Mineralogy of Ultramafic Dikes from the Sarfartoq, Sisimiut and Maniitsoq Areas, West Greenland

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ABSTRACT

The petrographic modes of consanguineous hypabyssal ultramafic dikes from the Sarfartoq, Maniitsoq and Sisimiut regions of West Greenland are dominated by macrocrystal and primary olivine, phlogopite, spinel, and dolomite. Some dikes contain aluminous diopside. Micas range in composition from Al-phlogopite to Al-biotite or from phlogopite to tetraferriphlogopite. Primary spinels are commonly Cr-poor relative to kimberlite spinels and range in composition from Ti-bearing magnesiochromite to Ti-magnetite. Mica and spinel compositional trends are unlike those found in kimberlite and similar to those of ultramafic lamprophyres. The rocks are characterized by macrocrystal Cr-rich, Nb-poor magnesian ilmenite mantled by spinel and prismatic primary groundmass Cr-poor, Nb-rich magnesian ilmenite- ilmenite solid solutions. Mineralogical-genetic characterization of the dikes indicates that they are unrelated to archetypal kimberlite. The dikes are classified as diverse ultramafic lamprophyres (macrocrystal aillikite, aillikite) and olivine spinel dolomitic carbonatite. There is a complete modal gradation between all petrographic varieties of dike. The dikes are considered to represent limited partial melts of an asthenospheric carbonated phlogopite lherzolite source. These melts, in the Maniitsoq region, have passed through and sampled diamond-bearing lithospheric mantle.

Keywords: lamprophyre, kimberlite, aillikite, carbonatite, spinel, mica, ilmenite, diamond, upper mantle

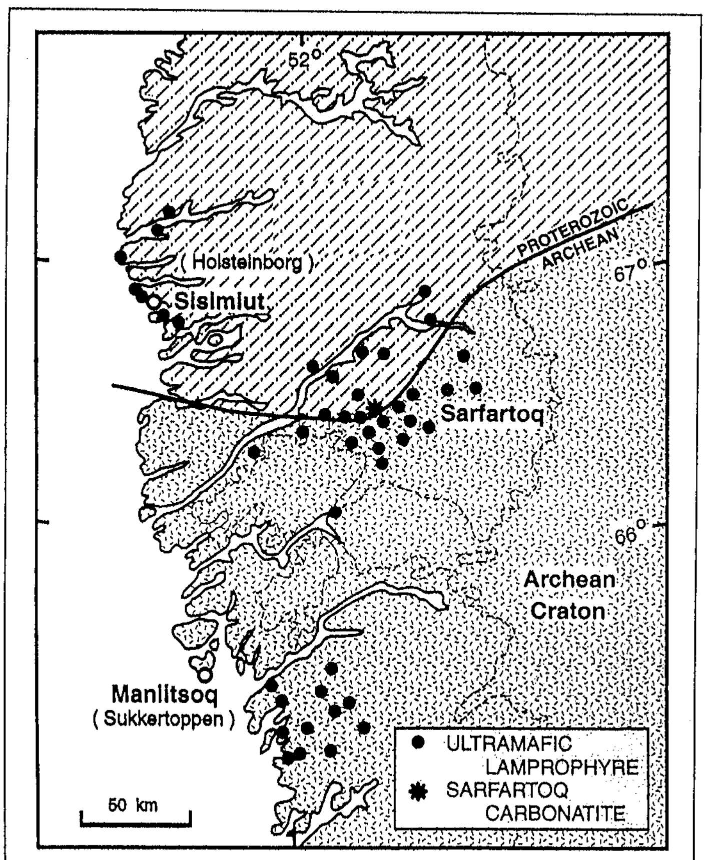


Figure 1. General geological setting and locations of ultramafic dikes (solid dots) in West Greenland. (After Larsen and Rønsbo, 1993).

1. INTRODUCTION

For more than 2500 million years West Greenland has been the site of ultramafic, potassic and carbonatitic activity (Scott, 1981; Larsen *et al.*, 1983; Larsen and Rex, 1992). Currently, West Greenland is the renewed focus of exploration for diamond which has led to the discovery by Lexam Explorations Inc., and Platinova A/S, and more recently by Aber Resources Ltd., of diamond-bearing ultramafic rocks and indicator minerals (subcalcic Cr-pyrope, magnesian ilmenite) in the vicinity of the town of Maniitsoq (Minex News, 1998). This area is one of three geographically distinct fields of 600 Ma carbonate-rich ultramafic dikes which have previously been regarded as kimberlite (Escher and Watterson, 1973; Goff, 1973; Scott, 1981; Larsen and Rex, 1992; Larsen and Rønsbo, 1993). Scott Smith and S.R. Shee (unpublished data) recognized that although the rocks are broadly similar in their petrographic character to *bona fide* kimberlite, they exhibit many mineralogical and textural features which are typical of the ultramafic lamprophyres currently regarded as *melnoite* (Mitchell, 1994, Scott Smith, 1995). This paper presents a mineralogical study of these West Greenland ultramafic dikes which, using a modern mineralogical-genetic classification scheme rather than a simple petrographic classification, permits assessment of their correct petrological status.

2. GEOLOGICAL SETTING

The ultramafic dikes which are the subject of this investigation occur in the Sarfartoq, Sisimiut (Holsteinsborg) and Maniitsoq (Sukkertoppen) areas of West Greenland (Fig. 1; Scott, 1981; Larsen and Rex, 1992). Although the fields are geographically distinct, radiometric age determinations have shown that they are contemporaneous (approx. 600 Ma; Scott, 1981; Larsen and Rex, 1992). The Sarfartoq suite of dikes is temporally associated with the Sarfartoq carbonatite complex (Secher and Larsen, 1980). This intrusion consists of concentric carbonatite sheets with interleaved screens of fenite but lacks associated silicate rocks apart from cone sheets of the Sarfartoq ultramafic dike suite which are centred upon this complex (Larsen, 1980). Contemporaneous carbonatite alkaline magmatism is not associated with the Maniitsoq and Sisimiut dike suites, although genetically unrelated 1200 Ma lamproites are geographically associated with the latter (Scott, 1981; Thy *et al.*, 1987; Larsen and Rex, 1992).

The West Greenland dikes are emplaced into Precambrian high-grade gneisses. Fig. 1 shows that the Maniitsoq dike field lies in the undeformed Archean craton, the Sarfartoq dike field straddles the craton boundary, and the Sisimiut dike field lies in the Proterozoic Nagssugtoqidian mobile belt. This mobile belt was formed by an early Proterozoic collision between two Archean continents, and the gneisses consist dominantly of reworked Archean material (van Gool *et al.*, 1996; Mengel *et al.*, 1998). The Sisimiut ultramafic dikes are emplaced in the juvenile, 1920 Ma Sisimiut charnockite complex (Kalsbeek and Nutman, 1996).

Regardless of this surface disposition of the fields relative to the craton boundary, it is considered that all of the parental magmas have probably passed through cratonic material during their emplacement (Scott Smith, 1987; Garrit *et al.*, 1995).

Each dike field is petrographically similar in consisting of hypabyssal rocks which are composed principally of widely varying modal amounts of olivine, spinel, phlogopite and carbonate. Differences consist of variations in their contents of ultramafic mantle-derived material (lherzolite xenoliths, xenocrystal sub-calcic Cr-pyrope, xenocrystal olivine), macrocrystal olivine and magnesian ilmenite, and primary groundmass phases such as phlogopite and carbonate. Dikes in the Maniitsoq region appear to be enriched in mantle-derived xenolithic components relative to the other areas, and it is in this field that diamond is found as a xenocrystal constituent of the dikes. For example, one dike evaluated by Lexam Explorations Inc. and Platinova A/S has yielded 16 macro- and 25 microdiamonds (Minex News, 1998). Although ultramafic xenoliths are common in the Sarfartoq dikes, these are poor in diamond indicator minerals and diamond, with only two microdiamonds being reported. The Sisimiut dikes are relatively-poor in mantle-derived material. Discussion of the mantle-derived xenolith and xenocryst suite is beyond the scope of this paper. Further information on this topic may be found in Goff (1973), Scott Smith (1987), Larsen and Rex (1992), Larsen and Rønsbo (1993) and Garrit *et al.* (1995).

