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Preliminary account of kimberlite intrusions from the Frederikshåb district, South-West Greenland

by

J. R. Andrews and C. H. Emeleus

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PRELIMINARY ACCOUNT OF KIMBERLITE INTRUSIONS FROM THE FREDERIKSHÅB DISTRICT, SOUTH-WEST GREENLAND

by

J. R. Andrews and C. H. Emeleus

With 8 figures and 2 tables

1971

Abstract

Kimberlite intrusions from three localities, Nigerdlikasik, Pyramidefjeld and Midternæs, show closely comparable petrographical, mineralogical and geochemical features. They contain ultramafic garnet, spinel and phlogopite peridotite inclusions which appear to have been derived from the Upper Mantle, though scapolite granulite nodules in the Nigerdlikasik kimberlite must have originated in the lower crust. Garnet and spinel peridotite were sampled at successively higher levels by the kimberlite magma and micaceous peridotites were produced by phlogopitisation of some of these inclusions during transport. Generation of the kimberlites took place during the early Mesozoic and forms part of the Mesozoic pattern of igneous activity in South-West Greenland.

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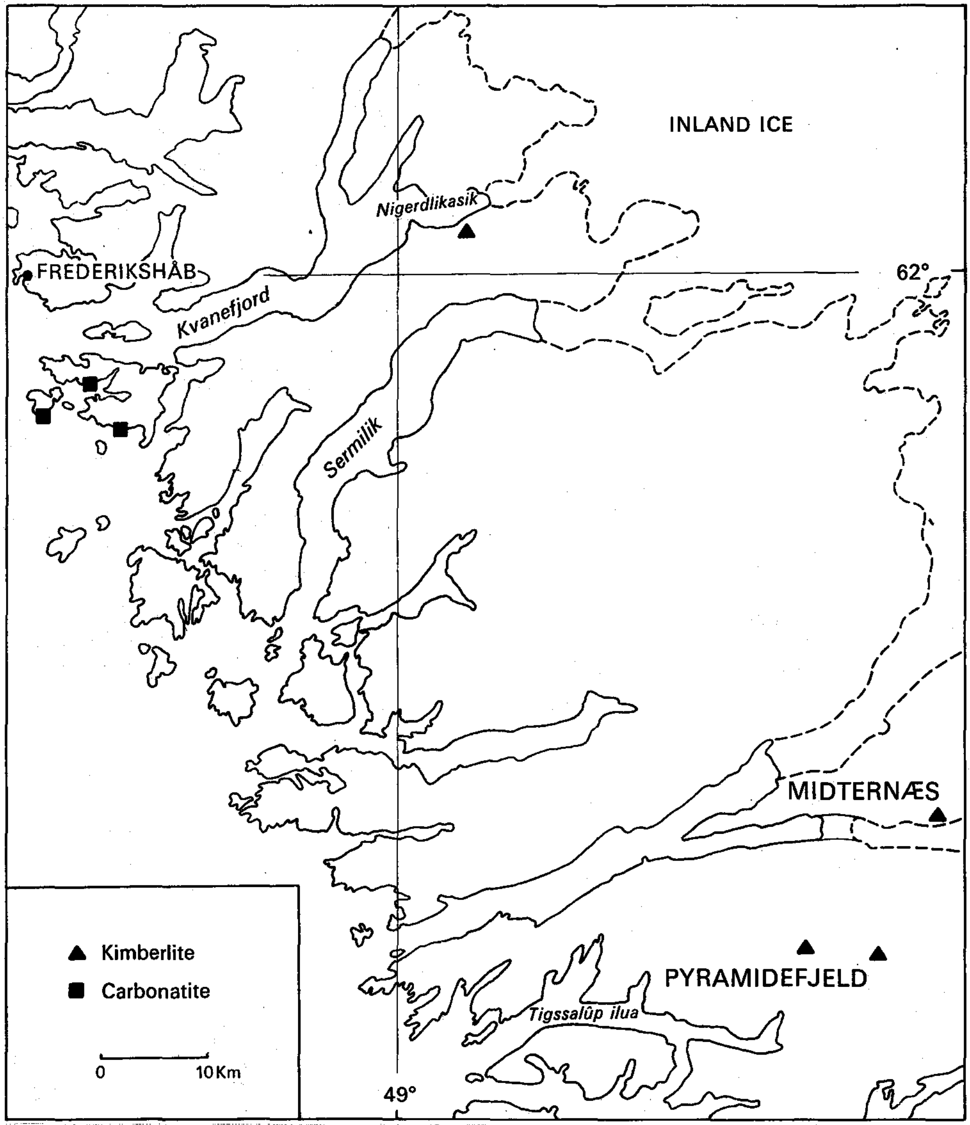

Fig. 1. Sketch map of the Frederikshåb District showing the location of kimberlite and carbonatite-lamprophyre occurrences.

INTRODUCTION

Minor alkaline intrusive activity has recently been investigated in the Frederikshåb District, South-West Greenland. Walton (1966) described a series of NW-trending carbonatite lamprophyres at the coast near Frederikshåb, and Andrews (1969) in a preliminary note described a kimberlite dyke in the Nigerdlikasik area, 45 km east of Frederikshåb. Simultaneously, C. H. Emeleus, investigating a set of carbonate mica peridotite sheets in the Pyramidefjeld granite (referred to in earlier literature as the Tigssaluk granite) about 20 km north of Ivigtut, recognised them as being closely comparable with the Nigerdlikasik material. A further set of thin sills has been located on Midternæs, 15 km north of the Pyramidefjeld granite (A. K. Higgins, personal communication). The location of the kimberlites and carbonatites is depicted in fig. 1.

The kimberlite intrusions in all cases appear to be the youngest geological events, apart from minor post-intrusion faulting. The Nigerdlikasik dyke cuts the pre-Ketilidian basement and a series of later, also pre-Ketilidian, basic dykes. The Pyramidefjeld sheets were intruded into a pre-Gardar granite and cut a NE-trending Gardar dyke swarm. The unmetamorphosed Midternæs sills transgress Ketilidian metasediments. Preliminary examination shows the sills to be almost identical with the dyke and sheet intrusions described below.

Isotopic ages

Two K/Ar whole rock age determinations have recently been obtained for the dyke and sheets. The dyke gave 609 $\pm$ 36 m.y. and the sheets 202 $\pm$ 6 m.y., a rather surprising result in view of the mineralogical and geochemical similarities between the two occurrences. To try and resolve the disparity Rb/Sr studies on two whole rock samples and mica separates were kindly undertaken by Dr. I. Pringle at the Department of Geodesy and Geophysics, University of Cambridge. His results show that the samples, one from each locality, are about the same age, both a little over 200 m.y. old. Individual determinations on the two mica separates are subject to a large error because of the small amount of Rb present in the micas and their relatively young age. When values for both intrusions are plotted as a conventional isochron the points fall on a line also suggesting a common age. The isochron gives an age of 225 $\pm$ 17 m.y. (using $\lambda = 1.39 \times 10^{-11} yr^{-1}$) and a low initial $^{87}Sr/^{86}Sr$ initial ratio: 0.7019 $\pm$ 0.0006. The older K/Ar age for the Nigerdlikasik dyke is clearly anomalous though the age for the Pyramidefjeld sheets seems in order.

