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Post-crystallisation modification of the igneous layering in the Nunarssuit and West Kûngnât syenites, South Greenland[1]

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Abstract

The chemistry and textures of the minerals in the layered syenites of Nunarssuit and West Kûngnât record a complex post-crystallisation history. The initial cumulus phases were alkali feldspar, pyroxene and olivine, apatite and opaque oxides. Grain size distributions of the pyroxenes and olivines have been modified since crystallisation, possibly during transport of these grains in a density current, prior to deposition in layers. Olivines and pyroxenes re-equilibrated with intercumulus melt. The lower ratio of mafic phases to intercumulus fluid in leucocratic layers has resulted in pyroxene and olivine in these layers undergoing more re-equilibration that in melanocratic layers, consequently pyroxenes and olivines in leucocratic layers are more ferroan. Pyroxenes reacted with either intercumulus or deuteric fluid to form amphibole. In West Kûngnât pyroxene and amphibole re-equilibrated via a later fluid. Olivines reacted with deuteric fluid to produce biotites, probably at temperatures < 550°C. After crystallisation alkali feldspars exsolved, the exsolution textures coarsened in the presence of deuteric fluids with a magmatic origin, possibly at temperatures as low as 450°C. Zoning patterns of apatites and zircons were modified during interactions with either, or both intercumulus or deuteric fluids. Leucocratic layers underwent more modification than melanocratic ones, probably due to the higher concentration of intercumulus melt in the former leading to a higher concentration of deuteric fluids as water exsolved from the magma during cooling. The syenites underwent little compaction during solidification.

KEYWORDS: syenites, subsolidus, fluids, igneous layering, Gardar, Greenland.

Introduction

THE Nunarssuit and West Kûngnât syenites are part of the Gardar alkaline province in South Greenland (Fig. 1). Reviews of the regional geology of the province have been published by Upton (1974), Emeleus and Upton (1976) and Upton and Emeleus (1987). The province is of note because of the wide variety of igneous layering phenomena which may be observed there (Ferguson and Pulvertaft, 1963;

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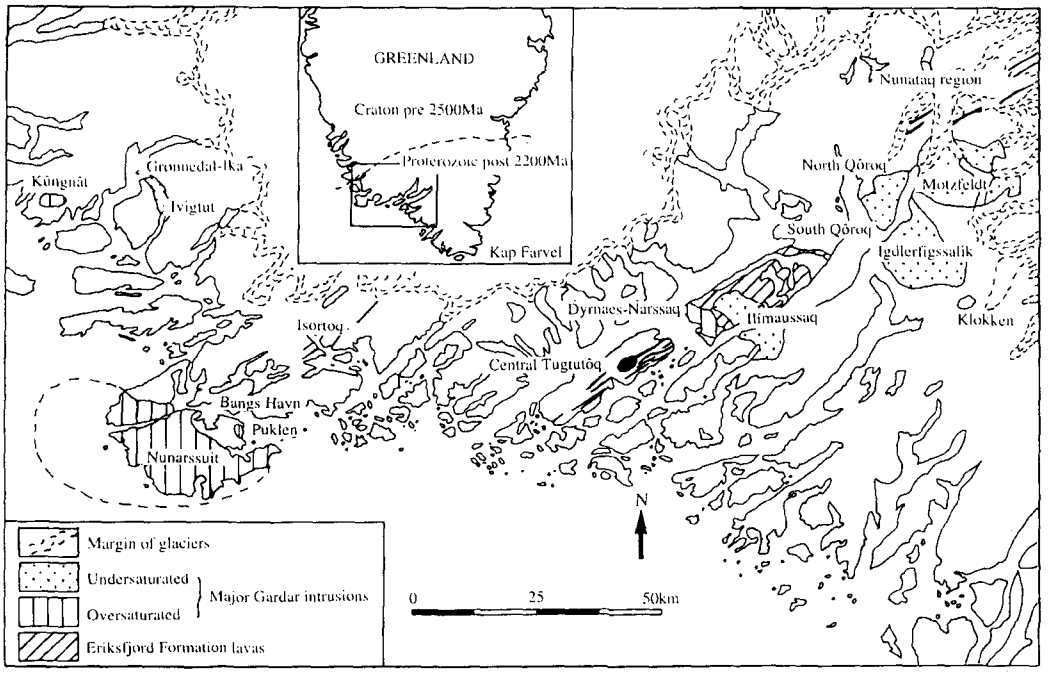

FIG. 1. Simplified geological map of south Greenland showing Gardar intrusions (after Emeleus and Upton, 1976).

papers in Parsons, 1987, Upton *et al.*, 1996). The Nunarssuit syenite was intruded 1154 ± 14 Ma BP (Rb-Sr date, Blaxland *et al.*, 1978), is at least 45 km by 25 km in areal extent and is part of a larger complex comprising the Alángorssuaq gabbro, Kitsigut syenite, main granites, Nunarssuit syenites and late granites. The West Kûngnât syenite was intruded 1245 ± 17 Ma BP (Rb-Sr date, Emeleus and Upton, 1976), is roughly circular in outcrop with a diameter of 1 km and is part of a small complex consisting of a marginal syenite unit, the intersecting cylindrical stocks of the West and East syenites and a near complete ring dyke of troctolite and syeno-gabbro.

Rhythmic modal layering is present in both the Nunarssuit and West Kûngnât syenites. Typically the layers are about 20 cm thick, consisting of a sharply defined melanocratic base rich in pyroxene, olivine and opaque oxides and sulphides which grades, over a few centimetres, into a more feldspathic layer. There is no universally accepted theory which explains how these layers form (Irvine, 1987*a*). Some theories suggest that the layers form essentially *in situ* (e.g. McBirney and Noyes, 1979) whilst others suggest that the layers consist of crystals that formed elsewhere in the magma chamber and were transported to their final resting place by currents (e.g. Irvine, 1987*b*). An understanding of how these layers formed would contribute significantly to our knowledge of magma chamber processes. In determining the mechanisms involved in forming the layers it is necessary to determine which characteristics of the layers are primary features and which are secondary, imposed on the crystals after layers had formed.

Diagenesis has been acknowledged for many years as a major process effecting the textures and composition of sedimentary rocks; diagenetic processes include compaction, recrystallisation, dissolution, replacement, authigenesis (development in place during or after deposition) and cementation. Diagenesis occurs at low temperatures but there is a continuum between diagenetic and metamorphic processes. In recent years many authors (Parsons and Brown, 1984; Boudreau, 1987; Hunter, 1987) have drawn attention to the processes that affect minerals in igneous rocks after they have crystallised. Parsons and Brown (1984) recognised three stages in the history of igneous rocks: (1) magmatic growth; (2) subsolidus transformation; (3) deuteric alteration, often involving a fluid. The deuteric stage is restricted to alteration that does not involve large amounts of water introduced from outside (i.e. hydrothermal alteration) which may occur subse-

quently. The subsolidus and deuteric stages are analogous to diagenesis in sedimentary rocks and it is this chapter of the history of the layered rocks of the Nunarssuit and West Kûngnât syenites that the present paper addresses.

First the petrography of the samples is described. The petrography and mineral chemistry are then interpreted in terms of post-crystallisation modification. Following this, the grain size distribution of the samples and evidence for compaction in the samples are considered. Finally suggestions are made as to what type of fluid(s) the rocks have interacted with and at what stage in the geological history of the rocks this interaction occurred.

Petrography of the layered syenites

The layered syenites from Nunarssuit and West Kûngnât may be texturally described as 'meso-cumulates' (after the definition of Irvine, 1982). Cumulate phases are; alkali feldspar, pyroxene, olivine (olivine is relatively rare in the West Kûngnât syenites), opaque minerals and apatite. Feldspar is also found in an intercumulate texture. Although some biotite and amphibole may be intercumulus in origin it is likely that the majority was produced in the subsolidus. Representative mineral analyses are shown in Tables 1 (Nunarssuit) and 2 (West Kûngnât). Additional analyses are given in Hodson and Finch (1997) and Hodson (1994).

