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The South Qôroq Centre nepheline syenites, South Greenland

Petrology, felsic mineralogy and petrogenesis

by

David Stephenson

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Abstract

The South Qôroq Centre is one of four high-level, major intrusive centres comprising the Igaliko Nepheline Syenite Complex. Three elliptical stocks of foyaite were emplaced in fairly rapid succession by ring fracture and block subsidence, followed by a partial ring-dyke of augite syenite. Inward-dipping microsyenite sheets appear to be associated with the ring-dyke; and four earlier, satellitic stocks occur around the periphery of the centre. Petrographic and mineralogical data show that the intrusions become successively less differentiated with time.

Felsic mineral phases (alkali feldspar, nepheline and sodalite) constitute over 80% of most rocks from the centre. Electron-microprobe analyses demonstrate the major role of felsics in the fractionation of the magma and, together with estimates of feldspar structural state from 2V measurements, give indications of the history and conditions of crystallisation. Nepheline compositions fall within a small range of decreasing Si content, but are outside the Morozewicz–Buerger convergence field and are not affected by sub-solidus alkali exchange. Feldspars form a continuous series from $Or_1Ab_{67}An_{32}$ to a K-enriched alkali feldspar $Or_{72}Ab_{28}An_0$. From comparison with other rock suites, this extended feldspar trend seems to be associated with the co-precipitation of nepheline, and increasing peralkalinity of the magma.

Major and trace element analyses of the rocks, made by X-ray fluorescence, give variation trends which may be interpreted mainly in terms of fractionation of feldspar and the ferromagnesian phases. In particular, trace element distributions are highly characteristic of fractional crystallisation series, but may not be compatible with fractional melting. Analyses of rocks with co-existing felsic phases compare favourably with phase equilibria in the experimental system Q–ne–ks at 1kb.

It is suggested that the centre evolved from an underlying differentiated magma chamber, formed by crystal fractionation and accumulation. Successively lower portions of the chamber were tapped, producing batches of fractionated magma. Later stages of crystallisation were influenced by a build-up in volatiles consisting of H_2O, CO_2, Cl and F, and post-emplacement differentiation was implemented mainly by outward diffusion of these volatiles together with alkalis under a thermal diffusion gradient.

Temperatures of crystallisation deduced from the nepheline geothermometer (Hamilton, 1961) and from phase equilibria in the Ab–Or–H_2O system are in reasonable agreement. Assuming a P_{H_2O} of about 1 kb, the foyaite feldspars crystallised at about 850°C and augite syenite feldspars slightly higher. Nephelines commenced crystallisation within the range 900–850°C but stabilised at 775–700°C irrespective of rock-type. Physico-chemical conditions during recrystallisation attributable to the later Igdlerfigssalik Centre are inferred from textural, geochemical and mineralogical changes. The recrystallised rocks provide evidence for the behaviour of trace elements during the initial stages of remelting under hydrous conditions in an open system.

Author's address:
Department of Geology and Oceanography
University College of Swansea
Singleton Park
Swansea SA2 8PP
U. K.

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INTRODUCTION

The South Qôroq Centre is one of four major intrusive centres comprising the Igaliko Nepheline Syenite Complex in the late Precambrian, Gardar alkaline igneous province of South Greenland. Reviews of the Gardar province have been given by Berthelsen & Noe-Nygaard (1965) and Upton (1974). A general description of the Igaliko Complex is given by Emeleus & Harry (1970) and fig. 1 is a simplification of their map, showing the major units of the complex in relation to the South Qôroq Centre. A 1:100 000 geological map of the area has recently been published by the Geological Survey of Greenland (map sheet 61 V.3 S Narssarssuaq). The present work is the result of a detailed petrographic, mineralogical and geochemical study on rocks of the centre. Aspects of the mafic mineralogy have already been published (Stephenson, 1972, 1974) together with preliminary observations on the magmatic evolution of the centre.