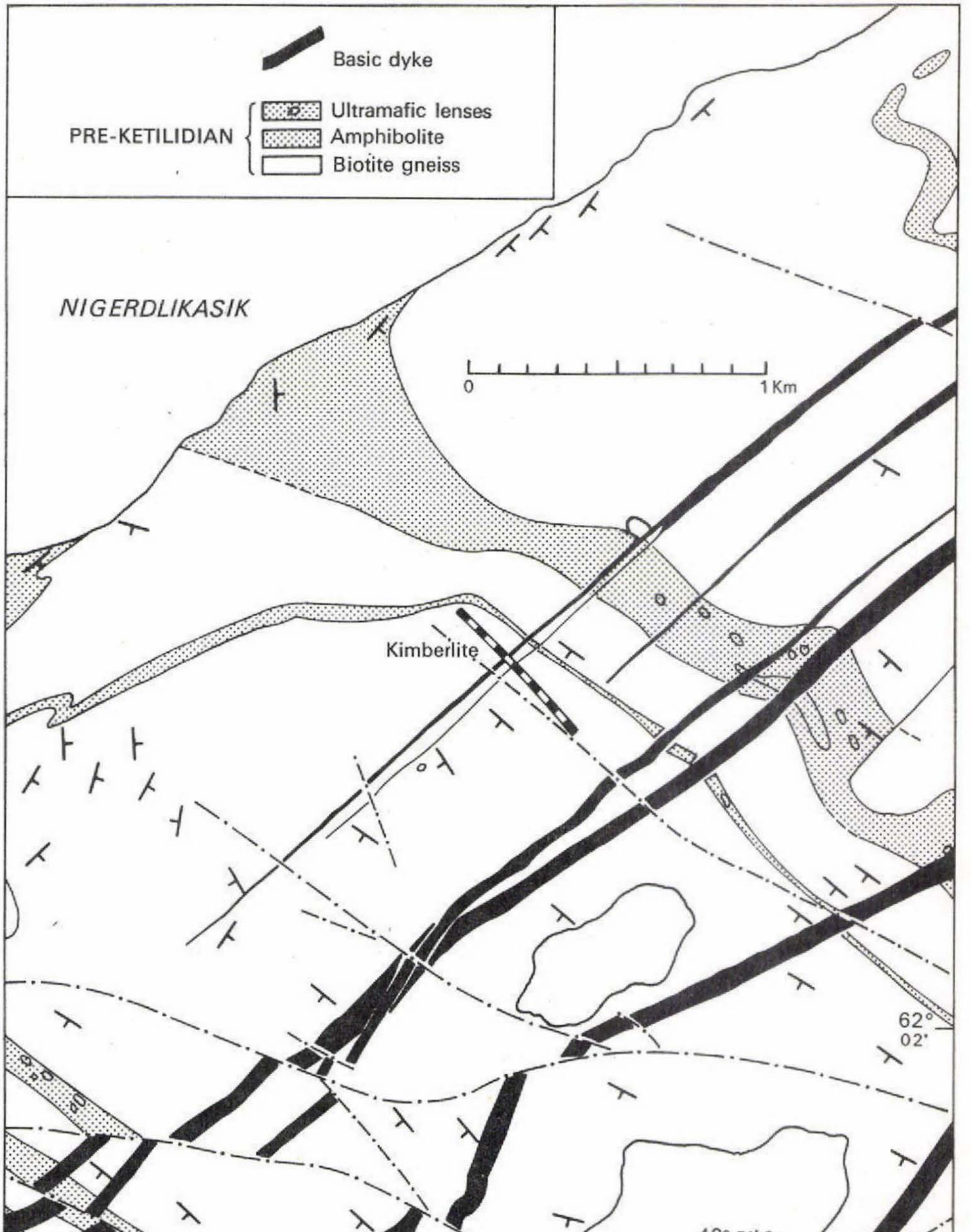

Fig. 2. Geological sketch map of the Nigerdlikasik area showing the setting of the kimberlite dyke.

THE NIGERDLIKASIK KIMBERLITE DYKE

The country rocks of the Nigerdlikasik area consist of pre-Ketilidian gneisses and amphibolites cut by a series of basic dykes whose ages range between pre-Ketilidian and Jurassic (Jensen, 1966; Watt, 1969). They are mostly olivine dolerites though rarer carbonatitic types have been reported (Walton, 1966). The basement is folded, faulted and intruded by a single isolated kimberlite dyke (fig. 2).

Occurrence and field characteristics

The 50 cm wide intrusion trending 140° can be traced 500 m through homogeneous biotite gneisses. It runs from the edge of a cliff 900 m in altitude overlooking Nigerdlikasik fjord into a shear zone trending about 135° where it is lost beneath rubble (fig. 2). The dyke cuts a NE-trending pre-Kitilidian basic dyke but appears to be offset two metres by a small fault trending 060° parallel to the basic dyke. Because of its high carbonate content the dyke weathers readily and tends to form a topographical depression. It has not been traced at the bottom of the cliff where it is likely to be beneath the substantial accumulation of scree.

Petrography and mineralogy

The dyke rock is dark grey tinged with olivine green; it is dense and very fresh, the fine-grained matrix glittering with flecks of mica. A rough finish on the brown weathered surface is caused by solution of carbonate material leaving protruding olivine xenocrysts up to 3 mm long. Clusters of elongate nodular inclusions up to 15 cm long occur in several places. Three types may be distinguished:

1. Angular fragments of country rocks exposed in the immediate neighbourhood.
2. Rounded nodules of high grade metamorphic rocks from deeper levels than the present level of exposure.
3. Rounded ultrabasic nodules, either garnet-, spinel- or phlogopite-bearing peridotites derived from great depths.

The nodules are often preferentially aligned, in one case perpendicularly to the dyke margins (fig. 3a).

Chemical information on minerals in both the dyke rock and the nodules has been obtained by electron probe microanalysis in Copenhagen. Data and details of the operating conditions are given in a recent doctorate thesis (Andrews, 1970). The results summarised below are being augmented by further analysis at Newcastle and will be published in full elsewhere.

The dyke rock

The rock consists of megacrysts of fresh or slightly serpentinised olivine lying in a groundmass composed of carbonate, serpentine and phlogopite (fig. 6a). Opaque minerals include magnetite, ilmenite and chromite. The assemblage is completed by accessory clinopyroxene, perovskite and apatite. Garnet, whilst not observed in section, has been recovered during mineral separation procedures. A modal analysis is given in table 1.

Table 1. Modal analyses of kimberlites

	Pyramidefjeld		Nigerdlikasik
GGU no.	31959B	39660C	59199
Olivine-large	31.0	9.4	9 (olivine-large and olivine-small together)
Olivine-small	4.7	1.8	
Clinopyroxene	10.0	8.9	tr.
Phlogopite	33.0	47.7	14
Carbonate	8.1	21.4	43
Perovskite	2.2	2.2	0.5
Opaques	7.7	5.1	4.5
Serpentine	3.5	3.7	29

(all as volume percentages)

Olivine. Two generations of olivine may be distinguished: (i) deformed large ragged, rounded xenocrysts up to 3 mm in diameter, and (ii) smaller euhedral to subhedral crystals up to 2 mm in diameter. They show a compositional range Fo_{88}-Fo_{92} (fig. 5). The smaller well-formed crystals are generally richer in iron; one example is zoned from a core Fo_{90} to margin Fo_{88}.

Phlogopite. Phlogopite forms euhedral to subhedral crystals 0.1-1.0 mm in diameter and constitutes 10-20% of the rock. Only rarely does carbonate replace the mica which is usually set firm in the groundmass. Most phlogopite exhibits narrow, incomplete rims or contains irregular patches which show strong reverse pleochroism, colourless to dark red-brown. Similar material has been investigated in the Pyramidefjeld sheets described below.

Carbonate. Carbonate constitutes 40-50% of the dyke rock. It forms anhedral grains between 0.1 and 1.0 mm wide though in areas of intermixed carbonate and serpentine the grains are below 0.1 mm in diameter. The carbonate is almost certainly primary, having crystallised before serpentine. It rarely replaces other minerals and does not penetrate the host gneisses.

