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Kimberlite and Lamproite dykes from Holsteinsborg, West Greenland

Barbara H. Scott

Geoscience

4 · 1981

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Kimberlite and Lamproite dykes from Holsteinsborg, West Greenland

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Numerous kimberlite and lamproite dykes occur to the south and east of Holsteinsborg in Central West Greenland. This paper gives details of the petrography, mineral chemistry, age relations and geochemistry of the dykes.

The kimberlites are composed of macrocysts of olivine, phlogopite, rare ilmenite and garnet in a matrix of olivine, phlogopite, diopside, perovskite, spinel, serpentine, carbonate and apatite. They can mostly be classified as clinopyroxene-phlogopite hypabyssal kimberlites. Mantle-derived inclusions are found in some of the dykes and include lherzolites, wehrlites, harzburgites and, most commonly, dunites. Both coarse and porphyroclastic inclusions occur. Garnet-granulites and eclogites, although rare, are present.

The lamproites have variable mineral assemblages and textures but the main constituents are phenocrysts of pseudoleucite, olivine, phlogopite and clinopyroxene set in a groundmass of phlogopite, potassic richterite, diopside, pseudoleucite and potassium feldspar. The mineralogy of these dykes is a reflection of unusual ultrapotassic, magnesian whole-rock compositions.

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This paper discusses the petrography and mineralogy of some post-tectonic dykes which occur in the region of Holsteinsborg, Central West Greenland. The majority of the dykes sampled occur in the coastal area between Holsteinsborg and Itivdleq but a few were also found north of the Sukkertoppen Iskappe (Fig. 1). Escher & Watterson (1973) reported numerous dyke localities, many of which were included in this study. Other possibly related dykes reported by these authors but not visited are also shown in Fig. 1. Some members of this suite of dykes were probably first found and reported as kersantitic dykes by Noe-Nygaard & Ramberg (1961) and Brooks et al. (1978) have since described some of them in more detail. Kimberlite dykes were first recorded in this area by Escher, Escher & Watterson (1970).

This study shows that the Holsteinsborg post-tectonic dykes include both kimberlites and lamproites. The petrogenesis of these dykes has been discussed by Scott (1979).

Larsen (in press) indicates additional and widespread occurrences of kimberlitic and lamprophyric intrusions in the area east of Søndre Strømfjord and north of the Sukkertoppen Iskappe.

Accepted 1980-09-29

Geological setting

The known occurrences of the Holsteinsborg post-tectonic kimberlite and lamproite dykes are confined to the southern part of the early Proterozoic Nagssugtoqidian mobile belt, just north of the boundary with the older Archaean block which has been stable since 2500 m.y. According to Bak et al. (1975) and Watterson (1974) the area between Itivdleq fjord and Sarfánguaqland approximately 40 km to the north represents a major shear zone, the Ikertôq shear zone. This shear zone consists of highly deformed amphibolite facies rocks bounded to the north and south by relatively undeformed granulite facies rocks. Within the shear zone there is a large block of granulite gneisses up to 12 km wide which is thought to be an augen-like structure. In the region of Sarfartûp Nunâ north of the Sukkertoppen Iskappe both kimberlite and lamproite dykes have intruded a supracrustal metavolcanic succession of greenschist and low amphibolite facies schists (Diggens & Talbot 1974).

Field relations

The kimberlite and lamproite dykes show no deformation features subsequent to emplacement apart from

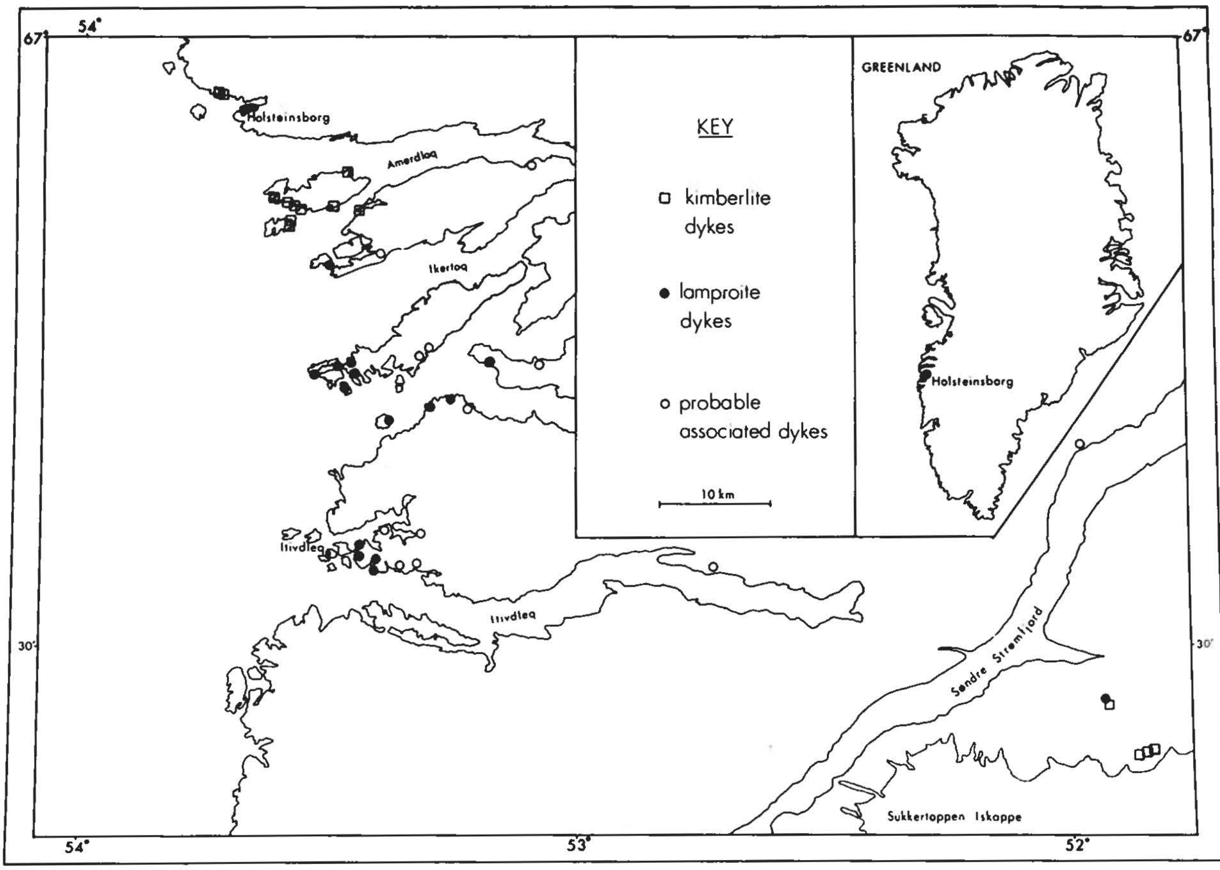

Fig. 1. Localities of kimberlite and lamproite dykes in the Holsteinsborg district, Central West Greenland. Also shown are additional, and probably related, dykes referred to by Escher & Watterson (1973).

some minor fracturing with virtually no displacement. The matrices of the dykes are often rich in carbonate and, therefore, more susceptible to solution than the country rock. The resulting gullies form distinct topographical features but exposure is still good. The dykes are fresh apart from narrow weathered rinds. The dykes are vertical intrusions with fairly constant strike directions, approximately east-west and a few occurrences are at least several kilometres in length. They occur singly or are concentrated in narrow zones with adjacent dykes sometimes separated by only a few centimetres of country rock. Apophyses to the dykes which may be as narrow as 2 cm are common. The dykes have sharp contacts (Fig. 2) and are usually transgressive to the gneissic foliation. The intrusion of the dykes has had little metamorphic effect on the country rock.

Many of the dykes, both kimberlites and lamproites, have internal contacts parallel to their margins indicating multiple phases of intrusion and resulting in a zoned appearance which is often emphasised on exposed surfaces by differential weathering (Fig. 3).

Two instances of cross-cutting, rather than parallel, internal contacts were observed in the kimberlites.

Kimberlites

The kimberlite dykes vary in width from a few centimetres up to 2 metres. The wider dykes (1–2m) have a central zone (approximately 0.5 m) which may locally contain up to 50% of rounded inclusions (Fig. 3). These inclusions which are predominantly ultrabasic are typically 10 to 20 cm in size but range up to 40 cm. A few sub-angular gneissose inclusions occur but are not confined to this central zone. The outer parts of these dykes and the narrower kimberlite dykes (generally less than 0.5 m wide) are similar and are zoned (Fig. 4).

Lamproites

The lamproite dykes are usually less than 1m wide, sometimes zoned and are often intruded in an en echelon manner. The only inclusions found in these dykes are angular country rock xenoliths which show only minor reaction rims and are often oriented parallel to dyke contacts (Fig. 2).

Fig. 2. Lamproite dyke intruding gneissose basement. Note the sharp contacts and the inclusion of local country rock.

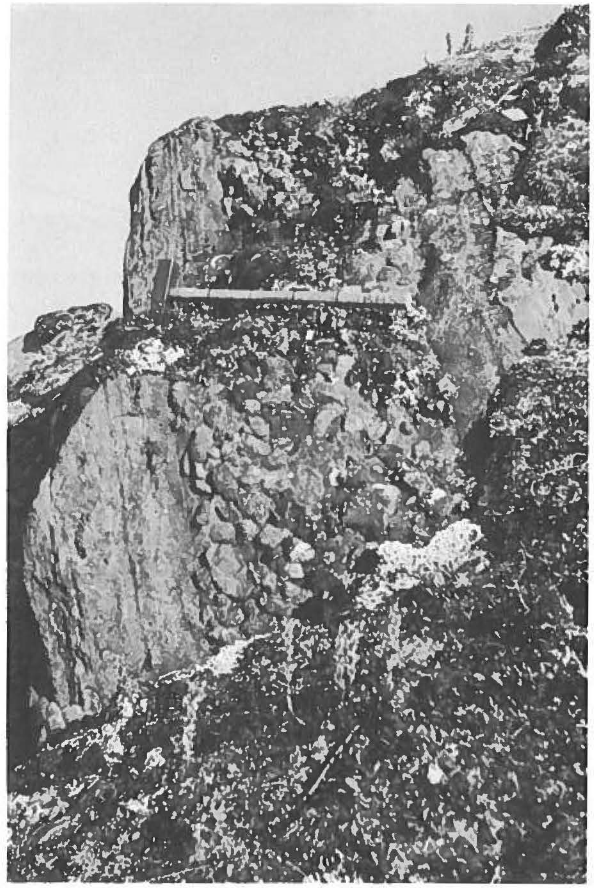

Fig. 3. A wide kimberlite dyke with a central zone containing abundant rounded ultrabasic inclusions. The outer zones are banded parallel to the dyke contacts. Graduations on hammer shaft at 10 cm intervals.

Other post-tectonic intrusions

Two types of other post-tectonic intrusions differ from the majority of dykes visited. Firstly, a few "anomalous" dykes have variable strike directions and contain phenocrysts of clinopyroxene. Secondly, one intrusion has an outcrop of 30 × 10m with no visible contacts. It is made up predominantly of coarse mica and in parts has high concentrations of rounded ultrabasic inclusions. The relationship of these intrusions to the kimberlites and lamproites is not understood and they will not be discussed in detail.

Petrography and mineralogy

Kimberlites

The kimberlites are characterised by an inequigranular texture (Fig. 5) with anhedral macrocrysts of olivine, rare garnet and ilmenite in a finer grained matrix. The matrix is microporphyritic with numerous microphenocrysts of olivine and phlogopite (Figs. 6 and 7) in a groundmass of phlogopite, clinopyroxene, perovskite, spinel, calcite, apatite and serpentine. The modal analyses of a few selected kimberlites (Table 1) show that the mineralogy of the dykes is variable but the majority contain abundant phlogopite and clinopyroxene in addition to olivine. Samples 5512 and 5904 are included in Table 1 to show more extreme mineralogies. Contrasts in the mineralogy and texture between different phases of intrusion within one dyke sometimes make internal contacts very distinct (Fig. 7).

Irregular segregations of calcite up to 1 cm in size occur in many dykes and are often concentrated towards the margin of a dyke where they may be elongate and parallel to the dyke contact.

