0.484	0.333	0.354	0.509
Mn	0.025	0.025	0.023	0.025	0.027	0.026	0.026	0.008	0.007	0.016
Ni	-	-	-	-	-	-	-	0.004	0.004	0.001
Mg	0.564	0.493	0.515	0.516	0.546	0.515	0.542	0.659	0.638	0.507
Ca	0.003	-	0.001	-	0.001	-	0.001	-	-	0.001
Na	-	-	-	-	0.001	-	-	-	-	0.002
K	-	-	-	0.001	-	-	-	-	-	0.005

Table C.6 Fe-Ti-Cr OXIDES FROM PERIDOTITE INCLUSIONS

(a) CHROME-SPINELS (continued)

Analysis number	483
Sample number	5925
SiO ₂	nd
TiO ₂	0.27
Al ₂ O ₃	1.93
Cr ₂ O ₃	54.11
FeO	37.41
MnO	0.84
NiO	0.05
MgO	3.18
CaO	nd
Na ₂ O	nd
K ₂ O	0.03
Total	97.82

Recalculated analysis

Fe ₂ O ₃	12.2
FeO	26.4
New total	99.01

Formula based on 4 oxygens

Si	-
Ti	0.007
Al	0.083
Cr	1.565
Fe ³⁺	0.336
Fe ²⁺	0.808
Mn	0.026
Ni	0.001
Mg	0.173
Ca	-
Na	-
K	0.001

(b) ILMENITES

511	512
5988	5988
nd	nd
52.16	51.96
0.34	0.35
1.43	1.43
34.59	33.78
0.25	0.25
0.08	0.08
10.62	10.71
0.03	0.04
nd	0.04
0.03	0.03
99.53	98.67

7.7	7.2
27.7	27.3
100.34	99.39

Formula based on 6 oxygens

-	-
1.828	1.835
0.019	0.019
0.053	0.053
0.270	0.254
1.080	1.072
0.010	0.010
0.003	0.003
0.738	0.750
0.001	0.002
-	0.004
0.002	0.002

Table C.7 PHLOGOPITES FROM PERIDOTITE INCLUSIONS

Analysis number	22	23	24	56	57	110	111	118	189	194
Sample number	5698(3)	5698(3)	5698(3)	5698(1)	5698(1)	5698(2)	5698(2)	5951	5518G	5518G
SiO ₂	41.25	41.27	41.73	41.87	40.47	41.22	40.55	40.17	41.62	41.72
TiO ₂	0.94	0.69	0.83	1.05	2.66	1.25	1.90	1.45	0.23	0.24
Al ₂ O ₃	11.45	11.43	11.32	11.54	12.93	11.80	12.09	12.05	11.21	11.24
Cr ₂ O ₃	nd	0.42	nd	0.36	0.59	0.53	1.08	0.02	0.21	0.15
FeO	3.35	2.85	3.11	3.36	3.58	3.85	3.87	6.46	3.98	3.82
MnO	nd	0.02	nd	0.03	0.03	nd	0.05	0.08	0.02	0.03
NiO	0.15	0.17	0.22	nd	nd	nd	nd	nd	0.19	0.13
MgO	25.74	25.79	25.78	25.10	23.83	24.62	23.94	24.07	26.95	26.40
CaO	0.04	nd	nd	nd	nd	nd	nd	nd	0.04	nd
Na ₂ O	0.13	0.24	0.18	0.24	0.18	0.19	0.22	0.31	0.41	0.51
K ₂ O	10.25	10.15	10.19	9.97	10.24	10.22	10.26	9.92	8.83	9.36
Total	93.30	93.03	93.36	93.52	94.51	93.68	93.96	94.53	93.69	93.60

Formula based on 22 oxygens

Si	5.964	5.975	6.016	6.021	5.791	5.949	5.856	5.821	5.969	5.999
Ti	0.102	0.075	0.090	0.114	0.286	0.136	0.206	0.158	0.025	0.026
Al	1.951	1.950	1.923	1.956	2.181	2.007	2.058	2.058	1.895	1.905
Cr	-	0.048	-	0.041	0.067	0.060	0.123	0.002	0.024	0.017
Fe	0.405	0.345	0.375	0.404	0.428	0.465	0.467	0.783	0.477	0.459
Mn	-	0.002	-	0.004	0.004	-	0.006	0.010	0.002	0.004
Ni	0.017	0.020	0.026	-	-	-	-	-	0.022	0.015
Mg	5.548	5.565	5.540	5.380	5.083	5.296	5.153	5.199	5.761	5.659
Ca	0.006	-	-	-	-	-	-	-	0.006	-
Na	0.036	0.067	0.050	0.067	0.050	0.053	0.062	0.087	0.114	0.142
K	1.891	1.874	1.874	1.829	1.869	1.882	1.890	1.834	1.616	1.717

Table C.7 PHLOGOPITES FROM PERIDOTITE INCLUSIONS (continued)

Analysis number	196	197	257	261
Sample number	5518G	5518G	5518OL	5518OL
	C	-	R	
SiO ₂	41.68	41.12	42.39	39.58
TiO ₂	0.25	0.23	0.12	0.06
Al ₂ O ₃	11.39	11.24	12.25	16.30
Cr ₂ O ₃	0.15	0.16	0.52	0.71
FeO	3.34	3.84	2.45	3.56
MnO	0.03	nd	0.02	0.11
NiO	0.17	0.14	0.17	0.06
MgO	26.62	26.78	26.66	24.85
CaO	nd	nd	nd	0.05
Na ₂ O	0.53	0.44	1.01	3.46
K ₂ O	9.38	8.94	8.67	3.04
Total	93.54	92.89	94.26	91.78

Formula based on 22 oxygens

Si	5.986	5.951	5.990	5.639
Ti	0.027	0.025	0.013	0.006
Al	1.928	1.917	2.040	2.737
Cr	0.017	0.018	0.058	0.080
Fe	0.401	0.465	0.290	0.424
Mn	0.004	-	0.002	0.013
Ni	0.020	0.016	0.019	0.007
Mg	5.699	5.777	5.615	5.277
Ca	-	-	-	0.008
Na	0.148	0.123	0.277	0.956
K	1.719	1.650	1.563	0.553

Table C.8 AMPHIBOLES FROM PERIDOTITE INCLUSIONS

Analysis number	262	478	481	503
Sample number	5518OL	5925	5925	5518OL
SiO ₂	53.36	56.37	55.35	52.78
TiO ₂	0.02	0.06	0.05	0.02
Al ₂ O ₃	3.83	1.20	1.96	3.76
Cr ₂ O ₃	1.05	0.65	0.28	1.04
FeO	2.32	1.90	1.91	2.46
MnO	0.08	0.07	0.10	0.03
NiO	0.05	0.12	0.12	0.08
MgO	22.33	23.05	23.12	22.27
CaO	9.12	11.79	12.52	8.73
Na ₂ O	4.32	1.45	1.40	4.54
K ₂ O	0.69	0.21	0.12	0.60
Total	97.17	96.87	96.93	96.31

Formula based on 23 oxygens

Si	7.461	7.810	7.685	7.663
Ti	0.002	0.006	0.005	0.002
Al	0.631	0.196	0.321	0.205
Cr	0.116	0.071	0.031	0.119
Fe	0.271	0.220	0.222	0.299
Mn	0.009	0.008	0.012	0.004
Ni	0.006	0.013	0.013	0.009
Mg	4.654	4.760	4.785	4.819
Ca	1.366	1.750	1.862	1.358
Na	1.171	0.390	0.377	1.278
K	0.123	0.037	0.021	0.111

Table C.9 OTHER MINERALS FROM GRANULITE INCLUSIONS

(a) POTASSIUM FELDSPAR

Analysis number	19
Sample number	5519
SiO ₂	64.28
TiO ₂	0.01
Al ₂ O ₃	18.33
Cr ₂ O ₃	nd
FeO	0.04
MnO	nd
NiO	-
MgO	0.21
CaO	0.09
Na ₂ O	3.52
K ₂ O	10.96
Total	97.44

(b) PLAGIOCLASE

205	212	216
5518G	5518G	5518G
64.39	64.55	64.44
0.01	nd	nd
21.24	21.76	21.71
nd	nd	nd
0.04	0.02	nd
0.02	0.01	0.04
0.04	nd	nd
0.01	0.04	0.01
2.68	2.68	2.80
9.53	9.89	9.77
0.47	0.45	0.47
98.43	99.40	99.24

(c) RUTILE

Analysis number	213	228
Sample number	5518G	5518G
SiO ₂	nd	0.19
TiO ₂	98.53	96.58
Al ₂ O ₃	0.17	0.20
Cr ₂ O ₃	0.10	0.04
FeO	0.68	0.68
MnO	nd	0.02
NiO	nd	0.04
MgO	0.02	0.03
CaO	0.01	0.04
Na ₂ O	0.03	0.02
K ₂ O	0.02	0.02
Total	99.56	97.86

(d) CALCITE

206	210
5518G	5518G
0.08	0.13
nd	nd
0.04	0.03
0.01	nd
0.15	0.06
0.03	nd
0.08	0.04
0.04	0.04
53.86	53.64
nd	nd
0.01	0.01
54.30	53.95

APPENDIX D WHOLE-ROCK CHEMICAL ANALYSES OF THE HOLSTEINSBORG
KIMBERLITE AND POTASSIC LAMPROPHYRE DYKES

Contents

Notes

Table D.1 Kimberlite dykes

Table D.2 Potassic lamprophyre dykes

Table D.3 Anomalous dykes

Notes

- (a) Major oxide contents are given in weight per cent.
- (b) Minor element concentrations are given in parts per million.
- (c) Abbreviation nd = not detected
- (d) CIPW norms were calculated using a departmental computer programme written by D.J. Humphries.
* denotes those analyses which gave a negative normative component using the above method of calculation.
- (e) The mineral assemblage (assem) for each rock refers to those given in Table 3.2 (in back pocket).

Table D.1 KIMBERLITE DYKES

	5503	5504	5505	5508	5511	5518	5603	5605	5606	5607
Major oxides										
SiO ₂	29.27	29.89	30.81	31.18	28.70	25.68	31.00	27.94	32.33	32.42
TiO ₂	2.35	2.42	2.62	2.57	2.25	1.54	3.75	2.09	3.74	3.88
Al ₂ O ₃	2.74	2.94	3.39	3.38	2.81	1.90	2.97	2.34	3.47	3.77
Cr ₂ O ₃	0.20	0.20	0.18	0.20	0.20	0.12	0.23	0.26	0.20	0.21
Fe ₂ O ₃	2.49	2.86	3.75	3.71	2.66	5.12	2.99	1.26	3.14	4.18
FeO	8.40	8.23	7.36	7.69	7.91	6.87	10.00	9.20	9.97	9.49
MnO	0.19	0.19	0.19	0.18	0.18	0.26	0.18	0.20	0.20	0.19
MgO	27.01	26.83	26.22	26.00	24.85	26.12	26.58	27.18	25.76	26.63
CaO	10.53	10.65	10.26	9.78	9.95	14.66	7.61	10.52	8.87	8.04
Na ₂ O	0.31	0.18	0.22	0.28	0.33	0.14	0.23	0.20	0.27	0.26
K ₂ O	2.38	2.67	2.74	2.84	2.55	1.08	1.78	2.02	1.93	2.10
H ₂ O ⁺	2.76	1.87	3.69	3.59	4.42	5.15	3.78	3.98	3.03	3.16
P ₂ O ₅	0.60	0.47	0.36	0.44	0.60	0.77	0.27	0.68	0.28	0.25
CO ₂	11.02	9.45	8.35	8.29	11.34	12.20	7.29	10.67	5.32	5.88
Total	100.05	98.65	98.96	99.93	98.55	101.49	98.43	98.28	98.31	100.25
Minor elements										
V	268	287	308	271	273	206	468	314	506	496
Cr	1396	1372	1261	1357	1362	865	1568	1772	1402	1467
Ni	842	901	818	770	776	738	727	1101	631	663
Cu	77	84	106	102	77	53	128	67	168	161
Zn	72	75	72	69	65	88	77	92	84	73
Rb	94	105	112	107	94	44	85	93	80	95
Sr	1227	1334	769	793	1164	1968	561	1276	551	499
Y	15	16	17	18	13	18	14	20	12	15
Zr	141	205	258	209	153	159	126	118	183	179
Ba	1094	1375	1556	1298	1222	3278	1174	1531	1193	1309
La	217	206	240	276	245	363	178	307	149	177
Ce	271	226	272	291	300	405	218	352	192	193
CIPW norm										
qtz	*					*				
c			0.07			0.53	0.71			0.59
or		1.42	11.48	10.45	1.38	6.69	11.29		11.21	12.73
ab						0.82	2.09			2.26
an									2.67	1.39
lc		11.83	4.22	5.56	11.98				0.56	
ne		0.15	1.05	0.89	0.15	0.23			1.26	
ac		1.17		0.73	2.47					
ns										
ks										
di									5.14	
hy							3.66			2.27
ol		56.60	52.87	53.36	56.17	52.97	54.91		53.27	52.33
cs										
mt		3.75	5.66	5.25	3.03	7.79	4.65		4.76	6.22
cm		0.31	0.28	0.31	0.33	0.20	0.36		0.31	0.32
il		4.81	5.18	5.10	4.73	3.07	7.64		7.43	7.56
ap		1.16	0.89	1.09	1.57	1.91	0.69		0.69	0.61
cc		18.82	18.31	17.26	18.19	25.79	13.99		12.65	13.72
H ₂ O ⁺		1.87	3.69	3.59	4.42	5.15	3.78		3.03	3.16
Assem										
	C	C	C	C	B	C	B	B	C	C

Table D.1. KIMBERLITE DYKES (continued)

	5696	5699	5820	5834	5903	5905	5907	5908	5915	5932
Major oxides										
SiO ₂	32.63	31.33	26.53	28.29	30.45	22.74	16.40	30.31	30.70	30.30
TiO ₂	4.39	3.80	1.84	2.93	2.12	2.27	1.94	3.10	3.21	3.36
Al ₂ O ₃	2.30	2.47	0.61	1.17	0.44	1.17	1.28	1.88	2.04	1.72
Cr ₂ O ₃	0.34	0.27	0.28	0.31	0.26	0.13	0.12	0.25	0.26	0.27
Fe ₂ O ₃	3.98	3.50	6.68	3.14	3.95	5.05	3.49	4.81	5.45	4.26
FeO	9.68	9.33	6.50	8.49	9.23	8.55	5.45	7.45	7.15	8.44
MnO	0.19	0.18	0.22	0.20	0.23	0.24	0.19	0.17	0.17	0.27
MgO	32.11	28.91	32.78	30.85	35.75	25.63	17.74	25.86	26.47	30.84
CaO	6.86	9.44	9.58	10.45	6.50	15.26	24.81	9.32	9.36	9.49
Na ₂ O	0.12	0.12	0.06	0.05	0.05	0.05	0.14	0.13	0.11	0.11
K ₂ O	1.47	1.88	0.09	1.03	0.29	0.41	0.99	0.89	0.93	1.40
H ₂ O ⁺	3.13	3.34	5.64	3.85	2.91	4.17	3.16	8.25	8.63	3.82
P ₂ O ₅	0.25	0.49	0.66	0.42	0.40	1.07	1.80	0.42	0.41	0.32
CO ₂	2.69	5.31	10.58	9.64	6.71	14.48	23.39	6.21	5.61	6.67
Total	99.80	100.10	101.72	100.51	99.03	101.09	100.78	98.80	100.24	101.00
Minor elements										
V	495	456	224	373	269	300	247	376	376	372
Cr	2342	1822	1912	2113	1756	893	816	1701	1758	1840
Ni	1047	918	840	964	1275	364	329	826	847	994
Cu	83	102	23	82	34	68	91	120	117	78
Zn	74	71	65	62	80	86	60	69	66	82
Rb	61	62	nd	43	9	26	53	38	39	43
Sr	620	1078	1090	1019	749	1351	2524	577	591	744
Y	15	19	16	12	13	22	25	18	13	17
Zr	165	234	327	81	90	307	412	204	198	101
Ba	623	754	789	1052	688	1322	2210	324	355	932
La	240	164	114	210	443	371	582	70	88	238
Ce	329	247	231	244	604	476	687	133	140	313
CIPW norm										
qtz							*			
c			0.45		0.07	0.69				
or			0.57	2.94	1.69	2.59		5.78	5.97	4.63
ab			0.55		0.45	0.25		1.21	1.01	
an	1.44	0.67						2.11	2.53	0.07
lc	7.01	8.96		2.70						3.01
ne	0.57	0.57		0.16		0.11				0.52
ac				0.13						
ns										
ks										
di	3.27	5.86						2.06	5.14	2.37
hy			2.02		0.19			15.56	10.99	
ol	62.57	56.53	63.36	63.38	74.56	54.52		42.10	43.80	59.82
cs	3.21	0.74								
mt	5.94	5.22	10.44	4.71	6.06	7.82		7.97	8.59	6.33
cm	0.52	0.41	0.44	0.48	0.40	0.20		0.40	0.42	0.41
il	8.58	7.42	3.77	5.84	4.26	4.60		6.47	6.63	6.54
ap	0.61	1.19	1.68	1.04	1.00	2.71		1.09	1.06	0.78
cc	6.29	12.42	16.72	18.61	11.33	26.51		15.53	13.86	15.54
H ₂ O ⁺	3.13	3.34	5.64	3.85	2.91	4.17		8.25	8.63	3.82
Assem										
	C	D	A	B	A	E	B		C	C