3. PETROGRAPHIC CHARACTER OF THE DIKES

Representative samples of the dikes from each field were examined by standard thin section petrographic methods and back-scattered electron imagery. Minerals were identified and analysed by qualitative and quantitative X-ray energy dispersive spectrometry using a Hitachi 570 scanning electron microscope (Lakehead University) or a Cameca SX-50 wavelength dispersive electron microprobe (Purdue University). Although individual dikes vary considerably with respect to the modal abundances of the major and accessory minerals present, they are all essentially variations on a common petrographic theme. Typically, olivine is the most abundant phase followed by either mica or dolomite. Fe-Ti oxides may comprise up to 30 vol% of some rocks. Minerals are described below in their approximate order of crystallization. The compositional variations of mica, ilmenite and spinel are discussed individually below.

All of the dikes contain macrocrysts of rounded fresh-to-partially serpentinized magnesian olivine. These are commonly associated with microxenoliths of lherzolite and dunite and are in part undoubtedly derived by fragmentation of these rocks, although crystals lacking strain cannot be unambiguously classified. Some macrocrysts containing randomly disposed inclusions of anhedral Mg-ilmenite may be cognate. Others contain small droplets of Fe-Ni sulphides and may have inclusions of chromite. Macrocrysts may be unzoned, normally-zoned (e.g. mg# = 90.8 - 84.5) or reversely-zoned (mg# = 77.9 - 83.7). The total range in mg# is 91.8 - 77.8, with the commonest being 90-84. In general these olivines are richer in FeO than those in archetypal kimberlite (mg# >87). In some instances, e.g. olivine spinel-carbonate-rich dike (sample 265870), rounded strain-free olivines are the only primary silicate phase.

Many dikes contain relatively few macrocrysts, and phenocrysts of euhedral-to-subhedral olivine are dominant. These olivines are weakly zoned to Fe-rich margins and not substantially different in their composition to macrocrystal olivine (e.g. Maniitsoq Lexam sample 4006 primary olivine mg#'s range from 91 to 89). Olivine compositional variation was not studied in any detail as it is not a sensitive indicator of magma type. Depending upon the proportions of macrocrysts to primary olivine the dikes may be described as having macrocrystal or porphyritic textures.

Microphenocrystal phlogopite occurs as anhedral-to-rectangular prisms and poikilitic plates. Flow-alignment around macrocrystal olivine may be pronounced or not present. In some instances micas are clumped together in glomeroporphyritic aggregates. Deformed and bent crystals are common and may be juxtaposed with deformation-free crystals. The micas are pale yellow, very weakly pleochroic and show no optical zonation. Many crystals possess thin rims of red tetraferriphlogopite. Relatively dark-coloured poikilitic plates of Fe-rich mica occur in the groundmass of most dikes.

Ilmenite is found as: anhedral inclusions in olivine macrocrysts; mantled macro- and microcrysts; and euhedral groundmass laths. Mg-ilmenite inclusions in olivine macrocrysts are relatively uncommon, but all rocks are characterised by irregular macrocrysts and microcrysts of Mg-ilmenite mantled by zoned Cr-poor, Mg-Ti-magnetite. The latter are compositionally identical to discrete primary groundmass spinels (see below). The ilmenite microcrysts may be polygranular or single crystals. Some examples contain exsolution lamellae of Cr-spinel, and anhedral chromite, rutile, PbS and ThO_2 may be found as inclusions. Microcrystal ilmenites of differing petrographic character are commonly juxtaposed. Primary Mg-rich to Mg-poor ilmenite occurs as thin euhedral prisms (20-70 x 10-30 μm) immersed in the groundmass carbonates and as overgrowths on earlier-formed spinels. In some instances quench-like aggregates of very fine-grained (10 x 1 μm) cryptocrystalline prisms of Mg-free ilmenite occur in a dolomite matrix.

Spinel occurs as mantles upon ilmenite macrocrysts and microcrysts and as subhedral-to-euhedral opaque groundmass discrete crystals. Atoll-textured spinels are absent. Typically, the spinels are continuously-zoned single crystals (20-150 μm), although in some dikes they consist of a discrete irregular core with a subhedral-to-euhedral mantle.

Some dikes contain subhedral-to-euhedral primary Cr-poor diopside. At Sisimiut, these contain 1-4 wt% TiO_2 and 1-8 wt% Al_2O_3; at Sarfartoq, they contain 1-5 wt% TiO_2 and 1-10 wt% Al_2O_3 (Table 1). These pyroxenes are considered primary as there is no evidence in these dikes of any significant wall-rock reaction. Significant contamination of the magma to a level sufficient to induce pyroxene crystallization would undoubtedly be reflected by the formation of other Ca-Al-silicate minerals. Primary pyroxene is apparently absent from the Maniitsoq suite. Aluminous primary pyroxene is not a typical groundmass mineral of kimberlite but is common in ultramafic lamprophyres and melilititic rocks (Mitchell, 1997). Fibrous aegirine is rarely present in the groundmass of some Sarfartoq dikes (e.g. sample 265399).

Perovskite occurs as subhedral-to-rounded crystals and as a part of reaction assemblages developed around ilmenite macrocrysts. All are relatively pure $CaTiO_3$-perovskite. Not all dikes contain perovskite; either it has apparently never crystallised or has been replaced by an intimate intergrowth of Mg-free ilmen-

Table 1. Representative compositions of pyroxene and clinohumite

wt.%	1	2	3	4	5	6	7	8	9	10
SiO_2	54.59	49.01	45.20	40.72	52.32	50.80	51.54	47.53	41.11	37.34
TiO_2	0.12	1.83	3.46	4.62	0.92	1.68	1.29	2.69	4.94	1.22
Al_2O_3	0.13	3.29	6.40	10.06	1.78	3.10	1.19	4.16	8.04	n.d.
Cr_2O_3	n.d.	n.d.	n.d.	n.d.	0.53	0.07	n.d.	0.02	0.04	n.d.
FeO_T	1.70	6.49	7.57	8.29	5.30	5.39	4.94	6.95	9.36	9.51
MnO	n.d.	n.d.	0.11	0.05	0.13	0.13	0.17	0.17	0.14	0.56
MgO	18.42	14.48	12.74	11.00	15.28	15.35	15.70	13.91	11.02	48.50
CaO	25.91	24.93	24.67	24.53	21.34	21.14	25.25	24.55	24.02	0.13
Na_2O	0.06	0.25	0.27	0.23	0.90	0.80	0.28	0.34	0.32	n.d.
	100.93	100.03	100.42	99.50	98.50	98.49	100.36	100.32	98.99	97.26

Compositions 1-9 pyroxene: 1-4 Sarfartoq 265265; 5-6 Sarfartoq 265348; 7-9 Sisimiut 5966; 10 clinohumite, Sarfartoq 265185. n.d. = not detected.

ite, anatase and kassite. Sr- and REE-poor apatite forms subhedral, commonly resorbed prisms, and irregular groundmass plates; most apatite has crystallised subsequent to spinel and contemporaneously with groundmass carbonates.

The mesostasis of the dikes is composed primarily of Fe-bearing dolomite plus minor calcite, intergrown in either an emulsion or irregular texture. Many dolomite-rich rocks from Sarfartoq and Maniitsoq are mica-poor and consist of microphenocrystal olivine and spinel set in a matrix of carbonate. Some dikes contain irregular patches of serpentine. Other minerals present as trace accessory phases are: (Ca,Ti)-Zr-oxide (zirconolite?), (Ca,Ti)-Nb-oxide, ZrO_2 (baddeleyite), TiO_2 (rutile and/or anatase), thorite, strontiobarite, barite, celestite, strontianite, Sr(REE)-carbonate (ancylite?), galena, chalcopyrite, pyrite, Ni-pyrite, and djerfisherite. One dike from Sarfartoq (sample 265185) contains subhedral pale yellow clinohumite (Table 1).