Serpentine. Serpentine forms about 30% of the rock. It occurs both as a primary groundmass constituent and as a secondary alteration product of olivine megacrysts. In the groundmass it infills cavities bounded mostly by carbonate and so appears to have been the last mineral to crystallise (cf. fig. 6b).

Accessory minerals. Finely disseminated magnetite occurs after olivine and in the groundmass as euhedral cubic crystals up to 0.2 mm in diameter. Rather larger grains of ilmenite form skeletal crystals or granular aggregates up to 0.5 mm in diameter. Brownish perovskite forms equant grains of less than 0.2 mm size and commonly surrounded by an opaque mineral, almost certainly ilmenite. A mineral with thin brown translucent edges is probably chromite.

Colourless prisms of clinopyroxene not more than 0.1 mm long are sparsely distributed in the groundmass and sometimes partially altered to, or surrounded by phlogopite. Apatite is a persistent accessory mineral, well formed and enclosed in either carbonate or serpentine.

The nodules

High grade metamorphic nodules

Most of these are orthopyroxene-bearing acid and basic types which have 0.5-4 mm granoblastic assemblages. Those characteristic of the acid rocks are

quartz + microcline + plagioclase + orthopyroxene

quartz + perthite + plagioclase + orthopyroxene + garnet

whilst the following assemblage occurs in three basic nodules

plagioclase + orthopyroxene + clinopyroxene + hornblende + scapolite + biotite.

Similar assemblages have been described from some of the highest grade crustal metamorphic complexes e.g. The Central Highlands of Ceylon and the charnockite series of Madras (Turner, 1968). Comparable inclusions have been noted in South African and Russian kimberlites and also in the basalt and breccia-filled pipes of eastern Australia (Lovering & White, 1964).

One inclusion contains the assemblage

garnet + soda-pyroxene + plagioclase

and is probably related to the plagioclase scapolite granulites. This assemblage has been noted by Verhoogen (1940) in Katanga kimberlites but does not appear to have been found in ordinary surface exposures of crustal rocks. The presence of plagioclase means that the assemblage cannot be grouped with those belonging to the eclogite (very high pressure) facies and Verhoogen (1940) suggests that the whole group of inclusions spans a transition between the granulite and the eclogite facies.

Peridotite nodules

These coarse-grained, dull dark-green rocks consist predominantly of olivine. Other minerals constituting the assemblage, in order of relative abundance, are orthopyroxene, clinopyroxene and an aluminous phase, either garnet, spinel or phlogopite (see table 2). In garnet peridotites the clinopyroxene is a rich grass-green colour and the garnet deep purple though the latter sometimes appears brown as a result of alteration. In other peridotites, spinel or phlogopite appears as black shiny flecks whilst the clinopyroxene loses some of its green colouration, especially in the micaceous variety.

Most nodules are fresh or very fresh with a 0.5-5 mm grain-size and granoblastic texture. Olivine is occasionally serpentinised, especially near nodule margins. Fresh orthopyroxene is present in amounts varying between 10-20% and pale green clinopyroxene is less common. Exsolution lamellae occur in both pyroxenes of some spinel peridotites. Garnet (5-10% by volume) is very pale pink in section. It is usually surrounded by a radiating cryptocrystalline, kelyphitic intergrowth, which grades to a mixture of picotite, orthopyroxene, carbonate and sometimes phlogopite. Deep golden brown picotite replaces garnet in spinel peridotites. Unlike the garnet it is always fresh even though it may form slender anhedral interstitial crystals. In two nodules garnet appears to coexist with primary spinel though the one has not been seen immediately adjacent to the other. In phlogopite peridotites the mica is often intergrown with orthopyroxene and a very dark spinel. It seems likely to have been derived from the breakdown of a pre-existing garnet.

Table 2. Modal analyses of peridotite nodules

Nigerdlikasik GGU no.	$59200G_1$	$59905G_1$	$72501G_1$	$72501G_2$	$58198S_1$	$59904S_1$	$72501S_1$	$72501P_1$
Olivine	78	77	68	80	80	75	79	77
Orthopyroxene	13	15	17	12	17	18	14	15
Clinopyroxene	4	2	3	2	2	6	5	
Garnet	5	6	13	6	–	–	–	–
Spinel	–	–	–	–	1	1	2	–
Phlogopite	–	–	–	–	–	–	–	8

Pyramidefjeld GGU no.	27703	39654	39660C
Olivine	86.1	98.1	77.7
Orthopyroxene	2.7	–	8.3
Clinopyroxene	2.5	0.2	10.8
Phlogopite	2.5	0.9	3.2
Opaques	–	0.8	–
Groundmass	6.2	–	–

(all as volume percentages)

Olivine in all peridotite nodules shows a very restricted compositional range, containing about 92% forsterite end-member molecule (fig. 5). Clinopyroxenes from both garnet and spinel peridotite are magnesium-rich varieties (fig. 7a) with appreciable chrome and soda contents. Their alumina content varies according to the co-existing aluminous phase. Diopsides in garnet peridotites commonly contain 1-3 wt.% Al_2O_3 whilst those in spinel peridotites have intermediate values varying between 3-5 wt.% Al_2O_3. Orthopyroxenes are enstatites (fig. 7a) whose alumina contents vary in sympathy with that of the coexisting clinopyroxene. In garnet peridotites they contain around 1.5% Al_2O_3, in spinel peridotites approximately 3% Al_2O_3 but less than 1% Al_2O_3 in phlogopite peridotites. The variation in alumina content shows that the pyroxenes reached equilibrium with the coexisting aluminous phase.

Garnets are all pyrope-rich varieties containing about 70% pyrope molecule. Unusually large amounts of chromium substitute for aluminium producing 10% or more of the chromium end-member molecule uvarovite. The primary spinel is picotite with an Al/Cr ratio considerably greater than one.

Contact relationships and internal structures

Intrusive contacts with the homogeneous gneiss are sharp. Thin sections show a diminution in grain size at the margins which is paralleled by a similar zone around nodular inclusions suggesting size-sorting of the crystals during flow rather than chilling of the magma. All but the most local xenoliths and some xenocrysts are polished, rounded and abraded. Nodules tend to be aligned and concentrated in groups (fig. 3a). Xenocryst-bearing matrix penetrates the finest channels, with some xenocrysts lodged in the passages. These features together with the high volatile content of the matrix ($CO_2 + H_2O = 15 - 25$ wt%) indicate a very low magma viscosity.

Thermal contact metamorphic effects are virtually absent but this need not be surprising considering the small size of the intrusion. The gneiss is penetrated by carbonate-filled cracks transgressing quartz, plagioclase, biotite and epidote, all of which remain unaltered. Minor brecciation of the wall rock is evident over a 1-2 mm zone with concomitant dislocation of material and sericitisation of the plagioclase. The intrusion of the dyke as a fluidised system (Reynolds, 1954) is consistent with the absences of thermal alteration, minor brecciation, abrasion of inclusions and the low magma viscosity suggested above.

There is some evidence of multiple intrusion provided by a 5 cm branch off the main body. The 1 cm wide margins are slightly finer grained than the core, a feature accentuated by weathering which produces a depressed central zone. Furthermore, a rounded nodular piece of matrix represents reworked material from an earlier magma pulse.