Feldspars are present as millimetre-scale hypidiomorphic crystals in the majority of the syenites. In mafic cumulate autoliths and in some trough structures feldspars are present only as sub-millimetre allotriomorphic crystals. Feldspars often mantle the smaller pyroxenes and olivines. Within melanocratic samples the majority of the feldspars are film perthites with coarser lamellae at grain rims. The proportion of patch perthite increases in more leucocratic samples. Feldspars from West Kûngnât samples have a higher proportion of patch perthite than samples from Nunarssuit with a similar content of mafic phases.

Pyroxenes are present as small (1 mm × 0.5 mm) sub-idiomorphic crystals. No regular chemical zoning has been observed although grains can show an irregular zoning, expressed as pale brown cores grading to pale green rims. Pyroxene grains sometimes show alteration to a brown/green pleochroic amphibole. The frequency of this alteration is higher in leucocratic samples than in melanocratic samples. Pyroxene alteration is more common in West Kûngnât than it is in Nunarssuit.

Olivines are present as small (*c.* 0.5 mm) rounded grains. No zoning has been observed. Olivines are fresh in the more melanocratic samples but in the more leucocratic samples they are heavily altered to iddingsite. Alteration of olivines is more common in West Kûngnât than it is in Nunarssuit.

Apatite occurs ubiquitously as sub-millimetre scale inclusions in all the other phases present. No zoning was detected optically but cathodoluminescence and back scattered electron images revealed a variety of zoning styles.

Opaque minerals including ilmenite, magnetite and chalcopyrite occur as either large anhedral grains within feldspar or small, subhedral grains within pyroxene and olivine. Pentlandite has been reported from the Kûngnât syenite (Upton, 1960).

Amphibole occurs predominantly as irregular patches within pyroxene grains and is interpreted as an alteration product. These patches range from forming less than 5% of the area of the pyroxene crystal to occupy over 90% of the crystal. In leucocratic samples from Nunarssuit a small number of millimetre-scale angular amphibole grains occupy interstitial positions between feldspars. These amphiboles may be postcumulus. In one locality in West Kûngnât amphiboles occur as large centimetre-scale oikocrysts within trough structures (Hodson, 1994, and Hodson and Finch, 1997). These amphiboles contain patches of olivine, pyroxene, biotite, opaque minerals and numerous apatite crystals and are thought to have crystallised shortly after the cumulus phases as a postcumulus phase. All the amphiboles have brown/green pleochroism and are irregularly zoned.

Biotite occurs predominantly as sub-millimetre crystals grouped together to form fringes on other crystals, usually magnetite and ilmenite grains. In leucocratic samples biotite also occurs as discrete angular, anhedral sub-millimetre crystals. Large centimetre-scale biotite oikocrysts are present in the trough structures of West Kûngnât (Hodson, 1994, and Hodson and Finch, 1997). The non-fringe biotites are irregularly zoned, the fringe biotites may also be irregularly zoned but crystals are on too small a scale for any zoning to be detected with an electron probe.

Trace amounts of titanite, calcite, zircon and quartz (Nunarssuit) are present. Intergrowths of low-temperature alteration products (chlorite and clay minerals) are present in leucocratic samples. These intergrowths often penetrate along the pleats at the rims of feldspars.

Interpretation of the petrography and mineral chemistry in terms of post-crystallisation modification

When interpreting the petrography and mineral chemistry, the simplest explanation which fits the observations has been sought. Thus whilst minerals may have reacted with a whole host of fluids, or

TABLE 1*a*. Representative elctron microprobe analyses of the major phases present in melanocratic layers from the Nunarssuit syenite

	Pyroxene		Olivine		Braid perthite		Biotite		Amphibole			Apatite	
SiO_2	48.37	48.70	29.46	29.27	66.01	66.16	35.40	34.90	43.86	44.14	SiO_2	0.92	0.45
TiO_2	0.74	0.37	0.04	0.06	–	–	10.97	10.93	4.63	4.23	P_2O_5	41.05	41.81
Al_2O_3	0.60	0.36	0.02	0.03	18.87	18.97	3.78	2.68	1.49	1.43	FeO	0.59	0.13
FeO	25.13	26.27	65.84	66.91	0.15	0.16	32.28	34.76	30.74	30.14	MnO	0.03	0.00
MnO	0.68	0.59	1.74	1.70	–	–	0.15	0.18	0.47	0.45	CaO	52.82	53.23
MgO	3.43	3.23	2.25	1.66	0.02	0.03	4.51	3.44	3.60	4.43	Na_2O	0.15	0.21
CaO	20.43	19.82	0.19	0.12	0.33	0.23	0.13	0.60	9.50	9.18	La_2O_3	0.46	0.50
Na_2O	0.53	0.63	–	–	6.53	6.89	0.03	0.34	2.21	2.39	Ce_2O_3	1.15	0.95
K_2O	0.00	0.00	–	–	7.44	7.14	8.81	6.50	1.04	1.05	Pr_2O_3	0.08	0.03
Cr_2O_3	0.01	0.02	0.02	0.00	–	–	0.02	0.01	0.00	0.02	Nd_2O_3	0.66	0.52
BaO	–	–	–	–	0.06	0.09	–	–	–	–	F	3.73	3.81
F	–	–	–	–	–	–	0.10	0.09	0.69	0.63	Cl	0.03	0.02
Total	99.93	100.00	99.56	99.73	99.40	99.66	96.17	94.43	98.22	98.06	Total	101.66	101.66

TABLE 1*b*. Representative electron microprobe analyses of the major phases present in leucocratic layers from the Nunarssuit syenite

	Pyroxene		Olivine		Braid perthite		Biotite		Amphibole			Apatite	
SiO_2	48.74	48.58	29.46	29.41	66.52	66.48	34.94	34.90	44.52	44.44	SiO_2	1.02	1.03
TiO_2	0.61	0.67	0.05	0.04	–	–	3.55	4.43	0.62	1.41	P_2O_5	40.21	41.86
Al_2O_3	0.52	0.67	0.01	0.01	18.81	18.66	10.76	10.52	4.29	4.33	FeO	0.28	0.56
FeO	25.10	24.61	66.35	66.28	0.15	0.18	33.06	34.34	31.52	29.65	MnO	0.06	0.01
MnO	0.66	0.70	1.81	1.66	–	–	0.14	0.16	0.47	0.50	CaO	52.23	52.72
MgO	3.66	3.97	2.16	1.90	0.02	0.01	4.05	1.67	3.66	4.56	Na_2O	0.22	0.19
CaO	20.57	19.75	0.14	0.14	0.20	0.12	1.23	0.05	9.26	9.74	La_2O_3	0.78	0.81
Na_2O	0.60	0.66	–	–	7.03	6.74	0.10	0.19	2.23	2.31	Ce_2O_3	1.75	1.59
K_2O	0.01	0.00	–	–	6.93	7.56	6.42	8.19	0.97	0.98	Pr_2O_3	0.20	0.11
Cr_2O_3	0.00	0.02	0.02	0.03	–	–	0.00	0.02	0.01	0.00	Nd_2O_3	0.81	0.69
BaO	–	–	–	–	0.05	0.21	–	–	–	–	F	3.82	3.40
F	–	–	–	–	–	–	0.28	0.09	0.70	0.67	Cl	0.01	0.01
Total	100.45	99.63	100.00	99.47	99.71	99.97	94.52	94.56	98.24	98.59	Total	101.38	102.98

TABLE 2*a*. Representative elctron microprobe analyses of the major phases present in melanocratic layers from the West Kungnat syenite