4. COMPOSITION OF MICA

Phenocrystal micas range in composition from aluminous phlogopite to magnesian aluminous biotite and commonly exhibit

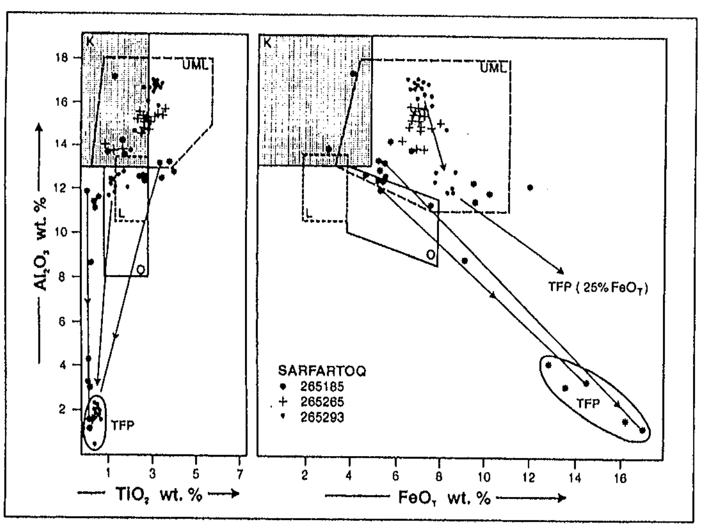


Figure 2. Compositional variation of mica in ultramafic lamprophyres from the Sarfartoq field expressed as Al_2O_3 versus TiO_2 or FeO_T (wt%). Sample 265185 lacks primary groundmass pyroxene. Samples 265265 and 265293 contain abundant primary groundmass pyroxene. Also shown are compositional fields of macrocrystal and groundmass mica from kimberlite (K) and primary phenocrystal mica from ultramafic lamprophyres (UML), lamproites (L) and orangeites (O); all data from Mitchell (1995). TFP = tetraferriphlogopite. FeO_T = total Fe expressed as FeO.

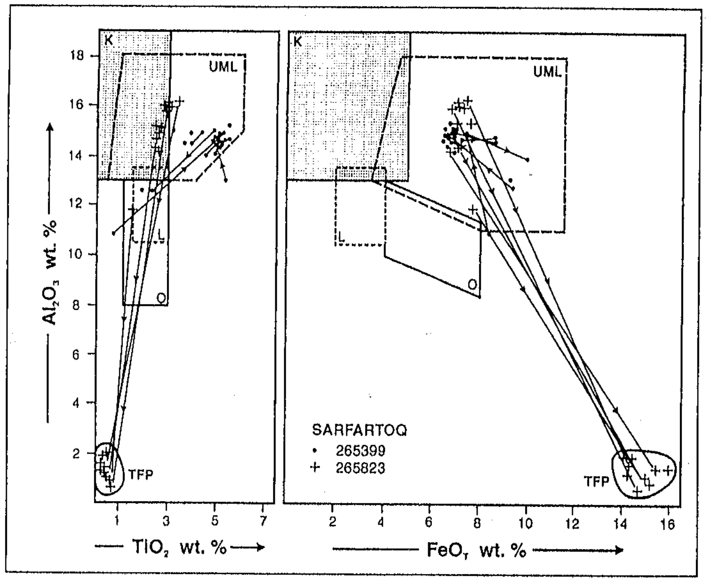


Figure 3. Compositional variation of mica in pyroxene-free ultramafic lamprophyres from the Sarfartoq field expressed as Al_2O_3 versus TiO_2 or FeO_T (wt%). See legend for Fig.2 for field identifications.

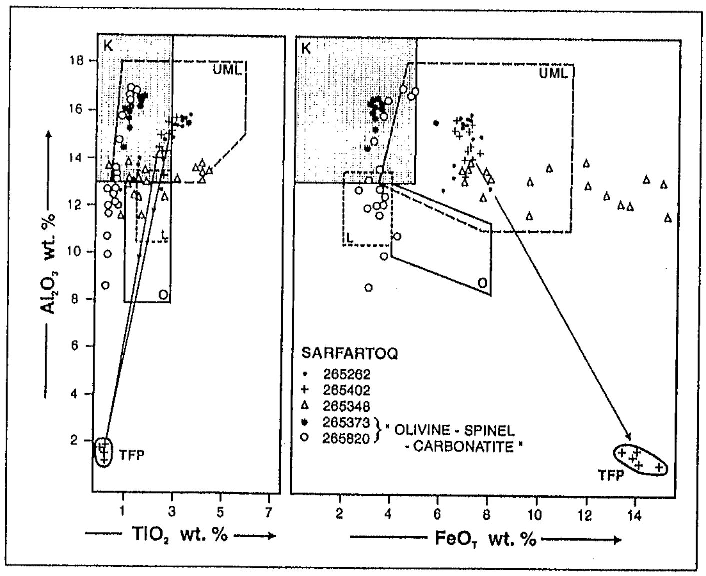


Figure 4. Compositional variation of mica from pyroxene-free (265402) and pyroxene-bearing (265202, 265348) ultramafic lamprophyres and carbonatites (265373,265820) the Sarfartoq field expressed as Al_2O_3 versus TiO_2 or FeO_T (wt%). See legend for Fig.2 for field identifications.

rims of tetraferriphlogopite. Groundmass micas are magnesian biotite. All micas are Cr-poor (<0.05 wt% Cr_2O_3), with low BaO contents (0.1 -1.1 wt%). TiO_2 ranges from 1-4.7 wt%, Al_2O_3 from 11.5 - 17.5 wt%, and FeO from 2 - 15 wt% FeOT. NiO is <0.1 wt%. Tetraferriphlogopite rims are low in TiO_2 (<1.0 wt%) and Al_2O_3 (<2.5 wt%) and have very high FeO_T (12 - 25 wt%) at high MgO contents. Ba and Cr contents are low (<0.3 wt%). Figures 2-5 illustrate the compositions of mica in diverse dikes from all three fields in terms of Al_2O_3 wt% versus TiO_2 or FeO_T wt%. The compositional trends of mica depicted in such diagrams have been shown (Mitchell, 1995; Mitchell and Bergman, 1991) to be indicative of the parental magma type.

4.1 Sarfartoq

Mica in pyroxene-free and pyroxene-bearing ultramafic dikes follows compositional zoning trends towards Fe-enrichment coupled with Ti- and Al-depletion. There are no significant petrographic differences between dikes which contain micas evolving towards biotite or tetraferriphlogopite. Dikes with or without groundmass primary pyroxene do not differ in their mica compositional trends (Figs.2-4). Mica in olivine-spinel-carbonate-rich dikes is characteristically poor in Ti and Fe compared to that in other dikes (Fig. 4), suggesting that these rocks formed from less-evolved batches of magma. Phenocrystal micas in other dikes have compositions which plot in the compositional field of primary mica from ultramafic lamprophyres associated with alkaline rock-carbonatite complexes (Figs. 2-4). Although micas from the carbonate-rich dikes plot in this diagram in the field of kimberlite groundmass mica (Fig. 4), they differ in that they are Ba-poor (< 1 wt% BaO) and the evolutionary trend is towards Al-depletion. Significantly, micas belonging to the phlogopite-kinoshitalite solid solution series, which are characteristic of *bona fide* kimberlites (Mitchell, 1997) are absent.

4.2 Sisimiut

The compositions of mica from Sisimiut were not studied in detail in this work as previous studies by Scott (1981) and Thy *et al.* (1987) have established their character and evolution. Representative compositions of mica from Sisimiut (Scott, 1981 samples 5966; 5512) are shown in Fig. 5, which demonstrates that phenocrystal mica is typically zonation-free and that although individual crystals differ slightly in their composition, they are all Ti-, Fe-rich aluminous phlogopite. Phenocrystal micas have compositions similar to those in the Sarfartoq dikes and to mica in ultramafic lamprophyres. Evolution is towards Al-depletion without Ba-enrichment and many crystals are mantled by thin rims of Ti-poor tetraferriphlogopite (Scott, 1981, Thy *et al.*, 1987).

4.3 Maniitsoq

Phenocrystal mica in Maniitsoq dikes is, in common with that from Sarfartoq and Sisimiut, typically aluminous (14-18 wt% Al_2O_3) phlogopite. However, comparison of Fig. 5 with Figs. 2-4 suggests that the Maniitsoq micas are relatively-poor in Ti and Fe. Although, individual crystals are zonation-free or very weakly zoned, the overall compositional trend is one of Al-depletion. This trend culminates with the formation of tetraferriphlogopite mantles. Maniitsoq micas have compositions similar to the least-evolved micas from ultramafic lamprophyres and kimberlites (Fig. 5).