The major intrusive units comprising the South Qôroq Centre are concentric stocks and ring intrusions with steep, outward-dipping contacts and elliptical cross sections. The centre was emplaced at a high structural level and cuts through the associated Eriksfjord Formation basalt and sandstone succession, which has a maximum known thickness in the province of 3 km, most of which has been removed by erosion in the Igaliko area. Contacts with country rock are usually sharp and the outer syenite SS2 frequently shows a marked chill. Angular xenoliths are usually restricted to the immediate vicinity of the contact and shearing is seen along the contact at one locality. Metamorphism of country rock is not very widespread, although certain areas close to the contact are heavily metasomatised. In the area around Narssarssuaq the inward dip of the basalt succession is seen to increase towards the intrusion, which together with the above evidence suggests a permissive intrusion by ring fracture and block subsidence.

Three similar foyaitic magmas were emplaced in the order SS2, SS3, SS5. Internal contacts between these intrusions are usually diffuse or gradational, marked only by zones of marginal pegmatites, suggesting three pulses of magma from a common source in fairly rapid succession (Harry & Richey, 1963). It is likely that the magmas were below their liquidus on emplacement, and in the chill of SS2 small feldspar phenocrysts are present, laminated parallel to the contact. Igneous lamination of platy feldspar is found in all the foyaites, but is best developed in SS5 where accumulation of mafic minerals is also occasionally seen in mafic bands conformable with the lamination.

The syenite SS4 has in general sharper contacts, often with associated minor crushing, and field relationships suggest that it is younger than both SS3 and SS5.