	Pyroxene		Olivine		Braid perthite	Biotite		Amphibole			Apatite	
SiO_2	49.83	48.13	29.35	28.54	65.84	34.09	33.73	39.54	43.54	SiO_2	0.33	1.51
TiO_2	0.14	0.54	0.08	0.08	–	4.71	3.42	3.25	1.16	P_2O_5	42.38	41.46
Al_2O_3	0.43	0.74	0.00	0.01	19.20	11.01	10.92	8.11	4.61	FeO	0.14	0.33
FeO	22.14	25.24	66.09	67.05	0.09	32.87	36.32	28.73	33.39	MnO	0.04	0.05
MnO	0.64	0.60	1.79	1.96	–	0.13	0.18	0.35	0.62	CaO	54.17	53.04
MgO	5.06	3.12	2.13	1.30	0.01	3.65	2.43	3.06	1.78	Na_2O	0.09	0.14
CaO	21.30	20.87	0.11	0.11	0.45	0.31	0.20	10.21	9.57	La_2O_3	0.29	0.43
Na_2O	0.46	0.50	–	–	6.85	0.30	0.12	2.39	2.46	Ce_2O_3	0.54	0.71
K_2O	0.01	0.01	–	–	6.93	8.00	8.22	1.38	0.82	Pr_2O_3	0.17	0.08
Cr_2O_3	0.00	0.04	0.01	0.00	–	0.03	0.00	0.03	0.02	Nd_2O_3	0.36	0.37
BaO	–	–	–	–	0.29	–	–	–	–	F	4.30	3.23
F	–	–	–	–	–	0.14	0.16	0.27	0.19	Cl	0.05	0.02
Total	100.02	99.78	99.56	99.05	99.66	95.23	95.70	97.31	98.15	Total	102.86	101.36

TABLE 2*b*. Representative elctron microprobe analyses of the major phases present in leucocratic layers from the West Kungnat syenite

	Pyroxene		Olivine		Braid perthite	Biotite		Amphibole			Apatite	
SiO_2	48.94	47.80	29.07	28.95	–	35.29	34.35	43.04	38.72	SiO_2	0.35	0.63
TiO_2	0.45	0.56	0.09	0.08	65.85	0.19	0.08	2.35	2.57	P_2O_5	42.18	41.37
Al_2O_3	0.69	0.70	0.00	0.02	19.07	10.75	10.36	5.46	8.03	FeO	0.26	0.21
FeO	23.53	25.78	66.27	67.72	0.09	32.74	35.21	31.00	30.52	MnO	0.01	0.02
MnO	0.63	0.67	2.06	2.06	–	0.17	0.19	0.51	0.46	CaO	54.49	53.89
MgO	4.01	2.89	1.78	1.04	0.02	4.29	2.53	3.09	1.82	Na_2O	0.13	0.09
CaO	20.55	20.63	0.13	0.16	0.36	0.10	0.02	9.71	10.46	La_2O_3	0.19	0.37
Na_2O	0.52	0.47	–	–	6.55	3.93	3.86	1.71	3.10	Ce_2O_3	0.66	0.88
K_2O	0.02	0.01	–	–	7.34	8.46	9.07	0.90	1.43	Pr_2O_3	0.18	0.05
Cr_2O_3	0.00	0.03	0.00	0.02	–	0.02	0.02	0.01	0.01	Nd_2O_3	0.40	0.38
BaO	–	–	–	–	0.08	–	–	–	–	F	3.28	4.18
F	–	–	–	–	–	0.32	0.44	0.16	0.23	Cl	0.02	0.01
Total	99.34	99.53	99.39	100.13	99.34	95.93	95.69	97.78	97.11	Total	102.14	102.09

formed via a string of reactions, such possibilities are only discussed if there is evidence that they occurred.

Feldspar

Hypersolvus feldspars are perhaps the mineral species that best illustrate subsolidus and deuteric alteration processes. At temperatures above the feldspar solvus a single homogeneous feldspar crystallises but as the temperature falls the solvus is crossed and the feldspar exsolves coherently producing sanidine- and albite-rich lamellae. By processes of coarsening (and simultaneous Si and Al ordering) a braid perthite is produced. This process can occur down to temperatures as low as 450°C (low microcline is present in the braid perthites observed at Klokken, another layered syenite body in the Gardar province, Parsons, 1979; Brown and Parsons, 1994). Below this temperature only deuteric processes modify the feldspar.

In the presence of deuteric fluids braid perthite may coarsen to produce incoherent or semi-coherent patch perthite; associated with this is the generation of micropores which give the feldspar a turbid appearance. Braid perthite sometimes coarsens at the edge of crystals to give 'pleated' rims; feldspar–feldspar grain boundaries develop 'swapped' rims (Smith and Brown, 1988, pp 603-604); these processes are thought to be linked to the passage of fluid along feldspar grain boundaries although the driving force may be the release of strain energy (Brown and Parsons, 1994). The formation of swapped rims, together with post-cumulus growth results in the loss of the original feldspar morphology. Formation of patch perthite involves dissolution and reprecipitation (Brown and Parsons, 1994) and oxygen isotopic exchange with the deuteric fluid is likely; in these circumstances the feldspars inherit the δO^{18} signature of the deuteric fluid.

Cathodoluminesence (CL) phenomena in feldspar have been used as a guide to subsolidus change in feldspars (e.g. Rae and Chambers, 1988; Finch and Walker, 1991). Pristine feldspars cathodoluminesce bright blue whilst feldspars that have interacted with a deuteric fluid luminesce red.

In both Nunarssuit and West Kûngnât feldspars have undergone more deuteric alteration in leucocratic samples than in melanocratic samples. This is seen by the relative proportion of turbid to non-turbid feldspar (Fig. 2); the more complex grain boundaries of feldspars in the leucocratic samples and the CL of the Nunarssuit feldspars (feldspars from all the samples in West Kûngnât luminesce red, Table 3). Oxygen isotope work carried out by previous workers and for the present study gives values of 4–7 ‰ δO^{18} for feldspars from both leucocratic and melanocratic samples which are consistent with juvenile fluids (Hodson, 1994).

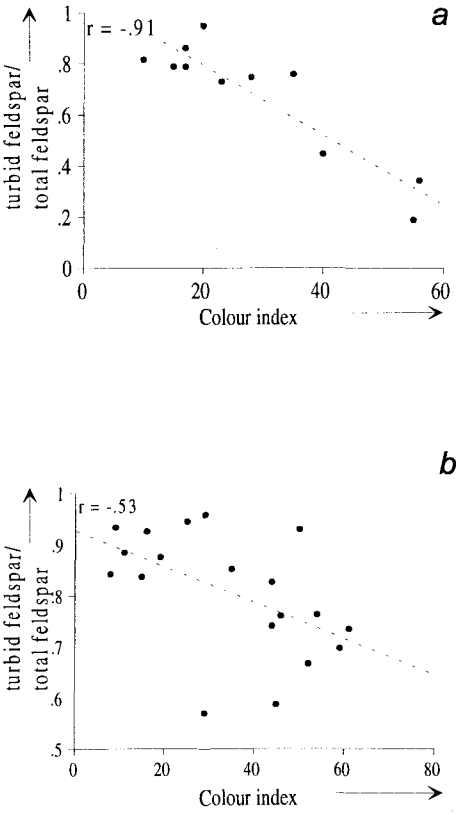

FIG. 2. Plot showing inverse correlation between colour index (= % vol mafic minerals in sample) and the proportion of feldspar in the sample which is turbid. *a*. Nunarssuit, *b*. West Kûngnât.

Pyroxene

The chemistry of the pyroxenes from Nunarssuit and West Kûngnât was affected by at least two different fluids following the crystallisation of the crystals.

Pyroxenes from the bases of layers are more magnesian than those from the overlying leucocratic portion of the layer (the differences in mean values are small but are statistically significant). This appears to be an example of the so called 'trapped liquid shift' (Barnes, 1986). According to this hypothesis minerals re-equilibrate with the surrounding liquid from which they have crystallised.