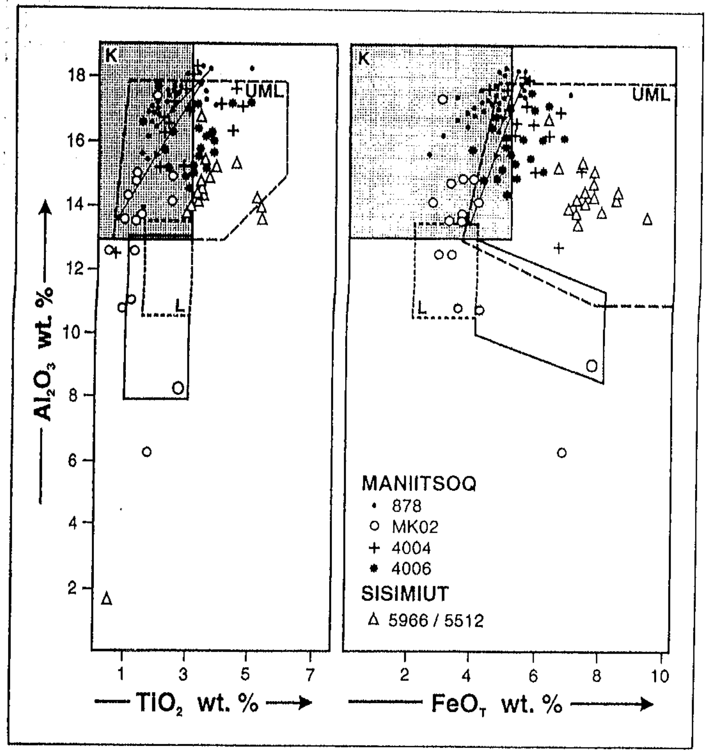
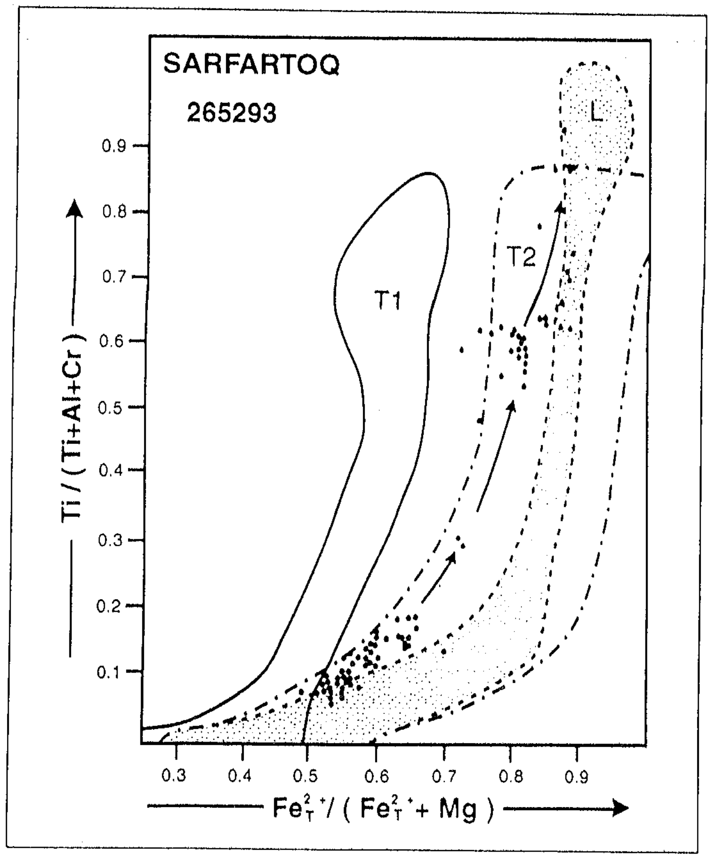


Figure 5. Compositional variation of mica in ultramafic lamprophyres from the Maniitsoq and Sisimiut fields expressed as Al_2O_3 versus TiO_2 or FeO_T (wt%). See legend for Fig.2 for field identifications.

Figure 6. Compositions of spinels from a Sarfartoq ultramafic dike (265293) projected onto the front face of the reduced spinel prism. Also shown are the compositional fields and evolutionary trends of spinels in archetypal kimberlite (T1), lamprophyre (T2) and lamproite (L). (After Mitchell, 1995).



5. COMPOSITION OF SPINEL

Spinels exhibit an extremely wide range in composition within and between fields. Representative data depicted as projections on to the front face of the "reduced" spinel prism (Mitchell, 1995, 1986) are shown in Figs. 6-9.

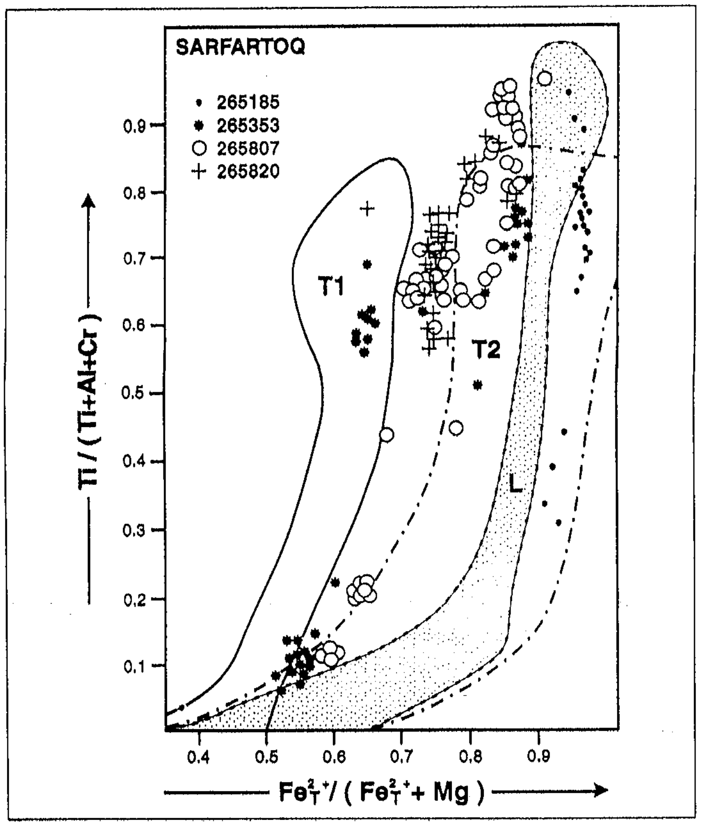


Figure 7. Compositions of spinels from Sarfartoq ultramafic dikes projected onto the front face of the reduced spinel prism. Also shown are the compositional fields and evolutionary trends of spinels in archetypal kimberlite (T1), lamprophyre (T2) and lamproite (L). (After Mitchell, 1995).

Table 2. Representative compositions of spinel from Sarfartoq and Maniitsoq

wt.%	1	2	3	4	5
TiO_2	5.63	20.54	10.56	2.34	22.48
Al_2O_3	8.61	8.37	2.09	52.57	9.62
Cr_2O_3	44.39	0.41	0.26	0.26	3.74
FeO_T	29.62	54.78	77.44	16.57	42.79
MnO	0.20	0.44	0.62	0.40	0.72
MgO	11.94	14.21	5.60	23.66	21.36
	100.39	98.75	96.57	99.28	98.45
Recalculated					
FeO	20.34	29.77	32.59	5.83	20.34
Fe_2O_3	10.32	27.79	49.85	11.93	24.95
	101.42	101.53	101.66	100.48	100.95
Mol% end member spinels					
$MgAl_2O_4$	14.6	11.2	2.9	74.1	12.4
Mg_2TiO_4	18.3	27.7	12.9	6.3	42.9
$MgCr_2O_4$	12.2	-	-	1.8	-
$MnCr_2O_4$	0.5	-	-	0.8	-
Mn_2TiO_4	-	0.6	0.6	-	1.0
$FeCr_2O_4$	37.7	0.4	0.2	0.9	1.3
Fe_2TiO_4	-	24.4	15.2	-	11.6
Fe_3O_4	16.7	35.7	67.8	16.1	30.8

Compositions 1-3 Sarfartoq 265353: 1 core; 2 inner mantle; 3 outer mantle; compositions 4-5 Maniitsoq MK-02; 4 core; 5 mantle.