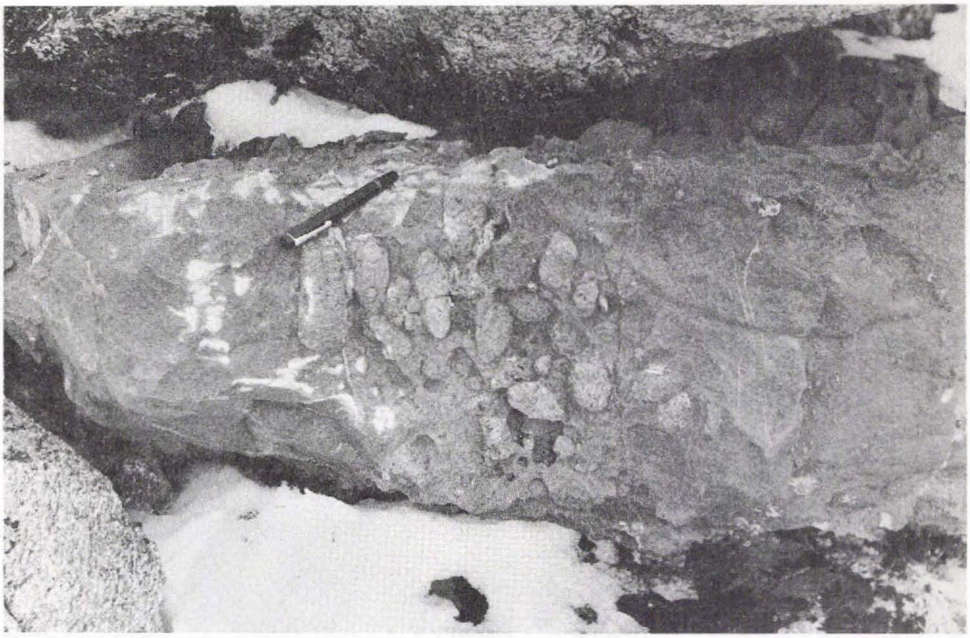

Fig. 3a. Plan view of peridotite and granulite inclusions in the Nigerdlikasik dyke. Note the apparent alignment of the nodules perpendicularly to the dyke walls. Scale: pen = 12 cm.

Fig. 3b. Loose boulder from kimberlite sheet at the south-east corner of Safirsø, Pyramidefjeld (Loc. A, fig. 4). The boulder is shown as in its original orientation. Note (a) the rough-weathered surface caused by protruding olivine megacrysts, (b) the concentration of nodules and megacrysts into distinct zones (3) parallel to the edge of the sheet, (c) the concentration of nodules towards the base of the sheet, and (d) the sub-parallel alignment of the nodules and the edge. Scale: hammer shaft = 25 cm.

THE PYRAMIDEFJELD KIMBERLITE SHEETS

The Pyramidefjeld granite complex is situated about 20 km north of Ivigtut; it falls within the limits of the 1 : 100 000 geological map of the Ivigtut area (Henriksen, 1969). In earlier papers this granite was referred to as the Tigssaluk granite, but since then "Tigssaluk" has been restricted to a locality 30 km to the west and the granite complex consequently renamed. The complex consists of two granitic stocks and associated hybrid rocks (Emeleus, 1963) which are of pre-Gardar age (Bridgwater, 1965; Larsen & Møller, 1968). A north-easterly Gardar dyke swarm of olivine dolerites, trachytes, feldsparphyric basalts and basalts cut the granites and diorites. The granite complex and the dykes are faulted and are intruded by several sheets of kimberlite, which were mapped and sampled during field seasons in 1957 and 1958, with additional sampling in 1969.

Occurrence and field characteristics

Several thin, sub-horizontal kimberlite sheets intrude the granites of Pyramidefjeld and Sfinksen and occasionally extend into the country rocks (fig. 4). The sheets are generally less than 1 m in thickness, they usually form single intrusions but several sub-parallel sheets may occur in close proximity. Individual sheets can usually be traced laterally for several tens of metres but are found to outcrop intermittently for distances of over a kilometre. They are invariably intruded along horizontal or flat-lying joints which are a pronounced structural feature of both granites. Because of their high carbonate content the sheets weather easily with a distinct tendency for undercutting to take place along granite joint planes, giving rise to small caves and rock shelters. The inweathering of the sheets has also led to large collapse structures which frequently almost conceal the intrusion. A careful search of overhangs, cliff features and collapse structures revealed at least nine sheets in the Pyramidefjeld granite, three in the Sfinksen granite, but only two intruding country rocks (fig. 4). It is probable that other sheets are present both inside and outside the granites but have escaped detection because of the tendency for collapse structures to form. Loose kimberlite blocks in the country south of Sfinksen may well come from an intrusion at the base of a prominent cliff feature at 900 m altitude on the south end of the mountain; another sheet may be present at the base of the cliffs on the north and west sides of the lake at 600 m altitude about 1.3 km south-west of Rødtop (fig. 4).

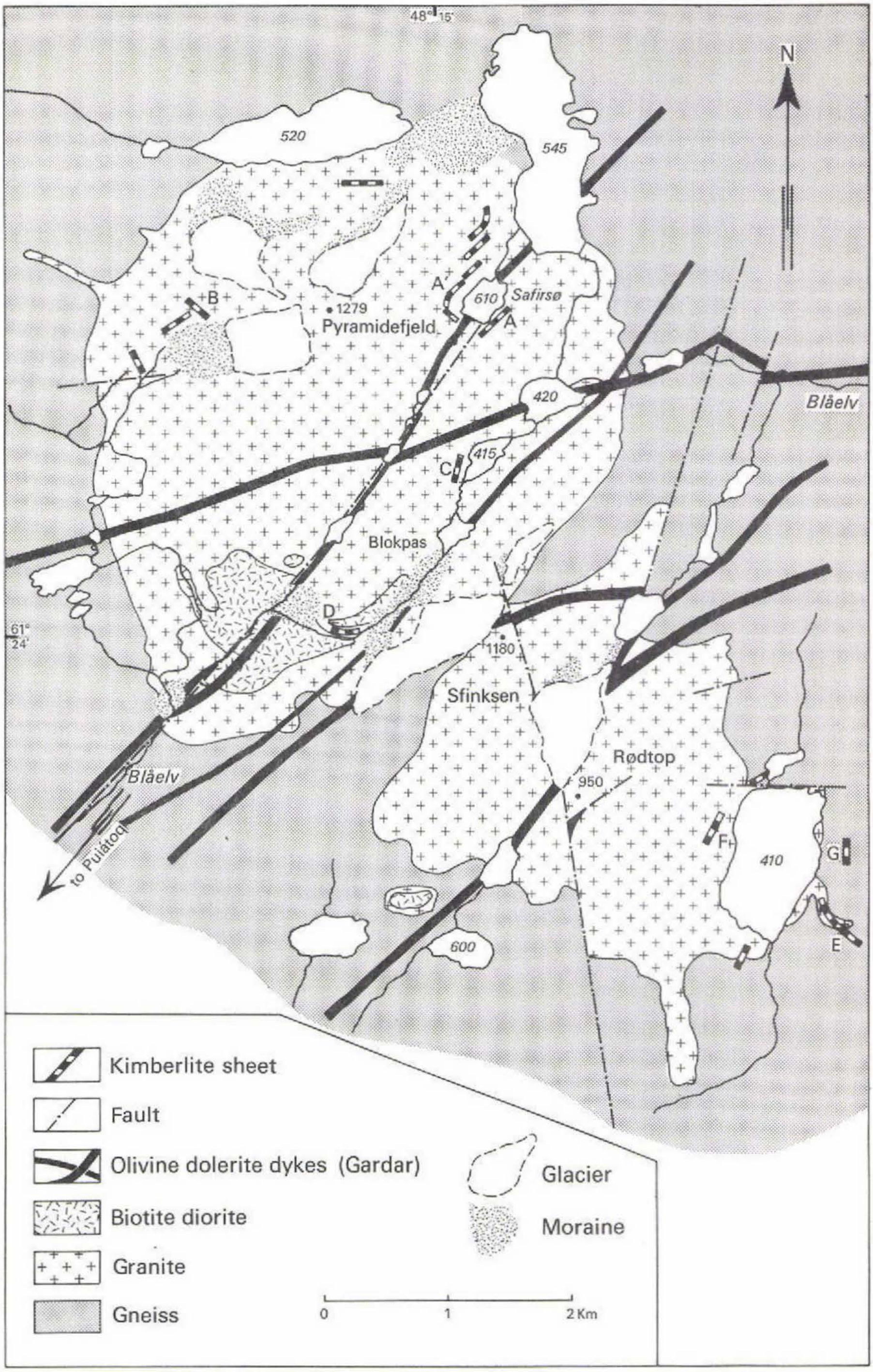

Fig. 4. Geological sketch map of the Pyramidefjeld area. The letters A, B, etc. refer to sills from which specimens mentioned in the text were obtained. (A = 39654, 39657, 39651; A[1] = 39660, 39660C, 39660/2; B = 27703, 126731 b & c, 126738; C = 39651; D = 31959; E = 39644; F = 39642).