Olivine. – The olivines show a gradation in size but are usually less than 2 cm (Fig. 5). The larger olivines are generally rounded (Fig. 5) while the smaller ones tend to be euhedral or subhedral (Figs. 6, 7). The olivines are generally fresh but may be partially or totally altered to serpentine with minor amounts of magnetite and carbonate.

Fig. 4. A narrow kimberlite dyke with sharp internal contacts parallel to the dyke margin.

Fig. 5. Photomicrograph of a kimberlite showing rounded macrocrysts, euhedral microphenocrysts and smaller matrix olivines which are partially altered to serpentine. A few phlogopite phenocrysts can also be seen. × 12.

In terms of Mg/Mg+Fe atomic percent ratios, olivine compositions range from $Mg_{78-92.5}$ as illustrated in Fig. 8. Selected olivine analyses are given in Table 2. The

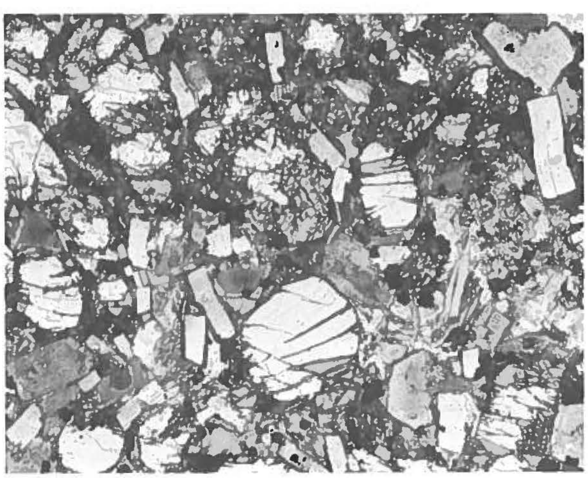

Fig. 6. A phlogopite kimberlite with numerous euhedral or subhedral olivines in a groundmass dominated by phlogopite. The opaque grains include both oxides and perovskite. × 26.

Table 1. Modal analyses of some kimberlites.

Sample no.	5512	5962	5603	5985	5904
Olivine	42	38	34	15	45
Phlogopite	31	20	26	24	4
Clinopyroxene	<1	12	17	37	–
Oxides	9	10	5	10	11
Perovskite	1	4	3	6	–
Carbonate	13	10	11	4	32
Serpentine	2	5	4	3	5
Apatite	1	1	1	1	3

NiO contents vary (0.08–0.48 wt. %) but tend to show a positive correlation with MgO. Although the sizes of the olivines analysed ranged from 0.25 to 20 mm there appears to be no relationship between size and composition. Usually the olivines are not zoned but both normal and reverse zoning occasionally occurs.

All the euhedral olivines analysed were less than 2 mm in size and have compositions of approximately Mg_{85} (e.g. analysis 267, Table 2).

One megacryst (i.e. greater than 1 cm in size) 3.5 cm in maximum dimension with broken rather than the usual rounded margins has a composition of Mg_{76} with high MnO and low NiO (analysis 338, Table 2, Fig. 8). This is the most Fe-rich olivine found in the Holsteinsborg dykes and the differences in composition from the other olivines seems to suggest that its origin is not related to either the kimberlite or the ultrabasic inclusions.

The olivines are more Fe-rich than those found in kimberlites elsewhere (e.g. Mg_{88-92}, Dawson 1967a). Such Fe-rich olivines, however, have been reported from Frank Smith and Monastery Mines in South Africa (Boyd 1974) and at Liquobong in Lesotho (Nixon & Boyd 1973).

Garnet. – Garnet macrocrysts, although rare, have been found in most of the kimberlite dykes. They are usually rounded, reach 5 mm in size and generally have narrow alteration rims. The two analysed garnet macrocrysts are Ti-rich peridotitic garnets (Table 2) and fall into Group 37 of Danchin & Wyatt (1979) or Group 1 of Dawson & Stephens (1975, 1976) and are typical mantle-derived garnets.

Phlogopite. – The phlogopites are strongly pleochroic (X = colourless to pale yellow, Y = Z = brown, orange-brown or greenish brown). The larger phlogopite macrocrysts are typically greater than 1.5 mm in size, have irregular corroded margins and are often deformed or broken. The smaller groundmass phlogopites (less than 1 mm) are usually well formed although some occur as deformed, tabular crystals, many of which have narrow and distinct rims which show reverse pleochroism (Fig. 9).

The phlogopites are somewhat variable in composition (Table 2) but appear to show no systematic variation with size. The TiO_2 contents (up to 7 wt %) are unusually high in comparison to phlogopites from other kimberlites.

The optically distinct rims of many of the phlogopites can also be distinguished chemically (compare analysis 176 to other phlogopite analyses in Table 2). The rims show varying degrees of enrichment in Fe and depletion in Al and are similar to those studied by Rimskaya-Korsakova & Sokolova (1966) who referred to them as tetraferriphlogopites. The rims also tend to be depleted in Na and enriched in Ca relative to the cores. Similar rims have been reported from other areas (e.g. Emeleus & Andrews 1975, Velde 1975). The chemistry of these rims probably reflects growth from an Al-depleted and Fe, Ca-enriched late-stage liquid.

Clinopyroxene. – Clinopyroxene is a common groundmass constituent of many of the kimberlite dykes. It occurs as pale-green slender crystals which reach 0.4 mm in length (Fig. 10). Analyses of the clinopyroxenes (Table 2) show that they are diopsides

Fig. 7. Sharp internal contact in a kimberlite dyke. Note the euhedral matrix olivines and phlogopite microphenocrysts. × 28.

with variable contents of TiO_2 (0.98–2.75 wt %), Al_2O_3 (0.97–4.52 wt %) and FeO (3.98–6.13 wt %). The compositions of the Holsteinsborg clinopyroxenes are, in general, similar to those from other kimberlites (e.g. Dawson et al. 1977, Emeleus & Andrews 1975, Scott & Skinner 1979) but the former are somewhat less magnesian and often richer in TiO_2.

Fe–Ti–Cr Oxides. – Magnesian ilmenite (picroilmenite) has two modes of occurrence, firstly as medium sized (greater than 1 mm) ragged crystals and secondly as small (0.1 mm) euhedral, needle-like crystals. The anhedral picroilmenite macrocrysts with 9.44 to 11.06 wt % MgO and up to 1.87 wt % Cr_2O_3 have compositions typical of kimberlitic ilmenites (analysis 90, Table 3). In contrast the late euhedral crystals have lower MgO contents, (0.85–8.62 wt %), higher MnO (up to 1.62 wt %) and no detectable Al_2O_3 (analysis 366, Table 3). It is interesting to note that the groundmass laths of ilmenite are often associated with primary carbonate and that high-Mn ilmenites are known to occur in carbonatites.

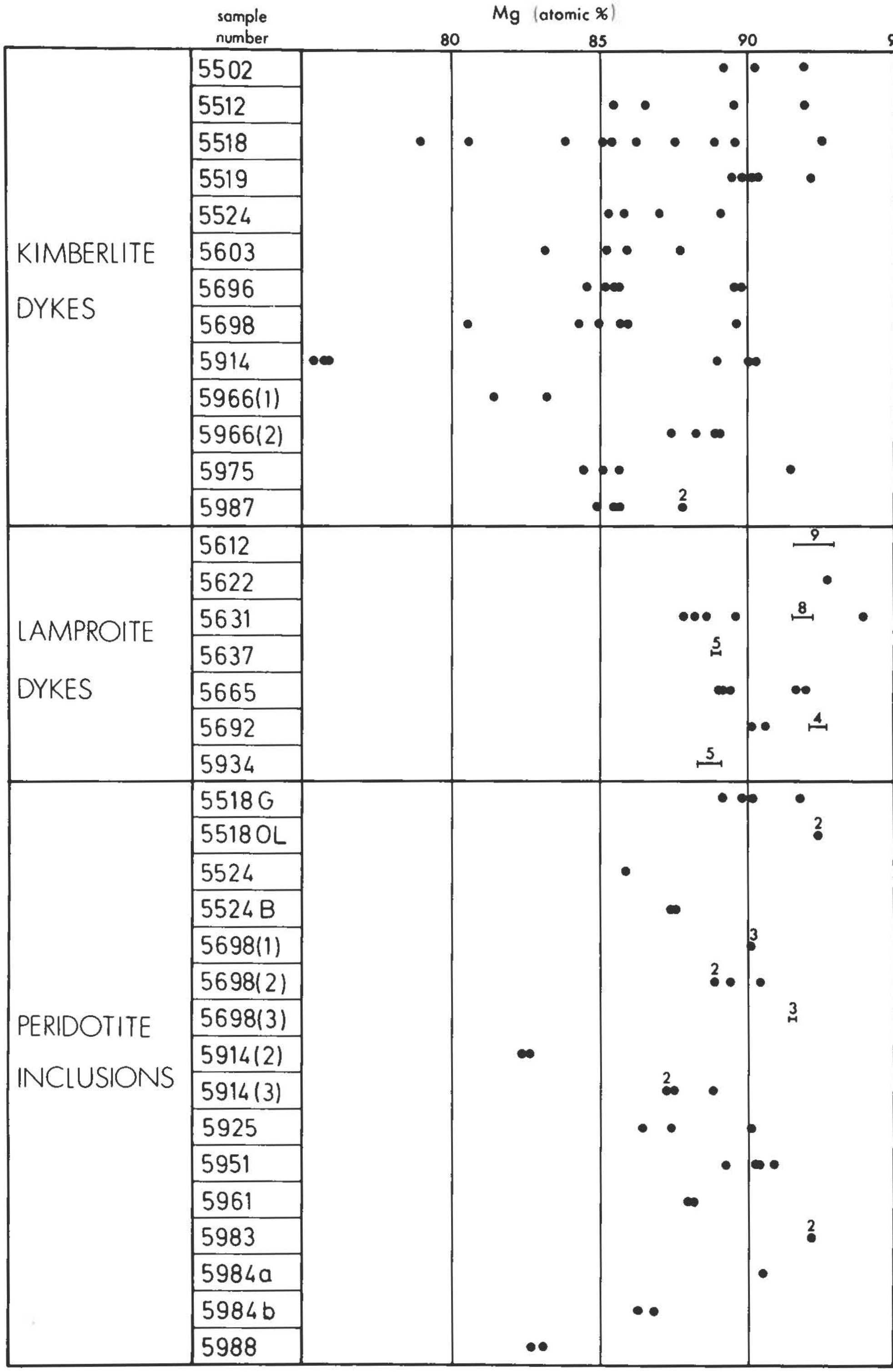

Fig. 8. Variation in olivine compositions for the Holsteinsborg dykes and inclusions. Peridotite inclusions – samples 5518G, 5524, 5698(3), 5914(2), 5914(3), 5951, 5983 and 5984b are dunites. Sample 5988 is an ilmenite-veined dunite. Samples 5518OL, 5698(1), 5698(2) and 5984a (+garnet) are lherzolites. Samples 5524B (+garnet), 5925 and 5961 are wehrlites.

Table 2. Selected mineral analyses from the Holsteinsborg kimberlite dykes. *267:* 0.5 mm euhedral olivine. *215:* fresh core of partly altered 0.5 mm anhedral olivine. *231:* 4 mm anhedral olivine, partially altered. *388:* 2.5 mm anhedral olivine, centre. *338:* 350 mm anhedral megacryst of olivine. *80:* 5 mm garnet macrocryst. *200:* 1 mm euhedral phlogopite macrocryst. *179:* centre of basal section of phlogopite macrocryst. *129* and *60:* groundmass phlogopite. *175:* centre of 1 mm euhedral phlogopite. *176:* rim of 175 – tetraferriphlogopite. *101:* and *460:* small groundmass clinopyroxene.