Table D.1 KIMBERLITE DYKES (continued)

	5947	5962	5964	5966	5966A	5966B	5966D	5973	5974	5975
Major oxides										
SiO ₂	31.41	30.88	31.85	29.98	31.07	28.49	29.06	32.98	32.37	30.72
TiO ₂	4.23	4.72	4.05	3.82	2.54	2.23	3.69	4.07	4.59	4.72
Al ₂ O ₃	2.44	2.43	3.04	2.37	3.00	2.60	2.50	3.50	2.44	2.61
Cr ₂ O ₃	0.23	0.23	0.21	0.23	0.23	0.25	0.24	0.17	0.28	0.21
Fe ₂ O ₃	3.26	4.39	3.44	2.77	3.47	3.00	2.39	5.42	4.55	4.58
FeO	10.14	9.56	9.70	9.57	8.22	7.80	9.50	8.42	9.59	8.33
MnO	0.21	0.19	0.20	0.18	0.19	0.20	0.18	0.20	0.19	0.21
MgO	27.09	26.98	25.65	27.49	28.41	25.18	26.88	23.24	30.33	26.60
CaO	9.09	9.55	10.36	8.34	8.33	11.25	8.33	12.02	7.26	7.70
Na ₂ O	0.23	0.24	0.22	0.25	0.20	0.21	0.25	0.17	0.28	0.79
K ₂ O	1.67	1.79	2.01	1.58	2.29	2.35	1.50	2.27	1.58	2.14
H ₂ O ⁺	2.71	3.66	3.31	3.29	3.92	3.77	3.55	3.86	3.52	3.41
P ₂ O ₅	0.69	0.49	0.57	0.41	0.50	0.65	0.43	0.91	0.32	0.04
CO ₂	5.48	4.20	4.67	9.61	7.77	10.28	10.57	2.72	2.94	7.92
Total	98.65	99.23	99.07	99.89	99.91	98.01	98.83	99.79	99.96	99.77
Minor elements										
V	545	616	524	450	288	326	462	518	535	565
Cr	1605	1580	1431	1565	1580	1692	1615	1172	1909	1562
Ni	867	873	805	880	900	1047	874	652	1031	878
Cu	118	108	140	79	64	114	79	157	109	60
Zn	90	89	80	73	74	86	79	82	84	89
Rb	62	54	71	58	94	111	59	75	67	68
Sr	841	1061	965	961	777	1297	1033	908	693	965
Y	16	18	16	13	7	16	16	18	14	12
Zr	279	264	371	229	155	219	208	535	184	126
Ba	779	693	857	649	1057	1577	664	766	794	822
La	218	197	195	153	236	319	153	82	189	170
Ce	273	225	234	249	290	256	249	173	264	253
CIPW norm										
qtz										
c				0.27	0.20		0.51			
or	10.24			10.01	8.58	4.75	9.72			7.25
ab	0.48			1.97			1.45			
an	0.72		1.43					2.16	0.76	
lc		8.65	9.69		4.48	8.03		10.93	7.56	4.77
ne	0.84	1.15	1.05	0.16	0.97	0.17	0.47	0.81	1.32	0.86
ac						1.41				4.81
ns										
ks										
di	4.42	8.53	10.59					14.54	6.66	
hy										
ol	55.07	51.57	49.98	59.14	59.21	54.87	59.62	41.05	57.70	53.40
cs		2.30	1.31					5.39	2.09	
mt	4.91	6.64	5.19	4.31	5.31	3.99	3.80	8.16	6.81	4.60
cm	0.35	0.35	0.32	0.36	0.36	0.40	0.39	0.26	0.43	0.33
il	8.34	9.35	8.00	7.78	5.09	4.57	7.63	8.03	9.00	9.46
ap	1.70	1.21	1.40	1.04	1.25	1.66	1.12	2.24	0.78	0.10
cc	12.93	9.97	11.05	14.97	14.54	20.15	15.24	6.43	6.90	14.43
H ₂ O ⁺	2.71	3.66	3.31	3.29	3.92	3.77	3.55	3.86	3.52	3.41
Assem										
		C	D	C	C	C	C	C		

Table D.1 KIMBERLITE DYKES (continued)

	5983	5985	5997	5998	5999A1	5999A2	5999B	E13	E15
Major oxides									
SiO ₂	32.71	33.50	30.78	32.24	33.06	32.49	31.71	30.84	30.84
TiO ₂	4.60	4.34	4.67	4.24	4.36	4.44	4.44	1.94	4.57
Al ₂ O ₃	4.04	4.13	2.64	2.91	3.34	3.29	3.53	0.46	2.76
Cr ₂ O ₃	0.20	0.18	0.26	0.22	0.20	0.22	0.19	0.22	0.23
Fe ₂ O ₃	5.03	5.32	3.82	3.87	4.53	4.31	5.12	3.83	4.15
FeO	8.42	8.35	9.50	9.70	9.50	9.28	8.53	8.99	9.29
MnO	0.16	0.18	0.18	0.20	0.20	0.20	0.21	0.22	0.18
MgO	24.26	22.71	29.33	27.10	25.01	24.43	23.29	36.80	29.71
CaO	10.18	11.90	7.09	9.77	10.16	9.96	10.68	6.19	7.45
Na ₂ O	0.21	0.23	0.35	0.49	0.31	0.28	0.49	0.06	0.34
K ₂ O	2.63	2.31	2.00	1.97	2.12	2.09	2.19	0.27	1.90
H ₂ O ⁺	2.95	2.78	3.51	2.84	3.12	2.90	3.41	3.11	3.04
P ₂ O ₅	0.42	0.59	0.34	0.56	0.50	0.63	0.40	0.36	0.29
CO ₂	3.47	3.57	6.10	4.61	3.78	4.25	5.56	6.38	5.52
Total	99.08	99.91	100.31	100.57	99.99	98.55	99.56	99.67	100.27
Minor elements									
V	546	549	550	518	574	562	584	193	475
Cr	1356	1250	1798	1527	1380	1475	1331	1505	1575
Ni	701	652	922	871	739	767	665	1140	864
Cu	171	187	87	126	145	145	119	34	84
Zn	68	78	78	85	86	78	81	74	73
Rb	106	86	82	69	68	73	63	13	80
Sr	854	889	918	994	806	844	996	769	930
Y	14	10	14	16	14	24	26	12	14
Zr	349	503	154	313	440	402	463	94	155
Ba	1164	990	906	844	848	797	932	627	716
La	145	131	251	192	201	182	160	319	196
Ce	209	189	288	251	217	228	214	409	197
CIPW norm									
qtz									
c								0.07	0.03
or			6.79			3.94	8.15	0.93	7.58
ab									
an	2.40	3.50			1.50	1.62	1.00		0.33
lc	12.63	10.98	4.23	9.31	10.10	7.01	4.12	0.59	3.09
ne	1.00	1.08	1.37	2.21	1.46	1.34	2.33	0.29	1.60
ac			0.47	0.13					
ns									
ks									
di	11.43	17.34		9.29	14.43	13.99	11.74		
hy									
ol	43.31	38.19	58.36	51.47	45.56	44.82	41.84	76.33	58.34
cs	3.10	2.49		1.35	1.32				
mt	7.56	7.91	5.47	5.66	6.76	6.52	7.69	5.85	6.18
cm	0.31	0.27	0.39	0.33	0.30	0.31	0.29	0.34	0.35
il	9.05	8.46	9.14	8.21	8.52	8.80	8.74	3.88	8.91
ap	1.03	1.43	0.83	1.35	1.22	1.56	0.98	0.90	0.71
cc	8.18	8.33	12.95	10.69	8.84	10.09	13.10	10.81	12.89

Table D.1 KIMBERLITE DYKES (continued)

	BS-19	BS-B
Major oxides		
SiO ₂	32.29	29.08
TiO ₂	3.55	3.03
Al ₂ O ₃	1.27	1.51
Cr ₂ O ₃	0.24	0.20
Fe ₂ O ₃	3.22	3.76
FeO	10.13	7.87
MnO	0.20	0.21
MgO	35.44	33.04
CaO	4.94	7.33
Na ₂ O	0.20	0.19
K ₂ O	0.53	0.76
H ₂ O ⁺	3.19	3.97
P ₂ O ₅	0.13	0.14
CO ₂	4.85	9.10
Total	100.18	100.19
Minor elements		
V	-	-
Cr	-	-
Ni	-	-
Cu	-	-
Zn	-	-
Rb	-	-
Sr	-	-
Y	-	-
Zr	-	-
Ba	-	-
La	-	-
Ce	-	-
CIPW norm		
qtz		
c	0.38	0.40
or	3.27	3.27
ab	1.76	
an		
lc		1.23
ne		0.94
ac		
ns		
ks		
di		
hy		
ol	71.86	67.64
cs		
mt	4.87	5.88
cm	0.37	0.32
il	7.03	6.20
ap	0.32	0.36
cc	8.88	13.75
H ₂ O ⁺	3.19	3.97

Table D.2 P O T A S S I C L A M P R O P H Y R E D Y K E S

	5611	5612	5616	5620	5621	5622	5622A	5623
Major oxides								
SiO ₂	38.28	38.29	48.99	45.95	47.30	39.29	39.21	41.58
TiO ₂	2.24	2.34	3.81	3.62	3.88	2.17	2.24	3.46
Al ₂ O ₃	5.60	5.73	8.45	8.19	8.36	4.90	5.01	7.11
Cr ₂ O ₃	0.11	0.10	0.02	0.04	0.03	0.11	0.11	0.07
Fe ₂ O ₃	2.33	2.22	2.30	3.52	2.92	1.35	1.49	1.28
FeO	4.83	4.93	3.95	3.31	3.77	6.25	6.14	6.19
MnO	0.09	0.09	0.07	0.09	0.07	0.10	0.10	0.09
MgO	15.30	14.89	6.72	8.37	6.81	22.55	21.61	12.02
CaO	8.99	8.40	5.60	5.34	5.64	4.73	5.02	7.40
Na ₂ O	1.60	1.52	1.92	1.32	1.91	1.00	1.13	1.59
K ₂ O	6.27	6.44	9.31	9.51	9.45	6.16	6.25	7.54
H ₂ O ⁺	3.30	2.75	1.18	2.11	1.42	2.82	3.36	2.25
P ₂ O ₅	0.76	0.83	1.85	2.18	1.75	0.94	0.94	1.60
CO ₂	9.00	9.04	2.74	3.40	3.67	5.14	5.94	5.33
Total	98.47	97.47	96.89	96.91	96.95	97.40	98.44	97.44
Minor elements								
V	219	228	309	378	375	220	236	364
Cr	755	703	178	280	211	756	744	509
Ni	557	541	19	94	50	856	782	250
Cu	30	33	21	33	28	28	28	41
Zn	75	76	91	111	101	88	81	82
Rb	144	149	141	232	164	168	162	180
Sr	1385	1394	2842	3458	2477	2563	2549	1582
Y	17	18	25	30	30	20	19	27
Zr	557	557	724	1051	1217	490	505	730
Ba	1730	1767	2560	7721	6271	3227	2838	6405
La	221	206	518	633	610	262	322	395
Ce	284	293	642	770	722	345	384	487
CIPW norm								
qtz			3.33		1.11			
c								
or	32.91	34.09	48.17	47.53	48.01	27.90	28.51	41.01
ab								
an								
lc						0.78	0.81	
ne								
ac	7.26	7.00	6.95	10.46	8.89	4.22	4.66	3.91
ns	1.47	1.41	2.11		1.61	1.01	1.17	2.27
ks	1.93	2.05	2.57	3.38	2.97	2.89	2.87	1.63
di								
hy	3.61	3.74	18.60	15.52	18.51			9.38
ol	30.64	30.21		4.77		49.18	47.29	20.22
cs								
mt				0.18				
cm	0.17	0.16	0.03	0.06	0.05	0.17	0.18	0.11
il	4.58	4.84	7.56	7.31	7.75	4.45	4.60	6.94
ap	1.94	2.14	4.58	5.49	4.36	2.40	2.40	4.00
cc	15.48	14.36	6.10	5.29	6.75	6.99	7.52	10.47
H ₂ O ⁺	3.30	2.75	1.18	2.11	1.42	2.82	3.36	2.25
Assem								
	N	M	S	S	S	F	F	S

Table D.2 POTASSIC LAMPROPHYRE DYKES (continued)

	5624	5625	5625A	5625B	5628	5629	5630	5632
Major oxides								
SiO ₂	40.63	39.98	40.79	38.28	40.52	40.22	41.37	42.75
TiO ₂	3.44	2.96	3.23	2.33	3.06	3.11	4.00	3.18
Al ₂ O ₃	6.66	6.47	7.07	5.14	6.60	6.47	7.44	8.47
Cr ₂ O ₃	0.08	0.08	0.07	0.09	0.08	0.08	0.04	0.06
Fe ₂ O ₃	1.51	0.88	1.24	0.70	0.96	0.12	1.31	1.74
FeO	6.38	6.54	6.14	6.68	6.55	7.41	7.86	5.01
MnO	0.11	0.10	0.11	0.10	0.11	0.09	0.10	0.09
MgO	11.32	14.17	11.17	17.27	12.52	13.44	8.75	12.16
CaO	7.05	6.92	7.34	6.12	7.00	7.37	9.69	7.38
Na ₂ O	1.46	1.38	1.54	0.34	1.42	1.55	1.14	0.96
K ₂ O	7.98	7.29	7.76	6.43	7.71	7.36	6.81	7.99
H ₂ O ⁺	2.56	2.26	2.47	3.37	2.31	2.96	2.84	2.65
P ₂ O ₅	1.45	1.23	1.32	0.95	1.57	1.39	1.65	0.73
CO ₂	5.94	6.99	7.33	7.26	6.65	6.29	4.45	4.96
Total	96.49	97.17	97.51	94.97	96.98	97.78	97.41	98.07
Minor elements								
V	350	320	347	259	319	352	407	320
Cr	518	546	492	623	547	536	285	378
Ni	226	392	207	650	291	294	94	174
Cu	39	37	38	26	38	28	39	16
Zn	97	92	91	89	99	91	73	77
Rb	173	168	163	153	165	133	180	242
Sr	2260	2089	2060	2374	2456	1940	857	1621
Y	22	25	32	19	25	21	30	16
Zr	861	686	716	546	717	759	714	279
Ba	4966	5571	5261	3850	4966	7002	2764	4224
La	459	397	432	341	412	486	390	209
Ce	515	475	517	400	478	598	477	287
CIPW norm								
qtz								
c								
or	39.28	38.11	41.66	31.65	38.97	37.75	42.44	45.27
ab							0.38	
an								
lc								2.39
ne								
ac	4.72	2.75	3.87	2.28	3.00	0.37	4.00	5.26
ns	1.86	2.21	2.25	0.15	2.23	3.16	1.22	0.59
ks	3.23	2.32	2.17	3.11	2.86	2.42		0.28
di							8.25	1.11
hy	11.11	6.42	9.02	12.05	10.33	10.68	3.86	8.95
ol	18.61	28.22	19.72	32.96	22.26	24.55	16.99	25.11
cs								
mt								
cm	0.13	0.13	0.11	0.15	0.13	0.13	0.06	0.09
il	7.06	6.07	6.62	4.99	6.29	6.31	8.01	6.31
ap	3.71	3.14	3.37	2.54	4.02	3.52	4.12	1.81
cc	10.30	10.65	11.21	10.12	9.91	11.11	10.67	11.79
H ₂ O ⁺	2.56	2.26	2.47	3.37	2.31	2.96	2.84	2.65
Assem								
	N	I	I	I	H	M	H	G

Table D.2 P O T A S S I C L A M P R O P H Y R E D Y K E S (continued)