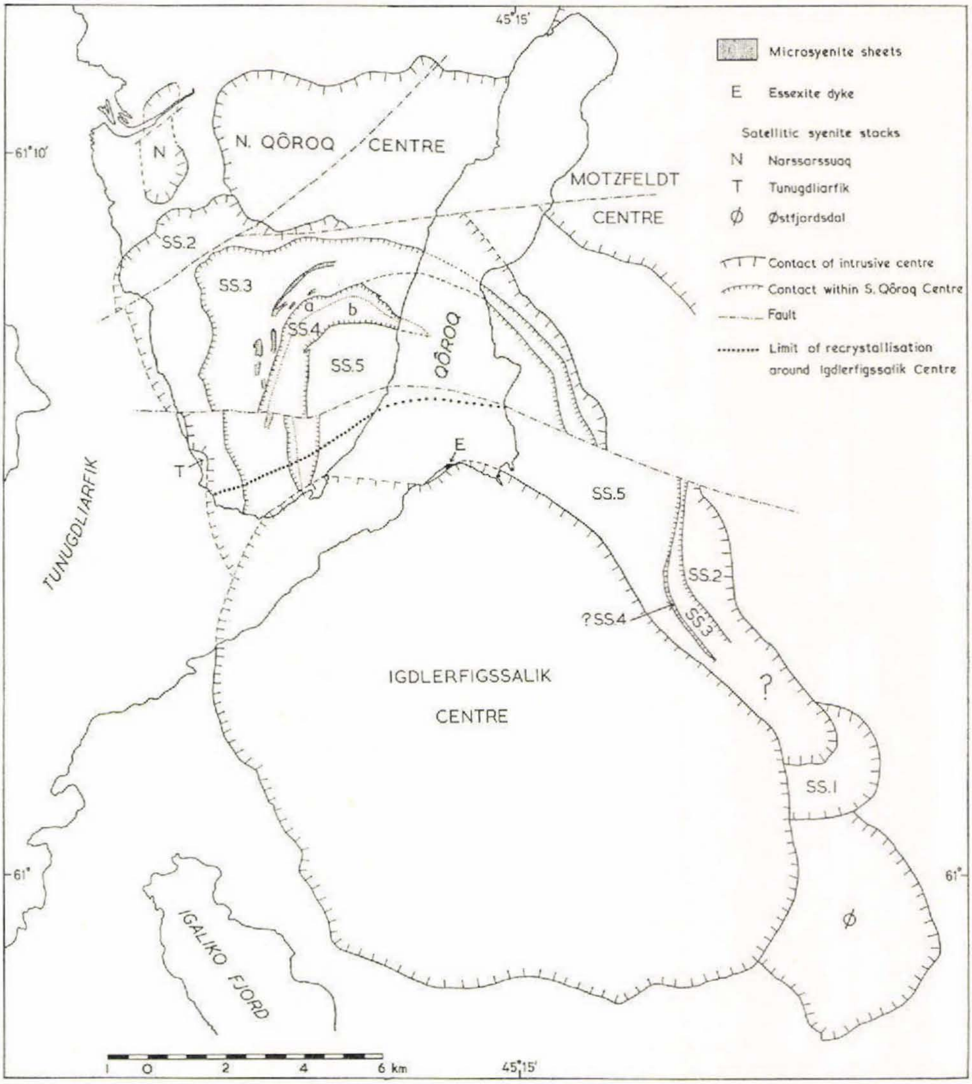


Fig. 1. The South Qôroq Centre showing major units within the centre, satellitic intrusions, adjacent centres in the Igaliko Complex and principal faults. (Modified after Emeleus & Harry, 1970).

The rock is an augite syenite, less differentiated than the foyaites, and in places steeply-dipping mafic banding is observed. These features suggest that it is probably a later ring-dyke. Internal contacts within SS4 suggest that it was emplaced in at least two pulses, SS4a and SS4b. Thus the original order of intrusion, as deduced by Emeleus & Harry (1970), has been modified to: SS2→ SS3→ SS5→ SS4a→ SS4b (table 1).

Inclined microsyenite sheets which cut SS3 and dip inwards towards SS4 have many mineralogical and geochemical features in common with SS4a. They would thus seem to be associated with the period of late ring-dyke intrusions as would a giant dyke of 'essexite' which cuts foyaite SS5. Small satellitic intrusions of nepheline syenite around the periphery of SS2 predate the main units but appear to be related bodies. Much of the southern part of the centre has been obliterated by the later Igdlerfigssalik Centre (fig. 1). Where seen, the contact is sharp and a zone of recrystallisation and veining up to 1 km wide in places is recognised within the South Qôroq Centre syenites.

The centre is cut by the Gardar regional swarm of alkaline dykes and has been affected by transcurrent faulting, some of which appears to have been contemporaneous with dyke emplacement. Some of the stress appears to have been taken up in the contemporaneous dykes by an apparent sinistral rotation in the northern part of the centre, producing an 'S' shaped deflection of the dykes (Emeleus & Stephenson, 1970; Stephenson, 1976).

Table 1. Principal units of the South Qôroq Centre

Pegmatite veins and patches within major units	Minor intrusions of various relative ages
Satellitic stocks of variable nepheline syenite around the periphery of SS2	
Essexite dyke – alkali gabbro	
Microsyenite sheets – possibly related to SS4a	
SS4b Augite Syenite (larvikitic)	Later ring-dykes
SS4a Transitional between foyaite and augite syenite	
SS5 Foyaite	Earlier concentric intrusions
SS3 Foyaite	
SS2 Foyaite	

(Nomenclature after Emeleus & Harry, 1970, with modified order of intrusion after Stephenson, 1972).

PETROGRAPHY

The principal syenites within the South Qôroq Centre may be classified as either foyaites (SS2, SS3, SS5) or augite syenites (SS4b) with intermediate compositions in SS4a and the microsyenite sheets.

Foyaites – SS2, SS3 and SS5

The three foyaitic syenites have a similar petrography, although significant differences occur in the compositions of certain mineral phases. The rock types are distinguishable in the field and descriptions may be found in Emeleus & Harry (1970).

Typically the foyaites contain about 80 per cent perthitic alkali feldspar and nepheline in approximately equal proportions, sodalite and aggregates of mafic minerals. The alkali feldspar and nepheline are usually subhedral to euhedral and appear to have co-precipitated for much of their history. Large, tabular crystals of orthoclase perthite up to 30 × 7 mm in size are particularly well developed in SS3 and SS5. Occasionally narrow rims of albite occur around the perthite crystals.