Mineral	Olivine					Garnet	Phlogopite					Clinopyroxene		
Sample number	5518	5518	5518	5696	5914	5603	5518	5518	5966(2)	5966(2)	5512	5512	5698	5983
Analysis number	*267*	*215*	*231*	*388*	*338*	*80*	*200*	*179*	*129*	*60*	*175*	*176*	*101*	*460*
SiO_2	40.18	41.83	39.78	40.64	38.52	42.92	40.76	38.10	37.49	37.05	35.57	40.77	52.46	51.35
TiO_2	0.03	nd	0.02	0.04	0.04	0.51	0.44	4.72	4.44	3.29	3.24	0.46	0.98	1.68
Al_2O_3	0.04	nd	0.04	0.04	0.04	20.66	11.52	14.33	15.36	15.46	16.71	1.59	0.97	2.42
Cr_2O_3	0.03	0.02	–	0.04	nd	3.38	nd	1.03	0.21	0.04	0.14	0.05	0.02	nd
FeO	14.07	7.52	18.38	10.00	22.44	6.57	10.21	6.09	7.26	6.57	6.17	15.51	3.98	5.56
MnO	0.14	0.11	0.23	0.13	0.30	0.30	0.09	0.06	0.05	0.04	0.06	0.19	0.10	0.10
NiO	0.25	0.28	0.10	0.39	0.11	–	0.03	0.05	–	–	0.04	0.05	–	0.05
MgO	46.26	51.57	42.88	49.31	39.67	21.80	21.99	20.52	19.64	21.67	21.59	24.45	15.74	14.80
CaO	0.06	nd	0.05	0.07	0.04	4.77	0.01	0.03	nd	nd	0.04	0.23	25.73	24.84
Na_2O	0.02	0.01	0.02	0.03	0.03	0.07	0.04	0.37	0.32	0.27	0.22	0.39	0.21	0.21
K_2O	nd	nd	nd	nd	nd	nd	10.17	9.67	9.59	9.61	9.04	8.96	nd	0.03
Total	101.08	101.34	101.50	100.69	101.19	100.98	95.26	94.97	94.36	94.00	92.82	92.65	100.19	101.04
Formula														
Si	0.994	1.001	0.999	0.992	0.991	6.039	5.958	5.508	5.467	5.411	5.246	6.359	1.930	1.888
Ti	0.001	–	–	0.001	0.001	0.054	0.048	0.513	0.487	0.361	0.359	0.054	0.033	0.046
Al	0.001	–	0.001	0.001	0.001	3.426	1.985	2.442	2.640	2.661	2.905	0.2.92	0.042	0.105
Cr	0.001	–	–	0.001	–	0.376	–	0.118	0.024	0.005	0.016	0.006	0.001	–
Fe	0.291	0.150	0.386	0.204	0.483	0.773	1.248	0.736	0.885	0.802	0.761	2.023	0.122	0.171
Mn	0.003	0.002	0.005	0.003	0.007	0.036	0.011	0.007	0.006	0.005	0.007	0.025	0.003	0.003
Ni	0.005	0.005	0.002	0.008	0.002	–	0.004	0.006	–	–	0.005	0.006	–	0.001
Mg	1.706	1.839	1.605	1.794	1.521	4.572	4.791	4.422	4.269	4.717	4.746	5.684	0.863	0.811
Ca	0.002	–	0.001	0.002	0.001	0.719	0.002	0.005	–	–	0.006	0.038	1.014	0.979
Na	0.001	–	0.001	0.001	0.001	0.019	0.011	0.104	0.090	0.076	0.063	0.118	0.015	0.015
K	–	–	–	–	–	–	1.896	1.783	1.784	1.790	1.701	1.783	–	0.001
O	4.000	4.000	4.000	4.000	4.000	24.000	22.000	22.000	22.000	22.000	22.000	22.000	6.000	6.000
Atomic ratio $\frac{Mg}{Mg+Fe}$	0.85	0.92	0.81	0.90	0.76	–	0.79	0.86	0.83	0.85	0.86	0.74	–	–

nd = not detected

Chrome spinels also occur in two different groups. The first group comprises medium-sized (up to 1 mm) irregular shaped crystals while the second is made up of smaller (less than 0.25 mm) euhedral hexagonal crystals. The anhedral grains have 38–53 wt % Cr_2O_3 and are depleted in Al_2O_3 and have relatively high FeO contents (analysis 272, Table 3). In comparison the euhedral crystals have 33–37 wt % Cr_2O_3 and are richer in Al_2O_3 and MgO but poorer in FeO (analysis 148, Table 3).

The most common opaque oxides, found as small and often euhedral crystals, are Fe- and Ti-rich spinels, which show variable solid solution between magnetite and ulvospinel. From Table 3 it can be seen that they are compositionally similar to titanomagnetites from other kimberlites (e.g. Clarke & Mitchell 1975, Emeleus & Andrews 1975). The Holsteinsborg titanomagnetites seem to form two groups, one with greater than 69 wt % total FeO and a second with less

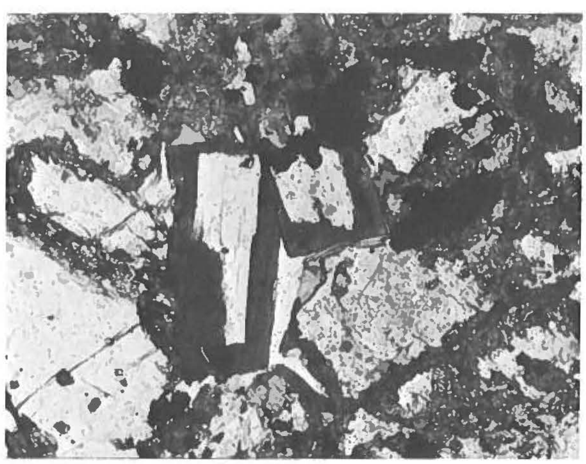

Fig. 9. Groundmass phlogopite with optically distinct rims showing reverse pleochroism in a kimberlite dyke. Other phases include olivine, oxides and groundmass serpentine. × 77.

Fig. 10. Clinopyroxene (high relief laths), phlogopite and oxides in the groundmass of a phlogopite, diopside kimberlite. × 128.

total FeO but up to 13.5 wt % Cr_2O_3 and generally higher Al_2O_3 (analyses 195 and 244 respectively).

Magnetite also occurs as euhedral or subhedral crystals and are often closely associated with the late-stage crystallisation of calcite.

Sulphides are also commonly present.

Perovskite. – Perovskite is a common accessory mineral and occurs as equant grains approximately 0.1 mm in size. It is similar in composition (Table 3) to perovskite found in other kimberlites (e.g. Mitchell 1972).

Serpentine. – Pale green or colourless serpentine occurs not only as an alteration product of olivine but also as a primary groundmass mineral. Serpentine also occurs in the core of some of the calcite-rich segregations. Analyses of primary serpentine (Table 3) show that it is rich in FeO (up to 12.2 wt %) and is similar to primary serpentine in other kimberlites.

Carbonate. – Carbonate is abundant in many of the dykes and occurs not only dispersed through the groundmass but also as irregular segregations. The occurrence of segregations, straight crystal boundaries, triple junctions and ophitic textures suggest that it is a primary groundmass constituent. Electron microprobe scans of some of the carbonate suggest that it is calcite with only minor Mg and Fe contents. It is often associated with primary serpentine and sometimes with extremely fine needles of clinopyroxene.

Calcite, sometimes with a core of serpentine, forms irregular segregations which can reach 1 cm in size. Elongate segregations are generally aligned parallel to the dyke margins. They may partly enclose silicate minerals from the surrounding groundmass, have small needles of clinopyroxene growing in from the walls of the segregation or may be rimmed by small phlogopite crystals.

Carbonate also occurs in secondary, cross-cutting veins which were occasionally observed transecting olivine macrocrysts.

Apatite. – Apatite is an accessory mineral which usually occurs as euhedral crystals associated with primary calcite. Apatite analyses (Table 3) indicate a high SiO_2 content which probably reflects the substitution of Si^{4+} for P^{5+} which is known in apatites (Cruft 1966).

Lamproites

These dykes exhibit a large variety of mineral assemblages, as can be seen from Table 4. Phlogopite is ubiquitous (Fig. 11) and most of the dykes contain pseudoleucite and olivine as important constituents. The dykes usually have porphyritic textures where phlogopite, pseudoleucite, olivine and clinopyroxene may occur as phenocrysts (Fig. 12). Groundmass minerals include phlogopite, amphibole, clinopyroxene and potassium feldspar. Apatite, rutile, priderite, sulphides, serpentine and carbonate also occur. Table 4 gives the modal analyses of some selected samples, but in most cases modal proportions vary substantially across the width of a dyke. This is particularly evident in porphyritic dykes where the phenocrysts are generally concentrated towards the centre presumably as the result of flow differentiation. Selected mineral analyses from these dykes are given in Table 5.

Phlogopite. – Phlogopites in the lamproites may occur as phenocrystal and/or groundmass lath-like crystals (Fig. 11) or as poikilitic plates enclosing pseudoleucite, apatite, clinopyroxene and occasionally olivine. The phlogopites are strongly pleochroic (X = pale yellow-brown, Y = Z = orange-brown) and have a distinctive colour typical of titaniferous phlogopite. The phenocrysts may be aligned parallel to the dyke contact and some larger crystals are deformed, in some cases with calcite invading split cleavage planes. Phlogopites of variable size have narrow rims with reverse pleochroism which are similar to those found in the kimberlite dykes.

The phlogopites have high TiO_2 contents (mostly 6–8 wt %, Table 5) and, compared with the kimberlite phlogopites they are richer in titanium, but poorer in sodium (< 0.16 wt % Na_2O) and alumina. Such titaniferous phlogopites are largely restricted to potassium-rich mafic rocks and these compositions compare well with phlogopites from the lamproites of West Kimberley, Australia (Carmichael 1967b) and the jumillites from Spain (Borley 1967). Phlogopites from other potassium-rich mafic rocks have different TiO_2 contents, for example those from the Leucite Hills, Wyoming are much lower (1–2 wt %, Carmichael 1967b) and those from Smoky Butte, Montana have higher TiO_2 contents (Velde 1975).

The optically distinct rims on the phlogopites are similar to those found in the kimberlites with higher Fe

Table 3. Selected mineral analyses from the Holsteinsborg kimberlite dykes. *90:* anhedral macrocryst of ilmenite, Fe_2O_3 = 10.4, FeO = 27.6*. *366:* 0.5 mm groundmass needle of ilmenite, Fe_2O_3 = 3.0, FeO = 37.9*. *272:* 0.8 mm anhedral chromite, Fe_2O_3 = 20.9, FeO = 24.8*. *148:* 0.25 mm euhedral chromite, Fe_2O_3 = 19.3, FeO = 18.9*. *195:* small subhedral groundmass spinel, Fe_2O_3 = 32.6, FeO = 32.7*. *244:* groundmass spinel, Fe_2O_3 = 50.9, FeO = 33.1*. *93:* groundmass perovskite. *341:* pale green serpentine in calcite/serpentine segregation. *249:* hexagonal 0.06 mm apatite in a calcite/serpentine segregation includes P_2O_5 = 36.83 and P is in formula = 5.312. * = recalculated after Carmichael 1967a.

Mineral	Ilmenite		Chromite		Spinel		Serpentine	Perovskite	Apatite
Sample number	5603	5975	5518	5605	5518	5987	5914	5698	5987
Analysis number	*90*	*366*	*272*	*148*	*195*	*244*	*341*	*93*	*249*
SiO_2	0.03	nd	nd	0.89	nd	0.03	39.01	0.02	2.16
TiO_2	50.54	52.85	4.10	6.38	19.97	10.39	0.15	57.14	0.01
Al_2O_3	0.49	nd	0.34	7.16	1.75	1.26	0.62	0.13	0.02
Cr_2O_3	1.12	0.14	42.21	33.77	0.99	0.05	0.03	0.03	nd
FeO	37.02	40.63	43.62	36.22	62.02	78.83	12.20	1.06	0.11
MnO	0.52	1.07	0.45	nd	0.79	0.96	0.09	0.03	0.07
NiO	–	0.07	0.27	nd	0.19	0.07	0.02	nd	nd
MgO	9.68	4.39	6.56	13.69	10.25	4.14	33.29	0.07	0.13
CaO	0.06	0.54	0.01	0.03	0.37	0.88	0.20	39.44	54.26
Na_2O	0.05	0.03	nd	0.05	0.07	0.03	0.08	0.23	0.07
K_2O	0.02	nd	0.02	nd	nd	nd	0.05	nd	0.02
Total	99.53	99.72	97.58	98.19	96.40	96.64	85.74	98.15	93.68
Formula									
Si	0.001	–	–	0.029	–	0.001	2.515	0.004	0.368
Ti	1.780	1.941	0.111	0.157	0.523	0.284	0.007	7.949	0.001
Al	0.027	–	0.014	0.276	0.072	0.053	0.047	0.028	0.004
Cr	0.041	0.005	1.197	0.874	0.027	0.001	0.002	0.004	–
Fe^{3+}	0.367	0.110	0.564	0.476	0.854	1.379	–	–	0.016
Fe^{2+}	1.081	1.548	0.744	0.518	0.952	0.996	0.658	0.164	–
Mn	0.021	0.044	0.014	–	0.023	0.029	0.005	0.005	0.010
Ni	–	0.003	0.008	–	0.003	0.002	0.001	–	–
Mg	0.676	0.320	0.351	0.668	0.532	0.222	3.199	0.019	0.033
Ca	0.003	0.028	0.001	0.001	0.014	0.034	0.014	7.817	9.904
Na	0.005	0.003	–	0.003	0.005	0.002	0.010	0.082	0.023
K	0.001	–	–	–	–	–	0.004	–	0.004
O	6.000	6.000	4.000	4.000	4.000	4.000	9.000	24.000	24.000
Atomic ratio $\frac{Mg}{Mg+Fe}$	–	–	–	–	–	–	0.83	–	–

nd = not detected.