5.1 Sarfartoq

Figure 6 shows that spinels in the commonest petrographic variety of Sarfartoq dike (e.g. aillikite; sample 265293) range in composition from magnesian chromite cores to mantles and discrete crystals of titaniferous magnetite. The compositional evolutionary trend in the reduced spinel prism follows spinel Trend 2 as defined by Mitchell (1995, 1986); consequently spinels are poor in the Mg-ulvöspinel molecule compared to spinel in *bona fide* kimberlite (Trend 1). Fig. 7 shows that other Sarfartoq dikes (265807, 265185) also follow similar trends, although spinels in each dike evolve to increasing Ti contents at a particular Fe/(Fe+Mg) ratio. Spinels in dike 265353 follow a unique compositional trend (Fig.7). Cores consist of Ti-Al-magnesiochromite [Cr/(Cr+Al) = 0.7-08; Fe/(Fe+Mg) = 0.5 - 0.6]. Mantles are zoned from spinel-magnesian ulvöspinel-ulvöspinel-magnetite solid solutions towards ulvöspinel-magnetite. The initial core compositions (Table 2) are similar to those of early-forming spinels of kimberlite spinel Trend 1. However, their subsequent evolution is horizontally across the spinel prism (Cr depletion at approximately constant Ti) rather than upwards towards the magnesian ulvöspinel- ulvöspinel apex. Consequently, mantle compositions (Table 2) actually plot on the rear face of the reduced spinel prism at very low Ti/(Ti+Al+Cr) ratios (<0.05). Further evolution is along this face, following a trend of decreasing Al and Mg, toward ulvöspinel-magnetite. Final spinel compositions are similar to those of evolved spinels in other Sarfartoq dikes (Table 2). That these spinels appear to plot in Fig.7 along kimberlite spinel Trend 1 is merely an artefact of the projection used. Spinels in olivine-spinel carbonate-rich dikes (e.g. 265820) are Ti-rich, Cr-poor evolved spinels which evolve along spinel Trend 2 (Fig.7), and are similar to spinels in the mica-rich ultramafic dikes.

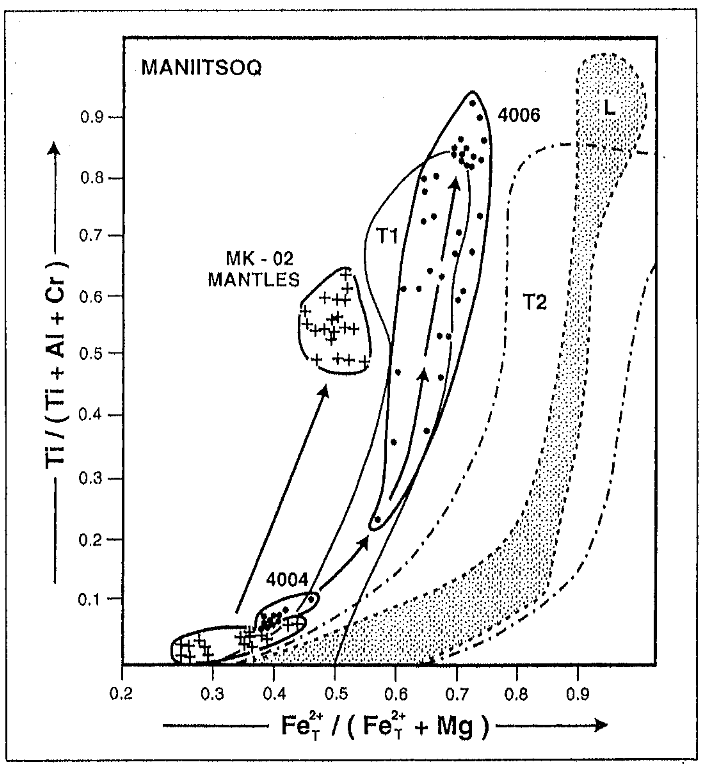


Figure 8. Compositions of spinels from Maniitsoq ultramafic dikes projected onto the front face of the reduced spinel prism. Also shown are the compositional fields and evolutionary trends of spinels in archetypal kimberlite (T1), lamprophyre (T2) and lamproite (L). (After Mitchell, 1995).

5.2 Maniitsoq

Spinels in the Maniitsoq dikes are Mg- and Al-rich relative to Sarfartoq spinels (Table 2). Fig. 8 shows that in projection their compositional evolution apparently follows kimberlite spinel Trend 1. However, compositions are typically Cr-poor [Cr/(Cr+Al) < 0.1] compared to kimberlite spinel [Cr/(Cr+Al) > 0.8; Mitchell, 1995, 1986) and the spinel compositions actually lie close to the rear face of the reduced spinel prism. Spinels in Lexam sample MK-02 are unusual in that irregular cores of Ti-poor spinel-magnetite solid solutions are mantled by spinels in which Mg-ulvöspinel is the dominant end-member component (Table 2). Similar Mg-ulvöspinel-rich spinels are known only from the Benfontein calcite kimberlite. The latter differ from the Maniitsoq spinels in that they are relatively MgO- (< 20 wt%) and Al_2O_3 (<8 wt%) -poor.

5.3 Sisimiut

Sisimiut spinels analysed in this study consist of cores of titanian magnesian chromite (3-4 wt% TiO_2, 11-13 wt% Al_2O_3, 11-14 wt% MgO) with discrete continuously zoned mantles of ulvöspinel-magnetite (13-18 wt% TiO_2, 3-5 wt% Al_2O_3, 1-11 wt% MgO). The compositional trend is unusual in that the initial Cr-rich core spinels appear to follow kimberlite spinel trend 1, whilst mantles essentially follow spinel trend 2 (Fig. 9) which culminates with the formation of Ti-free magnetite. These data are in accord with initial studies of Sisimiut spinel by Scott (1981) and Thy *et al.* (1981). Note that the latter authors claim that the Sisimiut spinel compositional trend is similar to that of kimberlite. However, Fig. 15 of Thy *et al.* (1981) actually depicts compositional relationships identical with those shown in Fig. 9 for Sisimiut sample Scott-5509; i.e cores of Trend 1-like magnesiochromites with mantles of Cr-poor ulvöspinel-magnetite with the high $Fe_T/(Fe_T + Mg)$ ratios [0.7-0.9] typical of spinel trend 2. In common with spinels from Maniitsoq, many Sisimiut spinels analysed by Thy *et al.* (1981) are Cr-poor and plot essentially on the Cr-free rear face of the reduced spinel prism.

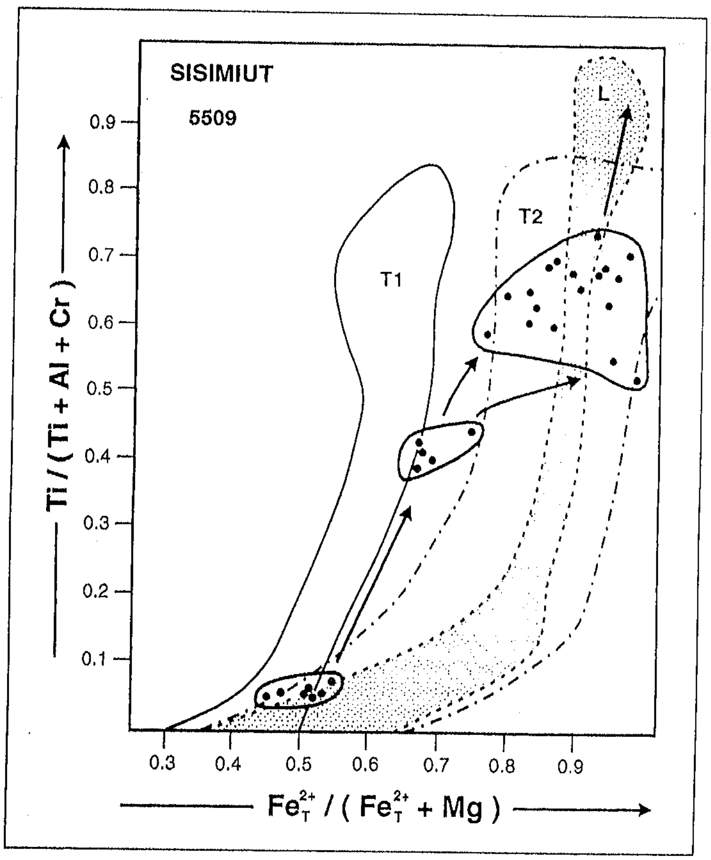


Figure 9. Compositions of spinels from a Sisimiut ultramafic dike projected onto the front face of the reduced spinel prism. Also shown are the compositional fields and evolutionary trends of spinels in archetypal kimberlite (T1), lamprophyre (T2) and lamproite (L). (After Mitchell, 1995).