Mafic aggregates, which are particularly well-developed in SS2, contain combinations of aegirine-augite, arfvedsonitic amphibole, biotite, fayalite, iron-titanium oxides, aenigmatite and apatite. Most of these minerals are also found separately in interstitial areas. A discontinuous reaction series is developed from aenigmatite (small cores in SS2 only) or fayalite, to zoned aegirine-augite, to arfvedsonite. Biotite is often present as an additional hydrous phase, and in parts of SS3 it is the only hydrous mafic present. Where present, fayalite occurs as small, rounded grains frequently rimmed by iron oxides. However, it is not found in SS3 and its distribution is sporadic in SS2. Magnetite is usually present as small, rounded grains with broad exsolution lamellae of ilmenite. In SS3 there are indications that magnetite has reacted with the residual liquid to form acmite (Stephenson, 1972). In parts of SS5 mafic bands are common, consisting largely of subhedral aegirine-augite, fayalite and magnetite with rims of biotite.

In most foyaite samples there is a considerable amount of interstitial, greenish-grey sodalite which fluoresces bright orange. It is thus seen to be confined to patches up to 1 cm wide scattered irregularly throughout the rock. Cancrinite also occurs interstitially. Occasional associated calcite suggests that reaction between nepheline and a CO_2-rich residual liquid may also produce cancrinite as part of the nepheline–cancrinite–calcite discontinuous reaction series (Saether, 1957). Prismatic apatite is a common accessory with occasional sphene and zircon.

The outermost foyaite, SS2, becomes finer-grained towards its contact with country rock and develops a pronounced lamination parallel to the contact. In places there is a marginal chill up to 1 m wide in which tabular alkali feldspar microphenocrysts are prominent in a groundmass of euhedral nepheline, alkali feldspar and interstitial mafics. Thus it is inferred that on intrusion the SS2 magma consisted essentially of feldspar + liquid. However, euhedral nepheline is frequently enclosed by the feldspar phenocrysts suggesting that nepheline was co-precipitating from quite an early stage in the crystallisation. Sharply-defined, euhedral cores are present in some pyroxene grains suggesting that pyroxene crystallisation may have commenced prior to intrusion. Magnetite also has euhedral tendencies. However, in general the mafic minerals (fayalite, aegirine-augite, alkali amphibole and biotite) are poikilitic or interstitial in the chill and show discontinuous reaction relationships. In unchilled foyaites the order of crystallisation is not clear, except that feldspar and nepheline appear to have crystallised at an early stage and that amphibole, biotite and sodalite are always interstitial.

The foyaites show very little variation within individual intrusions, except that irregular pegmatitic patches tend to develop towards the margins. These patches contain the same minerals as the normal rock but with additional cancrinite and calcite. The feldspar is more coarsely exsolved than normal and nepheline is frequently euhedral. Marginal pegmatites in SS3 contain aegirine, both as large twinned crystals and as overgrowths on arfvedsonite. Some SS3 pegmatites also contain aenigmatite with zoned, euhedral crystals of eucolite–eudialyte, and others are rich in blue sodalite.

Electron-microprobe studies on the mafic minerals of the foyaites reveal differences in fractionation state which are not apparent from optical observations (Stephenson, 1972). In particular, SS3 is seen to be the most fractionated of all the South Qôroq Centre syenites. Certain petrographic facts do support the quantitative data, i.e. an increased abundance of hydrous mafic phases compared with the other foyaites, the development of aegirine and eucolite–eudialyte in marginal pegmatites suggesting a higher peralkalinity; the common occurrence of the reaction magnetite + liquid = acmite; the instability of fayalite; and the sporadic appearance of fluorite.