TABLE 3. Average feldspar luminescence indices (feldspar luminescence index is defined here as the ratio of non-sky blue luminescing feldspar to total feldspar) for different facies from the Nunarssuit and West Kûngnât layered syenites

Nunarssuit Facies	Average feldspar luminescence index	Relative alteration
Melanocratic base of layer at base of faintly layered syenite (Unit 2)	0.85	High
Melanocratic base of layer at top of clearly layered syenite (Unit 3)	0.60	Moderate
Lower thick melanocratic unit (Unit 5)	0.20	Low
Mafic syenite xenolith (from Unit 4)	0.20	Low
Homogeneous unlayered syenite (Unit 1)	0.92	High
Leucocratic portion of layer at base of faintly layered syenite (Unit 2)	0.93	High
Leucocratic portion of layer at top of clearly layered syenite (Unit 3)	0.94	High
West Kûngnât Facies	**Average feldspar luminescence index**	**Relative alteration**
Melanocratic base of layer	0.98	High
Leucocratic portion of layer	1.00	High
Trough stack syenite	0.83	High
Syenite surrounding trough stack	1.00	High

During crystallisation the intercumulus liquid surrounding the pyroxene grains is more ferroan than the grains. Re-equilibration occurs and the pyroxene grains become more ferroan. The melanocratic portions of layers were less porous and contained more pyroxenes than the over lying leucocratic portions of layers (Hodson, 1994). The combined effect of these two factors is that the pyroxenes in the leucocratic portions of layers underwent a greater degree of Fe enrichment during re-equilibration than pyroxenes from the melanocratic portions of layers.

Pyroxenes in the layered syenites frequently have irregular zoning involving enrichment in the acmite component, with accompanying depletion in the diopside and hedenbergite components, along crystal edges and cracks. Similar zoning was reported by Parsons and Brown (1988) in pyroxenes from the Klokken intrusion. It was suggested that the zoning was due to reactions similar to the one shown below involving peralkaline deuteric fluids; this zoning is seen most intensely in the leucocratic samples.

$$CaFe^{2+}Si_2O_6 + Na^{+}_{(aq)} \rightleftharpoons NaFe^{3+}Si_2O_6 + Ca^{2+}_{(aq)} + e^{-}_{(aq)} \quad (1)$$

Hedenbergite + sodium from the fluid $\rightleftharpoons$ acmite + calcium in the fluid

It is thought that the two chemical changes outlined above represent separate events involving intercumulus and deuteric fluid respectively. The alteration of pyroxenes to form amphiboles is discussed below; it is not known at what stage in the rocks history this alteration occurred.

Biotite

In most studies of the Nunarssuit and West Kûngnât syenites (Upton, 1960; Butterfield, 1980) biotites have been treated as a post-cumulus phase which grew out of the inter-cumulus fluid. Powell (1978) suggested, on textural grounds, that biotite was probably a subsolidus phase in the Igdlerfigssalik syenites. Oxygen fugacity in the Gardar syenites was

probably controlled by the QFM buffer (Butterfield, 1980; Parsons, 1981). Hewitt and Wones (1984) suggested that iron-rich biotites are only stable below 800°C at the QFM oxygen fugacity buffer and *c.* 2 kbar. Using their data Parsons *et al.* (1991) calculated temperatures of formation for similar biotites from the syenites of the Klokken intrusion and concluded that the biotites formed at *c.* 600°C, about 300°C subsolidus. Subsequently Dachs (1994) showed that Fe-rich biotites are only stable at temperatures below *c.* 550°C at the QFM buffer. The Nunarssuit and West Kûngnât syenites probably crystallised between 900 and 750°C (Hodson, 1994) and therefore the biotites, which are compositionally similar to those from the Klokken syenites, must have formed after the syenite solidified. Parsons *et al.* (1991) suggested two reactions that could be responsible for the production of biotite in the Klokken syenites:

$$KAlSi_3O_8 + Fe_3O_4 + 2H_2O + 2e^- \rightarrow KFe_3AlSi_3O_{10}(OH)_2 + 2OH^- \quad (2)$$

sanidine + magnetite + water → annite + oxygen

and

$$KAlSi_3O_8 + \tfrac{3}{2}Fe_2SiO_4 + H_2O \rightarrow KFe_3AlSi_3O_{10}(OH)_2 + \tfrac{3}{2}SiO_2 \quad (3)$$

sanidine + fayalite + water → annite + silica

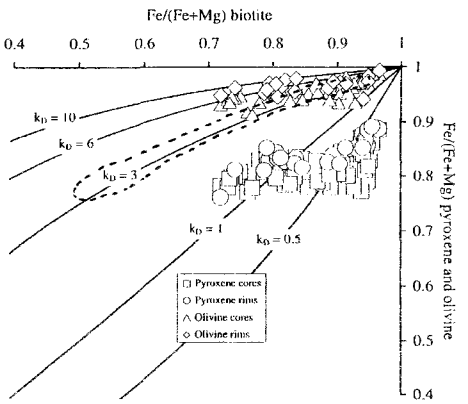

FIG. 3. Distribution of iron and magnesium between coexisting biotite and olivine or pyroxene for rocks from the West Kûngnât layered syenite. In Figures 3 to 6 all Fe is treated as Fe^{2+}, the pyroxenes contain less than 0.06 atoms of Fe^{3+} per 6 oxygens and the composition of the biotites prevent Fe^{3+} from being calculated, Droop, 1987. ($k_D = [(X^{Ol}_{Fe} \cdot X^{Biot}_{Mg})/(X^{Ol}_{Mg} \cdot X^{Biot}_{Fe})]$, where $X^{Ol}_{Fe} = [Fe/(Fe+Mg)]^{Olivine}$ etc.). Points are average values for individual rock samples. In Figs. 3 and 4 the dashed field represents the trend for Klokken from Parsons *et al.*, (1991).

For reaction (2) to be applicable to Mg-bearing biotites, other phases such as pyroxene would be required to participate in the reaction to provide magnesium.

Figures 3 and 4 are plots of Fe/(Fe+Mg) of biotite against Fe/(Fe+Mg) of coexisting pyroxene rims and cores and olivine rims and cores from the intrusions of West Kûngnât and Nunarssuit. Superimposed on this graph are k_D isopleths for the Fe–Mg partitioning between biotite and either olivine or pyroxene. For syenite samples from Klokken (Parsons *et al.*, 1991) plots of Fe/(Fe+Mg) of biotite against Fe/(Fe+Mg) of olivine fit a curve consistent with a constant k_D approximately equal to 3.02. Parsons *et al.* (1991) argued that this was good evidence for reaction (3) being the dominant biotite producing reaction in the Klokken syenites. The biotites and coexisting olivines and pyroxenes from the Nunarssuit and West Kûngnât syenite show a less exact relationship; however, the biotite–olivine data plot more closely along the isopleths than the biotite–pyroxene data. There is less scatter in the olivine rim data than in the olivine core data for Nunarssuit. The reason for the less exact relationship for Nunarssuit and West Kûngnât compared to Klokken may be due to the fact that data on biotites in gabbros were also plotted for Klokken which constrains the magnesian part of the curve. It seems likely that a reaction in the subsolidus involving olivine as a major reagent was responsible for the formation of biotite in Nunarssuit and West Kûngnât.

This interpretation, based on mineral chemistry, contradicts the textural interpretation that the large biotite oikocrysts in the trough stacks of West Kûngnât are postcumulus, not subsolidus (Hodson,

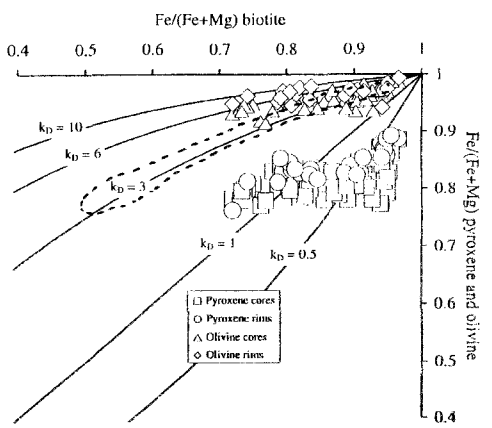

FIG. 4. Distribution of iron and magnesium between coexisting biotite and olivine or pyroxene for rocks from the Nunarssuit layered syenite.