	5634	5635	5636	5637	5641	5643	5645	5646
Major oxides								
SiO ₂	41.92	42.38	44.16	41.91	42.66	46.48	47.17	42.37
TiO ₂	3.15	2.34	3.66	2.65	3.08	3.38	3.62	2.82
Al ₂ O ₃	7.01	7.51	7.55	5.94	7.31	7.66	8.21	6.98
Cr ₂ O ₃	0.06	0.08	0.06	0.10	0.07	0.05	0.04	0.08
Fe ₂ O ₃	2.46	1.54	0.81	0.97	0.70	3.14	0.92	1.27
FeO	5.27	5.10	6.07	6.93	4.91	4.09	5.99	5.38
MnO	0.10	0.09	0.09	0.10	0.14	0.07	0.07	0.09
MgO	11.17	11.89	11.30	18.95	10.10	10.74	8.08	12.32
CaO	6.65	6.39	5.66	5.22	8.91	5.54	5.30	7.29
Na ₂ O	1.95	1.80	1.62	1.16	1.18	1.37	1.58	1.29
K ₂ O	7.54	7.89	8.42	6.10	7.38	8.14	8.85	7.22
H ⁺ O ⁺ ₂	2.43	2.34	2.03	2.36	1.22	2.92	1.93	2.89
P ₂ O ₅	1.31	0.86	1.40	0.88	1.30	1.43	1.24	1.14
CO ₂	6.68	7.62	4.29	4.73	8.49	3.05	3.21	6.92
Total	97.64	97.75	97.06	97.90	97.38	98.01	96.17	97.98
Minor elements								
V	318	222	348	288	261	291	330	267
Cr	393	514	408	657	465	331	286	553
Ni	291	296	259	728	284	332	150	412
Cu	53	28	38	42	30	24	17	27
Zn	99	78	92	89	70	101	110	81
Rb	159	159	202	175	154	171	174	164
Sr	2174	1738	2142	1578	2287	1467	1395	2320
Y	25	16	28	19	18	24	26	22
Zr	844	560	953	516	887	1078	1259	888
Ba	3149	2909	2073	6379	1607	1524	1385	2790
La	351	208	340	206	302	393	377	346
Ce	441	270	455	298	417	478	463	413
CIPW norm								
qtz							0.40	
c								
or	41.28	44.47	43.47	34.25	42.64	43.93	47.62	40.93
ab								
an								
lc								
ne								
ac	7.68	4.83	2.47	2.96	2.16	9.54	2.83	3.95
ns	2.11	2.57	2.71	1.63	1.91	0.31	2.56	1.69
ks	1.88	1.69	2.49	1.06	1.10	1.83	2.20	1.36
di								
hy	8.95	5.97	15.20	8.12	22.18	19.17	26.85	15.27
ol	18.56	23.00	15.38	36.17	6.52	7.85		16.72
cs								
mt								
cm	0.10	0.13	0.09	0.16	0.11	0.08	0.06	0.13
il	6.45	4.82	7.33	5.31	6.25	6.74	7.30	5.75
ap	3.35	2.21	3.50	2.20	3.29	3.56	3.12	2.90
cc	9.65	10.31	7.34	8.14	13.85	6.98	7.06	11.32
H ₂ O ⁺	2.43	2.34	2.03	2.36	1.22	2.92	1.93	2.89
Assem								
	M	O	N	G		H	S	F

Table D.2 P O T A S S I C L A M P R O P H Y R E D Y K E S (continued)

	5647	5651	5652	5653	5655	5658	5659	5663
Major oxides								
SiO ₂	42.11	46.51	49.60	40.13	38.73	43.68	39.55	40.03
TiO ₂	3.15	3.75	4.15	2.88	2.77	3.07	3.05	2.62
Al ₂ O ₃	6.95	8.23	8.64	6.59	6.50	8.15	6.41	6.72
Cr ₂ O ₃	0.07	0.03	0.02	0.07	0.08	0.05	0.09	0.07
Fe ₂ O ₃	1.38	1.39	2.21	1.36	2.31	0.81	0.72	3.10
FeO	5.26	5.39	4.75	5.97	5.96	6.30	7.23	4.29
MnO	0.07	0.08	0.07	0.10	0.10	0.10	0.09	0.10
MgO	10.00	8.20	6.32	12.53	13.38	10.39	14.41	12.32
CaO	7.37	4.77	4.32	7.47	7.37	6.46	5.45	7.00
Na ₂ O	1.70	1.59	1.60	1.54	1.27	1.38	1.66	1.29
K ₂ O	7.69	9.40	10.03	7.25	6.38	8.27	7.11	6.64
H ₂ O ⁺	2.37	1.23	1.12	2.27	3.14	2.20	3.22	2.77
P ₂ O ₅	1.34	1.25	1.26	1.05	0.89	1.05	1.33	1.06
CO ₂	7.40	4.60	2.93	8.81	8.09	6.51	5.58	8.38
Total	96.79	96.39	97.00	97.95	96.89	98.37	95.81	96.32
Minor elements								
V	304	372	359	300	299	299	319	293
Cr	409	198	164	486	519	334	647	469
Ni	294	163	54	342	392	123	293	303
Cu	31	25	26	46	36	36	35	40
Zn	74	96	111	79	74	89	81	81
Rb	151	192	216	170	140	138	163	139
Sr	2645	2367	2365	1994	1635	2488	1669	1998
Y	27	22	19	20	19	25	23	18
Zr	1061	1211	1648	586	531	720	637	722
Ba	2118	4457	2590	3017	3489	2097	2539	4461
La	388	366	344	235	217	313	367	266
Ce	483	463	423	364	321	412	474	381
CIPW norm								
qtz			3.53					
c								
or	41.35	48.08	49.48	39.09	39.02	47.38	38.96	40.77
ab								
an								
lc								
ne								
ac	4.35	4.30	6.71	4.28	7.35	2.50	2.31	9.97
ns	2.50	2.21	1.53	2.17	0.81	2.23	3.01	0.19
ks	2.26	3.15	3.52	2.07	0.67	1.29	2.15	0.78
dl								
hy	19.00	22.91	18.01	8.57	0.77	10.77	4.09	4.79
ol	9.37	2.19		23.03	30.71	17.08	32.12	23.54
cs								
mt								
cm	0.11	0.05	0.03	0.11	0.13	0.08	0.15	0.16
il	6.52	7.62	8.27	5.94	5.78	6.21	6.41	5.53
ap	3.46	3.17	3.13	2.70	2.32	2.65	3.49	2.79
cc	11.08	6.32	5.18	12.05	12.44	9.81	7.52	11.48
H ₂ O ⁺	2.37	1.23	1.12	2.27	3.14	2.20	3.22	2.77
Assem								
F		H	S	H	H	P	H	F

Table D.2 POTASSIC LAMPROPHYRE DYKES (continued)

	5664	5665	5692	5890	5891	5934	5935	5937
Major oxides								
SiO ₂	41.39	38.37	43.79	43.94	40.79	43.66	42.31	39.38
TiO ₂	2.84	2.34	2.67	3.25	4.59	2.89	3.07	4.55
Al ₂ O ₃	6.54	5.99	7.04	7.71	7.54	7.88	7.93	7.76
Cr ₂ O ₃	0.09	0.11	0.08	0.05	0.04	0.05	0.04	0.02
Fe ₂ O ₃	0.98	0.59	1.35	3.30	2.01	2.88	1.47	2.87
FeO	6.09	6.48	5.73	4.88	6.40	4.74	5.90	5.87
MnO	0.09	0.10	0.09	0.10	0.10	0.09	0.09	0.11
MgO	17.38	15.00	15.59	12.02	10.91	12.06	8.48	7.52
CaO	5.37	6.94	5.21	7.16	8.16	6.98	8.71	10.07
Na ₂ O	1.49	1.36	1.30	1.01	1.56	1.23	1.47	1.38
K ₂ O	7.09	6.25	7.06	7.53	7.77	7.66	7.70	7.45
H ₂ O ⁺	3.17	2.35	3.19	2.19	2.41	2.77	2.17	2.17
P ₂ O ₅	0.65	0.80	1.16	1.04	1.19	1.18	1.11	1.85
CO ₂	7.24	6.08	2.94	2.18	4.39	4.11	6.50	4.81
Total	100.32	92.65	97.12	96.31	97.82	98.13	96.90	96.29
Minor elements								
V	253	291	278	342	472	303	332	462
Cr	627	731	533	357	257	334	258	120
Ni	505	549	518	243	131	250	115	nd
Cu	35	27	36	30	33	30	33	38
Zn	76	75	84	95	100	94	93	96
Rb	138	189	135	245	213	199	179	184
Sr	1619	1683	2190	1710	1163	1209	1069	1283
Y	16	16	22	27	25	25	17	31
Zr	495	562	789	659	866	493	588	1033
Ba	2622	3971	6200	4677	4139	4548	3887	4725
La	215	228	373	340	284	254	322	363
Ce	312	286	447	398	365	368	409	537
CIPW norm								
qtz								
c								
or	38.05	36.60	40.72	33.11	37.37	44.96	45.90	37.81
ab								
an								
lc				8.98	4.42			5.53
ne								
ac	3.02	1.91	4.41	7.97	6.08	8.71	4.51	8.79
ns	2.33	2.49	1.62		1.60	0.23	1.88	0.55
ks	1.83	1.31	0.96	0.71	1.38	0.65	0.65	0.49
di			0.76	13.24	4.79	1.54		7.08
hy	2.10	6.62	8.78			2.11	12.27	
ol	36.34	31.71	27.49	20.44	21.81	23.29	11.75	14.34
cs								
mt				1.07				
cm	0.14	0.18	0.12	0.08	0.06	0.08	0.06	0.03
il	5.75	4.97	5.37	6.54	9.11	5.74	6.18	9.15
ap	1.64	2.12	2.91	2.61	2.95	2.92	2.79	4.64
cc	8.79	12.08	7.08	5.25	10.43	9.77	14.01	11.58
H ₂ O ⁺	3.17	2.35	3.19	2.19	2.41	2.77	2.17	2.17
Assem								
	F	I	J	K	S	J	F	R

Table D.2 P O T A S S I C L A M P R O P H Y R E D Y K E S (continued)

	5938	5940	5942	5943	5944	5945	E12	E14
Major oxides								
SiO ₂	38.93	38.29	49.06	41.20	43.41	41.63	39.17	41.34
TiO ₂	3.31	3.31	4.05	2.50	3.86	3.11	2.28	3.06
Al ₂ O ₃	7.90	7.29	9.26	8.48	7.38	7.70	5.80	7.72
Cr ₂ O ₃	0.04	0.05	0.03	0.06	0.03	0.04	0.11	0.05
Fe ₂ O ₃	2.35	2.81	1.41	2.38	1.37	1.28	2.39	1.56
FeO	5.04	5.15	5.65	3.85	6.16	6.14	4.84	6.00
MnO	0.08	0.12	0.08	0.09	0.09	0.10	0.08	0.10
MgO	8.70	10.01	7.32	12.30	7.26	9.88	15.42	10.33
CaO	10.90	12.24	4.98	9.68	7.89	10.14	8.38	10.93
Na ₂ O	1.37	1.16	1.56	1.11	1.88	1.34	1.57	1.35
K ₂ O	6.77	5.67	9.19	7.38	8.42	6.89	6.40	6.58
H ₂ O ⁺	2.54	2.91	1.86	2.70	2.01	2.71	2.34	2.66
P ₂ O ₅	1.46	1.00	1.30	0.46	1.25	1.26	0.85	1.16
CO ₂	5.87	8.97	1.98	6.90	4.90	7.10	9.06	7.05
Total	95.22	98.93	97.70	99.03	95.88	99.28	98.69	99.89
Minor elements								
V	346	362	400	250	396	298	228	274
Cr	255	351	208	399	200	257	752	342
Ni	82	151	89	286	nd	98	550	157
Cu	34	38	35	27	59	39	24	36
Zn	81	95	96	64	88	86	74	81
Rb	184	152	176	218	187	160	161	161
Sr	872	1052	2419	642	872	1114	1438	1184
Y	22	28	25	20	14	20	17	16
Zr	584	561	894	346	1181	648	583	593
Ba	4600	5758	3883	4075	3166	2738	2240	2778
La	293	367	421	174	242	308	201	210
Ce	394	439	523	256	356	413	253	314
CIPW norm								
qtz								
c								
or	36.13	34.84	52.60	38.88	42.82	42.21	33.95	40.87
ab		6.17				1.29		3.23
an								
lc	5.40			4.91				
ne	1.72			1.42				
ac	7.31	3.56	4.24	6.26	4.21	3.84	7.41	4.74
ns	0.23		2.08		2.82	1.42	1.36	0.79
ks			1.08		2.79		1.83	
di	7.12		3.70	1.80	0.55			2.23
hy		9.34	18.75		23.05	10.94	3.98	11.46
ol	17.19	13.85	2.10	23.92	0.93	15.10	30.42	10.75
cs								
mt		2.45		0.44				
cm	0.06	0.08	0.05	0.09	0.05	0.06	0.17	0.08
il	6.76	6.54	8.00	4.91	7.79	6.12	4.64	6.11
ap	3.72	2.46	3.20	1.13	3.15	3.09	2.16	2.89
cc	14.35	20.71	4.69	16.24	11.84	15.91	14.07	16.85
H ₂ O ⁺	2.54	2.91	1.86	2.70	2.01	2.71	2.34	2.66
Assem								
	Q	Q	T	Q	N	N	M	N

Table D.3 A N O M A L O U S D Y K E S

	5667	5668	5672	5688
Major oxides				
SiO ₂	39.38	39.79	40.45	44.15
TiO ₂	2.65	2.69	2.38	2.34
Al ₂ O ₃	8.45	9.08	6.43	6.02
Cr ₂ O ₃	0.18	0.17	0.26	0.28
Fe ₂ O ₃	2.75	3.83	2.72	2.85
FeO	9.16	9.08	9.76	3.21
MnO	0.16	0.21	0.19	0.09
MgO	10.66	10.52	15.84	9.72
CaO	13.64	12.62	13.66	13.95
Na ₂ O	1.90	2.05	0.84	1.82
K ₂ O	1.42	1.55	1.14	5.78
H ₂ O ⁺	2.82	3.02	3.65	1.80
P ₂ O ₅	0.49	0.52	0.33	0.87
CO ₂	2.96	4.01	0.77	5.56
Total	96.44	98.97	98.16	98.16
Minor elements				
V	481	470	437	251
Cr	1237	1184	1797	1919
Ni	166	148	306	35
Cu	164	152	159	27
Zn	63	99	82	77
Rb	36	32	30	163
Sr	649	881	409	1609
Y	26	26	18	23
Zr	252	277	142	451
Ba	1031	945	990	4277
La	124	129	42	307
Ce	176	205	103	378
CIPW norm				
qtz				
c				
or	8.95	9.52	2.54	33.94
ab	9.35	17.45		
an	11.03	11.43	10.97	
lc			3.57	
ne	4.23	0.32	4.06	
ac				8.51
ns				1.45
ks				0.37
di	30.57	19.24	42.60	23.67
hy				2.06
ol	17.57	19.94	24.26	9.80
mt	4.25	5.77	4.16	
cm	0.25	0.26	0.40	0.43
il	5.37	5.31	4.76	4.59
ap	1.24	1.28	0.82	2.13
cc	7.18	9.48	1.85	13.06
H ₂ O ⁺	2.82	3.02	3.65	1.80
Assem				
	K	K	K	T

APPENDIX E

RECALCULATED $\text{Ca}(\text{Mg})\text{CO}_3$ - AND H_2O^+ -FREE WHOLE-ROCK
CHEMICAL ANALYSES FOR THE HOLSTEINSBORG DYKES

Notes

- (a) All values are given as weight per cent oxides.
- (b) 14 oxides, excluding CO_2 and H_2O^+ , were used in the recalculation. The values for H_2O^+ and CO_2 were removed. All the CO_2 was removed as CaCO_3 by subtracting the wt% equivalent from CaO. If the resultant CaO value was negative, this was compensated for by removing an equivalent wt% of MgO and making CaO equal to zero. All the resulting oxide values were then readjusted to give a total of 100%.