Petrography and mineralogy

The fresh kimberlite is a dark green fine-grained rock studded with glassy olivine crystals up to 5 mm in length. The weathered surfaces are drab brown or green-brown, small olivine crystals standing out, imparting to the rock its characteristic rough, gritty surface (fig. 3b). Several of the sheets intruding the Pyramidefjeld granite carry numerous elongate, rounded nodular peridotite inclusions generally about 10 cm in length, although they are found up to 20 cm in length. The nodules consist of granular aggregates of olivine with variable, but minor, bright green clinopyroxene, red-brown mica and other minerals. The inclusions are concentrated in the lower parts of the sheets where their presence gives rise to rocks which superficially resemble conglomerates (fig. 3b). Weathering of the sheets results in extensive white staining of the granite. This is the result of the deposition of a thin layer of carbonate derived from the kimberlite; it does not penetrate the granite which is fresh and practically unaltered.

Analytical data on mineral phases in both the kimberlites and the nodules was obtained using the University of Durham Geoscan MK II electronprobe micro-analyser.

The kimberlites

The sheets are porphyritic with large olivines in a fine-grained matrix consisting of clinopyroxene, mica, opaques, perovskite, carbonate and serpentine. Other accessory minerals include pale blue-green to green amphibole, apatite and possibly melilite. The modes of two rocks are given in table 1.

Olivine dominates the mineral assemblage. It occurs as large rounded or ragged grains and as smaller well-formed crystals. Serpentinisation may be complete but the olivine is frequently fresh. There is a considerable compositional range within a single specimen (from Fo_{92} to Fo_{84} but usually from about Fo_{89} to Fo_{84} (fig. 5)). At least two generations of olivine are present. The large rounded and ragged xenocrysts have variable but generally forsterite-rich compositions. The smaller, well-formed crystals with lower forsterite content are considered to be true phenocrysts. Also present are occasional very large olivines (over 5 cm diameter); these are fosteritic (Fo_{90-93}).

The clinopyroxene forms small euhedral crystals. It is diopsidic (fig. 7b) with higher Ca and Al than clinopyroxenes in the nodules and lower Na and Cr. Slight zoning to relatively iron-rich margins was noted but the crystals are generally too small to detect zoning satisfactorily. The mica is phlogopitic with higher Fe, Al and Ti than mica in the nodules; Si is lower. Mica occurs as small well-formed plates or as large poikilitic crystals enclosing perovskite, opaques, olivine and clinopyroxene. Prominent, intensely pleochroic rims were noted on many of the kimberlite micas.

The pleochroic scheme (X = strong orange-brown; Y = Z = colourless), is the reverse of that normal in micas.

Perovskite forms small rounded and octahedral crystals with deep brown or purple-brown cores and a mantle of opaque alteration products. Rare earth elements

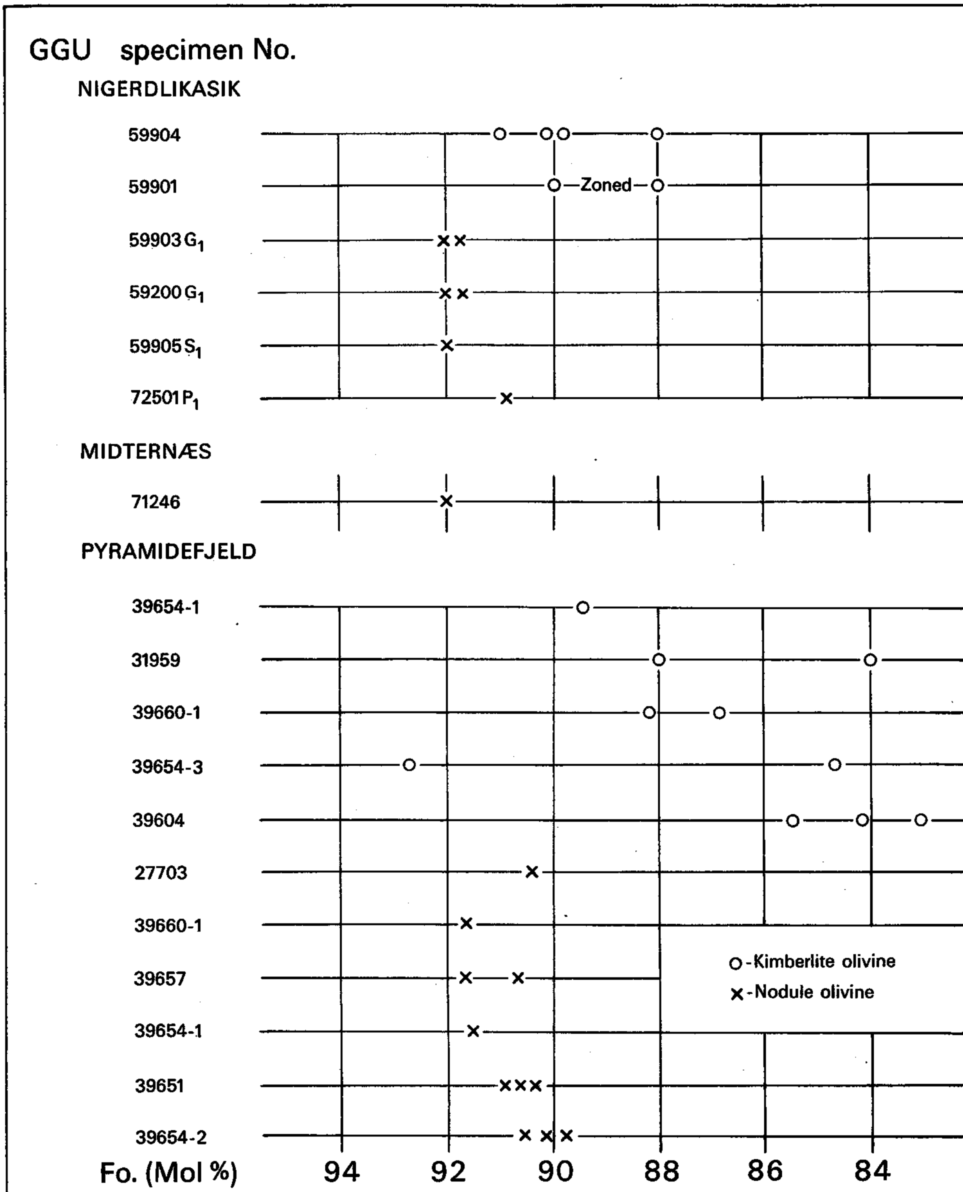

Fig. 5. Molecular proportions of forsterite in olivines from kimberlites and peridotite inclusions.

were not detected although these are often important constituents of perovskite from more differentiated rock types (Carmichael, 1967).