1994, and Hodson and Finch, in press). Also, it may have been expected that the fringe biotite found on opaque phases was produced in a reaction between those phases and fluid. It has been hypothesised that the initial composition of the oikocrysts in the trough stacks of West Kûngnât was modified by subsolidus fluids (see below and also Hodson and Finch, 1997) so in this case, textural evidence may be more reliable than chemical evidence. With regard to the biotites fringing opaque minerals, the inexact fit of the data to isopleths in Figs 3 and 4 indicates that phases other than olivine and pyroxene were probably involved in the biotite producing reactions, opaque minerals are another obvious source of the Fe and Mg present in biotite. However, the fact that one mineral mantles another does not mean that the mantling mineral formed from the mineral it is in contact with. The biotite may have preferentially nucleated on the opaque phases whilst being in equilibrium with olivine grains via a fluid.

It has been suggested that the halogen activity of the fluid that biotite last equilibrated with may be calculated from a consideration of biotite composition (Munoz, 1984). However, more recent work (Parsons *et al.*, 1991; Zhu and Sverjensky, 1992; Finch *et al.*, 1995) has called into question the equations used for this calculation and therefore no attempt was made to apply the equations in this study. Finch *et al.* (1995) calculated 'maximum fluorine lines' (maximum fluorine content for a given Fe/(Fe+Mg) ratio) for biotites from eight Gardar intrusions and, from a quantitative interpretation of these lines, drew conclusions about the composition of the fluid which had interacted with the rocks. It is pertinent here to note here that whilst Nunarssuit, like six of the other seven intrusions considered, showed a trend of increasing F with decreasing Fe/(Fe+Mg), the F content of biotites from West Kûngnât had a relatively constant F content for a range of Fe/(Fe+Mg) values. This was interpreted as being due to the relatively high Cl content of the West Kûngnât biotites (reflecting a relatively high Cl content in fluids with which the biotite was in equilibrium).

Amphibole

The majority of the amphiboles in Nunarssuit and West Kûngnât are present as irregular shaped patches replacing pyroxene and they are interpreted as forming by the modification of the pyroxene. A less common mode of occurrence is between large feldspar grains as triangular patches, almost as if filling pores between the surrounding crystals. No chemical difference was found between the amphiboles in the two different textures.

Following the methodology of Parsons *et al.* (1991), plots of the ratio Fe/(Fe+Mg) in amphiboles against Fe/(Fe+Mg) in pyroxenes have been produced, with k_D isopleths superimposed on them. Plots for amphiboles and pyroxene rims from West Kûngnât (Fig. 5) define a trend which lies between the lines $k_D = 1$ and $k_D = 0.5$. Plots for the amphiboles and pyroxenes of Nunarssuit (Fig. 6) do not plot on lines of constant k_D.

One possible interpretatin of the West Kûngnât plot is that pyroxene was involved in the reaction which generated amphibole, and that Fe and Mg mixed ideally in the two phases. The fact that the

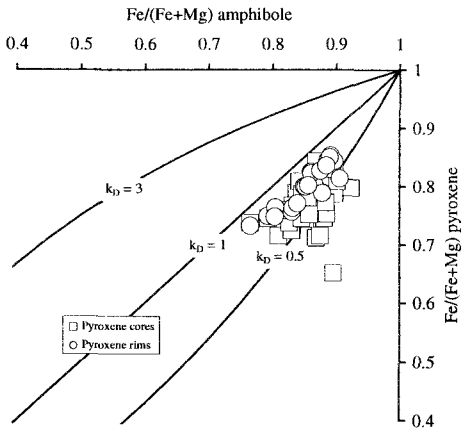

FIG. 5. Distribution of iron and magnesium between coexisting amphibole and pyroxene for rocks from the layered syenite of West Kûngnât.

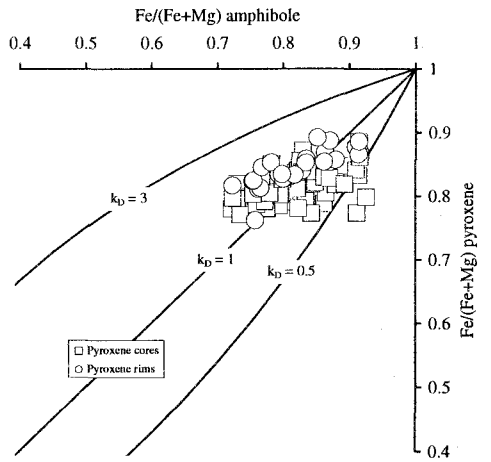

FIG. 6. Distribution of iron and magnesium between coexisting amphibole and pyroxene for rocks from the Nunarssuit layered syenite.

plots lie closer to lines of constant k_D when rim compositions of pyroxenes are used rather than cores may imply that the rims of pyroxenes reacted to produce the amphiboles and that the cores of pyroxenes were less involved in the reaction. Thus amphibole formation may have followed on from the reaction which caused an increase in the sodium and a decrease in calcium content of the pyroxenes (reaction (1)) together with a reaction involving the removal of Si and the addition of Al to the pyroxene. An alternative explanation is that, subsequent to amphibole formation, the pyroxene rims and amphiboles re-equilibrated with a later fluid though there is no textural evidence that this occurred.

The differences between the West Kûngnât and Nunarssuit plots can be interpreted in a number of ways. The reaction which produced the amphiboles in Nunarssuit may have involved Fe- and Mg-bearing phases other than pyroxene, but this seems unlikely. Chemical variation in the pyroxenes from Nunarssuit is reflected in the chemical variation of the amphiboles (Hodson, 1994). For example, pyroxenes and amphiboles from the lower part of the layered succession are the most sodic and samples with the most magnesian pyroxenes also contain the most magnesian amphiboles. Such trends are not seen in the compositions of olivine and the opaque oxides, the other primary mafic phases in the syenites. It thus seems likely that pyroxene was the dominant phase in the amphibole producing reaction. It is possible that the mixing of Fe and Mg in the Nunarssuit amphiboles and pyroxenes is non-ideal whilst in West Kûngnât it is ideal. However, given the similarities in the compositions of the pyroxenes and amphiboles from the two intrusions, this seems unlikely.

A more plausible possibility is that, subsequent to the formation of the amphibole, the pyroxenes and amphiboles from West Kûngnât re-equilibrated via another fluid. This suggestion is in agreement with the observation that the Nunarssuit syenites underwent less subsolidus alteration than those of West Kûngnât

It is not possible to state categorically whether the amphiboles grew in the presence of intercumulus melt or a subsolidus deuteric fluid. The amphiboles would have been stable at around 700°C (Gilbert *et al.*, 1982), the lower end of the estimated crystallisation temperature of the syenites. Most of the amphiboles have compositions which lie on the primary magmatic amphibole trend of Mitchell (1990). However, this corresponds to the magmatic/subsolidus trend of Strong and Taylor (1984). The textural evidence of the angular amphiboles between feldspar grains indicates growth from the intercumulus fluid. The replacement of pyroxene by amphibole indicated by the dominant mode of the occurrence of the amphibole could have occurred in the presence of intercumulus melt or a deuteric fluid.

Apatite

The apatites in the Nunarssuit and West Kûngnât syenites are fluorapatites. No halogen zoning was detected. Only trace amounts of Cl were present in the apatites analysed for this study. Fluorine contents are relatively high (2.5–5.2%) but within the precision of the analyses made ($\pm$ 0.65% at the 2σ level) variation was negligible both within individual crystals and between crystals. Zoning, when present, was confined to Ca, P, *REE*, Si and Na. Generally the Ca and P content of the apatites decreased from the centre of the grains to the edge.