6. COMPOSITION OF ILMENITE

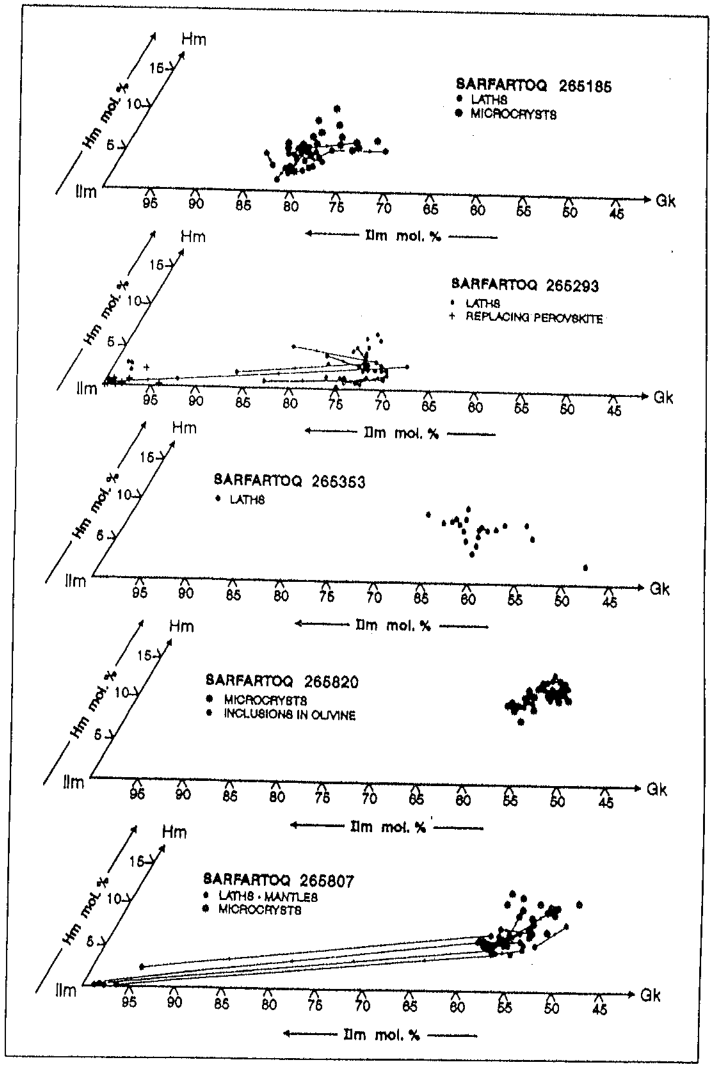
6.1 Inclusions in olivine

Ilmenite inclusions in olivine from Sarfartoq and Maniitsoq occur as anhedral crystals concentrated in the rims of mantled olivine macrocrysts. Individual grains within a single olivine crystal are essentially homogeneous, but may vary widely in their Mg and Cr contents (3-10 wt% Cr_2O_3). Nb_2O_5, Al_2O_3 and MnO contents are typically low (< 1 wt%). Individual dikes are characterized by ilmenite inclusions of a particular MgO content. Inclusions are compositionally similar to ilmenite microcrysts found in the same rock, e.g. Sarfartoq 265820 (Fig. 10).

6.2 Ilmenite microcrysts

Figures 10 and 11 show that ilmenite microcrysts from Sarfartoq and Maniitsoq exhibit a wide range of composition with respect

Figure 10. Compositions (mol%) of ilmenite from Sarfartoq ultramafic dikes plotted in the ternary system hematite (Hm) - ilmenite (Ilm) - geikielite (Gk).



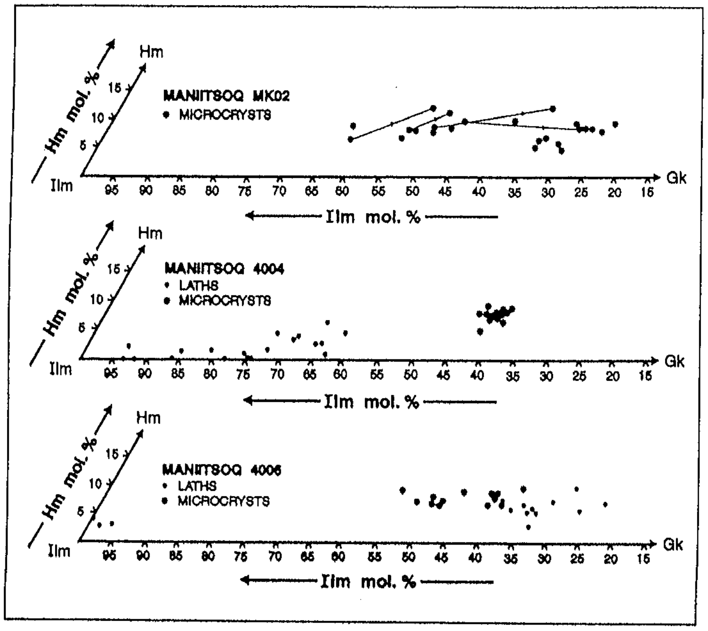


Figure 11. Compositions (mol%) of ilmenite from Maniitsoq ultramafic dikes plotted in the ternary system hematite (Hm) - ilmenite (Ilm) - geikielite (Gk).

to their MgO contents. Individual dikes are characterised by ilmenite with a particular range in MgO. Recalculated compositions typically indicate less than 10 mol% hematite. Individual microcrysts are commonly irregularly zoned with respect to Cr and Mg contents in a manner suggesting that they are fragments of larger crystals. Individual microcrysts vary widely with respect to their Cr_2O_3 contents (0.5 - 5 wt%) within and between dikes. Nb_2O_5, Al_2O_3 and MnO contents are all low (typically <1 wt%). Microcrysts of low Cr-content are relatively enriched in Nb. Some microcrysts have rims enriched in Mg relative to their core (Fig. 11). Similar microcrystal ilmenite occurs in the Sisimiut dikes (Scott, 1981; Thy *et al.*, 1987). Figures 10 and 11 also demonstrates that microcrysts from Maniitsoq are relatively enriched in MgO compared to those from Sarfartoq.

6.3 Primary groundmass ilmenite

Primary lath-shaped euhedral ilmenite exhibits a wide range in composition within and between dikes. There is no correlation with petrographic type of dike or field of origin. Ilmenite in individual dikes exhibits a discrete range in MgO content and is, in common with microcrystal ilmenite, poor in the hematite end-member. Unlike microcrysts, primary ilmenite is relatively poor in Cr_2O_3 (<0.3 wt%) and enriched in Nb_2O_5 (e.g. 0.3 -3.0 wt%) in the Sarfartoq dikes. Similar Nb contents are found in Maniitsoq ilmenites. Maniitsoq sample 4006 is unusual in containing ilmenites with up to 7 wt% Nb_2O_5. Primary ilmenite may be homogeneous or continuously zoned from core to margin with decreasing Mg and Nb and increasing Fe and Mn (0.5 -3 wt% MnO) contents.