Preliminary investigation of the opaque minerals shows that these are magnetites with fairly large amounts of Ti, Al and Mg, and small amounts of Si and Ca. No ilmenite has been detected nor any of the picroilmenite considered to be characteristic of kimberlites (Dawson, 1962).

Pale green serpentine occurs in two situations. It is developed as the alteration product of olivine and it also appears as the last crystallising mineral in the groundmass where it is found as microcrystalline, sometimes fibrous, aggregates filling the spaces between carbonate crystals (fig. 6b).

Of the remaining minerals, amphibole forms small needles and wispy aggregates, apatite occurs as small prisms and needles and melilite has been tentatively identified in small prisms. No garnet, orthopyroxene or feldspar has been found.

Two carbonates are present in the kimberlite groundmass. They are turbid, slightly ferriferous dolomite and later-crystallised, clear calcite. The latter may line serpentine-filled areas (fig. 6b).

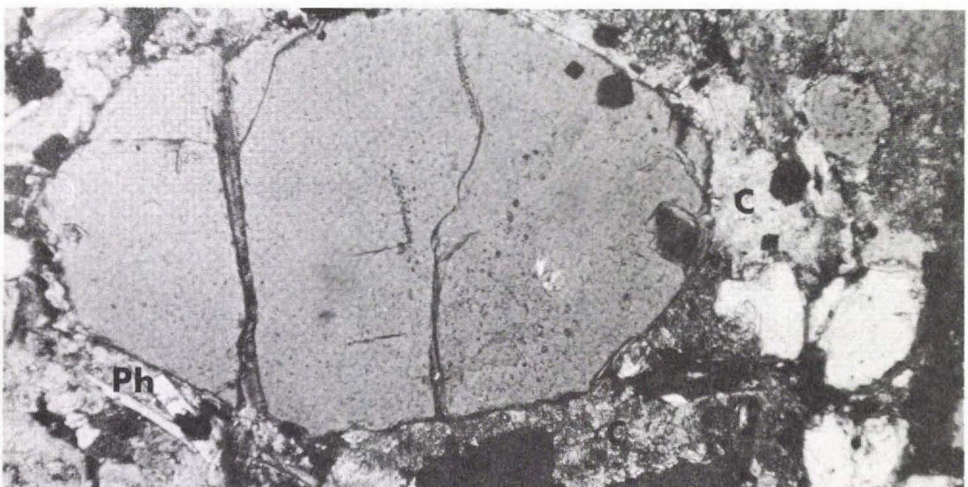

Fig. 6a. Nigerdlikasik kimberlite (59903), X-polars, x100. A fresh euhedral olivine phenocryst is enclosed in a groundmass containing phlogopite (Ph), carbonate (C) and opaques.

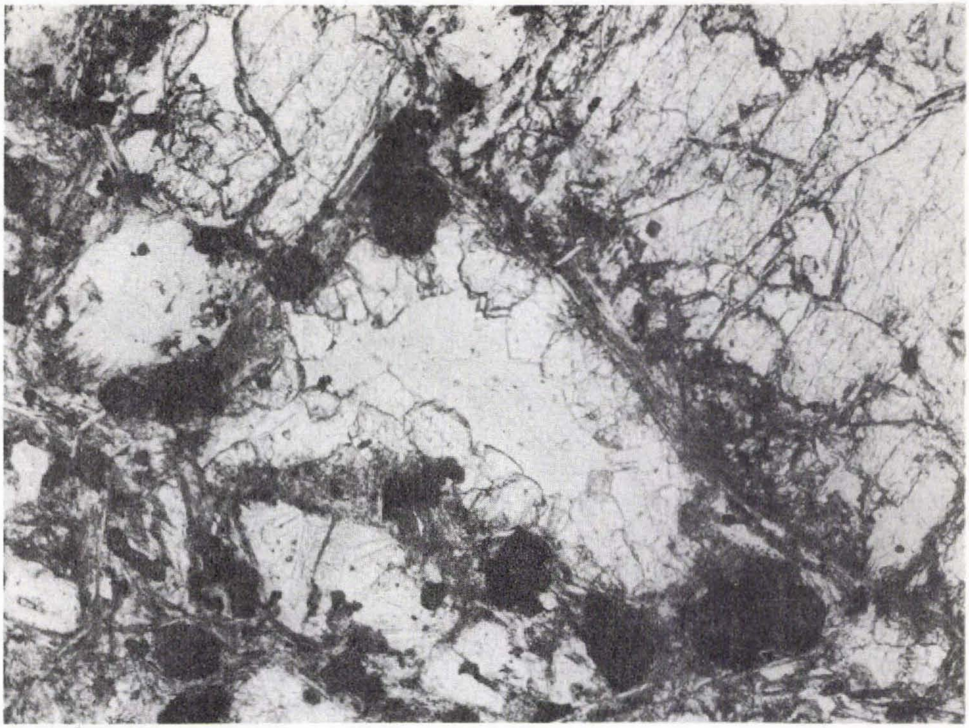

Fig. 6b. Pyramidefjeld kimberlite (39642), Plane-pol. light, x160. A central serpentine area (low relief) is lined with small carbonate crystals; opaques and perovskite are concentrated at the outer edge of the carbonate. Two olivine megacrysts occupy the upper part of the field; mica, opaques, perovskite and fibrous amphibole occur together in the lower and left hand parts of the picture.

Peridotite nodules

Olivine is accompanied by variable and generally minor amounts of orthopyroxene, clinopyroxene, phlogopite and opaques. No Mg-rich spinel has been identified but garnet is present in several specimens. Modal compositions of the nodules are given in table 2.

The olivine is forsterite-rich, falling in a narrow compositional range (fig. 5). All analyses show low Ca; two specimens contain about 0.35% NiO. The orthopyroxene is enstatite (fig. 7b), with low Ca and Al. The majority of the crystals are free from exsolution lamellae but sections cut from recently-collected nodules do contain enstatite with well-defined, thin lamellae, apparently of pyroxene. The clinopyroxenes are diopsidic (fig. 7b) with appreciable Na_2O (up to 1.9%) and Cr_2O_3 (up to 2.0%); they fall within the field of chromian diopsides. All the clinopyroxenes have low

Al_2O_3 (0.3-0.6%). The clinopyroxene is often closely associated with phlogopitic mica. The mica has not been fully analysed but from preliminary figures and optical properties, phlogopite with high MgO (25%) and low TiO_2 (0.9%) is indicated. Average figures for K_2O and total iron as FeO are 7.5% and 4% respectively. The crystals are virtually unzoned except where they adjoin opaques when there may be a pale reddish colouration. Opaque minerals are not common. They occur as large anhedra, often associated with mica. Optical properties suggest that they are chromites. The garnet, found in relatively few nodules, is a pyrope-rich variety with appreciable Cr. It is almost invariably separated from the other minerals of the host nodule by the development of a strong reaction rim containing small chromites, pyroxene and mica; however, olivine and chrome have been observed partially enclosed by garnet.

Texturally, the nodules consist of coarse- to medium-grained olivine crystals up to 4 mm diameter which interlock and occasionally are intergrown. These are usually free from marked strain effects, they frequently contain strings and trails of bubble-like inclusions partially filled by fluid (CO_2 under high pressure – S. Sawkins, personal communication). Serpentinisation is found but is generally slight. An unusual texture noted in several nodules (e. g. 126731b,c; 126738c) resembles a dunite mylonite or crush breccia. The pyroxenes are euhedral or anhedral towards each other and towards olivine; the diopside is frequently intergrown with mica. The phlogopite is usually in aggregates as well-formed crystals but larger crystals, anhedral towards olivine, are present. Although the nodule minerals are exceptionally fresh, nodules with diopside and mica associated are relatively readily attacked and disintegrated by the enclosing kimberlite (e. g. 39660/2); the clinopyroxene becomes charged with numerous minute opaque inclusions (?chromite) and the mica increases in depth of colour.