Augite syenites and related rocks within SS4

Syenite SS4b

SS4b is an augite syenite, very similar in texture and mineralogy to certain of the Oslo larvikites (Barth, 1945). In typical samples the feldspar occurs as irregularly-shaped grains of microperthite which are schillerised in hand specimen giving the rock a bluish tint. In marked contrast to the foyaites, nepheline occurs in interstitial areas crystallising later than the feldspar. Near the inner margin of the intrusion, nepheline constitutes only 10 per cent of the rock, but there is a tendency for it to become more abundant outwards, reaching about 30 per cent near the boundary with SS4a. A feature common to almost all the SS4 syenites, but absent from the foyaites, is the presence of irregular, rounded 'blebs' of nepheline within the alkali feldspar. Within a particular feldspar grain all the 'blebs' are in optical continuity and thus may be an exsolution feature. Identical textures are found in alkali feldspars from augite syenites of the Igdlerfigssalik Centre, and similar textures in the Oslo larvikites are considered to be due to sub-solidus exsolution by Widenfalk (1972).

Mafic minerals in the augite syenites form a distinctive assemblage. Iron-titanium oxides occur as rounded, subhedral grains and usually have radiating fringes of biotite. Olivine is present in almost all the samples and is frequently enclosed by other mafic minerals. It often has thick rims of iron oxide but is also frequently rimmed by a turquoise amphibole. The pyroxene is lilac-coloured titanaugite and only occasionally shows a slight green colouration on the edges. Well developed rims of muddy brown/green arfvedsonitic amphibole are common, sometimes enclosing euhedral pyroxene. Amphibole and biotite also occur as separate poikilitic areas. Euhedral apatite is commonly associated with the mafics, and occasional specks of pyrite are detected in reflected light. Sodalite is present only in very small amounts as thin rims around nepheline.

Mafic bands are common in SS4b, and most samples show a cumulus development of apatite, iron-titanium oxide, olivine and titanaugite to a greater or lesser extent, with these phases often constituting up to 60 per cent of the rock. The intercumulus material consists of small, irregular grains of microperthite, a little nepheline, barkevikitic amphibole and biotite.

Marginal pegmatites within SS4b are similar to the normal rock in their content of mafic minerals but are more coarsely crystalline and have large, irregular grains of very perthitic feldspar with interstitial nepheline rimmed by cancrinite. The earlier-formed mafics sometimes tend to be altered but interstitial amphibole is always fresh.

Since no chill is present in SS4b, it is difficult to establish the nature of the magma on intrusion and the subsequent order of crystallisation. However, feldspar was clearly an early phase and magnetite, olivine and clinopyroxene frequently show euhedral tendencies. These mafics may therefore have been co-precipitating from an early stage. Nepheline is interstitial to the feldspar and also to some of the earlier mafics. Amphibole and biotite are entirely intercumulus.

Syenite SS4a

SS4a has many features in common with SS4b such as the 'blebs' of nepheline in microperthitic alkali feldspar; rounded iron-titanium oxides with fringes of biotite; and fairly abundant olivine and apatite. However, it would appear to be transitional towards the foyaites, since the pyroxene is pale green, zoned aegirine-augite, usually with well developed rims of arfvedsonite, and nepheline is generally more abundant. In some samples the alkali feldspar occurs as large, irregular, interlocking grains with interstitial nepheline as in SS4b, but in others stumpy, rectangular perthite and square or hexagonal to subhedral nepheline are both early phases. Sodalite is frequently present and some samples have cancrinite. Marginal pegmatitic areas are developed but mafic bands are rare.

The microsyenite sheets

These sheets are generally of porphyritic microsyenite with a well developed lamination of platy feldspar phenocrysts. The groundmass is of sub-rectangular perthites, subhedral nepheline and mafics. Most of the mineral phases are similar to those of SS4a except that fayalite is less abundant.

Other intrusions associated with the centre

'Essexite'

The 100 m wide 'essexite' dyke contains large, irregular crystals of plagioclase, strongly zoned towards rims of microperthite and albite. Discrete laths of albite are also present with nepheline and analcime occurring interstitially. There are abundant, well-formed grains of apatite, olivine and iron-titanium oxide with large poikilitic crystals of titanaugite and deep red biotite. In general the feldspathoids comprise less than 10 per cent of the rock, which could therefore be more correctly termed an analcime nepheline monzonite (Streckeisen, 1967).