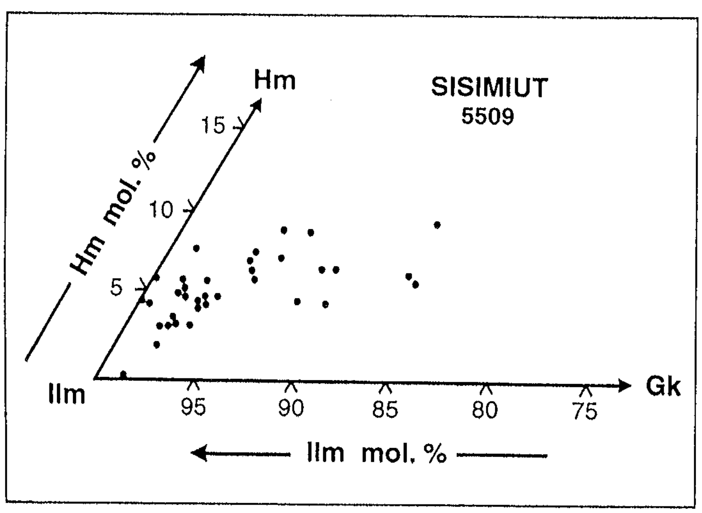


Figure 12. Compositions (mol.%) of ilmenite from Sisimiut ultramafic dikes plotted in the ternary system hematite (Hm) - ilmenite (Ilm) - geikielite (Gk).

Ilmenites from Sisimiut have not yet been studied in detail. Fig. 12 illustrates the compositional range found in primary ilmenite from a representative Sisimiut dike. The data are in agreement with preliminary data of Scott (1981). The ilmenites are depleted in Mg and enriched in Mn relative to most primary ilmenite from Sarfartoq and Maniitsoq. Individual grains may be normally- or reversely-zoned with respect to Mg contents and coupled with decreasing Nb_2O_5 (7 - 0.5 wt%) from core-to-margin. On the basis of these and Scott's (1981) data, it is very probable that individual dikes in the Sisimiut region contain distinct populations of ilmenite akin to those found in the Sarfartoq and Maniitsoq suites.

Figures 10 and 11 show that within a given dike from Sarfartoq and Maniitsoq primary and microcrystal ilmenite may or may not have similar compositions with respect to their major element contents. However, ilmenite of similar Mg content from each paragenesis differs with respect to its Nb and Cr content. Late stage ilmenite may be more- or less-magnesian than associated microcrystal ilmenite. Microcrystal ilmenites are in some instances zoned to margins whose compositions are similar to those of associated groundmass ilmenite. Ilmenites replacing perovskite are essentially pure $FeTiO_3$.

7. MINERALOGICAL-GENETIC CLASSIFICATION OF THE DIKES

The principal mineralogical characteristics of the dikes relevant to their classification are the presence of: primary forsteritic olivine phenocrysts; primary aluminous diopside; primary mica whose composition ranges from aluminous phlogopite to aluminous biotite or from aluminous phlogopite to tetraferriphlogopite; abundant primary groundmass magnesian ilmenite; spinels whose compositions are Cr-poor relative to kimberlite spinels and which evolve primarily along spinel compositional Trend 2; poikilitic late-stage apatite; a suite of accessory minerals which includes Ca-zirconates and K-Fe-sulphides. Spinel and mica compositional trends are typical of those of ultramafic lamprophyres rather than kimberlites (Mitchell, 1995).

Notably **absent** from the dikes are: monticellite; micas belonging to the phlogopite-kinoshitalite solid solution series; abundant large perovskites; primary serpophitic serpentine, nepheline, melilite, kalsilite, plagioclase and amphibole.

On the basis of the above data and the currently accepted IUGS definition of archetypal (or group 1) kimberlite (Mitchell, 1995, 1997; Woolley *et al.*, 1996), it is clear that the rocks have no mineralogical affinity with archetypal kimberlite. However, their mineralogy and petrography is similar to that of mineralogically diverse ultramafic lamprophyric dikes associated with alkaline rock-carbonatite complexes which are currently termed aillikite (Rock, 1986), alnöite (Mitchell, 1995, 1997) or melnoite (Mitchell, 1994; Scott Smith, 1995). Many of these rocks are now considered by Mitchell (1994, 1995, 1997) to represent the lamprophyric hypabyssal facies of the melilitite clan. Dike rocks which are modally-poor in mica commonly contain more than 50 vol% dolomite and may thus be considered as carbonatites (sensu lato) on a modal basis. However, we wish to emphasize that such rocks are modally-gradational with the more mica-rich lamprophyric rocks.

Some of the Sarfartoq and Maniitsoq dikes differ from many ultramafic lamprophyres in containing abundant mantle-derived xenocrystal material and Mg-ilmenite microcrysts. It is these characteristics plus the high contents of magmatic carbonate that have, in part, led to them being termed kimberlites by Larsen (1980) on a simple petrographic basis. In particular, the presence of lherzolite-derived rounded olivine crystals imparts a macrocrystal texture which is superficially similar to that of *bona fide* kimberlite. However, the macrocrystal olivine itself is different from that in kimberlite in containing inclusions of ilmenite. These West Greenland lamprophyres provide a good example of petrographic convergence as described by Scott Smith (1995), who notes that "extreme" varieties of ultramafic lamprophyres (melnoites) and kimberlite are at first sight petrographically identical. It is only by applying mineralogical-genetic methods of classification to suites of samples that such rocks may be correctly characterized as to their true petrogenetic affinity.

Macro- and microcrystalline magnesian ilmenite is common in the West Greenland lamprophyres but is typically absent in other suites of ultramafic lamprophyres (e.g. Alnö; von Eckermann, 1948). Macrocrystal Mg-ilmenite is one of the characteristic "indicator" minerals of *bona fide* kimberlite, and the common presence of this phase in the West Greenland lamprophyres has been used to indicate the "kimberlitic" affinity of the suite. However, other members of the kimberlite macrocryst or discrete nodule suite, such as Ti-pyrope (G1-garnet) and subcalcic diopside are apparently absent at Sarfartoq and Sisimiut. Goff (1973) has noted the rare occurrence of "nodules" which appear to belong to the macrocryst suite in the Alanguarssuk dike in the Maniitsoq region, and described single examples of diopside-ilmenite, olivine-ilmenite, diopside-pyrope-ilmenite, pyrope-ilmenite and enstatite-olivine ilmenite nodules. Goff (1973) suggests that these and monocrystalline ilmenite nodules are the products of high pressure crystallization. Garnet macrocrysts are indeed present in some of the dikes from Sisimiut and Sarfartoq (Scott, 1981), G10 garnets are known but these are rare and the majority are principally lherzolite-derived Cr-pyrope (G9-garnet). Macrocrystal garnets, including G10-types, are relatively more abundant in the Maniitsoq suit. However, Goff (1973) and Larsen and Rønsbo (1993) have noted that these are predominantly of eclogitic or lherzolite parentage and are thus true xenocrysts.

Detailed discussion of the origins of magnesian ilmenite macro/microcrysts in kimberlite and other mantle-derived rocks is beyond the scope of this work. Reviews may be found in Mitchell (1986, 1995). Textural relationships clearly indicate that the spinel-mantled, magnesian ilmenite microcrysts did not crystallise from the magma which formed their current hosts and thus they must have been transported from depth. Unfortunately, whether they are phenocrysts or xenocrysts cannot be unambiguously determined. Evidence against a xenocrystal origin is the relative paucity of magnesian ilmenite in ultramafic xenoliths occurring in these rocks (Goff, 1973; Larsen and Rønsbo, 1993; Garrit *et al.*, 1995). However, xenocrystal ilmenite could also be derived from other mantle-derived precursors unrelated to lherzolite (Hops *et al.*, 1992). Evidence in favour of a cognate origin is the common occurrence of similar ilmenite in basanitic rocks e.g. Tahalra (Leblanc *et al.*, 1982), Bamenda-Bambouto (Parfenoff, 1982), Armidale (Binns, 1969), or melilitites (alnöite) from Malaita (Nixon and Boyd, 1979). Experimental data (Green and Sobolev, 1975) also support the concept that magnesian ilmenite can be a high pressure liquidus phase in basanitic magmas. Currently, we consider magnesian ilmenite to be a high pressure liquidus phase. This may form monomineralic cumulates and crystallize contemporaneously with olivine. Magma mixing and cumulate disruption would give rise to the diverse population of ilmenite microcrysts found in these rocks. The presence of magnesian ilmenite in the West Greenland ultramafic lamprophyre suite is considered to be related to the greater depth of origin (see below) of their parental magmas relative to most other ultramafic lamprophyre suites.