Table E.1 KIMBERLITE DYKES

	5503	5504	5505	5508	5511	5518	5603	5605	5606	5607
SiO ₂	39.74	39.25	39.57	39.89	40.96	36.97	39.39	39.08	38.67	38.52
TiO ₂	3.19	3.18	3.37	3.29	3.21	2.22	4.76	2.92	4.47	4.61
Al ₂ O ₃	3.72	3.86	4.35	4.32	4.01	2.74	3.77	3.27	4.15	4.48
Cr ₂ O ₃	0.27	0.26	0.23	0.26	0.29	0.19	0.29	0.36	0.24	0.25
Fe ₂ O ₃	3.38	3.76	4.82	4.75	3.80	7.37	3.80	1.76	3.76	4.97
FeO	11.40	10.81	9.45	9.84	11.29	9.89	12.71	12.87	11.93	11.27
MnO	0.26	0.25	0.24	0.23	0.26	0.37	0.23	0.28	0.24	0.23
MgO	33.27	33.94	33.35	32.56	30.88	36.72	31.87	34.95	30.81	31.64
CaO	-	-	-	-	-	-	-	-	2.52	0.67
Na ₂ O	0.42	0.24	0.28	0.36	0.47	0.20	0.29	0.28	0.32	0.31
K ₂ O	3.23	3.51	3.52	3.63	3.64	1.55	2.26	2.83	2.31	2.49
P ₂ O ₅	0.81	0.62	0.46	0.56	0.86	1.11	0.34	0.95	0.33	0.30
NiO	0.14	0.14	0.13	0.13	0.14	0.13	0.11	0.20	0.10	0.10
BaO	0.16	0.20	0.22	0.18	0.20	0.53	0.17	0.24	0.16	0.18

	5696	5699	5820	5834	5903	5905	5907	5908	5915	5932
SiO ₂	35.82	36.79	36.03	37.31	37.17	34.86	35.43	39.45	38.73	36.72
TiO ₂	4.82	4.46	2.50	3.86	2.59	3.48	4.19	4.03	4.05	4.07
Al ₂ O ₃	2.52	2.90	0.83	1.54	0.54	1.79	2.77	2.45	2.57	2.08
Cr ₂ O ₃	0.37	0.32	0.38	0.41	0.32	0.20	0.26	0.33	0.33	0.33
Fe ₂ O ₃	4.37	4.11	9.07	4.14	4.82	7.74	7.54	6.26	6.87	5.16
FeO	10.63	10.96	8.83	11.20	11.27	13.11	11.78	9.70	9.02	10.23
MnO	0.21	0.21	0.30	0.26	0.28	0.37	0.41	0.22	0.21	0.33
MgO	35.25	33.95	40.69	38.97	41.85	35.81	30.67	33.66	33.39	37.37
CaO	3.78	3.16	-	-	-	-	-	1.85	2.81	1.22
Na ₂ O	0.13	0.14	0.08	0.07	0.06	0.08	0.30	0.17	0.14	0.13
K ₂ O	1.61	2.21	0.12	1.36	0.33	0.63	2.14	1.16	1.17	1.70
P ₂ O ₅	0.27	0.58	0.90	0.55	0.49	1.64	3.89	0.55	0.52	0.39
NiO	0.14	0.13	0.15	0.16	0.20	0.06	0.09	0.13	0.14	0.15
BaO	0.08	0.09	0.12	0.16	0.10	0.23	0.54	0.05	0.05	0.12

Table E.1 KIMBERLITE DYKES (continued)

	5947	5962	5964	5966	5966A	5966B	5966D	5973	5974	5975
SiO ₂	37.43	33.89	37.22	39.43	39.21	39.59	39.76	36.61	35.86	38.69
TiO ₂	5.04	5.18	4.73	5.02	3.21	3.10	5.05	4.52	5.09	5.94
Al ₂ O ₃	2.91	2.67	3.55	3.12	3.79	3.69	3.42	3.89	2.70	3.29
Cr ₂ O ₃	0.27	0.25	0.25	0.30	0.29	0.39	0.33	0.19	0.31	0.26
Fe ₂ O ₃	3.89	4.82	4.82	3.64	4.38	4.17	3.27	6.02	5.04	5.77
FeO	12.08	10.49	11.34	12.59	10.37	10.85	13.00	9.35	10.62	10.49
MnO	0.25	0.21	0.23	0.24	0.24	0.28	0.25	0.22	0.21	0.26
MgO	32.28	29.61	29.98	32.48	34.44	33.17	31.75	25.80	33.60	31.36
CaO	2.53	1.61	5.17	-	-	-	-	9.50	3.90	-
Na ₂ O	0.27	1.43	0.26	0.33	0.25	0.29	0.34	0.19	0.31	1.00
K ₂ O	1.99	7.75	2.35	2.08	2.89	3.27	2.05	2.52	1.75	2.70
P ₂ O ₅	0.82	1.27	0.67	0.54	0.63	0.90	0.59	1.01	0.35	0.05
NiO	0.13	0.07	0.12	0.14	0.15	0.18	0.11	0.09	0.14	0.14
BaO	0.10	0.76	0.12	0.09	0.15	0.25	0.10	0.10	0.10	0.05

	5983	5985	5997	5998	5999A1	5999A2	5999B	E13	E15	BS-19	BS-B
SiO ₂	36.89	37.48	36.70	36.80	37.29	37.70	37.80	37.23	36.33	37.41	37.89
TiO ₂	5.19	4.86	5.57	4.84	4.92	5.15	5.29	2.34	5.38	4.11	3.95
Al ₂ O ₃	4.56	4.62	3.15	3.32	3.77	3.82	4.21	0.56	3.25	1.47	1.97
Cr ₂ O ₃	0.23	0.20	0.31	0.25	0.23	0.23	0.23	0.27	0.27	0.28	0.26
Fe ₂ O ₃	5.67	5.95	4.55	4.42	5.11	5.00	6.10	4.62	4.89	3.73	4.90
FeO	9.50	9.34	11.33	11.07	10.71	10.77	10.17	10.85	10.94	11.74	10.26
MnO	0.18	0.20	0.21	0.23	0.23	0.23	0.25	0.27	0.21	0.23	0.27
MgO	27.36	25.41	34.71	30.93	28.21	28.35	27.76	42.75	35.00	40.04	39.08
CaO	6.50	8.23	-	4.46	6.04	5.29	4.30	-	0.51	-	-
Na ₂ O	0.24	0.26	0.42	0.56	0.35	0.32	0.58	0.07	0.40	0.23	0.25
K ₂ O	2.97	2.58	2.38	2.25	2.39	2.43	2.61	0.33	2.24	0.61	0.99
P ₂ O ₅	0.47	0.66	0.41	0.64	0.56	0.73	0.48	0.43	0.34	0.15	0.18
NiO	0.10	0.09	0.14	0.13	0.10	0.12	0.11	0.18	0.13	-	-
BaO	0.15	0.12	0.12	0.10	0.10	0.10	0.12	0.11	0.09	-	-

Table E.2 P O T A S S I C L A M P R O P H Y R E D Y K E S

	5611	5612	5616	5620	5621	5622	5622A	5623	5624	5625
SiO ₂	50.43	50.77	54.56	52.22	53.79	46.33	47.34	49.56	50.01	49.77
TiO ₂	2.95	3.10	4.24	4.11	4.41	2.56	2.70	4.12	4.23	3.68
Al ₂ O ₃	7.38	7.60	9.41	9.31	9.51	5.78	6.05	8.48	8.20	8.05
Cr ₂ O ₃	0.14	0.13	0.02	0.05	0.03	0.13	0.13	0.08	0.10	0.10
Fe ₂ O ₃	3.07	2.94	2.56	4.00	3.32	1.59	1.80	1.53	1.86	1.10
FeO	6.36	6.54	4.40	3.76	4.29	7.37	7.41	7.38	7.85	8.14
MnO	0.12	0.12	0.08	0.10	0.08	0.12	0.12	0.11	0.14	0.12
MgO	17.83	16.79	7.48	9.51	7.74	26.14	23.89	14.33	13.49	15.88
CaO	-	-	2.36	1.16	1.11	-	-	0.74	-	-
Na ₂ O	2.11	2.02	2.14	1.50	2.17	1.18	1.36	1.90	1.80	1.72
K ₂ O	8.26	8.54	10.37	10.81	10.75	7.26	7.55	8.99	9.82	9.07
P ₂ O ₅	1.00	1.10	2.06	2.48	1.99	1.11	1.13	1.91	1.78	1.53
NiO	0.09	0.09	0.01	0.01	0.01	0.01	0.12	0.04	0.04	0.06
BaO	0.25	0.27	0.32	0.98	0.80	0.42	0.39	0.85	0.68	0.77

	5625A	5625B	5628	5629	5630	5632	5634	5635	5636	5637
SiO ₂	51.22	49.99	50.25	49.29	48.77	50.47	51.82	53.42	51.11	48.78
TiO ₂	4.06	3.04	3.79	3.81	4.72	3.75	3.89	2.95	4.24	3.08
Al ₂ O ₃	8.88	6.71	8.18	7.93	8.77	10.00	8.67	9.47	8.74	6.91
Cr ₂ O ₃	0.09	0.12	0.10	0.10	0.05	0.07	0.07	0.10	0.07	0.12
Fe ₂ O ₃	1.56	0.91	1.19	0.15	1.54	2.05	3.04	1.94	0.94	1.13
FeO	7.71	8.72	8.12	9.08	9.27	5.91	6.51	6.43	7.03	8.07
MnO	0.14	0.13	0.14	0.11	0.12	0.11	0.12	0.11	0.10	0.12
MgO	12.24	19.63	14.23	15.92	10.32	14.36	12.17	12.00	13.08	21.39
CaO	-	-	-	-	4.75	1.27	-	-	0.24	-
Na ₂ O	1.93	0.44	1.76	1.90	1.34	1.13	2.41	2.27	1.87	1.35
K ₂ O	9.74	8.40	9.56	9.02	8.03	9.43	9.32	9.94	9.74	7.10
P ₂ O ₅	1.66	1.24	1.95	1.70	1.95	0.86	1.62	1.08	1.62	1.02
NiO	0.04	0.10	0.05	0.04	0.01	0.02	0.05	0.05	0.96	0.10
BaO	0.74	0.56	0.68	0.96	0.37	0.55	0.30	0.24	0.27	0.83

Table E.2 POTASSIC LAMPROPHYRE DYKES (continued)

	5641	5643	5645	5646	5647	5651	5652	5653	5655	5658
SiO ₂	54.91	52.57	54.12	52.81	53.62	54.36	55.39	52.00	50.49	53.15
TiO ₂	3.96	3.82	4.15	3.51	4.01	4.38	4.63	3.73	3.61	3.74
Al ₂ O ₃	9.41	9.42	9.42	8.70	8.85	9.62	9.65	8.54	8.47	9.92
Cr ₂ O ₃	0.09	0.05	0.05	0.10	0.09	0.04	0.02	0.09	0.10	0.06
Fe ₂ O ₃	0.90	1.06	1.06	1.58	1.76	1.62	2.47	1.76	3.01	0.99
FeO	6.32	4.63	6.87	6.71	6.70	6.30	5.30	7.74	7.77	7.67
MnO	0.18	0.08	0.08	0.11	0.09	0.09	0.08	0.13	0.13	0.12
MgO	11.26	12.15	9.27	14.00	10.87	8.68	7.06	12.76	14.71	11.05
CaO	-	1.88	1.40	-	-	-	0.66	-	-	-
Na ₂ O	1.52	1.81	1.81	1.61	2.16	1.86	1.79	2.00	1.66	1.68
K ₂ O	9.50	10.15	10.15	9.00	9.79	10.99	11.20	9.40	8.32	10.06
P ₂ O ₅	1.67	1.62	1.42	1.42	1.71	1.46	1.41	1.36	1.16	1.28
NiO	0.04	0.05	0.02	0.06	0.05	0.02	0.01	0.05	0.07	0.01
BaO	0.23	0.19	0.17	0.39	0.31	0.58	0.32	0.44	0.51	0.28

	5659	5663	5664	5665	5692	5890	5891	5934	5935	5937
SiO ₂	48.96	52.61	50.34	49.62	49.72	48.95	47.45	50.41	52.59	47.62
TiO ₂	3.78	3.44	3.45	3.03	3.03	3.62	5.34	3.34	3.82	5.43
Al ₂ O ₃	7.93	8.83	7.95	7.75	7.99	8.59	8.77	9.10	9.86	9.27
Cr ₂ O ₃	0.11	0.13	0.11	0.14	0.09	0.06	0.05	0.06	0.05	0.02
Fe ₂ O ₃	0.89	4.07	1.19	0.76	1.53	3.68	2.34	3.33	1.83	3.43
FeO	8.95	5.64	7.41	8.38	6.51	5.44	7.45	5.47	7.33	7.01
MnO	0.11	0.12	0.11	0.13	0.10	0.11	0.12	0.10	0.11	0.13
MgO	16.37	12.74	17.78	18.66	17.70	13.39	12.69	13.93	10.54	8.98
CaO	-	-	-	-	1.67	4.89	3.00	2.02	0.55	4.72
Na ₂ O	2.05	1.70	1.81	1.76	1.48	1.13	1.81	1.42	1.83	1.65
K ₂ O	8.80	8.73	8.62	8.08	8.02	8.39	9.04	8.84	9.57	8.90
P ₂ O ₅	1.65	1.39	0.79	1.03	1.32	1.16	1.38	1.36	1.38	2.21
NiO	0.05	0.05	0.07	0.09	0.07	0.03	0.02	0.02	0.01	-
BaO	0.35	0.66	0.35	0.57	0.78	0.58	0.54	0.59	0.53	0.63

Table E.2 POTASSIC LAMPROPHYRE DYKES (continued)

	5938	5940	5942	5943	5944	5945	E12	E14
SiO ₂	48.72	50.15	53.44	50.74	52.23	51.52	50.89	50.70
TiO ₂	4.14	4.34	4.41	3.08	4.64	3.85	2.96	3.75
Al ₂ O ₃	9.89	9.55	10.09	10.44	8.88	9.53	7.54	9.51
Cr ₂ O ₃	0.05	0.07	0.03	0.07	0.04	0.05	0.14	0.06
Fe ₂ O ₃	2.94	3.68	1.54	2.93	1.64	1.58	3.11	1.91
FeO	6.31	6.74	6.15	4.74	7.41	7.60	6.29	7.36
MnO	0.10	0.16	0.09	0.11	0.11	0.12	0.10	0.13
MgO	10.89	13.11	7.97	15.15	8.73	12.23	17.10	12.67
CaO	4.30	1.09	2.68	1.12	2.00	1.38	-	2.39
Na ₂ O	1.71	1.52	1.70	1.37	2.26	1.66	2.04	1.65
K ₂ O	8.47	7.43	10.01	9.09	10.13	8.53	8.31	8.07
P ₂ O ₅	1.83	1.31	1.42	0.57	1.50	1.56	1.10	1.42
NiO	0.01	0.03	0.01	0.04	-	0.01	0.09	0.02
BaO	0.64	0.84	0.47	0.55	0.42	0.38	0.32	0.38

Table E.3 ANOMALOUS DYKES

	5667	5668	5672	5688
SiO ₂	45.25	45.66	43.41	52.27
TiO ₂	3.04	3.09	2.55	2.77
Al ₂ O ₃	9.71	10.42	6.90	7.13
Cr ₂ O ₃	0.18	0.20	0.28	0.33
Fe ₂ O ₃	3.16	4.40	2.92	3.37
FeO	10.52	10.42	10.48	3.80
MnO	0.17	0.24	0.20	0.11
MgO	12.25	12.07	17.00	11.51
CaO	11.35	8.63	13.61	8.15
Na ₂ O	2.18	2.35	0.90	2.16
K ₂ O	1.63	1.78	1.22	6.84
P ₂ O ₅	0.56	0.60	0.35	1.03
NiO	0.02	0.02	0.04	0.01
BaO	0.14	0.13	0.12	0.53

APPENDIX FANALYTICAL TECHNIQUESF.1 Whole-rock analysisF.1.1 Sample preparation

The rock specimens were cut into thin slices (less than 1.5cm wide) using a diamond saw to enable unwanted material, such as xenoliths and weathered surfaces, to be removed. From these slices a sample was chosen, where possible, using the scheme proposed by Mercy (unpublished) and referred to by Wager and Brown (1960) which is given in Table F.1.

grain size	sample weight
10 - 20mm	1500g
1 - 10mm	1000g
0 - 1mm	500g

Table F.1 Recommended sample weights for given grain sizes

The chosen slices were reduced to small rock chips using a Sturtevant open door roll crusher; the samples were crushed twice, the second time with a narrower jaw setting. The chips were then coned and quartered a suitable number of times to give approximately 200g of sample. To obtain optimum grinding conditions two 100g samples were ground separately using a 250cc tungsten carbide grinding barrel with a fast Tema (1000 rpm). Each sample was ground for seven minutes

in order to obtain 200mesh powders. After thirty seconds of grinding a small sample was removed from the barrel for subsequent ferrous determinations (after Fitton and Gill 1970). After grinding, the original 2x100g samples were mixed for two hours and all aliquots were dried overnight at 110°C before use in any of the determinations.

From a comparison of analyses of different aliquots given in Table F.2, it seems that the aliquot of rock chips used for each sample preparation was representative of the original rock specimen. (5966D is not a strict aliquot but another part of the original rock specimen which was prepared without the use of the jaw crusher to show that there was no apparent contamination).

F.1.2 Accuracy and Precision

When presenting experimental results it is useful to include some estimation of accuracy and precision and this is often given in the form of a standard deviation. To make these estimates meaningful, however, a considerable number of replicate results are required. In this study it was not thought meaningful to perform the suitable number of replicate determinations, particularly as most of the methods are well established departmental techniques and previous workers using these methods have presented estimates of precision and accuracy (Strong 1970, Appleton 1970 and Hill 1974). It was thought that a rigorous statistical analysis of the precision of these results would not make a useful addition to this study because of the uncertainty, when working with such coarse-grained rocks, of obtaining representative rock samples, particularly for kimberlite which is characteristically heterogeneous.