Satellitic nepheline syenite intrusions

The four satellitic intrusions shown on fig. 1 have quite a variable petrography encompassing most of the features seen in the main centre. The Tunugdliarfik Syenite is fundamentally similar to the foyaites as are parts of syenite SS1 (previously regarded as part of the main centre) and the Østfjordsdal Syenite. However, the latter show considerable variation, particularly with regard to the habit of nepheline which often occurs interstitially and in exsolved 'blebs' as in the augite syenites. The distribution of fayalite is also irregular and it is frequently absent. Most features of the Narssarssuaq Syenite are obscured by intense alteration and shearing throughout the whole outcrop. However, it can be seen to be texturally variable with perthitic alkali feldspar, interstitial nepheline and altered mafics.

Veins cutting the syenites

Apart from the marginal pegmatic patches already described under each intrusion, the syenites are also cut by several veins of pegmatite and carbonatite. The pegmatite veins usually have long blades of aegirine growing perpendicular to the vein margin. Between the pyroxene blades small laths of albite occur with larger, but less abundant nepheline, occasional poikilitic antiperthite and interstitial cancrinite. There are also small amounts of iron oxide, biotite and zircon. The central parts of these veins are similar to the marginal groundmass but with the development of much calcite.

Occasional irregular 5–10 cm veins of carbonate-rich, feldspathic material cut the syenites on the west coast of Qôroq, and around the margins of the centre more regular, 1 m thick carbonatite sheets occur. These consist of interlocking grains of calcite with poikilitic ?diopside and small grains of magnetite. Towards the edge, magnetite and hematite become more abundant and occasional bands contain finely disseminated fluorite.

The development of carbonate and CO_2-rich minerals such as cancrinite is a marked feature of the South Qôroq Centre, both in late-stage veins and in interstitial areas within the foyaites. The magma was thus clearly evolving towards a CO_2-rich residuum and a nepheline syenite–carbonatite association such as in the Grønnedal-Íka Complex (Emeleus, 1964). Widespread areas of carbonatite do not occur, but small diatremes of alkali ultramafic and/or carbonatite composition are common around the centre in the Narssarssuaq area (Stewart, 1970) including one which cuts the North Qôroq Centre.

Elsewhere in the province, CO_2-rich residua are apparent in the silica-oversaturated East Kûngnât Centre (Upton, 1960), Ivigtut Complex and Assorutit dyke (B. G. J. Upton, personal communication, 1973). However, CO_2 is markedly absent from the predominantly silica-undersaturated Ilímaussaq Complex where Cl-enrichment is much more pronounced than in the South Qôroq Centre.

FELSIC MINERALOGY

The work is based principally upon 118 analyses of nephelines from 14 samples and 158 feldspar analyses from 18 samples. The analyses were made using a Geoscan electron-microprobe, and analytical details are as given in Stephenson (1972), except that an accelerating voltage of 12 kv was used for the nephelines in order to reduce volatilisation of alkalis. Feldspars could be analysed at 15 kv since a broad electron-beam was being used (see below). Overall accuracy is considered to be ± 2 per cent of the amount present for major constituents but less for elements present below about 3 to 5 per cent. Detection limits are of the order of 0.01 per cent for most elements.