Table 4. Modal analyses of some lamproites.

Sample no.	5647	5659	5622	5692	5632	5652
Olivine	2	1	11	9	3	–
Leucite	17	11	16[1]	16	–	–
Phlogopite	31	55	48	32	36	28
Clinopyroxene	4	–	8	10	24	–
Amphibole	15	12	6	16	–	33
Potassium feldspar	13	8	–	13	32[3]	29
Opaques	3	3	–	1	1	3
Serpentine	1	–	4[2]	–	–	–
Carbonate	13	10	6	3	4	2
Apatite	1	1	1	1	–	4
Texture*	P	P	K	K	K	F

* Texture of phlogopite: P = porphyritic, K = poikilitic, F = fine grained; 1 = may include minor potassium feldspar; 2 = includes some chlorite; 3 = may include minor leucite.

and lower Al contents relative to the main core of each crystal (analysis 31, Table 5).

Olivine. – The modal proportion of olivine varies considerably (Table 4) but it is present in the majority of the dykes. In most instances the olivines are anhedral, up to 1.5 cm in size, and may be fresh, partly or totally altered to serpentine and in some cases replaced by carbonate. Many of these olivines have conspicuous reaction rims. In a few instances the dykes contain numerous euhedral phenocrysts of olivine which sometimes occur as multiple growth aggregates. The euhedral olivines are generally smaller than the anhedral olivines. They are commonly altered with only one sample containing fresh euhedral olivine (sample 5631).

All the olivines fall within the compositional range

Table 5. Selected mineral analyses from the Holsteinsborg lamproite dykes. *163:* 2 mm phlogopite phenocryst. *316:* 2.5 mm basal section of phlogopite phenocryst, also BaO = 0.80, F = 0.5 wt %. *145:* groundmass phlogopite. *321:* small groundmass phlogopite, also BaO = 0.60 wt %. *30:* centre of phlogopite phenocryst. *31:* rim of 30 – tetraferriphlogopite. *418:* 1.5 mm anhedral olivine. *424:* 3 mm anhedral olivine. *434:* 0.3 mm anhedral olivine.

Mineral	Phlogopite					
Sample number	5646	5641	5693	5641	5622	5622
Analysis number	*163*	*316*	*145*	*321*	*30*	*31*
SiO_2	39.61	38.82	39.28	39.65	38.79	41.57
TiO_2	7.12	7.26	7.51	6.92	6.68	3.33
Al_2O_3	11.67	11.28	10.49	10.29	10.51	4.24
Cr_2O_3	0.40	0.24	nd	0.04	0.13	0.05
FeO	5.66	5.68	8.25	8.02	7.63	13.65
MnO	0.02	0.06	0.07	0.06	0.06	0.06
NiO	0.15	0.14	0.04	0.18	–	–
MgO	21.09	20.33	19.38	19.73	19.61	20.00
CaO	nd	0.01	0.05	0.11	–	–
Na_2O	0.09	0.07	0.13	0.12	0.15	0.04
K_2O	9.98	10.01	9.88	9.99	9.91	10.04
Total	95.79	93.90	95.08	95.11	93.47	92.98
Formula						
Si	5.666	5.664	5.732	5.773	5.747	6.380
Ti	0.766	0.797	0.824	0.758	0.744	0.384
Al	1.968	1.940	1.804	1.766	1.835	0.767
Cr	0.045	0.028	–	0.005	0.015	–
Fe	0.677	0.693	1.007	0.977	0.945	1.740
Mn	0.002	0.007	0.009	0.007	0.008	0.008
Ni	0.017	0.016	0.005	0.021	–	–
Mg	4.497	4.421	4.215	4.282	4.331	4.575
Ca	–	0.002	0.008	0.017	–	–
Na	0.025	0.020	0.037	0.034	0.043	0.012
K	1.821	1.863	1.839	1.855	1.873	1.966
O	22.000	22.000	22.000	22.000	22.000	22.000
Atomic ratio $\frac{Mg}{Mg+Fe}$	0.87	0.86	0.81	0.82	0.82	0.72

nd = not detected

$Mg_{87.5-93}$ (Fig. 8). The NiO content is generally high (0.32–0.50 wt %) but does not correlate with MgO. Zoning is not usually apparent but when present is normal. The olivines tend to be more MgO-rich than the Holsteinsborg kimberlites and other potassium-rich mafic rocks (e.g. $Fo_{85-90.6}$ from Carmichael 1967b or $Fo_{82.5-88.7}$ from Borley 1967) but have similarly high NiO contents.

Pseudoleucite. – Another common phenocryst, which is pale pink in hand specimen, is pseudoleucite. The phenocrysts (up to 5 mm in diameter) are usually euhedral with polygonal outlines (Fig. 12). They often form aggregates and phenocrysts may partially enclose clinopyroxene crystals (Fig. 12). Small crystals of pseudoleucite also occur in the groundmass and may be poikilitically enclosed by phlogopite. In samples where potassium feldspar is abundant in the groundmass it can be difficult to distinguish the pseudoleucite. Each pseudoleucite grain is composed of a mosaic of feldspar crystals which may be somewhat turbid when altered to flakes of sericite. Analyses indicate that the feldspar is almost pure $KAlSi_3O_8$ although some contain considerable amounts of BaO (Table 5). Potassium feldspar is usually an important constituent of pseudoleucite but is more commonly intergrown with nepheline (Fudali 1963) but there is no evidence to suggest the presence of nepheline in the Holsteinsborg pseudoleucites. The original phenocrysts, probably crystallised as almost pure leucite, with little or no sodium in solid solution, as is the case in other lamproites (e.g. Carmichael 1967b). The breakdown of pure leucite to potassium feldspar has been suggested by experimental work (e.g. Seki & Kennedy 1964) and may account for the compositions of the pseudoleucites in the Holsteinsborg lamproites.

Clinopyroxene. – Clinopyroxene is the least common phenocryst and is only present in some of the dykes. They can form radiating or stellate clusters associated with other phenocryst phases. Clinopyroxene also occurs in the groundmass but is seldom particularly fine-grained. The clinopyroxene is often partially altered, usually to amphibole. The latter can generally be distinguished optically from the primary groundmass

43: pseudoleucite phenocryst. *305:* pseudoleucite phenocryst, also BaO = 1.69 wt %. *307:* clinopyroxene phenocryst. *171:* 0.25 mm groundmass needle of amphibole. *304:* green groundmass amphibole. *519:* groundmass feldspar, interstitial.

Olivine			Pseudoleucite		Cpx	Amphibole		Feldspar
5612	5612	5631	5622	5640	5640	5646	5640	5632
418	*424*	*434*	*43*	*305*	*307*	*171*	*304*	*519*
41.18	41.20	40.21	63.37	64.08	53.09	54.44	53.21	63.30
nd	nd	nd	0.03	0.18	0.99	1.07	2.67	0.30
–	–	–	18.47	17.45	0.48	0.17	0.12	15.94
0.02	0.05	0.05	0.02	nd	0.76	0.05	nd	nd
7.19	8.10	11.63	0.11	0.06	3.03	11.86	10.58	2.85
0.08	0.12	0.19	0.03	nd	0.04	0.11	0.13	nd
0.44	0.37	0.46	–	nd	0.10	–	0.02	nd
50.25	49.63	46.59	0.07	0.03	17.11	16.50	15.92	0.03
0.02	0.06	0.13	–	0.03	23.27	0.46	2.88	0.03
–	–	–	0.02	0.06	0.40	6.98	5.71	0.40
–	–	–	16.63	16.25	0.02	5.12	5.14	15.73
99.18	99.53	99.26	98.75	98.14	99.29	96.76	96.38	98.58
1.006	1.007	1.003	11.907	12.027	1.955	8.027	7.883	12.049
–	–	–	0.004	0.025	0.027	0.119	0.297	0.043
–	–	–	4.093	3.860	0.021	0.030	0.021	3.576
–	0.001	0.001	0.003	–	0.022	0.006	–	–
0.147	0.165	0.243	0.017	0.009	0.093	1.463	1.311	0.454
0.002	0.002	0.004	0.005	–	0.001	0.014	0.016	–
0.009	0.007	0.009	–	–	0.003	–	0.002	–
1.830	1.808	1.733	0.020	0.008	0.939	3.626	3.515	0.009
–	0.002	0.003	–	0.006	0.918	0.073	0.457	0.006
–	–	–	0.007	0.002	0.029	1.996	1.640	0.148
–	–	–	3.986	3.891	0.001	0.963	0.971	3.820
4.000	4.000	4.000	32.000	32.000	6.000	23.000	23.000	32.000
0.93	0.92	0.87	–	–	–	–	–	–

amphibole. Analyses show them to be mostly diopsides (Table 5) with variable, but high Cr_2O_3 contents (up to 1.2 wt %) similar to diopside phenocrysts found in other lamproites (Carmichael 1967b). Compared to the groundmass diopsides from the Holsteinsborg kimberlites, those from the lamproites have lower Ca and Al but higher Cr, Mg and Na.

Amphibole. – Amphibole is a common groundmass constituent of many of the lamproites occurring as poorly formed tabular crystals, usually less than 0.5 mm long, which are green and pleochroic (X = dark greenish brown or pale green, Z = darkish green). Analyses (Table 5) show them to be potassic richterites (using the classification of Leake, 1968). As Na is in excess of K in the unit formula, they are not magnophorite which is a common mineral in the lamproites of Western Australia (Prider 1939). Richterites similar in composition to those from Holsteinsborg have been reported from a jumillite (analysis S. I. Carmichael 1967b) but in general the Holsteinsborg amphiboles are much richer in total alkalis (12 wt % K_2O + Na_2O) and Fe and also extremely depleted in Ca relative to most other potassic richterites.

Alkali feldspar. – Many of the dykes contain feldspar in the groundmass. It usually occurs interstitially to the other groundmass phases but in two instances the feldspar occurs as lath-like crystals which may form poorly developed radiating textures. Analyses of the feldspar (Table 5) show that it is potassium feldspar which has relatively high FeO contents (up to 3.84 wt %).

Opaque minerals. – Fine-grained opaque minerals occur in a few dykes but are not particularly abundant. The majority of them are sulphides. The few analysed grains were Fe-sulphides. Rutile is also a common accessory and appears to often have a high FeO content (up to 10 wt %).

Table 6 gives analyses of some unusual opaque oxide grains which are anisotropic in reflected light. The composition of these grains is similar to priderite (Norrish 1951).