Some estimations of the precision of this work can

Sample number	<u>5966</u>	<u>5966D</u>	<u>5999a(1)</u>	<u>5999a(2)</u>	<u>5622</u>	<u>5622A</u>
Major oxides (wt%)						
SiO ₂	29.98	29.06	33.06	32.49	39.29	39.21
TiO ₂	3.82	3.69	4.36	4.44	2.17	2.24
Al ₂ O ₃	2.37	2.50	3.34	3.29	4.90	5.01
Fe ₂ O ₃	2.77	2.39	4.53	4.31	1.35	1.49
FeO	9.57	9.50	9.50	9.28	6.25	6.14
MnO	0.18	0.18	0.20	0.20	0.10	0.10
MgO	27.49	26.88	25.01	24.43	22.55	21.61
CaO	8.34	8.33	10.16	9.96	4.73	5.02
Na ₂ O	0.25	0.25	0.31	0.28	1.00	1.13
K ₂ O	1.58	1.50	2.12	2.09	6.16	6.25
H ₂ O ⁺	3.29	3.55	3.12	2.90	2.82	3.36
P ₂ O ₅	0.41	0.43	0.50	0.63	0.94	0.94
CO ₂	9.61	10.57	3.78	4.25	5.14	5.94
Minor elements (ppm)						
V	450	462	574	562	220	236
Cr	1565	1615	1380	1475	756	744
Ni	880	874	739	767	856	782
Cu	79	79	145	145	28	28
Zn	73	79	86	78	88	81
Rb	58	59	68	73	168	162
Sr	961	1033	806	844	2563	2549
Y	13	16	14	24	20	19
Zr	229	208	440	402	490	505
Ba	649	664	848	797	3227	2838
La	153	139	201	182	262	322
Ce	249	263	217	228	345	384

Table F.2 Comparison of analyses of different aliquots of rock chips

be obtained from the duplicate XRF results which are presented in Table F.3 or from replicate results obtained during wet chemical determinations where standard deviations may be quoted (see part F.1.5). Standard deviations were calculated from equation (1) for replicate analyses but using equation (2) for a set of duplicate results (from Welcher 1963 p. 320).

$$s = (\sum (X - \bar{X})^2 / N - 1)^{\frac{1}{2}} \quad - \text{equation (1)}$$

$$s = (\sum d^2 / 2n)^{\frac{1}{2}} \quad - \text{equation (2)}$$

where s = standard deviation
 N = number of replicate analyses
 d = difference in values of duplicate analyses
 X = measured value
 $\bar{X}$ = mean of measured values
 n = number of pairs of duplicate results

It was found that for XRF determinations the main source of error lay in the quality of the calibration curves. The major oxide calibration curves were good and most of the trace element curves were satisfactory. Some of the trace element calibration curves were, however, very poor and the Cu, Ce and La values quoted should be treated with some caution.

A further measure of accuracy can be obtained by comparing the new standard determinations with values obtained for the same rock specimen during the routine whole-rock analysis of this study. A comparison of the following samples can be made:

(a) Duplicate sample powder aliquots with separate preparation

Sample number	5624	5624 fus	5907	5907 fus	5964	5964 fus
SiO ₂	41.30	40.96	16.44	16.37	32.03	31.66
TiO ₂	3.44	3.43	1.95	1.92	4.06	4.04
Al ₂ O ₃	6.69	6.63	1.28	1.28	3.07	3.01
Fe ₂ O ₃	8.51	8.70	9.61	9.49	14.26	14.18
MnO	0.10	0.12	0.19	0.18	0.20	0.20
MgO	11.38	11.26	17.58	17.89	25.66	25.63
CaO	7.02	7.08	24.76	24.87	10.30	10.42
K ₂ O	7.88	8.08	0.99	0.99	2.03	1.99
P ₂ O ₅	1.43	1.46	1.78	1.83	0.57	0.56

(b) Duplicate pressed discs from one fused pellet

Sample number	5509	5509 dis	5655	5655 dis	5903	5903 dis
SiO ₂	29.77	29.55	38.45	39.00	30.48	30.41
TiO ₂	4.17	4.17	2.77	2.76	2.12	2.12
Al ₂ O ₃	6.05	6.03	6.47	6.52	0.46	0.42
Fe ₂ O ₃	14.04	14.06	7.89	7.97	14.36	14.06
MnO	0.32	0.32	0.09	0.10	0.23	0.22
MgO	11.63	11.72	13.17	13.59	35.54	36.03
CaO	17.19	17.09	7.42	7.33	6.49	6.50
K ₂ O	3.57	3.57	6.39	6.37	0.29	0.29
P ₂ O ₅	0.80	0.83	0.89	0.88	0.40	0.41

Table F.3 Duplicate XRF results (in weight per cent)

El3 and El5 from Table F.4 with 5903 and 5997 in Table D.1 (Appendix D)
El2 and El4 from Table F.4 with 5612 and 5945 in Table D.2 (Appendix D).
Each pair of samples (e.g. El3 and 5903), although taken from one
original rock specimen, are not strict aliquots because different grinding
techniques were used, but it can be seen from these tables that the
results show good agreement.

F.1.3 Standards

The departmental collection of standards was found
to be inadequate when concerned with such ultrabasic rock types. Six
new whole-rock analyses (including some minor elements), therefore,
were determined using wet chemical techniques (see Table F.4; analyst
M. J. Saunders, University of Edinburgh). These samples included four
from the Holsteinsborg dykes (El2-El5 from Table F.4) and two other
rocks of extreme compositions, a jacupirangite (El1) and a dunite (El6).
Two other whole-rock analyses of samples from the Holsteinsborg dykes,
determined by wet chemistry during a preliminary study, were also used
as standards (BS-19 and BS-B from Table F.4; analyst A. C. S. Smith,
then at University College London). All these standards were found
to be extremely satisfactory.

Additional standards were used for XRF determinations
and these included the U.S.G.S. standards DTS-1, G2, AGV-1, GSP-1,
Tl, BCR-1, W1 and PCC-1 and the well established departmental standards
El and E2. For certain elements it was found useful to include the
ultrabasic rock samples 40402, 50141, 85955, 85974 and 85976 from the
Tugtutoq - Narssaq area, Greenland, which were recently analysed by
J. Thomas (University of Reading).

It was also found necessary to determine by wet

Table F.4 New wet chemical determinations for use as standards (wt%)

	<u>E11</u>	<u>E12</u>	<u>E13</u>	<u>E14</u>	<u>E15</u>	<u>E16</u>
SiO ₂	33.20	39.17	30.84	41.34	30.84	40.78
TiO ₂	7.52	2.28	1.94	3.06	4.57	0.01
Al ₂ O ₃	4.58	5.80	0.46	7.72	2.76	0.28
Cr ₂ O ₃	0.07	0.11	0.22	0.05	0.23	0.84
Fe ₂ O ₃	11.31	2.39	3.83	1.56	4.15	0.54
FeO	10.55	4.84	8.99	6.00	9.29	6.09
MnO	0.22	0.08	0.22	0.10	0.18	0.09
NiO	0.04	0.07	0.14	0.02	0.11	0.31
MgO	16.05	15.42	36.80	10.33	29.71	50.50
CaO	13.59	8.38	6.19	10.93	7.45	0.06
Na ₂ O	0.28	1.57	0.06	1.35	0.34	0.01
K ₂ O	0.84	6.40	0.27	6.58	1.90	<0.01
P ₂ O ₅	0.59	0.85	0.36	1.16	0.29	0.01
CO ₂	<0.02	9.06	6.38	7.05	5.52	<0.03
H ₂ O ⁺	1.26	2.34	3.11	2.66	3.04	0.54
SrO	0.07	0.17	0.09	0.14	0.11	nd
Total	100.17	98.93	99.90	100.05	100.49	100.06

	<u>BS-19</u>	<u>BS-B</u>		
SiO ₂	32.29	29.08		
TiO ₂	3.55	3.03		
Al ₂ O ₃	1.27	1.51	SrO	0.16
Cr ₂ O ₃	0.24	0.20		
Fe ₂ O ₃	3.22	3.76		
FeO	10.13	7.87		
MnO	0.20	0.21	SrO	0.31
MgO	35.44	33.04		
CaO	4.94	7.33		
Na ₂ O	0.20	0.19		
K ₂ O	0.53	0.76	Zr	1700 ppm
P ₂ O ₅	0.13	0.14		
CO ₂	4.85	9.10		
H ₂ O ⁺	3.19	3.97		
Total	100.18	100.19		

Analysts -

E11 - E16: M. J. Saunders, University of Edinburgh

BS-19 and BS-B: A. C. S. Smith, then at University College London.

chemistry the Sr and Zr contents of selected samples from the Holsteinsborg dykes and the results are given in Table F.4. This allowed the initial calibration curves to be either extended or checked to cater for samples which had extremely high concentrations of these elements.

F.1.4 X-ray Fluorescence Spectroscopy

Initially it was decided to analyse for both major and minor elements using pressed powder discs. This technique and computer programme were developed by Brown, Hughes and Esson (1973) and first used in Edinburgh by Chapman (1975). During the processing of the data obtained for the major elements, however, it was found that (i) the calibration curves were unsatisfactory or unusable and (ii) the computer programme effectively did not take into account the possibility that a rock might contain volatiles which was important for the Holsteinsborg dykes where a sample might contain up to 25 wt% of volatiles. Another problem was encountered when attempting to determine sodium using the pressed powder discs. For the Holsteinsborg dykes this determination was unsuccessful because of apparently substantial interference by phosphorous, which in some samples occurs in higher concentrations than sodium itself. It was, therefore, decided to determine sodium using wet chemical techniques.

The method finally adopted for major element analysis was similar to that of Rose et al. (1963) and a well established method at Edinburgh. Each sample together with lanthanum oxide and lithium tetraborate (in proportions 1:1:8) was fused at 1050°C. The glass bead was ground in a tungsten carbide Tema and the resulting powder pressed into a disc with a backing of boric acid.

The trace elements were determined using the pressed rock powder discs, the discs being pressed to 15 tons with a boric acid support.

All determinations were made using the twenty-four channel automatic, Philips PW1212 X-ray fluorescence spectrometer at Edinburgh. The operating conditions are given in Table F.5. Major elements were determined using a Cr-tube, except for Mn. All the trace elements and Mn were determined using a W-tube. The mass absorptions of the pressed powder discs were determined using the single channel Philips PW1540 spectrometer.

Counts for Zr and Y were obtained using the 220 diffracting plane of the LiF crystal to allow the discrimination of these peaks from those for Sr and Rb respectively.

The data was processed using a departmental computer programme (written by R. F. Cheeney), which checks for misfit counts, corrects for drift, recalculates the counts using user specified equations (i.e. subtracting backgrounds and correcting for interference), checks for statistical consistency and then estimates the concentrations. The programme uses the 'regression' method for major elements which calculates a 'best fitting' regression constant or the 'Davies' method for trace elements which performs a regression calculation on counts corrected for matrix effects. The programme rejects standards if the difference of the estimated concentration is greater than a suggested rejection level. All concentrations were calculated using (peak - background) equations.

Element	Peak	kV	mA	crystal	spacing	diffracting plane	counter	peak counting time	background counting time	collimator	vacuum
Al	K α	60	24	PE	8.74	002	F	40	-	C	Y
Ba	K α	80	24	LiF	4.028	200	S	20	20	F	N
Ca	K α	40	16	PE	8.74	002	F	10	-	F	Y
Ce	L β	80	24	LiF	4.028	200	S	40	20	F	N
Cr	K α	80	24	LiF	4.028	200	F	20	40	F	Y
Cu	K α	80	24	LiF	4.028	200	S	40	40	F	N
Fe	K α	60	24	LiF	4.028	200	F	20	-	C	Y
K	K α	60	24	PE	8.74	002	F	10	-	C	Y
La	L α	80	24	LiF	4.028	200	S	40	20	F	N
Mg	K α	40	32	KAP	26.63	001	F	100	100	C	Y
Mn	K α	60	24	LiF	4.028	200	F	20	20	F	Y
Ni	K α	80	24	LiF	4.028	200	S	20	20	F	N
P	K α	60	24	PE	8.74	002	F	40	40	F	Y
Rb	K α	80	24	LiF	2.85	220	S	40	40	F	N
Si	K α	60	24	PE	8.74	002	F	20	-	C	Y
Sr	K α	80	24	LiF	2.85	220	S	40	40	F	N
Ti	K α	60	24	LiF	4.028	200	F	20	-	C	Y
V	K α	80	24	LiF	4.028	200	F	20	20	F	Y
Y	K α	80	24	LiF	2.85	220	S	40	40	F	N
Zn	K α	80	24	LiF	4.028	200	S	40	40	F	N
Zr	K α	80	24	LiF	2.85	220	S	40	40	F	N

key

counter F = flow

S = scintillation

collimator C = coarse

F = fine

vacuum Y = yes

N = no

counting time given in seconds

Table F.5 Operating conditions for X-ray fluorescence spectroscopy

F.1.5 Wet Chemistry Techniques

(a) Ferrous Iron

Ferrous iron was determined using a method after Wilson (1955). The sample was decomposed in the cold with hydrofluoric and nitric acids, in the presence of ammonium metavanadate. For many rock types three days is sufficient for this solution process. With the Holsteinsborg samples, however, it was found (M. J. Saunders) that after this period duplication was extremely poor and this was apparently caused by incomplete dissolution. It was found suitable to leave the samples in acid for two weeks.

The excess vanadate was then titrated against ferrous ammonium sulphate using the indicator sodium diphenylamine p-sulphonate. The maximum difference in replicate results was 0.56 wt%. The estimated standard deviations for ten replicate and 17 duplicate results were 0.1 and 0.2 respectively.

(b) Sodium

The sample was decomposed by evaporating with a mixture of hydrofluoric and nitric acids. The residue was fumed with sulphuric acid to remove the fluorides and then dissolved in very dilute sulphuric acid. The sodium concentrations were determined using an EEL (model A) flame photometer, bracketing readings with a series of standard solutions. It has been found (M. J. Saunders) that it is best to work in a solution of sulphuric acid to reduce calcium interference. Calcium sulphate is not very soluble and does not volatilise easily in the flame. A double sodium filter was used to remove any remaining calcium interference. The maximum difference between determinations on one sample was 0.07 wt%. The standard deviation for both 6 duplicate and 7 replicate results was 0.03.

(c) Carbon dioxide

Carbon dioxide was determined using a rapid pressometric method after Welcher (1963). The carbon dioxide was liberated by addition of acid and measured using a manometer.

The accuracy of the method was checked by the determination of carbon dioxide gravimetrically on three samples. The comparison of results is given in Table F.6 and shows the pressometric method to be very satisfactory. In the gravimetric method the carbon dioxide was evolved by addition of acid and then absorbed by soda asbestos and weighed directly. Nitrogen was used as the carrier gas and the carbon dioxide purified by passage through absorbers. The maximum difference between results on one sample was 0.74 wt% and the estimated standard deviations on both 15 duplicate and 8 replicate results were 0.2.

sample number	gravimetric method	pressometric method
5907	23.73	23.39
5944	4.82	4.90
E14	7.05*	7.05*
		6.85

* determinations by M. J. Saunders

Table F.6 A comparison of carbon dioxide determinations using
pressometric and gravimetric methods.

(Values expressed in weight per cent)

(d) Water

H_2O^+ was determined gravimetrically using the method of Shapiro and Brannock (1955, 1962). The sample, however, was heated with a flux of 2:1 lead oxide and lead chromate (after Peck 1964). The water evolved was absorbed on filter paper and weighed directly. The maximum difference in results on one sample was 0.48 wt%. The estimated standard deviations on 20 duplicate and 4 replicate results were 0.07 and 0.2 respectively.

(e) Strontium

The samples were fused with lithium metaborate and the product dissolved in nitric acid. The strontium concentrations were determined by standard addition using a Varian Techtron Atomic Absorption Spectrophotometer (type AA5). To prevent ionisation of the strontium, potassium chloride, to give a concentration of 1000ppm, was added to each aliquot. Duplicate results for SrO were 0.420 and 0.417 wt%.

(f) Zirconium

3g of sample was fused with sodium carbonate. Zirconium was determined gravimetrically in the residue using p-bromomandelic acid, following a method adapted from Rafiq et al. (1963).

(g) Fluorine and Chlorine

These elements were determined using a rapid spectrophotometric method after Huang and Johns (1967). The method involves taking separate aliquots of a single sample dissolution. Fluorine was determined using the colour development of zirconium-erichrome cyanine R and chlorine was determined using the stable coloured iron (III) thiocyanate complex. The absorbances of the resulting sample solutions and standard solutions were measured using a Unicam S.P. 500 Spectrophotometer.

(h) Boron

Boron was analysed using a photometric method after Fleet (1967). Carmine was used for colour development and an ion-exchange resin was used to separate interfering ions. The optical densities were measured using a Unicam S.P. 500 Spectrophotometer with reference to a standard calibration curve.

The method was not very satisfactory as reagent blanks were high and fluorine interfered. Addition of known quantities of fluorine to a standard solution showed considerable interference, e.g. 0.6% fluorine added to the 10µg/litre boron standard showed a 20% decrease in the spectrophotometer reading for that solution. The method did, however, show there to be less than 0.05 wt% boron in the selected samples.

F.2 Mineral analysis

All mineral analyses were determined on polished thin sections using the Cambridge Scientific Instruments Microscan 5 Electron Probe Microanalyser in Edinburgh. The procedure essentially follows that of Sweatman and Long (1969).