Contact relationships and internal structures

The sheets have sharp intrusive contacts with the enclosing granites and gneisses. Some size sorting of larger crystals is evident in the field, bands of varying grain size parallel the sheet edges (fig. 3b). In thin section, similar features are seen on a smaller scale together with a weak orientation of micas and elongate olivines parallel to the contacts (fig. 8). The distribution of large crystals (olivines) and nodules towards the base of the sheets, where the long axes of nodules are parallel to the floor, points to considerable fluidity within the sills during their emplacement. Occasionally, the grain size variation within a sheet suggests more than one period of injection (figs. 3b and 8). Size sorting during movement probably accounts for the small variations in grain size at the contacts (fig. 8).

There is little contact alteration of the granite in contact with, or enclosed by the

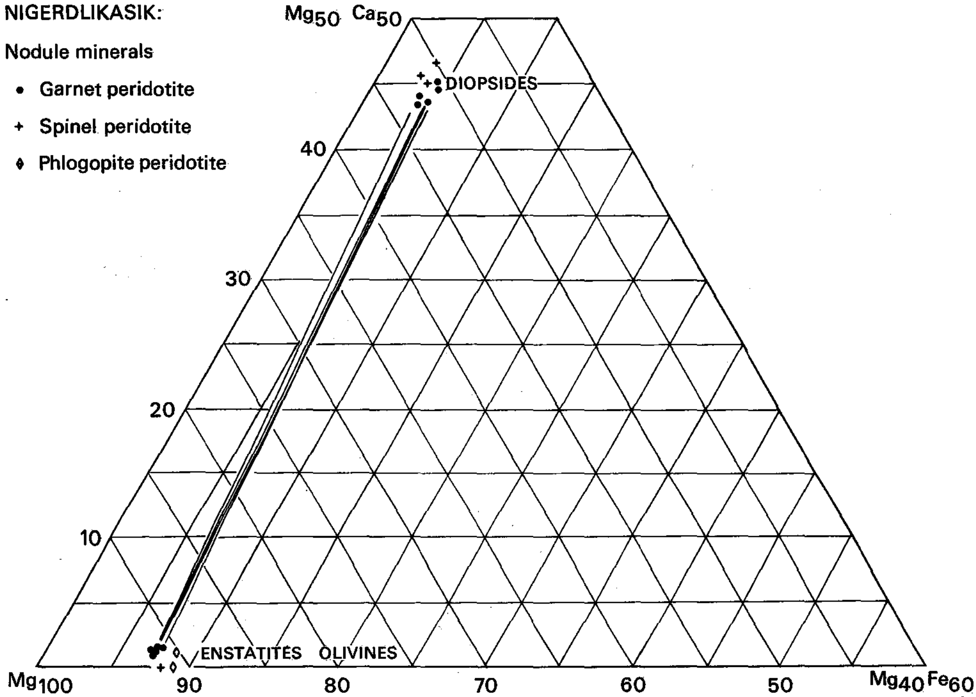

Fig. 7a. Ca-Fe-Mg variation diagram for Nigerdlikasik nodule olivines and pyroxenes. The tie-lines join analyses from the same nodules.

sheets. The normal granite contains quartz, microline, zoned plagioclase, biotite with accessory sphene, orthite, zircon, opaques, and apatite. Biotite and microline are not affected but the calcic cores of plagioclase are sericitised. Although thermal contact effects are virtually absent there has been small-scale mechanical shattering of the granite. Crystals in granite adjoining the sheets are brecciated and dislocated, and thin shatter veins may penetrate the granite for several millimetres. The relationships suggest explosive brecciation rather than mechanical crushing, the thin veinlets have features resembling those described from tuffisites (Reynolds, 1954).

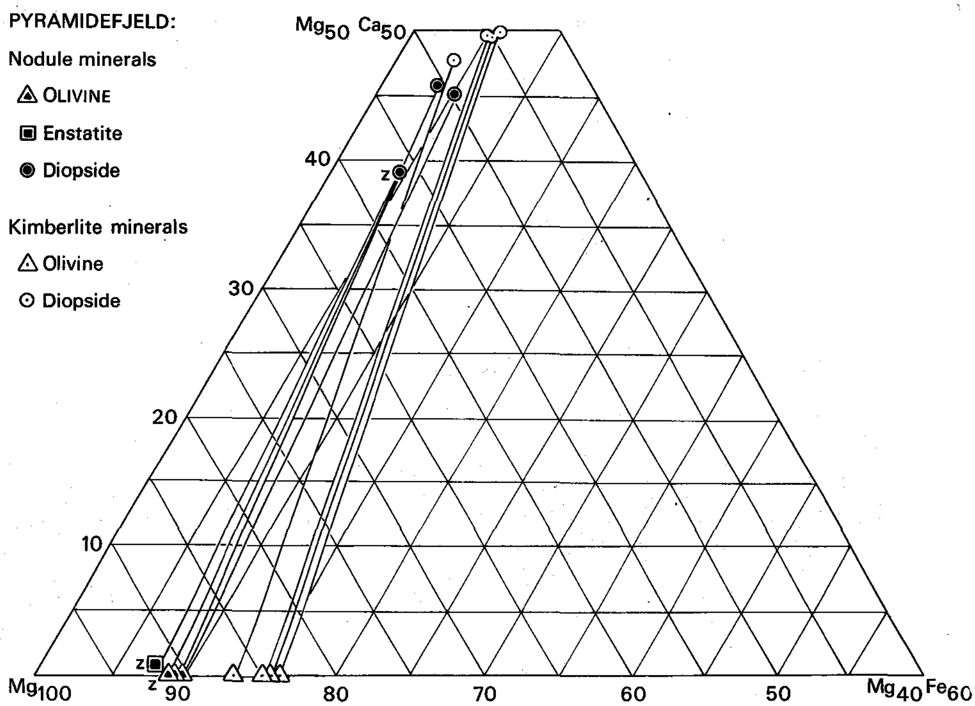

Fig. 7b. Ca-Fe-Mg variation diagram for Pyramidefjeld kimberlite and nodule olivines and pyroxenes. Tie-lines join analyses from the same kimberlite or nodule; but note that the analyses Z-Z-Z refer to specimen 27703: the remaining diopsides from nodules are distinctly more calcic although less calcic than diopsides from the kimberlites.

DISCUSSION

Most petrographical and mineralogical features of the kimberlite intrusions are shared by the Nigerdlikasik dyke and Pyramidefjeld sheets. Both are micaceous tuffs complying with the modern petrological definition of kimberlite by Dawson (1967a). Further unifying features include the absence of thermal contact effects, evidence of crystal sorting during flow, minor brecciation of the wall rock, the suggestion of multiple intrusion and the presence of rounded peridotite xenoliths. Modal analyses may be compared in tables 1 and 2.

Fig. 8. Pyramidefjeld kimberlite (39644), Plane-pol. light, x5. Kimberlite in contact with granite-gneiss (left) shows good size-sorting parallel to the contact; similar size-sorting 0.5 cm from the contact suggest a later injection of magma. Note the indications of alignment of kimberlite minerals parallel to the contact and the slight shattering of granite-gneiss near the contact (top-left) with penetration of the shattered rock by a thin, dark kimberlite stringer.