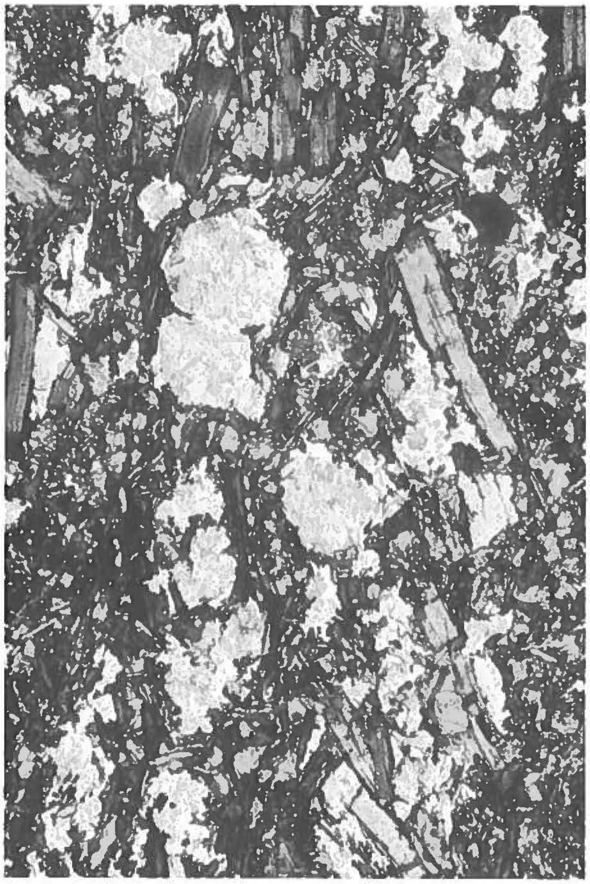

Fig. 11. Photomicrograph of a lamproite. Phenocrysts and groundmass laths of phlogopite and often euhedral, polygonal pseudoleucite are the main constituents. × 29.

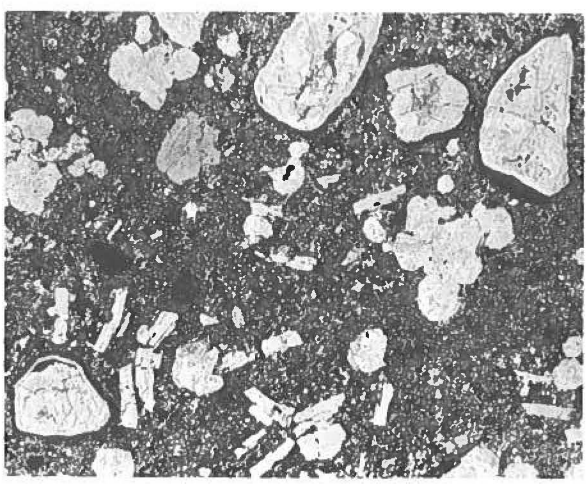

Fig. 12. Lamproite with phenocrysts of anhedral, serpentinised olivines, phlogopites, pseudoleucites (often in clusters) and rare clinopyroxene set in a fine-grained groundmass. One clinopyroxene phenocryst partially included in a euhedral pseudoleucite can be seen (lower left). × 3.9.

Table 6. Analyses of priderite from a lamproite (sample 5637).

Analysis number	526	529
SiO_2	nd	nd
TiO_2	81.56	78.86
Al_2O_3	0.02	0.05
Cr_2O_3	0.42	0.48
FeO	9.51	9.62
K_2O	8.65	9.59
BaO	0.26	0.76
Total	100.42	99.36

nd = not detected.

No titanomagnetite or other spinels were encountered in the lamproites during this study. Titaniferous magnetite does not occur either in the lamproites from Wyoming, Spain or Australia except for one madupite from the Leucite Hills, Wyoming (Carmichael 1967b).

Other minerals. – Apatite, carbonate, serpentine and chlorite also occur in many of the dykes. Apatite is a constant accessory mineral and in some cases is an important constituent. Carbonate also occurs in most of the dykes and is usually concentrated in patches. Texturally it appears to be a primary constituent of the rock. It is often associated with apatite, minor serpentine and fibrous green chlorite all of which appear to be primary. This association may represent the crystallisation of pockets of residual fluid.

Inclusions in the kimberlites

Rounded inclusions are common in parts of some of the kimberlite dykes (Fig. 3) and consist mostly of peridotites but two eclogites and two granulites were identified. Escher & Watterson (1973) have also reported inclusions in these dykes. Some of these inclusions were examined during this study.

Peridotites. – Olivine-rich inclusions appear to be more abundant in these dykes than in other kimberlites and 44 dunites, 10 lherzolites, 9 wehrlites and 8 harzburgites were identified. Garnet was only observed in one coarse wehrlite (Sample 5524B) and one coarse lherzolite (Sample 5984(a)).

Using the textural classification of Harte (1977) the peridotite inclusions generally have either coarse or porphyroclastic textures but a few have mosaic-porphyroclastic and granuloblastic textures.

The coarse inclusions (Fig. 13) are fairly equigranular with olivine grains usually greater than 2 mm in size and ranging up to 8 mm. The grain boundaries are normally serrated but may be straight or smoothly curved and many of the olivines have undulose extinction. Minor amounts of clinopyroxene and orthopyroxene are found as irregular or globular grains approximately 2 mm in

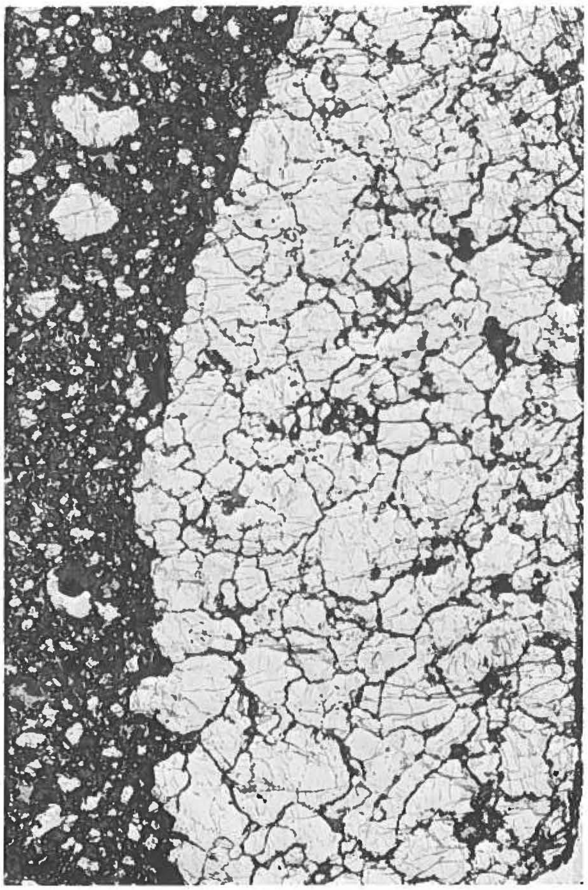

Fig. 13. Coarse dunite inclusion set in a relatively dark, porphyritic kimberlite matrix. × 4.5.

size. Two inclusions, which appear to be layered, contain abundant pyroxene. Chrome-spinels occur as small irregular grains (less than 0.25 mm) which may be enclosed within olivine. A few peridotite inclusions have coarse-tabular textures.

Inclusions with porphyroclastic textures (Fig. 14) contain relatively large (2–7 mm) and often strained porphyroclasts of olivine which are surrounded by distinctly smaller (less than 1 mm) neoblasts. Scarce pyroxene usually occurs as porphyroclasts. Chrome-spinels are more abundant in the recrystallised parts of these peridotites and appear to be similar in grain size to, and in textural equilibrium with, the other neoblasts.

Some of the porphyroclastic inclusions show evidence of metasomatism and late-secondary alteration (terminology after Harte, Cox & Gurney 1975). The late-secondary alteration is comparatively easy to identify. It is indicated by serpentine, phlogopite, ilmenite and sometimes carbonate occurring along grain boundaries and as veins or isolated patches in the rocks. These minerals are out of equilibrium with the primary peridotite minerals. The phlogopites sometimes have rims with reverse pleochroism similar to those found in the host kimberlite. This suggests that the alteration may be caused by the host kimberlitic fluids, perhaps close to the time of eruption.

The occurrence of phlogopite and sometimes ilmenite in recrystallised parts of inclusions, where they are of similar grain size and in textural equilibrium to the other silicates, is probably indicative of metasomatism. Phlogopite and ilmenite are absent in most of the coarse grained inclusions. Vein-like areas are also sometimes enriched in phlogopite. Clouded pyroxenes, particularly orthopyroxenes also occur in some of the inclusions.

A few inclusions have relatively large patches or vein networks of ilmenite which has a composition (10.7 wt % MgO) similar to the macrocrysts in the host kimberlite. These ilmenite-bearing inclusions are similar to those described by Harte & Gurney (1975) from Matsoku.

Table 7 gives a representative selection of analyses of the minerals from the peridotitic inclusions. The total range in olivine compositions is $Mg_{82.5-92.5}$ but for individual inclusions the range is usually less than 2.5 wt % (Fig. 8). The NiO content varies from 0.25 to 0.39 wt % and shows a poorly defined, positive correlation with MgO. These olivines also have consistently low CaO values, less than 0.1 wt %. The dunites in particular have a wide range of olivine compositions including some which are more iron-rich than those typically found in peridotities from other kimberlites. The dunites, therefore, probably represent cumulates.

The clinopyroxenes are diopsides or endiopsides (after Deer, Howie & Zussman 1962) with Mg/Mg+Fe ratios between 0.87 and 0.93. The diopsides are rich in chrome (1–2 wt % Cr_2O_3) and restricted in composition with 2–3 wt % FeO, 16–18 wt % MgO and 19–22 wt % CaO (e.g. analyses 505 and 466, Table 7). The calcium-poor clinopyroxenes were found in only one inclusion, a coarse garnet wehrlite, and they are poorer in chrome and richer in iron (e.g. analysis 488, Table 7) compared with the diopsides.

The orthopyroxenes analysed have restricted compositions, $En_{89.7-92.9}$ but with variable Al_2O_3 from 0.09 to 2.54 wt %.

Garnet was analysed from both the garnet-bearing peridotites found (Table 7). The garnets from the coarse lherzolite (analysis 462, Table 7) fall in group 16 of Danchin & Wyatt (1979) and Group 9 of Dawson & Stephens (1975, 1976) and are similar to garnets from lherzolites and macrocrysts from other kimberlites. The garnets from the coarse wehrlite are relatively low in Cr_2O_3 (analysis 485, Table 7) and fall in group 24 of Danchin & Wyatt (1979) and group 1 of Dawson & Stephens (1975, 1976).

Spinels which are considered to be primary occur in both coarse and porphyroclastic inclusions. They have 57–62.2 wt % Cr_2O_3 and 9.8 to 11.2 wt % MgO (e.g. analysis 112, Table 7). One chromite with a composition equivalent to chromites found as inclusions in diamond occurs in a dunite. Spinels associated with

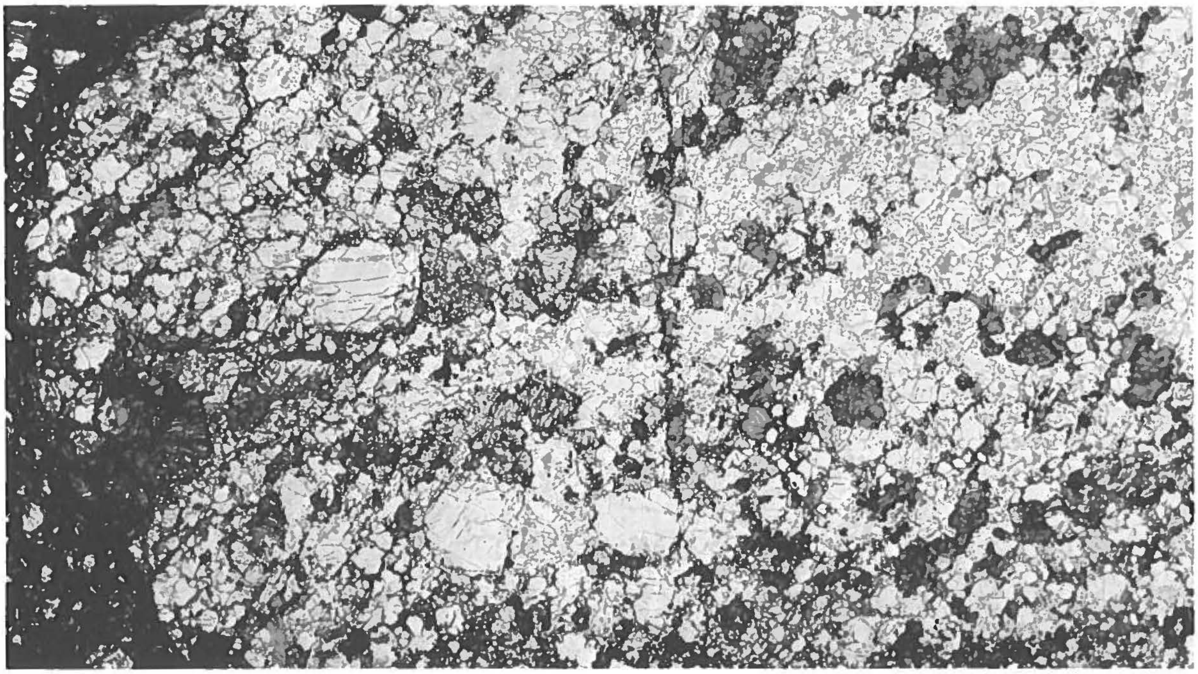

Fig. 14. Porphyroclastic lherzolite inclusion. Relatively large porphyroclasts are surrounded by smaller olivine neoblasts. × 4.4.

late-secondary green phlogopites are considered to be secondary and contain significantly less Cr_2O_3 but have high Al_2O_3 contents (e.g. analysis 259, Table 7).