Some of the operating conditions along with the standards used are given in Table F.7. The accelerating potential was 20 kV and the probe current 0.03 microamps. The analyses were determined using four, ten second counts on the peak and two, ten second background counts.

The peak counts were corrected for dead time, the backgrounds subtracted and then the apparent concentrations were calculated with reference to the standards. The apparent concentrations were corrected for atomic number, mass absorption and characteristic

fluorescence differences. When fluorine was analysed for the elemental concentration was calculated first to obtain the fluorine concentration. Finally the oxide weight per cents were calculated for each analysis. These calculations were all performed using departmental computer programmes (written by D. J. Humphries).

<u>Element</u>	<u>Standard</u>	<u>Crystal</u>	<u>20</u>
Si	wollastonite	RAP	31°44'
Ti	'specpure' metal	PET	36°39'
Al	corundum	RAP	37°17'
Cr	'specpure' metal	LiF	69°18'
Fe	'specpure' metal	LiF	57°26½'
Mn	'specpure' metal	LiF	62°53'
Mg *	periclase	RAP	44°31'
Ca	wollastonite	LiF	113°
Na	jadeite	RAP	54°17'
K	orthoclase	PET	50°40½'
P	apatite	PET	89°25½'
Ni	'specpure' metal	LiF	48°34½'
Ba	barytes	LiF	87°4½' (L α line)
F	Synthetic Co/Zn fluoride	RAP	89°

* Mg concentrations in olivines with analysis numbers between 410 and 500 (inclusive) were determined using the St. John's Island olivine standard referred to in Sweatman and Long (1969).

Table F.7 Standards and settings used for microprobe analysis

BIBLIOGRAPHY

- AKELLA, J. 1974 Solubility of Al_2O_3 in orthopyroxene co-existing with garnet and clinopyroxene for compositions on the diopside-pyrope join in the system CaSiO_3 - MgSiO_3 - Al_2O_3 . Carnegie Inst. Wash. Yearb. 73, 273-278.
- ALLENS, J.B. and DEANS, T. 1965 Ultrabasic eruptives with alnöitic-kimberlitic affinities from Malaita, Solomon Islands. Mineralog. Mag. 34, 16-34.
- ALLSOPP, H.L. and BARRETT, D.R. 1975 Rb-Sr age determinations on South African kimberlites. Physics Chem. Earth 2, 605-617.
- ANDREWS, J.R. and EMELEUS, C.H. 1971 Preliminary account of kimberlite intrusions from the Frederikshab district, south west Greenland. Grønlands geol. Unders. Rapp. 31.
- ANDREWS, J.R. and EMELEUS, C.H. 1976 Kimberlites in West Greenland. In: Geology of Greenland, Editors A. Escher and W.S. Watt, Grønlands geol. Unders., p. 574-581.
- AOKI, K. 1975 Origin of phlogopite and potassic richterite bearing peridotite xenoliths from South Africa. Contrib. Mineral. Petrol. 53, 145-156.
- APPLETON, J.D. 1970 The petrology of the potassium-rich lavas of the Roccamonfina Volcano, Italy. Ph.D. Thesis, University of Edinburgh (unpubl.).
- ARSENYEV, A.A. 1962 The laws of distribution of kimberlites in the eastern part of the Siberian platform. Dokl. (Proc.) Acad. Sci. USSR, Earth Science Section 137, 355-357.
- BAK, J., SØRENSEN, K., GROCOTT, J., KORSTGARD, J.A., NASH, D. and WATTERSON, J. 1975 Tectonic implications of Precambrian shear belts in western Greenland. Nature, Lond. 254, 566-569.
- BARRETT, D.R. 1975 The genesis of kimberlites and associated rocks: strontium isotopic evidence. Physics Chem. Earth 2, 637-653.
- BARRETT, D.R. and BERG, G.W. 1975 Complementary petrographic and strontium-isotope ratio studies of South African kimberlite. Physics Chem. Earth 2, 619-635.

- BARTON, M. 1976 Melting relations of some ultrapotassic volcanic rocks. Progress in Experimental Petrology, Third Progress Report, N.E.R.C., p. 91-94.
- BECKMANN, G.E.J. and MITCHELL, J.G. 1976 Palaeomagnetic and geochronological work in Central West Greenland. Earth Planet. Sci. Lett. 30, 269-280.
- BERG, G.W. and ALLSOPP, H.L. 1972 Low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in fresh South African kimberlites. Earth Planet. Sci. Lett. 16, 27-30.
- BESWICK, A.E. 1976 K and Rb relations in basalts and other mantle derived materials. Is phlogopite the key? Geochim. cosmochim. Acta 40, 1167-1184.
- BHATTACHARJI, S. 1967 Mechanics of flow differentiation in ultramafic and mafic sills. J. Geol. 75, 101-112.
- BIGGAR, G.M. 1969 Phase relationships in the join $\text{Ca}(\text{OH})_2\text{-CaCO}_3\text{-Ca}_3(\text{PO}_4)_2\text{-H}_2\text{O}$ at 1000 bars. Mineralog. Mag. 37, 75-82.
- BLOOMER, A.G. and NIXON, P.H. 1973 The geology of Letseng-la terae kimberlite pipes. In: Lesotho Kimberlites, Editor P.H. Nixon, Lesotho National Development Corporation, Maseru, p. 20-32.
- BOBRIEVICH, A.P., BONDARENKO, M.N., GNEVUSHEV, M.A., KRASOV, A.M., SMIRNOV, G.I. and YURKEVICH, R.K. 1957 Diamonds of Siberia, Gosgeoltekhizdat, Moscow (Russian).
- BOBRIEVICH, A.P., BONDARENKO, M.N., GNEVUSHEV, M.A., KRASOV, A.M., SMIRNOV, G.I. and YURKEVICH, R.K. 1959 The Diamond Deposits of Yakutia, Gosgeoltekhizdat, Moscow (Russian).
- BOETTCHER, A.L., MYSEN, B.O. and MODRESKI, P.J. 1975 Melting in the mantle: phase relationships in natural and synthetic peridotite- H_2O and peridotite- $\text{H}_2\text{O}\text{-CO}_2$ systems at high pressures. Physics Chem. Earth 2, 855-867.
- BORLEY, G.D. 1967 Potash-rich volcanic rocks from southern Spain. Mineralog. Mag. 36, 364-379.
- BOULLIER, A.M. and NICOLAS, A. 1973 Texture and fabric of peridotite nodules from kimberlite. In: Lesotho Kimberlites, Editor P.H. Nixon, Lesotho National Development Corporation, Maseru, p. 57-66.
- BOULLIER, A.M. and NICOLAS, A. 1975 Classification of textures and fabrics of peridotite xenoliths from South African kimberlites. Physics Chem. Earth 2, 467-475.

- BOYD, F.R. 1970 Garnet peridotites and the system $\text{CaSiO}_3\text{-MgSiO}_3\text{-Al}_2\text{O}_3$. Mineral. Soc. Am. Spec. Pap. 3, 63-75.
- BOYD, F.R. 1974 Olivine megacrysts from the kimberlites of the Monastery and Frank Smith Mines, South Africa. Carnegie Inst. Wash. Yearb. 73, 282-285.
- BOYD, F.R. 1975 Ultramafic xenoliths from the Frank Smith Mine and the Kimberley area. Abstracts of the Kimberlite Symposium, Cambridge, England, p. 9-14.
- BOYD, F.R. and NIXON, P.H. 1970 Kimberlite diopsides. Carnegie Inst. Wash. Yearb. 68, 324-329.
- BOYD, F.R. and NIXON, P.H. 1972 Ultramafic nodules from the Thaba Putsoa kimberlite pipe. Carnegie Inst. Wash. Yearb. 71, 362-373.
- BOYD, F.R. and NIXON, P.H. 1973 Origin of the ilmenite-silicate nodules in kimberlites from Lesotho and South Africa. In: Lesotho Kimberlites, Editor P.H. Nixon, Lesotho National Development Corporation, Maseru, p. 254-268.
- BOYD, F.R. and NIXON, P.H. 1975 Origins of the ultramafic nodules from some kimberlites of Northern Lesotho and the Monastery Mine, South Africa. Physics Chem. Earth 9, 431-454.
- BRAVO, M.S. and O'HARA, M.J. 1975 Partial melting of phlogopite-bearing synthetic spinel- and garnet-lherzolites. Physics Chem. Earth 9, 845-854.
- BRIDGWATER, D. 1971 Routine K/Ar age determinations on rocks from Greenland carried out for G.G.U. in 1970. Grønlands geol. Unders. Rapp. 35, 52-60.
- BRIDGWATER, D., ESCHER, A., NASH, D.F. and WATTERSON, J. 1973 Investigations on the Nagssugtoqidian boundary between Holsteinsborg and Kangamuit, central west Greenland. Grønlands geol. Unders. Rapp. 55, 22-25.
- BRIDGWATER, D., ESCHER, A. and WATTERSON, J. 1973 Tectonic displacements and thermal activity in two contrasting Proterozoic mobile belts from Greenland. Grønlands geol. Unders. Miscell. Pap. 111 (reprinted from Phil. Trans. Roy. Soc. Lond. Ser. A 273, 513-533).
- BROWN, G.C., HUGHES, D.J. and ESSON, J. 1973 New XRF data retrieval techniques and their applicability to U.S.G.S. standard rocks. Chem. Geol. 11, 223-229.

- CARMICHAEL, I.S.E. 1967a The iron-titanium oxides of salic volcanic rocks and their associated ferromagnesian silicates. Contrib. Mineral. Petrol. 14, 36-64.
- CARMICHAEL, I.S.E. 1967b The mineralogy and petrology of the Leucite Hills, Wyoming. Contrib. Mineral. Petrol. 15, 24-66.
- CARMICHAEL, I.S.E., TURNER, F.J. and VERHOOGEN, J. 1974 Igneous Petrology, McGraw-Hill.
- CARSWELL, D.A. 1975 Primary and secondary phlogopites and clinopyroxenes in garnet lherzolite xenoliths. Physics Chem. Earth 2, 417-429.
- CHAPMAN, N.A. 1975 Petrology of inclusions from some late palaeozoic British volcanic rocks. Ph.D. Thesis, University of Edinburgh (unpubl.).
- CLARKE, D.B. and MITCHELL, R.H. 1975 Mineralogy and petrology of the kimberlite from Somerset Island, N.W.T., Canada. Physics Chem. Earth 2, 123-135.
- CLEMENT, C.R. 1975 The emplacement of some diatreme-facies kimberlites. Physics Chem. Earth 2, 51-59.
- CLEMENT, C.R., GURNEY, J.J. and SKINNER, E.M.W. 1975 Monticellite - an abundant groundmass mineral in some kimberlites. Abstracts of the Kimberlite Symposium, Cambridge, England, p. 71-73.
- COX, K.G., GURNEY, J.J. and HARTE, B. 1973 Xenoliths from the Matsoku pipe. In: Lesotho Kimberlites, Editor P.H. Nixon, Lesotho National Development Corporation, Maseru, p. 76-92.
- CROSS, W. 1897 Igneous rocks of the Leucite Hills and Pilot Butte, Wyoming. Am. J. Sci., series 4, 4, 115-141.
- CRUFT, E.F. 1966 Minor elements in igneous and metamorphic apatite. Geochim. cosmochim. Acta 30, 375-398.
- CUNDARI, A. 1973 Petrology of the leucite-bearing lavas in New South Wales. J. geol. Soc. Aust. 20, 465-492.
- CUNDARI, A. and LE MAITRE, R.W. 1970 On the petrogeny of the leucite-bearing rocks of the Roman and Birunga volcanic regions. J. Petrology 11, 33-47.
- CUNDARI, A. and O'HARA, M.J. 1976 Experimental study at atmospheric and high pressures of a mafic leucitite from New South Wales, Australia. Progress in Experimental Petrology, Third Progress Report, N.E.R.C., p. 260-261.

- CURRIE, K.L. and FERGUSON, J. 1970 The mechanism of intrusion of lamprophyre dikes indicated by "offsetting" of dikes. *Tectonophysics* 2, 525-535.
- DANCHIN, R.V. and BOYD, F.R. 1975 The geochemistry of ultramafic nodules from three Angolan kimberlites. Abstracts of the Kimberlite Symposium, Cambridge, England, p. 15-21.
- 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 Chem. Earth* 2, 235-245.
- DAVIDSON, C.F. 1967 The kimberlites of the U.S.S.R. In: *Ultramafic and Related Rocks*, Editor P.J. Wyllie, Wiley, New York, p. 251-261.
- DAVIS, B.T.C. and BOYD, F.R. 1966 The join $Mg_2Si_2O_6$ - $CaMgSi_2O_6$ at 30 kilobars pressure and its application to pyroxenes from kimberlites. *J. geophys. Res.* 71, 3567-3576.
- DAWSON, J.B. 1960 A comparative study of the geology and petrography of kimberlites of the Basutoland Province. Ph.D. Thesis, University of Leeds (unpubl.).
- DAWSON, J.B. 1962 Basutoland kimberlites. *Bull. geol. Soc. Am.* 73, 545-559.
- DAWSON, J.B. 1967a A review of the geology of kimberlite. In: *Ultramafic and Related Rocks*, Editor P.J. Wyllie, Wiley, New York, p. 241-251.
- DAWSON, J.B. 1967b Geochemistry and origin of kimberlite. In: *Ultramafic and Related Rocks*, Editor P.J. Wyllie, Wiley, New York, p. 269-278.
- DAWSON, J.B. 1968 Recent researches on kimberlite and diamond geology. *Econ. Geol.* 63, 504-511.
- DAWSON, J.B. 1970 The structural setting of African kimberlite magmatism. In: *African Magmatism and Tectonics*, Editors T.N. Clifford and I.G. Gass, Oliver and Boyd, p. 321-335.
- DAWSON, J.B. 1971a Advances in kimberlite geology. *Earth Sci. Rev.* 7, 187-214.
- DAWSON, J.B. 1971b The genesis of kimberlite. In: *Diamond Research for 1971*, Industrial Diamond Information Bureau, London, p. 2-7.
- DAWSON, J.B., GURNEY, J.J. and LAWLESS, P.J. 1975 Palaeogeothermal gradients derived from xenoliths in kimberlite. *Nature, Lond.* 257, 299-300.

- DAWSON, J.B. and HAWTHORNE, J.B. 1970 Intrusion features of some hypabyssal South African kimberlites. Bull. volcan. 34, 740-757.
- DAWSON, J.B. and HAWTHORNE, J.B. 1973 Magmatic sedimentation and carbonatitic differentiation in kimberlite sills at Benfontein, South Africa. Jl. geol. Soc. Lond. 129, 61-85.
- DAWSON, J.B., POWELL, D.G. and REID, A.M. 1970 Ultrabasic xenoliths and lava from the Lashaine volcano, northern Tanzania. J. Petrology 11, 519-548.
- DAWSON, J.B. and STEPHENS, W.E. 1975 Statistical classification of garnets from kimberlite and associated xenoliths. J. Geol. 83, 589-607.
- DAWSON, J.B. and STEPHENS, W.E. 1976 Statistical classification of garnets from kimberlite and associated xenoliths - Addendum. J. Geol. 84, 495-496.
- DEER, W.A., HOWIE, R.A. and ZUSSMAN, J. 1962 Rock Forming Minerals (Five Volumes), Longmans.
- DEMPSTER, A.N. and RICHARD, R. 1973 Regional geology and structure. In: Lesotho Kimberlites, Editor P.H. Nixon, Lesotho National Development Corporation, Maseru, p. 1-19.
- DIGGENS, J. and TALBOT, C. 1974 Nagssugtoqidian supracrustal metavolcanic rocks of Sarfartup Nuna, Søndre Strømfjord, Central West Greenland. Grønlands geol. Unders. Rapp. 65, 37-39.
- DOIG, R. 1970 An alkaline rock province linking Europe and North America. Can. J. Earth Sci. 7, 22-28.
- DU TOIT, A.L. 1906 Geological Survey of the eastern portion of Griqualand West. Sect II, The diamondiferous and allied pipes and fissures. In: 11th Ann. Report Geol. Commission, Cape of Good Hope, p. 87-176.
- ECKERMANN, H. von 1948 The alkaline district of Alnø Island (Alnø Alkalina Omrade). Sver. geol. Unders. Ser. Ca. 36, 1-176.
- EGGLER, D.H. 1975 CO₂ as a volatile component of the mantle : the system Mg₂SiO₄-SiO₂-H₂O-CO₂. Physics Chem. Earth 2, 869-881.
- EGGLER, D.H. 1976 Does CO₂ cause partial melting in the low-velocity layer of the mantle ? Geology 4, 69-72.