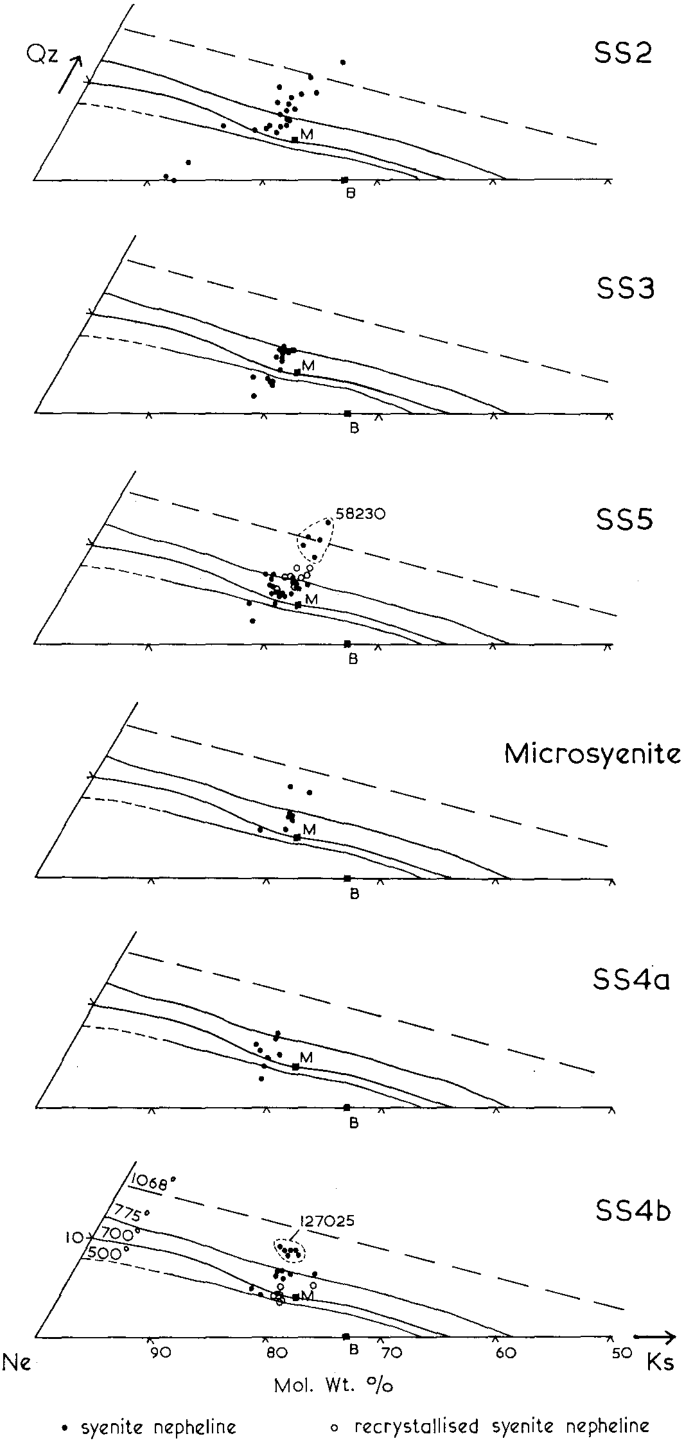
Nepheline

Nepheline is a major constituent of all the syenitic rocks in the centre. In the foyaites it has crystallised early along with the feldspar, and frequently shows euhedral tendencies. In SS4b and parts of SS4a, the nepheline occurs interstitially and is clearly later than the feldspars and certain mafics. Similar relationships are found in the augite syenites and foyaites of the Hviddal dyke, Tugtutôq (Upton, 1964c). In SS4a, SS4b and certain of the satellitic syenites it also occurs as rounded 'blebs' within feldspar crystals in a manner which suggests an exsolution relationship (Widenfalk, 1972).

In all rocks nepheline is the mineral most prone to deuteric alteration and weathering, generally to the micaceous mineral gieseckite which occurs as fine flaky aggregates and gives the nepheline a pink colour in hand specimen. Such samples also have an increased H_2O and decreased Na_2O content in whole-rock analyses, relative to the unaltered rocks. Reaction with CO_2-rich residua is seen as radiating rims of cancrinite on some nepheline grains, particularly near interstices filled by calcite.