Finch (1990) defined a number of zoning styles exhibited by apatites (Fig. 7), his scheme is also applicable to the apatites from Nunarssuit and West Kûngnât. Bouch *et al.* (1996) observed sector-zoned apatites in sandstones, where the sector zoning is present in diagenetic overgrowths. No sector zoning was observed in the present study. The apatites in this study are interpreted as being primary and the zoning is thought to represent either primary zoning, or a modification of that zoning due to exchange reactions with late-stage fluids. Concentric and fracture zoning observed in CL or back scattered electron images are

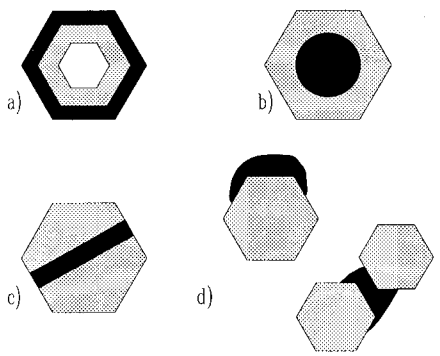

FIG. 7. Apatite zoning classification scheme. a: Oscillatory, primary magmatic zoning; b: Irregular, concentric zoning, produced by post-crystallisation modification by fluids; c: Fracture zoning produced by the percolation of fluids along cracks; d: Overgrowth produced by precipitation of apatite after crystallisation of primary grains, may occur in magma or subsequent to solidification. Chaotic zoning (not figured) is either a complex superposition of many types of zoning pattern or irregular dissolution and reprecipitation. After Finch (1990).

produced by the action of late-stage fluids on the apatite. The exchange reactions which are thought to occur between apatite and fluid are well documented (e.g. Finch, 1990; Rae *et al.*, 1996), examples are shown below:

$$2Ca^{2+}_{(s)} \rightleftharpoons REE^{3+}_{(aq)} + Na^{+}_{(aq)} \quad (4)$$

$$Ca^{2+}_{(s)} + P^{5+}_{(s)} \rightleftharpoons REE^{3+}_{(aq)} + Si^{4+}_{(aq)} \quad (5)$$

Exchange reactions appear to have been more prevalent in the Nunarssuit apatites than in those from West Kûngnât (Fig. 8.) Reaction (5) appears to have been dominant in the apatites from both Nunarssuit and Kungnat (Fig. 8a). This trend was also observed by Rae *et al.* (1996) for the North Qôroq syenites. As with the North Qôroq syenites there is minor scatter in this trend and analyses lie marginally below the 1:1 line. This suggests that other substitutions do occur. As can be seen from Fig. 8*b*, if reaction (4) has occurred it must have been relatively minor as scatter about the 1:1 line is marked. Other possible substitutions, as listed by Rae *et al.* (1996) are:

$$3Ca^{2+}_{(s)} \rightleftharpoons 2REE^{3+}_{(aq)} + \text{vacancy} \quad (6)$$

$$Ca^{2+}_{(s)} + P^{5+}_{(s)} \rightleftharpoons Fe^{3+}_{(aq)} + Si^{4+}_{(aq)} \quad (7)$$

Apatites which are unzoned or show oscillatory zoning are believed to have been unaffected by late-stage fluids (Finch, 1990). However, it is possible that unzoned apatites have been modified by late-stage fluids, with the apatites loosing any trace of zoning. Thus apatite zoning patterns are not as definitive as feldspar microstructures for determining the extent of rock–fluid interactions. In Nunarssuit a higher proportion of apatites are unzoned or preserve oscillatory zoning in melanocratic samples than in leucocratic samples whilst in West Kûngnât there is no systematic variation (Table 4). The proportion of unzoned plus oscillatory zoned apatites in West Kûngnât syenites is greater than in Nunarssuit, indicating that the Nunarssuit syenites have been exposed to more late-stage fluid than the West Kûngnât syenites. Whilst this conclusion is in agreement with that drawn from Fig. 8. it contradicts conclusions drawn on the basis of the degree of modification of feldspars, pyroxenes and olivines. However the Nunarssuit apatites generally preserve a higher proportion of oscillatory zoning than those from West Kûngnât. If only oscillatory and concentrically zoned apatites are considered it is concluded that the Nunarssuit syenites have been exposed to less late-stage fluid than the West Kûngnât syenites, a conclusion in agreement with that reached from a consideration of feldspar, pyroxene and olivine textures. The apatites within the large biotites and amphiboles in the trough stacks

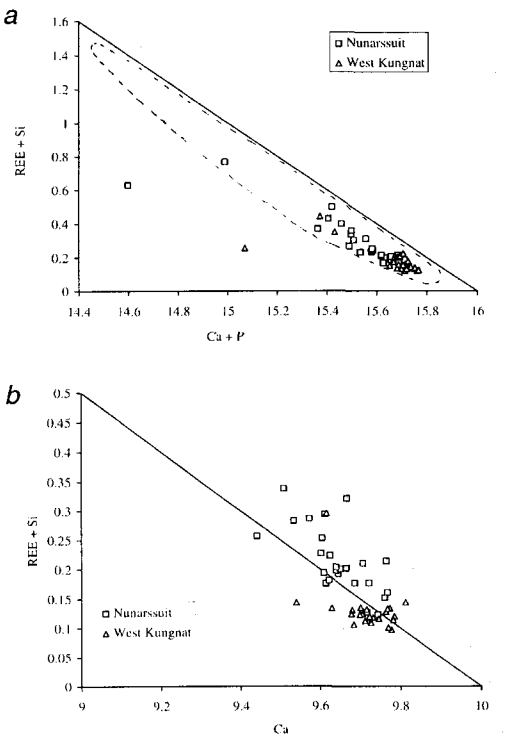

FIG. 8. Rare-earth element substitution in Nunarssuit and West Kûngnât apatites. Axes are plotted in cations per formula unit. (*a*) the line on the diagram represents the ideal substitution $Ca^{2+} + P^{5+} \rightleftharpoons REE^{3+} + Si^{4+}$. The dashed field represents the trend from Rae *et al*, 1996. (*b*) the line on the diagram represents the ideal substitution $2Ca^{2+} \rightleftharpoons Na^{+} + REE^{3+}$

of West Kûngnât exhibit more concentric zoning than those outside. This suggests that the apatites within these oikocrysts experienced more fluid than those in the surrounding syenite. For this reason it is felt that the primary chemical composition of these amphiboles and biotites has been altered by interaction with subsolidus fluids so that the chemistry of these phases indicates a subsolidus origin whilst the texture indicates a postcumulus origin (see Hodson and Finch, 1997).

Magnetite — ulvöspinel and zircon

At magmatic temperatures magnetite-ulvöspinel crystallises as a single Fe-Ti oxide phase, but, as the temperature falls a solvus is crossed at about 600°C and ulvöspinel exsolves from the magnetite. Various geometries of exsolution exist: trellis and

TABLE 4. Average % of zoning styles in apatites from different facies of the Nunarssuit and West Kûngnât layered syenites

Nunarssuit Facies	Oscillatory (Fig. 7*a*)	Concentric (Fig. 7*b*)	Fracture (Fig. 7*c*)	No zoning
Melanocratic base of layer (Unit 3)	14	18	2	66
Leucocratic portion of layer (Unit 3)	5	25	1	69
Thick melanocratic unit (Unit 5)	18	18	3	61
West Kûngnât Facies				
Trough stack	7	3	1	87
Large amphiboles and biotites within trough stacks	7	25	0	68
Syenite surrounding trough stacks	4	7	0	89
Melanocratic base of layer	4	12	3	81
Leucocratic portion of layer	7	12	3	78

sandwich intergrowths and granular exsolution (Buddington and Lindsley, 1964). Buddington and Lindsley (1964) demonstrated that granular exsolution occurs in titanomagnetites which have been more extensively deuterically altered than those which exhibit trellis and sandwich intergrowths.

Magnetite occurs rarely in the syenites of Nunarssuit and West Kûngnât. Whenever it is present it shows either trellis or sandwich intergrowths. No granular exsolution has been observed in magnetites from the layered series of the two intrusions.