A variety of phlogopites have been analysed from the peridotite inclusions. The brown metasomatic phlogopites have greater than 1 wt % TiO_2 and no detectable NiO while the secondary green phlogopites have lower TiO_2 but greater than 0.15 wt % NiO (e.g. analyses 110 and 257 respectively, Table 7). The difference in Cr_2O_3 between the primary metasomatic and late-secondary phlogopites at Matsoku (Harte & Gurney 1975) does not hold for the Holsteinsborg peridotites.

Analyses of amphiboles show that both tremolite and richterite (after Leake 1968) occur as fibrous patches apparently resulting from the alteration of clinopyroxene in otherwise fresh coarse inclusions.

Only a few of the peridotite inclusions have mineral assemblages suitable for pressure/temperature estimations. This precludes the determination of a geotherm. Application of data of Davis & Boyd (1966), Mac Gregor (1974), Wood & Banno (1973) and Akella (1974) to some of the lherzolite (± garnet) and wehrlite inclusions suggests that they equilibrated at temperatures between 1000 and 1100°C and at pressures greater than 40 kb. One garnet wehrlite indicated equilibration temperatures of approximately 1300°C. The occurrence of a chromite similar to diamond inclusions in some of the dunites is consistent with the derivation of these inclusions from within the diamond stability field.

Granulites. – Two small (less than 3 cm) garnet granulites were identified. They have inequigranular textures with garnets (up to 4 mm) occurring in a finer-grained mosaic of feldspar, green clinopyroxene, amphibole, minor rutile and some carbonate. Grain boundaries tend to be straight or curved.

Three analyses are given in Table 8. The garnets are rich in almandine and pyrope while the clinopyroxene is omphacite. The feldspars in the two inclusions are different, either potassium feldspar or sodic plagioclase.

Table 8. Selected mineral analyses from one garnet-granulite inclusion from a kimberlite dyke.

Mineral	Garnet	Feldspar	Clinopyroxene
Sample number	5518G	5518G	5518G
Analysis number	*235*	*212*	*218*
SiO_2	39.62	64.55	52.75
TiO_2	0.13	nd	0.53
Al_2O_3	21.74	21.76	7.36
Cr_2O_3	0.05	nd	0.04
FeO	23.11	0.02	6.64
MnO	0.41	0.01	0.04
NiO	nd	nd	nd
MgO	8.54	0.04	10.46
CaO	7.07	2.68	17.76
NaO	0.03	9.89	4.04
K_2O	nd	0.45	nd
Total	100.70	99.40	99.62

nd = not detected

Table 7. Selected mineral analyses from peridotite inclusions found in the Holsteinsborg kimberlite dykes. *383:* olivine from coarse dunite. *109:* olivine from porphyroclastic lherzolite. *461:* olivine from coarse garnet-lherzolite. *505:* clinopyroxene from porphyroclastic lherzolite. *466:* clinopyroxene from coarse garnet-lherzolite. *488:* sub-calcic clinopyroxene from coarse garnet-wehrlite. *506:* orthopyroxene from porphyroclastic lherzolite. *493:* orthopyroxene from coarse garnet-lherzolite. *485:* garnet from coarse garnet-wehrlite. *462:* garnet from coarse garnet-lherzolite. *112:* chromite from porphyroclastic lherzolite (primary) Fe_2O_3 = 8.2, FeO = 18.5. *259:* small spinel (<1 mm) from coarse lherzolite associated with secondary phlogopite 257, Fe_2O_3 = 7.1, FeO = 13.6. *110:* brown phlogopite from porphyroclastic lherzolite. *257:* green phlogopite from coarse lherzolite. Groups of analyses from a single inclusion are *a:* 109, 505, 506, 112, 110. *b:* 461, 466, 493, 462. *c:* 259, 257. *d:* 485, 488.

Mineral	Olivine			Clinopyroxene			Orthopyroxene		Garnet		Spinel		Phlogopite	
Sample number	5914(2)	5698(2)	5984a	5698(2)	5984a	5524B	5698(2)	5984a	5524B	5984b	5698(2)	55180L	5698(2)	55180L
Analysis number	*383*	*109*	*461*	*505*	*466*	*488*	*506*	*493*	*485*	*462*	*112*	*259*	*110*	*257*
SiO_2	39.80	40.71	40.35	54.06	54.93	55.19	57.55	55.36	42.51	42.92	0.04	nd	41.22	42.39
TiO_2	0.03	nd	0.07	0.25	0.11	0.52	0.13	0.08	0.69	0.20	2.59	0.02	1.25	0.12
Al_2O_3	0.03	nd	0.04	0.55	2.24	2.90	0.09	0.85	21.63	19.87	2.52	32.05	11.80	12.25
Cr_2O_3	nd	0.08	0.02	1.04	1.54	0.38	0.15	0.21	0.90	4.28	57.27	31.78	0.53	0.52
FeO	16.69	10.69	9.18	3.20	2.64	4.62	7.27	5.49	9.08	8.45	25.87	19.94	3.85	2.45
MnO	0.22	0.17	0.12	0.12	0.08	0.14	0.15	0.10	0.29	0.47	0.81	0.32	nd	0.02
NiO	0.27	–	0.36	0.06	0.04	0.06	0.12	0.10	0.04	nd	–	0.19	nd	0.17
MgO	44.38	48.38	49.57	18.23	16.41	18.06	33.99	35.70	20.86	19.77	10.09	15.10	24.62	26.66
CaO	0.02	0.09	0.03	20.98	19.62	16.17	0.83	0.47	4.44	5.27	0.02	nd	nd	nd
Na_2O	0.05	nd	–	0.75	1.96	1.91	0.07	0.09	0.05	0.04	nd	nd	0.19	1.01
K_2O	0.01	nd	–	0.04	0.01	0.04	0.01	0.01	nd	0.02	0.01	nd	10.22	8.67
Total	101.50	100.12	99.74	99.28	99.58	99.99	100.36	98.46	100.49	101.29	99.22	99.40	93.68	94.26
Formula														
Si	0.993	1.000	0.991	1.979	1.991	1.984	1.989	1.941	6.032	6.096	0.001	–	5.949	5.990
Ti	0.001	–	0.001	0.007	0.003	0.014	0.003	0.002	0.074	0.021	0.067	–	0.136	0.013
Al	0.001	–	0.001	0.024	0.096	0.123	0.004	0.035	3.617	3.326	0.102	1.105	2.007	2.040
Cr	–	0.002	–	0.030	0.044	0.011	0.004	0.006	0.101	0.481	1.550	0.735	0.060	0.058
Fe^{3+}	–	–	–	–	–	–	–	–	–	–	0.211	0.156	–	–
Fe^{2+}	0.348	0.220	0.189	0.098	0.080	0.139	0.210	0.161	1.078	1.004	0.530	0.333	0.465	0.290
Mn	0.005	0.004	0.002	0.004	0.002	0.004	0.004	0.003	0.035	0.057	0.023	0.008	–	0.002
Ni	0.005	–	0.007	0.002	0.001	0.002	0.003	.0003	0.005	–	–	0.004	–	0.019
Mg	1.651	1.772	1.814	0.995	0.887	0.968	1.751	1.865	4.412	4.185	0.515	0.659	5.296	5.615
Ca	0.001	0.002	0.001	0.823	0.762	0.623	0.031	0.018	0.675	0.802	0.001	–	–	–
Na	0.002	–	–	0.053	0.138	0.133	0.005	0.006	0.014	0.011	–	–	0.053	0.277
K	–	–	–	0.002	–	0.002	–	–	–	0.004	–	–	1.882	1.563
O	4.000	4.000	4.000	6.000	6.000	6.000	6.000	6.000	24.000	24.000	4.000	4.000	22.000	22.000
Atomic ratio $\frac{Mg}{Mg+Fe}$	0.83	0.89	0.91	–	–	–	0.89	0.92	–	–	–	–	0.92	0.95

nd = not detected

Eclogites. – The two small (approximately 2 cm), rounded, eclogite inclusions have reaction rims against the kimberlite. Garnet and clinopyroxene occur in approximately equal amounts but the garnets tend to be coarser grained (up to 5 mm).

Other post-tectonic intrusions

Anomalous lamprophyres. – The so-called anomalous lamprophyres differ from the other dykes in that clinopyroxene is the main constituent. Mineral analyses from one of these dykes is given in Table 9. The clinopyroxene occurs both as euhedral phenocrysts (up to 5 mm) and as long slender laths up to 2 mm in length forming the main constituent of the groundmass. They are either salites or endiopsides and are generally richer in Fe than those from the other Holsteinsborg dykes.

Deep brown phlogopite is an abundant groundmass constituent but phenocrysts (up to 3 mm) which are often deformed occur only in the coarser central parts of the dykes. Occasionally the large phlogopites have a poikilitic texture enclosing small crystals of clinopyroxene. These phlogopites are similar to those in the other dykes being rich in titanium but the former have higher Na_2O and FeO contents.

The groundmass amphibole is kaersutite which is typical of certain alkaline rocks such as camptonite and chemically distinct from the amphibole occurring in the

Table 9. Selected analyses from one anomalous lamprophyre dyke (sample 5669). *322:* 2 mm clinopyroxene phenocryst. *333:* small needle of clinopyroxene included in phlogopite. *329:* groundmass amphibole. *327:* groundmass phlogopite, 0.2 mm long. Also BaO = 0.67, F = 0.15 wt %. *331:* centre of phlogopite phenocryst. Also BaO = 0.90, F = 0.13 wt %. *326:* groundmass feldspar. Also BaO = 0.26 wt %. *336:* centre of 0.5 mm opaque mineral, Fe_2O_3 = 10.6, FeO = 16.4.

Mineral	Clinopyroxene		Amphibole	Phlogopite		Feldspar	Spinel
Analysis number	*322*	*333*	*329*	*327*	*331*	*326*	*336*
SiO_2	53.87	49.02	40.13	36.12	36.56	63.40	0.08
TiO_2	0.24	1.86	4.02	4.48	4.89	0.07	1.78
Al_2O_3	1.22	3.54	12.19	15.24	15.18	21.22	8.09
Cr_2O_3	1.19	nd	0.01	nd	0.05	nd	51.17
FeO	3.98	7.49	11.47	9.02	9.12	0.68	25.90
MnO	0.11	0.18	0.31	0.11	0.07	nd	0.37
NiO	0.10	0.04	nd	0.03	nd	nd	0.22
MgO	18.86	14.07	13.36	19.09	18.80	0.16	12.02
CaO	19.58	22.81	11.79	0.08	0.06	1.89	0.03
Na_2O	0.50	0.29	2.96	1.26	0.93	8.75	nd
K_2O	nd	0.03	0.99	8.51	8.87	1.59	nd
Total	99.65	99.33	97.23	93.94	94.53	97.76	99.66
Formula							
Si	1.962	1.847	5.741	5.332	5.360	11.472	0.003
Ti	0.007	0.053	0.432	0.477	0.539	0.010	0.044
Al	0.052	0.157	2.055	2.651	2.623	4.525	0.313
Cr	0.034	–	0.001	–	0.006	–	1.327
Fe^{3+}	–	–	–	–	–	–	0.262
Fe^{2+}	0.121	0.236	1.372	1.114	1.118	0.103	0.450
Mn	0.003	0.006	0.038	0.014	0.009	–	0.010
Ni	0.003	0.001	–	0.004	–	–	0.006
Mg	1.024	0.790	2.849	4.200	4.108	0.043	0.588
Ca	0.764	0.921	1.807	0.013	0.009	0.366	0.001
Na	0.035	0.021	0.821	0.361	0.264	3.070	–
K	–	0.001	0.181	1.603	1.659	0.367	–
O	6.000	6.000	23.000	22.000	22.000	32.000	6.000

nd = not detected

Holsteinsborg lamproites. Titanomagnetite occurs as a cubic groundmass mineral and as overgrowths on larger chrome spinels. Alkali feldspar occurs as a late-stage groundmass mineral and has variable K/Na ratios. These dykes also have irregular segregations which are usually composed of calcite although sanidine may also be an important constituent.