- EMELEUS, C.H. and ANDREWS, J.R. 1975 Mineralogy and petrology of kimberlite dyke and sheet intrusions and included peridotite xenoliths from south-west Greenland. *Physics Chem. Earth* 9, 179-197.
- ERLANK, A.J. 1973 Kimberlite potassic richterite and the distribution of potassium in the upper mantle. *Extended Abstracts of the International Conference on Kimberlites, Cape Town, South Africa*, p. 103-106.
- ESCHER, A., ESCHER, J.C. and WATTERSON, J. 1970 The Nagssugtoqidian boundary and the deformation of the Kangamuit dyke swarm in the Søndre Strømfjord area. *Grønlands geol. Unders. Rapp.* 28, 21-23.
- ESCHER, A., ESCHER, J.C. and WATTERSON, J. 1975 The reorientation of the Kangamuit Dike swarm, West Greenland. *Can. J. Earth Sci.* 12, 158-173.
- ESCHER, A., JACK, S. and WATTERSON, J. 1976 Tectonics of the North Atlantic Proterozoic dyke swarm. *Phil. Trans. Roy. Soc. Lond. A* 280, 529-539.
- ESCHER, A. and WATTERSON, J. 1973 Kimberlites and associated rocks in the Holsteinsborg - Søndre Strømfjord region, central West Greenland. *Grønlands geol. Unders. Rapp.* 55, 26-27.
- ESCHER, A. et al. 1970 Tectonic/geological map of Greenland, scale 1:2500,000. *Grønlands geol. Unders.*
- FERGUSON, J. and CURRIE, K.L. 1971 Evidence of liquid immiscibility in alkaline ultrabasic dikes at Callander Bay, Ontario. *J. Petrology* 12, 561-585.
- FERGUSON, J., DANCHIN, R.V. and NIXON, P.H. 1973 Petrochemistry of kimberlite autoliths. In: *Lesotho Kimberlites*, Editor P.H. Nixon, Lesotho National Development Corporation, Maseru, p. 285-293.
- FERGUSON, J., MARTIN, H., NICOLAYSEN, L.O. and DANCHIN, R.V. 1975 Gross Brøkkaros : a kimberlite-carbonatite volcano. *Physics Chem. Earth* 9, 219-245.
- FESQ, H.W., BIBBY, D.M., ERASMUS, C.S., KABLE, E.J.D. and SELLSCHOP, J.P.F. 1975 A comparative trace element study of diamonds from Premier, Finsch and Jagersfontein Mines, South Africa. *Physics Chem. Earth* 9, 817-836.
- FESQ, H.W., KABLE, E.J.D. and GURNEY, J.J. 1975 Aspects of the geochemistry of kimberlites from Premier Mine and other

- selected South African occurrences with particular reference to the rare earth elements. *Physics Chem. Earth* 2, 687-707.
- FITTON, J.G. and GILL, R.C.O. 1970 The oxidation of ferrous iron in rocks during mechanical grinding. *Geochim. cosmochim. Acta* 34, 518-524.
- FLEET, M.E. 1967 Spectrophotometric method for determining trace amounts of boron in rocks and minerals. *Analyt. Chem.* 39, 253-255.
- FLOWER, M.F.J. 1969 Phlogopite from Jan Mayen Island (North Atlantic). *Earth Planet. Sci. Lett.* 6, 461-466.
- FORBES, W.C. and FLOWER, M.F.J. 1974 Phase relations of titan-phlogopite, $K_2Mg_4TiAl_2Si_6O_{22}(OH)_4$: a refractory phase in the mantle. *Earth Planet. Sci. Lett.* 22, 60-66.
- FRANTSESSON, E.V. 1970 The Petrology of Kimberlites, Translator D.A. Brown, Australian National University, Dept. Geology Publ. 150 (from Petrologiya Kimberlitov, Moscow Nedra 1968).
- FRANZ, G.W. and WYLLIE, P.J. 1967 Experimental studies in the system $CaO-MgO-SiO_2-CO_2-H_2O$. In: *Ultramafic and Related Rocks*, Editor P.J. Wyllie, Wiley, New York, p. 323-326.
- FUDALI, R.F. 1963 Experimental studies bearing on the origin of pseudoleucite and associated problems of alkalic rock systems. *Bull. geol. Soc. Am.* 74, 1101-1126.
- GOFF, S.P. 1973 The mineralogy and geochemistry of a kimberlite dyke from Søndre-Isortoq Fjord, south west Greenland. M.Phil. Thesis, University of Leicester (unpubl.).
- GORANSON, R.W. 1938 Silicate-water systems : phase equilibria in the $NaAlSi_3O_8-H_2O$ and $KAlSi_3O_8-H_2O$ systems at high temperatures and pressures. *Am. J. Sci.* 35A, 71-91.
- GREEN, D.H. and RINGWOOD, A.E. 1967 The genesis of basaltic magmas. *Contrib. Mineral. Petrol.* 15, 103-190.
- GURNEY, J.J., HARTE, B. and COX, K.G. 1975 Mantle xenoliths in the Matsoku kimberlite pipe. *Physics Chem. Earth* 2, 507-523.
- HAGGERTY, S.E. 1973 Spinel of unique composition associated with ilmenite reactions in the Liquobong kimberlite pipe, Lesotho. In: *Lesotho Kimberlites*, Editor P.H. Nixon, Lesotho National Development Corporation, Maseru, p.149-158.

- HAGGERTY, S.E. 1975a The chemistry and genesis of opaque minerals in kimberlites. *Physics Chem. Earth* 2, 295-307.
- HAGGERTY, S.E. 1975b An analysis of correlative and non-correlative oxide parameters for spinels and ilmenites in groundmass kimberlite. Abstracts of the Kimberlite Symposium, Cambridge, England, p. 43-45.
- HAGGERTY, S.E., BOYD, F.R., COLLERSON, K.D. and GURNEY, J.J. 1975 Sulphide assemblages in contrasting kimberlite associations. Abstracts of the Kimberlite Symposium, Cambridge, England, p. 48-49.
- HARRIS, J.W. 1968 The recognition of diamond inclusions. *Ind. Diamond Rev.* 28, 402-410 (Part I), 458-461 (Part II).
- HARRIS, J.W. and GURNEY, J.J. in press Inclusions in diamonds. In: *Properties of Diamonds*, Editor J.E. Field, Academic Press.
- HARRIS, P.G. 1957 Zone refining and the origin of potassic basalts. *Geochim. cosmochim. Acta* 12, 195-208.
- HARRIS, P.G. and MIDDLEMOST, E.A.K. 1970 The evolution of kimberlites. *Lithos* 3, 77-88.
- HARTE, B. in press Rock nomenclature with particular relation to deformation and recrystallisation textures in olivine-bearing xenoliths. *J. Geol.*
- HARTE, B., COX, K.G. and GURNEY, J.J. 1975 Petrography and geological history of upper mantle xenoliths from the Matsoku kimberlite pipe. *Physics Chem. Earth* 2, 477-506.
- HARTE, B. and GURNEY, J.J. 1973 Evolution of clinopyroxene and garnet in an eclogite nodule from the Roberts Victor kimberlite pipe. Extended Abstracts of the International Conference on Kimberlites, Cape Town, South Africa, p.159-162.
- HARTE, B. and GURNEY, J.J. 1975 Ore mineral and phlogopite mineralization within ultramafic nodules from the Matsoku kimberlite pipe. *Carnegie Inst. Wash. Yearb.* 74, 528-536.
- HASKIN, L.A., FREY, F.A., SCHMITT, R.A. and SMITH, R.H. 1966 Meteoric, solar and terrestrial rare-earth distributions. *Physics Chem. Earth* 7, 169-321.
- HAWTHORNE, J.B. 1968 Kimberlite sills. *Trans. geol. Soc. S. Afr.* 71, 291-311.
- HAWTHORNE, J.B. 1975 Model of a kimberlite pipe. *Physics Chem. Earth* 2, 1-15.

- HIGAZY, R.A. 1954 Trace elements of volcanic ultrabasic potassic rocks of south western Uganda and adjoining part of the Belgian Congo. Bull. geol. Soc. Am. 65, 39-70.
- HILL, P.G. 1974 The petrology of the Aden Volcano, People's Democratic Republic of Yemen. Ph.D. Thesis, University of Edinburgh (unpubl.).
- HOLMES, A. 1936 A contribution to the petrology of kimberlites and its inclusions. Trans. geol. Soc. S. Afr. 39, 379-428.
- HOLMES, A. 1950 Petrogenesis of katungite and its associates. Am. Miner. 35, 772-792.
- HOLMES, A. and HARWOOD, H.F. 1937 The petrology of the volcanic area of Bufumbira. Geol. Surv. Uganda Mem. 3, 1-300.
- HOWELLS, S. 1975 Discrepancies in the apparent solubility of Al_2O_3 in enstatite at high pressure. Extended Abstracts of the International Conference on Geothermometry and Geobarometry, Pennsylvania State University.
- HUANG, W.H. and JOHNS, W.D. 1967 Simultaneous determination of fluorine and chlorine in silicate rocks by a rapid spectrophotometric method. Analytica chim. Acta 37, 508-515.
- JAMIESON, B.G. 1969 Natural rock projection into a pseudo-quaternary system. Progress in Experimental Petrology, First Progress Report, N.E.R.C., p. 152-155.
- JAMIESON, B.G. 1970 Phase relations in some tholeiitic lavas illustrated by the system R_2O_3 - XO - YO - ZO_2 . Mineralog. Mag. 37, 537-554.
- KABLE, E.J.D., FESQ, H.W. and GURNEY, J.J. 1975 The significance of inter-element relationships of some minor and trace elements in South African kimberlites. Physics Chem. Earth 2, 709-734.
- KRESTEN, P. 1973 The coating on kimberlitic zircons : a preliminary study. In: Lesotho Kimberlites, Editor P.H. Nixon, Lesotho National Development Corporation, Maseru, p.220-223.
- LANG, A.R. 1970 Diamond accumulation in the upper mantle. Nature, Lond. 226, 345.
- LARSEN, O. and MØLLER, J. 1968 K/Ar age determinations from West Greenland. I Reconnaissance programme. Grønlands geol. Unders. Rapp. 15, 82-86.

- LEAKE, B.E. 1968 A catalog of analyzed calciferous and subcalciferous amphiboles together with their normal nomenclature and associated minerals. Spec., Pap. geol. Soc. Am. 98.
- LEECH, G.B., LOWDON, J.A., STOCKWELL, C.H. and WANLESS, R.K. 1963 Age determinations and geological studies (including isotopic ages - Report 4). Geol. Surv. Pap. Can. 63-17.
- LEWIS, H.C. 1887 On diamontiferous peridotite and the genesis of diamond. Geol. Mag. 4, 22-24.
- LEWIS, H.C. 1888 The matrix of diamond. Geol. Mag. 5, 129-131.
- LINDSLEY, D.H. 1966 Melting relations of KAlSi_3O_8 : effect of pressure to 40kb. Am. Miner. 51, 1793-1799.
- LORENZ, V. 1975 Formation of phreatomagmatic maar-diatreme volcanoes and its relevance to kimberlite diatremes. Physics Chem. Earth 2, 17-27.
- LUTH, W.C. 1967 Studies in the system KAlSiO_4 - Mg_2SiO_4 - SiO_2 - H_2O . I. Inferred phase relations and petrologic applications. J. Petrology 8, 372-416.
- MACGREGOR, I.D. 1970 An hypothesis for the origin of kimberlite. Mineral. Soc. Am. Spec. Pap. 3, 51-62.
- MACGREGOR, I.D. 1974 The system $\text{MgO-Al}_2\text{O}_3$ - SiO_2 : solubility of Al_2O_3 in enstatite for spinel and garnet peridotite compositions. Am. Miner. 59, 110-119.
- MACGREGOR, I.D. 1975 Petrologic and thermal structure of the upper mantle beneath South Africa in the Cretaceous. Physics Chem. Earth 2, 455-466.
- MCIVER, J.R. and LENTHALL, D.H. 1974 Mafic and ultramafic extrusives of the Earberton Mountain Land in terms of the CMAS system. PreCamb. Res. 1, 327-343.
- MACKENZIE, D.E. and WHITE, A.J.R. 1970 Phonolite globules in basanite from Kiandra, Australia. Lithos 3, 309-317.
- METAIS, D. and CHAYES, F. 1963 Varieties of lamprophyre. Carnegie Inst. Wash. Yearb. 62, 156-157.
- METAIS, D., RAVIER, J. and DUONG, P.K. 1962 Nature et composition chimique des micas de deux lamprophyres. Bull. Soc. fr. Miner. Cristallogr. 85, 321-328.
- MEYER, H.O.A. 1976 The kimberlites of the continental United States : a review. J. Geol. 84, 377-403.
- MEYER, H.O.A. and BOYD, F.R. 1972 Composition and origin of crystalline inclusions in natural diamonds. Geochim. cosmochim. Acta 36, 1255-1273.

- MILLHOLLEN, G.L., IRVING, A.J. and WYLLIE, P.J. 1974 Melting interval of peridotite with 5.7 per cent water to 30 kilobars. J. Geol. 82, 575-587.
- MITCHELL, R.H. 1970 Kimberlite and related rocks - a critical appraisal. J. Geol. 78, 686-704.
- MITCHELL, R.H. 1972 Composition of perovskite in kimberlite. Am. Miner. 57, 1748-1753.
- MITCHELL, R.H. 1973 Magnesian ilmenite and its role in kimberlite petrogenesis. J. Geol. 81, 301-311.
- MITCHELL, R.H. and BRUNFELT, A.O. 1975 Rare earth geochemistry of kimberlite. Physics Chem. Earth 2, 671-686.
- MITCHELL, R.H. and CROCKETT, J.M. 1971 The isotopic composition of strontium in some kimberlites. Contrib. Mineral. Petrol. 30, 277-290.
- MYSEN, B.O. and BOETTCHER, A.L. 1975a Melting of a hydrous mantle: I. Phase relations of a natural peridotite at high pressures and temperatures with controlled activities of water, carbon dioxide and hydrogen. J. Petrology 16, 520-548.
- MYSEN, B.O. and BOETTCHER, A.L. 1975b Melting of a hydrous mantle: II. Geochemistry of crystals and liquids formed by anatexis of mantle peridotite at high pressures and high temperatures as a function of controlled activities of water, hydrogen and carbon dioxide. J. Petrology 16, 549-593.
- NIELSEN, B.L. 1976 Economic minerals. In: Geology of Greenland. Editors A. Escher and W.S. Watt, Grønlands geol. Unders. p. 460-486.
- NIXON, P.H. 1973a (Editor) Lesotho Kimberlites, Lesotho National Development Corporation, Maseru.
- NIXON, P.H. 1973b Perspective. In: Lesotho Kimberlites, Editor P.H. Nixon, Lesotho National Development Corporation, p. 300-312.
- NIXON, P.H. and BOYD, F.R. 1973a Petrogenesis of the granular and sheared ultrabasic nodule suite in kimberlite. In: Lesotho Kimberlites, Editor P.H. Nixon, Lesotho National Development Corporation, Maseru, p.48-56.
- NIXON, P.H. and BOYD, F.R. 1973b The discrete nodule (megacryst) association in kimberlites from Northern Lesotho. In: Lesotho Kimberlites, Editor P.H. Nixon, Lesotho National Development Corporation, Maseru, p. 67-75.

- NIXON, P.H. and BOYD, F.R. 1973c Deep seated nodules. In: Lesotho Kimberlites, Editor P.H. Nixon, Lesotho National Development Corporation, Maseru, p. 106-109.
- NIXON, P.H. and BOYD, F.R. 1973d The Liquobong intrusions and kimberlitic olivine compositions. In: Lesotho Kimberlites, Editor P.H. Nixon, Lesotho National Development Corporation, Maseru, p. 141-148.
- NIXON, P.H., KNORRING, O. von and ROOKES, J.M. 1963 Kimberlites and associated inclusions of Basutoland: a mineralogical and geochemical study. *Am. Miner.* 48, 1090-1132.
- NIXON, P.H. and KRESTEN, P. 1973 Butha-Buthe dyke swarm and associated kimberlite blows. In: Lesotho Kimberlites, Editor P.H. Nixon, Lesotho National Development Corporation, Maseru, p. 127-206.
- NOCKOLDS, S.R. 1954 Average chemical composition of some igneous rocks. *Bull. geol. Soc. Am.* 65, 1007-1032.
- NOE-NYGAARD, A. and RAMBERG, H. 1961 Geological reconnaissance map of the country between latitudes 69°N and 63°45'N, West Greenland. *Grønlands geol. Unders. Map 1* (also Meddr. Grønland 123, 5).
- O'HARA, M.J. 1968 The bearing of phase equilibria studies in synthetic and natural systems on the origin and evolution of basic and ultrabasic rocks. *Earth Sci. Rev.* 4, 69-133.
- O'HARA, M.J., BIGGAR, G.M., HILL, P.G., JEFFRIES, B. and HUMPHRIES, D.J. 1974 Plagioclase saturation in lunar high-titanium basalts. *Earth Planet. Sci. Lett.* 21, 253-268.
- O'HARA, M.J., SAUNDERS, M.J. and MERCY, E.L.P. 1975 Garnet-peridotite, primary ultrabasic magma and eclogite; interpretation of upper mantle processes in kimberlite. *Physics Chem. Earth* 2, 571-604.
- O'HARA, M.J. and YODER, H.S. 1967 Formation and fractionation of basic magmas at high pressures. *Scott. J. Geol.* 3, 67-117.
- OXBURGH, E.R. 1964 Petrological evidence for the presence of amphibole in the upper mantle and its petrogenetic and geophysical implications. *Geol. Mag.* 101, 1-19.
- PEARCE, T.H. 1968 A contribution to the theory of variation diagrams. *Contrib. Mineral. Petrol.* 19, 142-157.
- PEARCE, T.H. 1970 Chemical variations in the Palisade Sill. *J. Petrology* 11, 15-32.