Zoning in zircons may be observed using both Back-Scattered Electron imaging or cathodoluminescence. Zoning may be: parallel to crystal edges, interpreted as a primary feature; parallel to some crystal edges yet cutting other parallel zoning, which may be interpreted as growth, cessation of growth and then growth again with zoning forming in a new orientation or; transgressive and massive which may be interpreted as being due to post-crystallisation modification of the zircon (Hodson, 1994). All these types of zoning were observed in zircons in leucocratic and melanocratic syenites from both Nunarssuit and West Kungnat. No consistent zoning in terms of *REE*, Zr or Hf was observed.

Crystal size distribution as an indicator of post-crystallisation modification of primary grain distributions

Crystal size distribution theory was developed by Marsh, Cashman and Ferry (Marsh, 1988; Cashman and Marsh, 1988; Cashman and Ferry, 1988). The parameter crystal population density (= n) is defined as the gradient of the curve on a cumulative frequency graph of the number (N) of crystals of a length less than a stated length, L; length is defined as maximum length parallel to direction of elongation of a grain in thin section.

Such curves were plotted for olivines and pyroxenes from the layered series of Nunarssuit and West Kûngnât. The equations which define the curves were obtained mathematically (using the Computer Associate program CA-Cricket Graph v1.3) to an order of 2 decimal places and up to cubic L terms. Curves fit the equations to a precision of $r^2 = 0.99$. The equations were differentiated to obtain the gradient of the curves. Plots of ln (n) against L were produced.

According to Cashman and Marsh (1988) the shape of such plots is affected by a variety of processes (Fig. 9*a*). If the crystals grew and the rock solidified with no modification the plots should be straight lines. Depletion of the fine fraction of grains due to annealing processes would result in a plot with a negative slope at the small grain size end. Crystal settling through a boundary layer onto the floor of a magma chamber resulting in an enrichment in the coarse grain fraction at the site of deposition would result in a plot with a flattening of the slope towards the large grain size end. Deposition of grains from a moving current in a fashion analogous to sedimentary currents would result in an initial enrichment in the coarse grain fraction, however, later deposits from the same current would be depleted in the coarsest grains. This would result in a steepening of the plot at large grain sizes. Typical CSDs generated during the

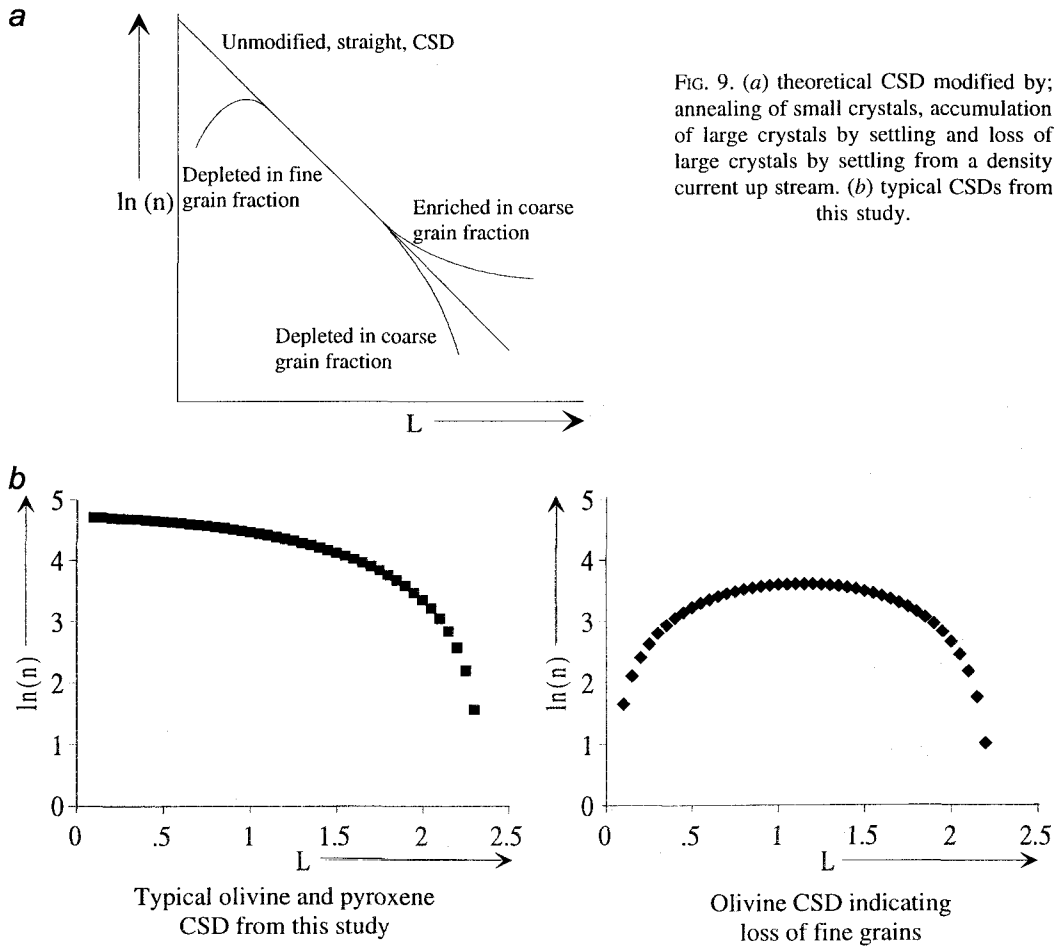

FIG. 9. (*a*) theoretical CSD modified by; annealing of small crystals, accumulation of large crystals by settling and loss of large crystals by settling from a density current up stream. (*b*) typical CSDs from this study.

present study are shown in Fig. 9*b*. Most of the samples yielded problematic curves which may be interpreted as indicating a depletion in either the coarse or fine fraction. Some olivine populations gave curves which indicate loss of fine grained material which is most likely to be due to annealing. The curves indicate grain size populations that are unlike those produced by simple nucleation and growth.

Compaction

Sparks *et al.* (1985) calculated that compaction of a cumulate pile can reduce porosities to less than 1% and, if only one cumulus mineral is involved, generate essentially monomineralic rocks. Compaction can alter texture and, indirectly, mineral composition (by dissolution–reprecipitation mechanisms). Higgins (1991) suggested that compaction can generate lamination in igneous rocks. Hunter (1993) concluded that rocks do not reach full textural equilibrium with angles of 120° between adjacent grain boundaries at the triple junction of three grains unless they have been compacted and that compaction is a potential mechanism for the formation of adcumulate textures.

Most of the layered syenites of Nunarssuit and West Kûngnât possess no igneous lamination, have non-equilibrium angles between adjacent grain boundaries at grain triple junctions and possess orthocumulate textures. This suggests that little compaction has occurred. Most rocks which show mineral lamination are associated with slumps indicating that flow of a crystal mush affected the degree of lamination of mineral grains, probably by producing a shear stress in excess of any stress due to

convection currents. Other mineral lamination occurs in and around melanocratic autoliths. These were probably denser than the surrounding magma and the crystal pile on which they must have come to rest; the mineral lamination could have been produced by a local increase in the degree of compaction.

The fluid involved in the post-crystallisation modification

Feldspar, pyroxene and olivine textures indicate that the syenites from West Kûngnât have undergone more fluid interaction than those from Nunarssuit, evidence from apatites is inconclusive. Pyroxenes and amphiboles from West Kûngnât appear to have re-equilibrated subsequent to their formation, whilst those from Nunarssuit have not. These indicators imply significant differences between the fluids, and nature of interaction with those fluids, that the two syenites underwent. This conclusion is in agreement with the conclusions drawn by Finch *et al.* (1995) on the basis of biotite F, Fe and Mg contents from the two intrusions. However, the following conclusions are equally applicable to both intrusions.