8. DISCUSSION

It has been shown above that the West Greenland ultramafic dikes are not kimberlites and are better described as **aillikites** (*sensu* Rock, 1986) or **melnoites** (sensu Mitchell, 1994; Scott Smith, 1995). Many associated rocks may be described as **carbonatites** (*sensu lato*) and there appears to be a complete modal gradation between these and mica-rich aillikites. The apparent absence of melilite or its alteration products precludes terming any of the rocks alnöite.

Melilite-free, (and melilite-bearing rocks), which are mineralogically similar to the West Greenland rocks are typically associated with melilititic magmatism and form lamprophyric facies hypabyssal intrusions e.g. Alnö, Sweden (von Eckermann, 1948); Plounice, Czech Republic (Ulrych *et al.*, 1988). Consequently, it is not unreasonable to suggest that the magmas which formed the West Greenland dikes are either in some manner related to the melilitite clan or derived from similar mantle sources. In support of this contention is the fact that West Greenland ultramafic lamprophyres and diverse melilitites have similar initial Sr and Nd isotopic compositions, indicating both were derived from similar long-term light-REE-depleted mantle sources (Nelson, 1989; Wilson *et al.*, 1995). Interestingly, the isotopic composition of archetypal kimberlite (Smith, 1983) is similar to that of the West Greenland rocks and melilitites, suggesting similar asthenospheric sources at least with respect to their Rb/Sr and Sm/Nd ratios. Mantle sources with these isotopic characteristics are currently considered to be located in the asthenosphere (Smith, 1983).

The high dolomite content and silica-undersaturated nature of the Greenland lamprophyres suggests that the asthenospheric source region of the parental magmas was a carbonated phlogopite lherzolite (Canil and Scarfe, 1990). Limited, but variable degrees, of partial melting of such a source could, in part, give rise to the spectrum of lamprophyre-carbonatite dikes found in West Greenland. This conclusion is in agreement with the experimental studies of Dalton and Presnall (1997, 1998) who show that a spectrum of melts ranging from "carbonatitic" to "kimberlitic" (sensu lato) can be produced by the partial melting (0-1 %) of carbonated lherzolite at 6 GPa. To account for the absence of *bona fide* kimberlites (or melilitites) in this region the partial melting process must have been terminated before such relatively silica-rich melts could be generated. Partial melting must have occurred at temperatures close to the solidus and involved principally the low-melting point phases magnesite and phlogopite. It is important to note that the West Greenland lamprophyres cannot represent late differentiates of a melilititic magma as they have the mineralogical (this work) and geochemical (Scott, 1981) characteristics of unevolved magmas.

Larsen and Rex (1992), have previously noted that the three geographically distinct fields are consanguineous and comprise a 270 x 100 km alkaline province, and suggest that regional compositional differences are indicative of a lithospheric imprint. This is undoubtedly correct with respect to the lithospheric xenolith suite (see below). However, the overall modal, and hence compositional, variations evident in the West Greenland lamprophyres undoubtedly result from a combination of differing degrees of partial melting, lithospheric mantle contamination, high pressure crystallization and magma mixing, together with limited low pressure differentiation. Consequently, whole rock bulk compositions *cannot* represent parental magma compositions, even though they may retain an unevolved geochemical signature.

The nature of the lithospheric mantle xenoliths, and the presence of subcalcic Cr-pyrope xenocrysts and diamond clearly demonstrates that the magmas have undergone variable degrees of lithospheric mantle contamination. Data presented by Goff (1973), Scott Smith (1987), Larsen and Rønsbo (1993) and Garrit *et al.* (1995), suggest that the source depths and amounts of lithospheric mantle-derived components appear to increase southwards from Sisimiut to Maniitsoq. Thus, Sisimiut magmas have only sampled dunites and lherzolites derived from depths of less than 120 km but no diamond-bearing harzburgitic material, whereas Sarfartoq magmas have sampled lherzolites, dunites, wehrlites and rare sub-calcic Cr-pyrope-bearing harzburgite and diamond derived from depths of up to 180 km. In contrast, Maniitsoq dikes contain abundant lherzolite and harzburgite, G10-garnet and diamond derived from depths up to at least 220 km. Given that these West Greenland asthenosphere-derived magmas sample the available overlying lithosphere during their ascent we suggest, on the basis of these data, that the lithosphere-asthenosphere boundary increases in depth from the Sisimiut area towards Maniitsoq. Accordingly, magmas passing through the deeper parts of the craton in the Maniitsoq region should have the greater potential for sampling diamond-bearing material.

The presence of diamond in these rocks must reflect the deeper sources of their parental magmas relative to those of most ultramafic lamprophyres. Mitchell (1995) has noted that there probably exists a spectrum of asthenosphere-derived carbonated ultrabasic magmas which are produced from carbonated phlogopite lherzolite sources. Depending upon the depth and degree of partial melting these may range in composition from kimberlite to melilitite. As these magmas are derived from the asthenosphere there is no *a priori* reason why they should not intersect and disrupt diamond-bearing lithospheric mantle during their ascent, e.g. the diamond-bearing melilitites of the north-eastern flank of the Anabar craton (Mitchell, 1995).

The following model is proposed for the genesis of the West Greenland lamprophyres. Variable, but low degrees (<2 %) of partial melting of carbonated phlogopite lherzolite at pressures of 5-6 GPa gives rise to carbonated aluminous ultrabasic magma of variable composition over a broad region of the asthenosphere. Individual batches of magma will be highly fluid and may or may not coalesce during ascent from their source regions. Ascending magmas interact with the lithospheric mantle entraining and disrupting garnet lherzolite. This material is mechanically sorted and/or assimilated. Diamond-bearing horizons are also intersected at this stage of ascent. During further ascent, primary olivine and magnesian ilmenite begin to crystallize as primary liquidus phases. In some instances pooling or flow differentiation of magma leads to the formation of "cumulates" of olivine or ilmenite and other cognate high pressure phases. These "cumulates" are disrupted by other batches of magma resulting in further hybridization and magma mixing. Ascent into the crust is accompanied by olivine and phlogopite crystallization together with flow differentiation and mica concentration or depletion in a given batch of magma. Emplacement in the crust is controlled by the local structure (Larsen and Rex, 1992) and the hybridized-contaminated magma crystallises as low temperature (approx. 600 °C) hypabyssal intrusions at pressures of 2-4 kb (Thy *et al.*, 1987). Primary liquidus phases at this stage crystallized in the sequence; phlogopite, spinel, apatite, and dolomite.

The conclusion that the spectrum of ultramafic lamprophyres found in West Greenland represents a primary partial melting sequence has also been advanced by Dalton and Presnall (1998). Regardless that these authors, following the terminology of Larsen and Rex (1992), refer to the rocks as "kimberlite", it is encouraging to note that similar conclusions regarding their petrogenesis have now been reached on the basis of experimental (Dalton and Presnall, 1998) and mineralogical (this work) studies.

The Sarfartoq carbonatite is undoubtedly cogenetic with the regional dike swarm and merely represents a larger batch of the same type of magma formed by the smallest degrees of partial melting. Thus, Dalton and Presnall (1998) consider that it represents a carbonatite-like solidus melt. This hypothesis explains the absence of silicate rocks in this complex and the fact that the dominant carbonatite lithology is dolomitic carbonatite (hematite-dolomite carbonatite or rauhaugite). This conclusion is in agreement with the contentions of Harmer and Gittins (1997) that dolomitic carbonatites are primary mantle-derived magmas formed by the partial melting of carbonated mantle peridotite.

In summary, the ultrabasic dikes of the Sarfartoq, Sisimiut and Maniitsoq regions are considered to be ultramafic lamprophyres (aillikites or melnoites) and not archetypal kimberlites. They represent a series of consanguineous partial melts derived from an asthenospheric carbonated phlogopite lherzolite source. The province represents one of the few *bona fide* examples of ultramafic lamprophyre which contains diamonds. However, the question of whether or not similar rocks of economic significance may be found in this region remains unresolved. A further interesting aspect of the central West Greenland alkaline province is that *bona fide* kimberlites do not appear to be present. Resolution of this question is beyond the scope of this work but must be related to character and thermotectonic history of the asthenosphere below West Greenland.

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