Pipe-like intrusion. – The main constituent of this intrusion is mica which occurs as pale brown and generally deformed books up to 1.5 cm long. The mica encloses irregular oxides and serpentinised subhedral olivines (up to 2 mm). A few subhedral clinopyroxenes also occur. The rounded inclusions are mostly coarse wehrlites that contain chrome spinel and amphibole. Olivine compositions for this inclusion (5925) are illustrated in Fig. 8.

Whole rock geochemistry

Figs. 15 and 16 summarise the major and trace element data for a total of 93 samples. It can be seen from these figures that the Holsteinsborg dykes show a wide range of compositions but generally form two chemically distinct groups which are consistent with their division into kimberlites and lamproites using petrographic criteria. Table 10 gives some selected whole-rock analyses (from Scott 1977).

The kimberlites have the characteristic major and trace element chemistry of this rock type and compare well with the micaceous kimberlites discussed by Dawson (1967b). The Holsteinsborg kimberlites, however, do have lower H_2O^+ contents and Fe^{3+}/Fe^{2+} ratios which presumably reflects the general lack of alteration relative to many kimberlites.

The lamproites are distinguished from the kimberlites by higher SiO_2, K_2O, Al_2O_3, P_2O_5, Rb, Sr, Y, Zr, Ba, Ce and La but lower MgO, FeO, Fe_2O_3, CaO, MnO, H_2O^+, Cr, Ni and Cu. These dykes are characterised by high K_2O values (up to 10 wt %) and high K/Na ratios which is unusual for such magnesian rock types.

A more detailed evaluation of the whole-rock geochemistry of these dykes and their petrogenesis is given by Scott (1979). The hypothesis (Scott 1979) suggested that firstly a kimberlitic magma was generated in the mantle and with some modifications this magma was intruded to form the kimberlite dykes. Se-

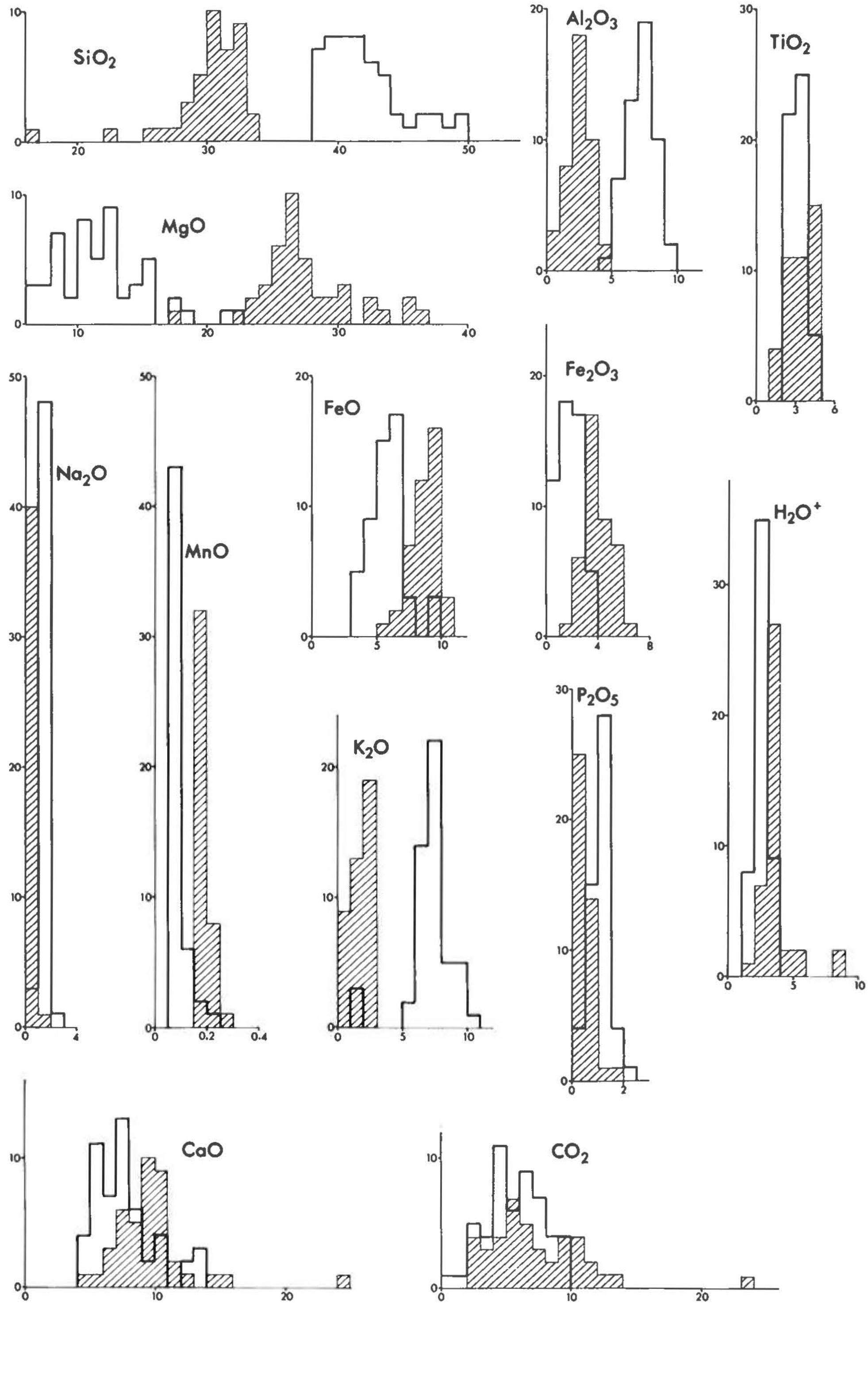

Fig. 15. Frequency distribution diagrams of major oxide concentrations in wt. % for the Holsteinsborg dykes. Shaded = kimberlites; white = lamproite.

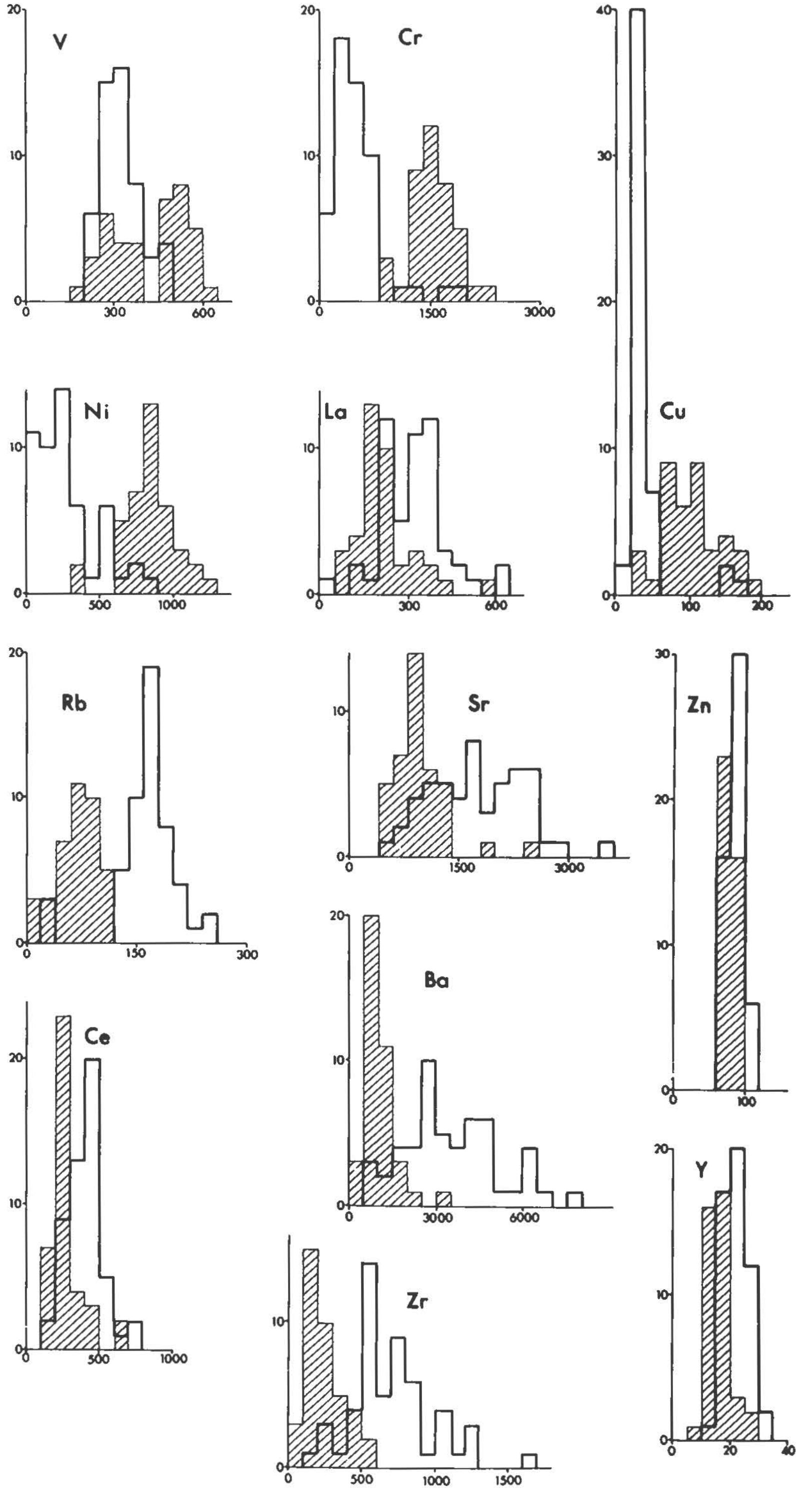

Fig. 16. Frequency distribution diagrams of the trace element concentrations in ppm in the Holsteinsborg dykes. Shaded = kimberlites; white = lamproites.

Table 10. Representative whole-rock analyses of Holsteinsborg kimberlite and lamproite dykes.

	Kimberlites						Lamproites						Anomalous lamprophyre
Sample	5503	5518	5603	5696	5974	5985	5622	5632	5643	5692	5940	5943	5668
Major oxides													
SiO_2	29.27	25.68	31.00	32.63	32.27	33.50	39.29	42.75	46.48	43.79	38.29	41.20	39.79
TiO_2	2.35	1.54	3.75	4.39	4.59	4.34	2.17	3.18	3.38	2.67	3.31	2.50	2.69
Al_2O_3	2.74	1.90	2.97	2.30	2.44	4.13	4.90	8.47	7.66	7.04	7.29	8.48	9.08
Fe_2O_3	2.49	5.12	2.99	3.98	4.55	5.32	1.35	1.74	3.14	1.35	2.81	2.38	3.83
FeO	8.40	6.87	10.00	9.68	9.59	8.35	6.25	5.01	4.09	5.73	5.15	3.85	9.08
MnO	0.19	0.26	0.18	0.19	0.19	0.18	0.10	0.09	0.07	0.09	0.12	0.09	0.21
MgO	27.01	26.12	26.58	32.11	30.33	22.71	22.55	12.16	10.74	15.59	10.01	12.30	10.52
CaO	10.53	14.66	7.61	6.86	7.26	11.90	4.73	7.38	5.54	5.21	12.24	9.68	12.62
Na_2O	0.31	0.14	0.23	0.12	0.28	0.23	1.00	0.90	1.37	1.30	1.16	1.11	2.05
K_2O	2.38	1.08	1.78	1.47	1.58	2.31	6.16	7.99	8.14	7.06	5.67	7.38	1.55
H_2O^+	2.76	5.15	3.78	3.13	3.52	2.78	2.82	2.65	2.92	3.19	2.91	2.70	3.02
P_2O_5	0.60	0.77	0.27	0.25	0.32	0.59	0.94	0.73	1.43	1.16	1.00	0.46	0.52
CO_2	11.02	12.20	7.29	2.69	2.94	3.57	5.14	4.96	3.05	2.94	8.97	6.90	4.01
Total	100.05	101.49	98.43	99.80	99.86	99.91	97.40	98.01	98.01	97.12	98.93	99.03	98.97
Minor elements													
V	268	206	468	495	535	549	220	320	291	278	362	250	470
Cr	1396	865	1568	2342	1909	1250	756	378	331	533	351	399	1184
Ni	842	738	727	1047	1031	652	856	174	332	518	151	286	148
Cu	77	53	128	83	109	187	28	16	24	36	38	27	152
Zn	72	88	77	74	84	78	88	77	101	84	95	64	99
Rb	94	44	85	61	67	86	168	242	171	135	152	218	32
Sr	1227	1968	561	620	693	889	2563	1621	1467	2190	1052	642	881
Y	15	18	14	15	14	10	20	16	24	22	28	20	26
Zr	141	159	126	165	184	503	490	279	1078	789	561	346	277
Ba	1094	3278	1174	623	794	990	3227	4224	1524	6200	5758	4075	945
La	217	363	178	240	189	131	262	209	393	373	367	174	129
Ce	271	405	218	329	264	189	345	287	478	447	439	256	205

condly, a separate portion of the initial kimberlitic magma underwent extensive fractionation of olivine and Fe–Ti-spinel producing a liquid which was lamprophyric in character. With some modification this magma was intruded to form the lamproite dykes.