- PECK, L.C. 1964 Systematic analysis of silicates. Bull. U.S. geol. Surv. 1170, 17-21, 61, 83.
- PHILPOTTS, A.R. 1972 Density, surface tension and viscosity of the immiscible phase in a basic, alkaline magma. Lithos 5, 1-18.
- PHILPOTTS, A.R. and HODGSON, C.J. 1968 Role of liquid immiscibility in alkaline rock genesis. XXIII Int. Geol. Congr. 2, 175-188.
- PIRSSON, L.V. 1905 Petrography and geology of the igneous rocks of the Highwood Mountains, Montana. Bull. U.S. geol. Surv. 237, 208pp.
- POWELL, J.L. 1966 Isotopic composition of strontium on carbonatites and kimberlites. Min. Soc. India Internat. Min. Soc. Papers 4th Gen. Meet. 58-66.
- PRAST, W.G. 1973 Greenland - mines and prospects. Min. Mag. 128, 25-30.
- PRIDER, R.T. 1939 Some minerals from the leucite-rich rocks of the West Kimberley area, Western Australia. Mineralog. Mag. 25, 373-387.
- PRIDER, R.T. 1960 The leucite lamproites of the Fitzroy Basin, Western Australia. J. geol. Soc. Aust. 6, 71-118.
- PRINZ, M., MANSON, D.V., HLAVA, P.F. and KEIL, K. 1975 Inclusions in diamonds : garnet lherzolite and eclogite assemblages. Physics Chem. Earth 2, 797-815.
- RAFIQ, M., RULFIS, C.L. and ELVING, P.J. 1963 Determination of small amounts of zirconium. I: Gravimetric procedures using mandelic acid and its derivatives. Talanta 10, 696-701.
- RAHEIM, A. and GREEN, D.H. 1974 Experimental determination of the temperature and pressure dependence of the Fe-Mg partition coefficient for coexisting garnet and clinopyroxene. Contrib. Mineral. Petrol. 48, 179-203.
- RAMSAY, J.J. 1955 A camptonitic dyke suite at Monar, Ross-shire and Inverness-shire. Geol. Mag. 92, 297-309.
- REID, A.M., DONALDSON, C.H., BROWN, R.W., RIDLEY, W.I. and DAWSON, J.B. 1975 Mineral chemistry of peridotite xenoliths from the Lashaine Volcano, Tanzania. Physics Chem. Earth 2, 525-543.

- RICKWOOD, P.C. 1968 On recasting analyses of garnet into end-member molecules. *Contrib. Mineral. Petrol.* 18, 175-198.
- RIMSKAYA-KORSAKOVA, O.M. and SOKOLOVA, E.P. 1966 Iron-magnesium micas with reverse absorption. *Mineralog. Abstr.* 17, 504.
- RIVALENTI, G. and SIGHINOLFI, G.P. 1971 Geochemistry and differentiation phenomena in basic dykes of the Frederikhab District, south west Greenland. *Grønlands geol. Unders. Miscell. Pap.* 96.
- ROBERT, R-L. 1973 Etude experimentale de micas, dans le système $K_2O-MgO-TiO_2-Al_2O_3-SiO_2-H_2O$. Application aux phlogopites titanifères. These 3^e cycle, Université de Paris Sud. (cited in Velde 1975).
- ROBERT, R-L. 1976a Phlogopite solid solutions in the system $K_2O-MgO-Al_2O_3-SiO_2-H_2O$. *Chem Geol.* 17, 195-212.
- ROBERT, R-L. 1976b Titanium solubility in synthetic phlogopite solid solutions. *Chem Geol.* 17, 213-228.
- ROSE, H.J., ADLER, I. and FLANAGAN, F.J. 1963 X-ray fluorescence analysis of the light elements in rocks and minerals. *Appl. Spectrosc.* 17, 81-85.
- SAHAMA, G. 1974 Potassium alkaline rocks. In: *Alkaline Rocks*, Editor H. Sørensen, p. 96-109.
- SCARFE, C.M. and WYLLIE, P.J. 1967 Serpentine dehydration curves and their bearing on serpentinite deformation in orogenesis. *Nature, Lond.* 215, 945-946.
- SCHILLING, J.G. and WINCHESTER, J.W. 1969 Rare earth contribution to the origin of Hawaiian lavas. *Contrib. Mineral. Petrol.* 23, 27-37.
- SEKI, Y. and KENNEDY, G.C. 1964 An experimental study of the leucite-pseudoleucite problem. *Am. Miner.* 49, 1267-1280.
- SHAPIRO, L. and BRANNOCK, W.W. 1955 Rapid determination of water in silicate rocks. *Analyt. Chem.* 27, 560-562.
- SHAPIRO, L. and BRANNOCK, W.W. 1962 Rapid analysis of silicate, phlogopite and phosphate rocks. *Bull. U.S. geol. Surv.* 1144A, 46-48.
- SHEPPARD, S.M.F. and DAWSON, J.B. 1975 Hydrogen, carbon and oxygen isotope studies of megacryst and matrix minerals from Lesothan and South African kimberlites. *Physics Chem Earth* 9, 747-764.

- SHIMIZU, N. 1975 Geochemistry of ultramafic inclusions from Salt Lake Crater, Hawaii and from Southern African kimberlites. *Physics Chem. Earth* 2, 655-669.
- SIMKIN, T. 1967 Flow differentiation in the picritic sills of North Skye. In: *Ultramafic and Related Rocks*, Editor P.J. Wyllie, Wiley, New York, p. 64-69.
- SIMKIN, T. and SMITH, J.V. 1970 Minor-element distribution in olivine. *J. Geol.* 78, 304-325.
- SMITH, J.V. and DAWSON, J.B. in press Chemistry of micas from kimberlites and xenoliths, with implications for volatiles in the upper mantle. *Geochim. cosmochim. Acta*.
- SMITH, R.E. 1967 Segregation vesicles in basaltic lava. *Am. J. Sci.* 265, 696-713.
- SØRENSEN, H. 1974 (Editor) *The Alkaline Rocks*, Wiley, London.
- STRONG, D.F. 1970 Petrology of the lavas of Grande Comore. Ph.D. Thesis, University of Edinburgh (unpubl.).
- STRONG, D.F. and HARRIS, A. 1974 The petrology of Mesozoic alkaline intrusives of central Newfoundland. *Can. J. Earth Sci.* 11, 1208-1219.
- SUKHESWALA, R.N. and AVASIA, R.K. 1971 Carbonatitic-alkalic complex of Panwad-Kawant, Gujarat, and its bearing on the structural characteristics of the area. *Bull. volcan.* 35, 564-578.
- SUTHERLAND, D.S. 1965 Potash-trachytes and ultra-potassic rocks associated with the carbonatite complex of Toror Hills, Uganda. *Mineralog. Mag.* 35, 363-378.
- SWEATMAN, T.R. and LONG, J.V.P. 1969 Quantitative electron-probe microanalysis of rock forming minerals. *J. Petrology* 10, 332-379.
- TALJAARD, M.S. 1936 South African melilite basalts and their relations. *Trans. geol. Soc. S. Afr.* 39, 281-316.
- THORNTON, C.P. and TUTTLE, O.F. 1960 Chemistry of igneous rocks : part I, differentiation index. *Am. J. Sci.* 258, 664-684.
- TROGER, W.E. 1935 *Spezielle Petrographie der Eruptivgesteine, Ein Nomenklatur - Kompendium*, Berlin.
- TURNER, F.J. and VERHOOGEN, J.V. 1960 *Igneous and Metamorphic Petrology*, McGraw-Hill, New York.
- TUTTLE, O.F. and GITTINS, J. 1966 (Editors) *Carbonatites*, Interscience, Wiley, New York.

- UPTON, B.G.J. 1965 The petrology of a camptonite sill in South Greenland. *Meddr. Grønland* 169, 11.
- VELDE, D. 1967 Sur un lamprophyre hyperalcalin potassique : la minette de Sisco (Ile de Corse). *Bull. Soc. fr. Mineral. Cristallogr.* 90, 214-223.
- VELDE, D. 1975 Armalcolite-Ti-phlogopite-diopside-analcite-bearing lamproites from Smoky Butte, Garfield County, Montana. *Am. Miner.* 60, 566-573.
- VINOGRADOV, A.P., KROPOTOVA, O.I. and USTINOV, V.I. 1965 Possible sources of carbon in diamonds as indicated by the C^{12}/C^{13} ratios. *Geochemistry International* 495-503.
- WADE, A. and PRIDER, R.T. 1940 The leucite-bearing rocks of the West Kimberley Area, Western Australia. *Jl. geol. Soc.* 96, 39-98.
- WAGER, L.R. and BROWN, G.M. 1960 Collection and preparation of material for analysis. In: *Methods in Geochemistry*, Editors A.A. Smales and L.R. Wager, Interscience, London, p. 4-32.
- WAGNER, P.A. 1914 The Diamond Fields of South Africa. Transvaal Leader, Johannesburg.
- WALTON, B.J. and ARNOLD, A.R. 1970 Plutonic nodules in lamprophyric carbonatite dykes near Frederikshab, south west Greenland. *Meddr. Grønland* 190, 5.
- WATSON, K.D. 1967 Kimberlites in Eastern North America. In: *Ultramafic and Related Rocks*, Editor P.J. Wyllie, Wiley, New York, p. 312-323.
- WATTERSON, J. 1974 Investigations on the Nagssugtoqidian boundary in the Holsteinsborg district, Central West Greenland. *Grønlands geol. Unders. Rapp.* 65, 33-37.
- WATTERSON, J. 1975 Mechanism for the persistence of tectonic lineaments. *Nature, Lond.* 253, 520-522.
- WELCHER, F.J. 1963 (Editor) *Standard Methods of Chemical Analysis*, Vol. 2, part A, D. Van Nostrand Co., New Jersey.
- WILLIAMS, A.F. 1932 *The Genesis of Diamond* (2 volumes), Ernest Benn Ltd., London.
- WILLIAMS, H. 1936 Pliocene volcanoes of the Navajo-Hopi country. *Bull. geol. Soc. Am.* 47, 111-172.
- WILSON, A.D. 1955 A new method for determination of ferrous iron in rocks and minerals. *Bull. geol. Surv. Gt. Br.* 2, 56-58.

- WOOD, B.J. and BANNO, J. 1973 Garnet-orthopyroxene and orthopyroxene-clinopyroxene relationships in simple and complex systems. Contrib. Mineral. Petrol. 42, 109-124.
- WOOLSEY, T.S., McCALLUM, M.E. and SCHUMM, S.A. 1975 Modeling of a diatreme emplacement by fluidization. Physics Chem. Earth 2, 29-42.
- WRIGHT, T.L. and DOHERTY, P.C. 1970 A linear programming and least squares computer method for solving petrologic mixing problems. Bull. geol. Soc. Am. 81, 1995-2008.
- WYLLIE, P.J. 1967 (Editor) Ultramafic and Related Rocks, Wiley, New York.
- WYLLIE, P.J. in press Experimental studies on the influence of CO₂ and H₂O in the upper mantle. In: High Pressure Research Applications to Geophysics, Editors M.H. Manghnani and S. Akimoto, Academic Press.
- WYLLIE, P.J. and HUANG, W.L. 1975a Influence of mantle CO₂ in the generation of carbonatites and kimberlites. Nature, Lond. 257, 297-299.
- WYLLIE, P.J. and HUANG, W.L. 1975b Peridotite, kimberlite and carbonatite explained in the system CaO-MgO-SiO₂-CO₂. Geology 3, 621-624.
- WYLLIE, P.J. and HUANG, W.L. 1976 High CO₂ solubilities in mantle magmas. Geology 4, 21-24.
- YODER, H.S. 1975 Relationship of melilite-bearing rocks to kimberlite : a preliminary report of the system akermanite-CO₂. Physics Chem. Earth 2, 883-894.
- ZHABIN, A.G. 1968 Carbonatite-kimberlite from Abarastakh (Yakutia, U.S.S.R.). Dokl. Akad. Nauk. S.S.S.R., Earth Sci. Sec. 177, 167-170 (cited in Goff 1973).

Addendum

- HART, S.R., DAVIS, K.E., KUSHIRO, I. and WATSON, E. 1976 Partitioning of nickel between olivine and silicate liquids. Abstracts of 1976 Annual Meetings, geol. Soc. Am., 8, no. 6, 906-907.

Table 3.1. Proportions of the major modal constituents in selected samples from the Holsteinsborg dykes

		KIMBERLITES							POTASSIC LAMPROPHYRES					
Sample number		5903	5696	5997	5603	5518	5511	5985	5622	5692	5632	5643	5940	5942
OLIVINE -	<2mm	59	60	43	45	34	40	20	10	3	4		5	
	>2mm <5mm	11		7	2	7			10	<1		7		
	>5mm					2								
	polycrystalline					7								
PHLOGOPITE -	megacryst												13	
	groundmass				45				45	48	30	40	30	32
	indeterminable	7	28	26		6	20	29						
PSEUDOLEUCITE									5	23			16	
CLINOPYROXENE										5			6	7
GROUNDMASS -	sanidine													44
	amphibole								20		} 66	} 53		
	indeterminable*	18	13	17	6	42	34	34	10	20			30	17
	oxides	5	7	7	<1	2	6	17						
GARNET					trace									
MgO wt%		35.75	32.11	29.33	26.58	26.12	24.85	22.71	25.55	15.59	12.16	10.74	10.01	7.32

*Includes primary serpentine and carbonate

Table 3.2. The main mineral assemblages found in the Holsteinsborg dykes

[illegible]

LEFT

TABLE 1 SUMMARY OF ROCK CLASSIFICATION

ROCK TYPE	PORPHYROCLASTS	GRAIN SIZE	GRAIN BOUNDARIES	SUBTYPES AND ILLUSTRATIONS IN LITERATURE
<u>Coarse</u>	Absent	Average grain size greater than 2.0mm	Variable. Often largely straight or smoothly curving but may be less regular	<p>Equant ----- Boullier & Nicolas, 1973, Plates 19A, 19B " " " , 1975, Fig. 1A Cox et al. 1973, Plates 26A, 26B Harte et al. 1975, Figs. 1, 2. Mercier and Nicolas, 1975, Figs. 1, 14A, 14B</p> <p>Tabular----- Boullier & Nicolas, 1973, Plate 20A " " " , 1975, Fig. 1A</p>
<u>Porphyroclastic</u>	Present. More than 10% of olivine occurs as porphyroclasts	Two major populations one represented by porphyroclasts, the other by finer-grained matrix.	Irregular in porphyroclasts, straight in neoblasts.	<p>(neither Boullier & Nicolas, 1973, Plate 20B disrupted nor " " " , 1975, Figs. 1C, 2A. laminated) Mercier & Nicolas, 1975, Fig. 4</p> <p>Disrupted----- Cox et al. 1973, Plate 27A Harte et al. 1975, Figs. 5, 6.</p> <p>Fluidal----- Boullier (pers. comm.)</p> <p>Laminated and disrupted----- Dawson (pers. comm.) Fig. 1A, this paper</p>
<u>Mosaic-porphyroclastic</u>	Present. Less than 10% of olivine occurs as porphyroclasts	Two major populations one represented by porphyroclasts, the other by finer-grained matrix.	Irregular in porphyroclasts, straight in neoblasts.	<p>(neither Boullier & Nicolas, 1973, Plate 21A disrupted nor " " " , 1975, Fig. 2B laminated) Poirier & Nicolas, 1975, Fig. 13</p> <p>Fluidal----- Boullier & Nicolas, 1973, Plate 21B " " " , 1975, Figs. 2C, 3A.</p> <p>Laminated and disrupted----- Dawson et al. (1975) Fig. 1B, this paper.</p>
<u>Granuloblastic</u>	Absent or rare for all mineral species.	Small size range for each mineral species (excepting rare porphyroclasts). Grain size generally less than 2.0mm.	Straight or smoothly curving, bounding grains of polygonal or polygonal tabular shape.	<p>Equant----- Cox et al. 1973, Plate 27B Harte et al. 1975, Fig. 9 Mercier & Nicolas, 1975, Fig. 6B</p> <p>Tabular----- Harte et al., 1975, Fig. 8 Mercier & Nicolas, 1975, Fig. 6A</p>

Fig. 5.10

A stereo pair of the Holsteinsborg kimberlite and potassic lamprophyre dykes plotted in the C-M-A-S tetrahedron (using selected points).

open squares = kimberlites

solid circles = potassic lamprophyres

ol = olivine

sp = spinel (analysis 192)