At least two fluids have been involved in the chemical modification of the phases present in the Nunarssuit and West Kûngnât syenites, the inter-cumulus fluid and a lower temperature one. The contrast in pyroxene and olivine chemistry between grains from adjacent melanocratic bases and over lying leucocratic layers is thought to be due to re-equilibration with intercumulus fluid (the trapped liquid effect described by Barnes, 1986), whilst the enrichment in the acmite component is probably due to interactions with a deuteric fluid in the subsolidus (Parsons and Brown, 1988). The modification of pyroxenes to amphiboles probably occurred in the subsolidus though amphibole may have started to crystallise as an intercumulus phase. In the West Kûngnât syenite amphiboles and pyroxenes re-equilibrated subsequent to amphibole formation, almost certainly via a deuteric fluid. The biotite producing reaction, the development of micropores in feldspars and the exsolution of ulvöspinel from magnetite must have occurred in the subsolidus. The zoning seen in zircons indicates several stages of growth in the magma followed by modification by either, or both, inter-cumulus and deuteric fluids. The modification of the apatites may have occurred either in the inter-cumulus or subsolidus. As suggested by others (Rubin *et al.*, 1989; Hole *et al.*, 1992) it is thought that the fluid involved in the modification of the apatite and zircon was rich in fluorine. F forms soluble complexes with *REE*s, Zr, Hf etc. making these elements mobile in deuteric fluids.

Differences in packing were first suggested by Upton (1961) to explain differences in alteration in the syenites in the north-west of the Grønnedal-Íka complex, another Gardar syenite. This argument is applicable to modifications involving crystals and intercumulus fluid. In the Nunarssuit and West Kûngnât syenites, intercumulus fluid would have been more concentrated in the leucocratic samples than in the melanocratic samples by virtue of the larger average crystal size and therefore pore size in the crystal pile which went on to solidify to produce the leucocratic rocks. Also there are volumetrically more pyroxenes in the melanocratic rocks than in the leucocratic ones. Thus the ratio of intercumulus fluid to pyroxene grains would be greater in the leucocratic rocks than the melanocratic rocks and consequently the pyroxenes in the leucocratic rocks would undergo more modification.

Modification of feldspars and olivines in the subsolidus is also more marked in the leucocratic rocks than in the melanocratic rocks. This can not be directly related to packing of the crystal pile since the modification occurred subsequent to solidification. Thus two questions must be addressed when considering the subsolidus fluid, what was the origin of this fluid and why was it concentrated in the leucocratic samples?

The oxygen isotope signatures of the feldspars in Nunarssuit and other Gardar intrusions all indicate that the deuteric fluid involved in the alteration of the feldspars was magmatic in origin. It is assumed that the fluid involved in the reaction of the olivines to produce biotite was also magmatic in origin. The simplest explanation for the origin of the fluid is that it was directly related to the one from which the syenites crystallised in the first place, it was probably a hydrous residue exsolved from the magma as the syenite solidified.

Perhaps the simplest explanation for the higher degree of modification of the leucocratic rocks in the subsolidus relative to the melanocratic rocks is as follows. As the intercumulus magma solidified a hydrous phase was exsolved. As there was more intercumulus fluid present in the leucocratic rocks than in the melanocratic ones the exsolved fluid phase was concentrated in the leucocratic samples. This fluid was preserved in cracks, inclusions and small pores as the syenite solidified and subsequently reacted with the surrounding crystals. Two additional explanations are presented below.

It has been suggested that the development of feldspar micropores is intimately linked to the exsolution of structural water incorporated into the feldspar during crystallisation (Worden *et al.*, 1990) though more recent work (Thompson, 1996) has suggested that this may not be the dominant process. If the feldspars in the leucocratic portions of layers originally contained more structural water than those in melanocratic portions then, subsequent to exsolu-

tion, this water may have been responsible for modifying the chemistry and textures of the surrounding crystals. Also after the development of micropores the feldspars in the leucocratic portions of layers, and thus the leucocratic portions of layers themselves, would be more porous to fluids. Feldspars in the leucocratic portions of layers may have contained more structural water than those in the melanocratic portions purely because there was more water dissolved in the surrounding magma when the leucocratic portions of layers formed. This would be the case if layering was produced by oscillating degrees of undercooling in the magma chamber controlled by the water content of the magma, with leucocratic layers being produced when the water content of the magma was relatively high (as suggested by Parsons, 1979, for the layering at Klokken). Alternatively, assuming that the concentration of dissolved water in the magma increased as crystallisation proceeded, the higher concentration of intercumulus fluid in the leucocratic portions of layers compared to the melanocratic portions would have resulted in more water being present as well.

Alternatively or additionally micro-cracks might open up in the crystal pile as it contracted on cooling. These cracks could act as conduits for deuteric fluids. Data on thermal expansion coefficients is sparse but suggest that values for feldspars are lower (and in some cases negative) than those for pyroxenes and olivines (volume expansion coefficients of *c.* 2.0×10^{-5} K^{-1} for feldspar (Smith and Brown, 1988), 3.0×10^{-5} K^{-1} for pyroxene (Deer *et al.*, 1978) and 3.1×10^{-5} K^{-1} for olivine (Deer *et al.*, 1982)). If these values are correct this implies that feldspars would under go less contraction (in the case of negative values they would expand) than pyroxenes and olivines as they cooled and thus it might be expected that the melanocratic rocks contain more contraction cracks than the leucocratic rocks. If these cracks did act as conduits for the flow of deuteric fluids it is unclear why the leucocratic rocks under went more alteration than the melanocratic ones. However, doubt has been cast on the validity of many of the values of coefficients of thermal expansion published in the literature (Adams *et al.*, 1975; J.L. Rosenfeld, pers. comm., 1996) and more data are required on the thermal expansivity of the minerals involved and also data on the tendency of the minerals to crack, before this hypothesis can be fairly assessed.

Summary

Both leucocratic and melanocratic rocks form the Nunarssuit and West Kûngnât layered syenites have undergone some degree of subsolidus modification. It would appear that whereas feldspars, pyroxenes and olivines from leucocratic rocks are more modified than those in melanocratic rocks, ilmenospinels and zircons are modified to a similar degree regardless of the colour index of the host rock. Apatites from melanocratic rocks in Nunarssuit are less modified than those from leucocratic rocks whilst apatites from syenites in West Kûngnât are all modified to a similar degree regardless of the colour index of the rock. Syenites from Nunarssuit are modified to a lesser degree than syenites from West Kûngnât with a similar colour index. Evidence from apatites may contradict this though conclusions drawn from apatite chemistry and zoning patterns are contradictory. Feldspars have lost their original shapes, a variety of minerals no longer preserve their original chemistry along the grain rims. Pyroxenes reacted to produce amphibole and olivines probably produced biotite, both these reactions probably occurred in the sub-solidus. Crystal size distributions indicate that the original grain size distribution of olivines and pyroxenes has been modified subsequent to crystallisation. The non-equilibrium dihedral angles between grains and the orthocumulate textures indicate that little compaction occurred. Mineral lamination is most marked around slump structures (indicating that the lamination is due to flow of the crystal mush) and dense melanocratic autoliths (indicating that the lamination is due to compaction).

The reason that pyroxenes in the leucocratic rocks underwent more intercumulus modification than those in the melanocratic rocks is probably that the cumulus minerals in the leucocratic rocks were less well packed so that more intercumulus liquid was present. This liquid fractionated, leaving a water-rich residue which reacted with the surrounding syenite modifying feldspars and olivines. In the case of West Kûngnât pyroxene and amphibole may have re-equilibrated with this fluid. The fluid which modified the apatites and zircons was probably F rich, the F forming soluble, mobile complexes with *REE*s, Zr and Hf. It seems simplest to suggest that the subsolidus fluid and the F-rich fluid which modified the apatites and zircons was the same but one may have been derived from the other via secondary boiling.

Both textures and chemistry of minerals and the rocks as a whole have been altered since their crystallisation. It is important to recognise this fact before drawing conclusions about magma chamber processes. Conversely the textures and chemistry of the syenites reveal a lot more information about their history other than the conditions in which they crystallised.

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