Age

The results of Rb-Sr isotopic analyses of phlogopite concentrates from three of the kimberlite and three of the lamproite dykes which are discussed in this paper were reported by Smith (1979). Additional details of the methods and results of these determinations are given here (C. B. Smith, personal communication).

Samples were analysed by conventional isotope dilution mass spectrometry methods used at the Bernard Price Geophysical Institute, University of the Witwatersrand, for the determination of kimberlite emplacement ages (e.g. Allsopp & Barrett, 1975). Two to three phlogopite concentrates from each dyke and an additional groundmass amphibole concentrate from one lamproite were cleaned by handpicking and ultrasonic washing in a mixture of alcohol and distilled water. Analysed separates are better than 98 percent pure, except for the amphibole which is considered to be better than 90 percent pure. Samples of about 0.01 gm were dissolved in purified HF and $HClO_4$ after spiking with ^{87}Rb and ^{84}Sr spikes. Rb and Sr were separated and purified by standard ion exchange procedures. The high purity ^{84}Sr spike allowed $^{87}Sr/^{86}Sr$ ratios to be determined on the spiked aliquots. Rb and Sr blanks varied between 1 and 10 nanograms, and are negligible for the amounts of sample dissolved. The data was regressed by the method of York (1966), and ages were calculated using an ^{87}Rb decay constant of 1.42×10^{-11} y^{-1}. Sr standard SRM987 gave $^{87}Sr/^{86}Sr = .71024 \pm 6$ (2σ) during this work.

Analytical results are given in Table 11, and plotted on an isochron diagram in Fig. 17. The calculated age for the lamproite dykes is 1227 ± 12 m.y. and for the kimberlite dykes is 587 ± 24 m.y. (Fig. 17). The data arrays for both rock types are isochrons as opposed to errorchrons by the definition of Brooks et al. (1972). These ages are interpreted as being emplacement ages and show that the kimberlites and lamproites are not related.

The initial $^{87}Sr/^{86}Sr$ ratios (Ro) of both dyke suites are low (lamproite – Ro = .7038 ± 5, kimberlite – Ro = .701 ± 6; 2 σ errors) and are indicative of a mantle origin for these rocks. The difference between the initial

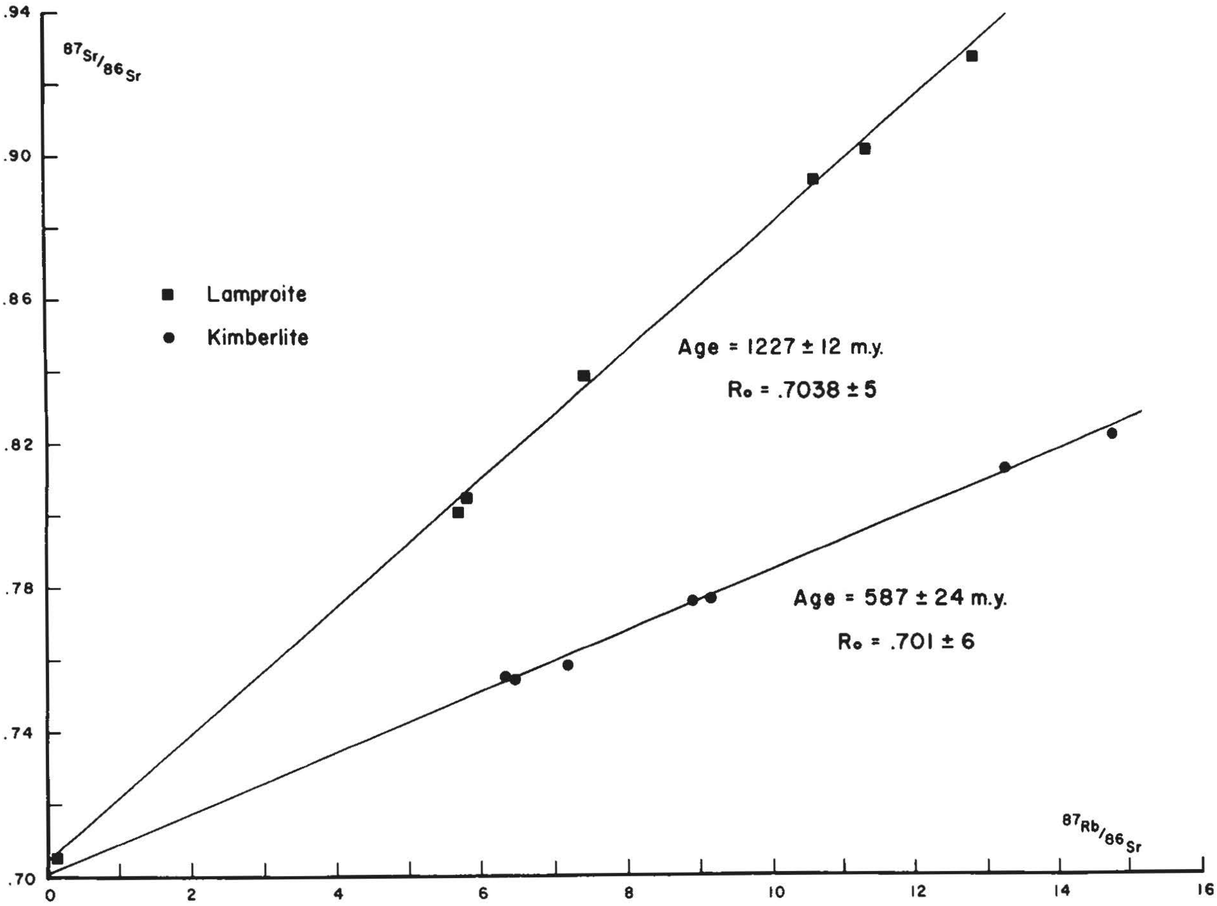

Fig. 17. Isochron diagram for phlogopite concentrates from the Holsteinsborg kimberlite and lamproite dykes (after Smith 1979).

ratios is not significant because the kimberlite initial ratio is very imprecise.

These ages are in agreement with previous determinations. MacIntyre (personal communication) determined an age of 570 m.y. by K–Ar on phlogopite for a kimberlite dyke very close to Holsteinsborg. Brooks et al. (1978) determined an age of 1206 ± 18 m.y. by K–Ar on mica from a lamproite (probably the same dyke as locality 11 described by Scott 1977). None of these earlier studies, however, included both lamproites and kimberlites from the Holsteinsborg area. Bridgwater (1971) reports an age of 584 ± 18 m.y. determined by K–Ar for a kimberlitic dyke which occurs approximately 100 km east of Itivdleq, but expresses some doubt in the reliability of the results.

Conclusions

The dykes from the region of Holsteinsborg examined in this study can be divided into two main groups using petrographic, mineralogical, whole-rock geochemical and age criteria.

One group of the Holsteinsborg dykes show features consistent with them being kimberlites using the definition proposed by Clement et al. (1977). Using the mineralogical classification put forward by Skinner & Clement (1979) these dykes include phlogopite-, phlogopite-clinopyroxene and clinopyroxene-phlogopite kimberlites. Texturally they are all hypabyssal kimberlites (after Clement & Skinner 1979).

The ultrabasic inclusions found in the kimberlites include both coarse (granular) and porphyroclastic (sheared) varieties and are dominated by dunites. The olivines in the dunites display a wide overall range of Mg/Fe ratios which suggests that they may have formed as cumulates. Rather sparse data from less common lherzolites and wehrlites suggests that the kimberlite magma originated from pressures greater than 40 kb and temperatures greater than 1000°C and probably more than 1300°C.

Th other main group of Holsteinsborg dykes can be referred to as lamproites, after Trøger (1935) who defined them simply as K- and Mg-rich lamprophyres. The term is virtually synonomous with potassic lamprophyre which was used to describe these dykes by Scott (1979).

Table 11. Sr and Rb concentrations, and atomic $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios of kimberlites and lamproites.

Lamproite

Sample	Sr	Rb	Atomic $^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
5623 Amph	1437	57.4	0.11	.70682 ± 2
5623 A	116.8	236.6	6.80	.8052 ± 1
5623 B	119.7	237.2	5.68	.8007 ± 2
5659 A	123.6	318.3	7.41	.8389 ± 2
5659 N	89.2	327.0	10.60	.8931 ± 3
5943 B	93.3	366.1	11.34	.9014 ± 1
5943 C	73.4	324.7	12.82	.9268 ± 2

Kimberlite

Sample	Sr	Rb	Atomic $^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
5605 A	88.6	454.9	14.73	.8221 ± 1
5605 B	98.3	451.4	13.23	.8131 ± 1
5699 A	172.2	535.8	8.89	.7765 ± 2
5699 B	261.9	657.7	7.17	.7583 ± 3
5699 C	219.1	495.9	6.45	.7540 ± 3
5997 A	186.0	527.7	8.10	.7698 ± 2
5997 B	184.3	589.2	9.13	.7745 ± 7
5997 C	246.0	546.7	6.34	.7558 ± 3

Sample 5623 Amph is groundmass amphibole. All other samples are phlogopite separates.

Rb and Sr concentrations are in ppm, and are accurate to ± 2 percent.

Errors on the $^{87}Sr/^{86}Sr$ ratios are 2 σ.

The term lamprophyre, however, should not be used to describe rocks with felsic phenocrysts. It is now considered that the term lamproite is more appropriate not only because leucite phenocrysts do occur in many of the dykes but also because of the similarity of these rocks to the lamproites in Western Australia (Wade & Prider 1940) and Wyoming (Carmichael 1967b), and also to emphasise their unusual nature. These rocks have high K_2O contents for magnesian rocks and have extremely high K/Na ratios. These features are reflected in their mineralogy with the occurrence of ubiquitous potassium-bearing minerals (phlogopite, pseudoleucite, potassic richterite, potassium feldspar, priderite). No ultrabasic inclusions were found in the lamproites.

It has been shown (Smith, 1979 and discussed here) that the age of the lamproite dykes is 1227 ± 12 m.y. and the age of the kimberlite dykes is 587 ± 24 m.y. The initial $^{87}Sr/^{86}Sr$ ratios for both the lamproites and the kimberlites is indicative of a mantle origin.

In a discussion on the petrogenesis of the Holsteinsborg dykes Scott (1979) suggested a genetic relationship between the lamproites and kimberlites by a simple fractionation process. This model implied that all the dykes were derived from the same body of magma. This implication is obviously not supported by the substantial age difference indicated by radiometric dating. As noted by Scott (1979) the model, however, may apply to processes whereby lamproites, in general, could be derivatives of kimberlitic magmas which have been substantially modified. The parental magma need not be represented at the surface. The strontium isotope data support a mantle origin for the lamproites.

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