The kimberlites

Two generations of olivine are common in the dyke and sheet rock (fig. 5). The large ragged rounded forsterite-rich crystals are considered to have been derived from the mechanical breakdown of peridotite inclusions. The smaller, well-formed crystals with higher Fe/Mg rations were precipitated from the kimberlite magma. Xenocrystal and phenocrystal olivine showing a similar compositional range commonly occurs in South African kimberlites and is thought by other workers (Wagner, 1914; Nixon, von Knorring & Rooke, 1963) to have a comparable mode of origin.

Intensely pleochroic rims to the matrix phlogopite feature in both occurrences. Investigation of the Pyramidefjeld material shows that these are distinctly richer in Fe and Si, slightly richer in Mg, and low in Ti and especially Al when compared with the normal mica of the kimberlite. Values for Al_2O_3 as low as 1 wt % have been obtained. Similar rims to micas are fairly well known from kimberlites and carbonatites (Heinrich, 1966; Watson, 1967); they have been described in some detail by Rimskaya-Korsakova & Sokolova (1964) from alkali-rich, alumina-poor rocks from the Kola peninsula. The low Al is compensated for by increased Fe^{+3}: the name proposed by these authors for this mineral is tetraferriphlogopite.

Both types of intrusion show identical crystallisation sequences discernable from textural relations. Early olivine, clinopyroxene, opaques and perovskite were followed by phlogopite (sometimes overlapping earlier phases) which zoned to Fe-rich rims, then dolomite crystallised followed by calcite and finally serpentine (fig. 6b).

Several whole rock analyses have been made by X-ray fluorescence and wet chemical methods. The following general points are worth noting. All have low SiO_2 (25-30%), low Al_2O_3 (about 3%), MgO is high (25-30%) and $CO_2 + H_2O^+$ variable but high for igneous rocks (5-25%). The K/Na ratio is high, similar to that quoted by Dawson (1967b) for micaceous kimberlite (7.5). All analyses show a low Rb concentration and a high K/Rb ratio (over 3000). The complete analyses will be published elsewhere.

The nodules

Rounded peridotite nodules are common to all three kimberlite occurrences. Nodules of high grade metamorphic rocks occur in the Nigerdlikasik kimberlite but have not been found in the Pyramidefjeld sheets. They are undoubtedly xenoliths of the lower part of the crystalline basement accidentally incorporated into the kimberlite magma, a common feature in kimberlite diatremes from other continental shield areas (Dawson, 1967a).

The peridotite nodules may be classified into three types according to the aluminous phase. Garnet- and phlogopite-bearing examples have been noted in the Nigerdlikasik dyke and Pyramidefjeld sheets, whilst spinel peridotite has only been observed in the former. No aluminous phase was detected in the one nodule examined from the Midternæs sills though garnet, spinel and/or phlogopite probably exist in many of the numerous inclusions. Garnet peridotites are the most common type of ultrabasic nodule in South African kimberlites though rarer spinel- and phlogopite-bearing varieties have been reported (Nixon et al., 1963).

Analytical data from the Pyramidefjeld area is at present restricted to phlogopite peridotite whilst most, but not all, of that obtained from Nigerdlikasik is concerned with garnet and spinel peridotites (table 2; figs 5 and 7). There is nevertheless a marked compositional correspondence between olivine, orthopyroxene and clinopyroxene from both localities. It is significant that the closest comparison may be made between minerals from phlogopite peridotites. Besides similar Fe/Mg ratios, their pyroxenes have low alumina contents and contain similar amounts of chromium. The spinel peridotites in the Nigerdlikasik kimberlite closely approach those occurring as nodules in alkaline olivine basalts (Ross, Forster & Myers, 1954). The olivines in the latter are slightly less magnesium rich and the aluminium content of the clinopyroxenes slightly higher.

Petrogenesis

The peridotite inclusions have an important bearing on kimberlite petrogenesis. The relatively low alumina content of the pyroxenes coexisting with garnet and spinel indicates that they underwent subsolidus equilibration (O'Hara, 1967) and are not crystal accumulates from the kimberlitic magma. The presence of garnet, spinel or phlogopite as the aluminous phase is interpreted as a function of the pressure of equilibration and of environment. The transformation of natural garnet peridotite to spinel peridotite with decreasing pressure has been experimentally accomplished by Ito & Kennedy (1967). It occurs at pressures equivalent to a depth of 40-60 km, well within the Upper Mantle. The alteration of garnet to spinel- and phlogopite-bearing rims associated with the ascent of garnet peridotite in kimberlite supports the proposition that both spinel and phlogopite are lower pressure phases. Inspection of the nodule clinopyroxene analyses plotted in fig. 7 shows that they do not show fractionation towards more Fe rich compositions but instead a range of solid solution towards enstatite. A similar trend is apparent from other kimberlite clinopyroxene analyses and is interpreted as being due to variable depth of subsolidus equilibration (Boyd, 1969). It seems most likely that spinel peridotite is derived from a spinel-bearing layer and garnet peridotite from an underlying layer of the Upper Mantle. On the other hand, phlogopitisation is a characteristic feature in kimberlites (Dawson, 1962) and is probably responsible for the development of phlogopite peridotite inclusions which often show signs of alteration.

The marked similarity of the dyke and sheet occurrences and the kimberlitic nature of the Midternæs sills defines a close kinship. Geographical considerations suggest derivation from different sources, a proposition supported by the slight differences in the mineralogy of the dyke and sheet intrusions. The former contains almost no clinopyroxene and is considerably less micaceous (table 1). Furthermore, it is an established fact that South African kimberlites contain distinctive suits of diamonds within individual diatremes sometimes as little as 1.5 km apart indicating that each body was a discrete entity during diamond crystallisation (Dawson, 1967b). Nevertheless, the Greenland intrusions define a kimberlite province akin to those of the Siberian and African Shields. Because of the concealed nature of the intrusions it is probable that further examples occur throughout the region and have been overlooked during the initial 1 : 20 000 mapping programme.

The parental kimberlite magma presumably arose by partial fusion of a peridotite substratum and sampled the wall rock during a rapid ascent to the surface. Slight variations in the late magma composition are shown by sympathetic variation in the

Fe/Mg ratios of coexisting olivine and clinopyroxene of the Pyramidefjeld sheets (fig. 7). The low initial $^{87}Sr/^{86}Sr$ magma ratio indicated by isotope work is only compatible with derivation from the Mantle. A magma derived from a crustal source would have a significantly higher $^{87}Sr/^{86}Sr$ ratio because of the relative enrichment of the crust in ^{87}Rb.

CONCLUSIONS

The Nigerdlikasik dyke, Midternæs sills and Pyramidefjeld sheets are established as true, though apparently non-diamondiferous kimberlites. Their similar petrography, mineralogy and geochemistry suggests that the Frederikshåb district forms a province in which kimberlites have been emplaced as volatile-rich, xenocryst-bearing magmas showing features suggesting the operation of fluidisation processes (Reynolds, 1954).

Inclusions of relatively unaltered peridotite are common. They consist predominantly of olivine with lesser amounts of orthopyroxene, clinopyroxene and an aluminous phase (garnet, spinel or phlogopite). Mineralogical data implies that the xenoliths are not crystal accumulates but accidental inclusions derived from great depths, well within the Upper Mantle. The data supports the existence of a sub-crustal peridotite layer of fairly uniform composition similar to that inferred to exist under the African and Russian Shields from inclusions in other kimberlites.

Isotopic age data show that the kimberlites were intruded about 225 m.y. ago during the early Mesozoic. They are probably part of the pattern of Mesozoic igneous activity in South-West Greenland which produced a series of coast-parallel basic dykes and is tentatively linked with the rifting between Greenland and Labrador leading to the opening of the Labrador Sea (Watt, 1969).

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