Table 2. Representative nepheline analyses from the South Qôroq Centre

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	SS2	SS2	SS2	SS3	SS3	SS5	SS5	SS4a	SS4a	Micro-syenite	SS4b	SS4b	SS4b (rexst)	SS5 (rexst)
SiO_2	46.24	45.69	43.39	44.49	44.31	44.84	44.72	45.24	44.42	44.75	45.39	44.03	44.77	44.99
Al_2O_3	31.59	32.02	31.91	31.89	31.62	32.12	31.39	31.50	31.55	32.38	32.19	31.02	32.26	32.69
Fe_2O_3	0.61	0.76	0.59	0.72	0.66	0.69	0.78	0.66	0.72	0.47	1.22	0.24	0.50	0.53
CaO	0.23	0.01	0.01	0.01	0.01	0.13	0.01	0.01	0.11	0.01	0.33	0.22	0.10	0.01
Na_2O	14.83	15.99	18.86	16.50	16.78	15.86	16.65	16.20	17.59	16.18	15.27	16.53	16.63	15.66
K_2O	5.41	5.46	3.78	5.40	5.72	5.54	5.66	5.11	5.54	5.64	5.24	5.61	5.58	5.45
	98.91	99.93	98.54	99.01	99.10	99.18	99.21	98.77	99.93	99.43	99.64	97.85	99.84	99.33
Atomic proportions on the basis of 32 oxygen atoms														
Si	8.854	8.710	8.436	8.595	8.582	8.628	8.642	8.723	8.555	8.596	8.664	8.624	8.581	8.618
Al	7.132	7.197	7.315	7.264	7.221	7.286	7.152	7.161	7.164	7.333	7.247	7.209	7.291	7.383
Fe^{3+}	0.088	0.109	0.086	0.105	0.096	0.100	0.113	0.096	0.104	0.068	0.175	0.035	0.072	0.076
Ca	0.047	0.002	0.002	0.002	0.002	0.027	0.002	0.002	0.023	0.002	0.068	0.046	0.021	0.002
Na	5.509	5.913	7.113	6.183	6.305	5.920	6.241	6.078	6.572	6.029	5.656	6.280	6.183	5.819
K	1.312	1.328	0.938	1.331	1.414	1.360	1.396	1.257	1.361	1.382	1.277	1.402	1.365	1.332
End member compositions (molecular weight %)														
Qz	10.47	7.73	1.94	5.61	4.41	6.86	5.15	7.26	2.93	6.19	8.72	4.38	5.17	7.81
Ne	70.65	73.81	85.51	76.14	76.49	74.17	75.94	75.38	78.88	74.73	72.94	76.58	76.13	73.46
Ks	18.88	18.46	12.55	18.25	19.10	18.97	18.91	17.36	18.20	19.08	18.33	19.04	18.71	18.73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SS2
M
B
SS3
M
B
SS5
58230
M
B
Microsyenite
M
B
SS4a
M
B
SS4b
1068°
775°
700°
500°
10
127025
M
B
Ne
90
80
70
60
50
Ks
Mol. Wt. %
• syenite nepheline
○ recrystallised syenite nepheline

Representative nepheline analyses from the centre are shown in table 2. The analyses have been recalculated in terms of molecular weight percent nepheline ($NaAlSiO_4$), kalsilite ($KAlSiO_4$), anorthite $CaAl_2Si_2O_8$), and excess Si (expressed as SiO_2), and are plotted in fig. 2 in the system nepheline–kalsilite–quartz.

It has been shown that nephelines change their composition during crystallisation in two ways (Tilley, 1954): (a) the Si/Al ratio decreases with decreasing temperature, giving an indication of crystallisation temperature, particularly in rapidly cooled rocks; (b) sub-solidus exchange of Na and K atoms frequently occurs between coexisting nepheline and feldspar. In the latter, nepheline compositions move towards an ideal Na:K ratio of 3:1, bringing them into a field between the ideal Morozewicz and Buerger compositions marked 'M' and 'B' in fig. 2. Most plutonic nephelines are found within this field, and the nepheline geothermometer of Hamilton (1961) becomes inapplicable.

The South Qôroq Centre nephelines do not fall within the Morozewicz–Buerger convergence field, a feature which is also found in the plutonic nepheline syenites of Kangerdlugssuaq (Kempe & Deer, 1970). This suggests that sub-solidus exchange of Na and K has been minimal, and therefore the compositions do reflect crystallisation temperature. Most of the analyses (for both foyaites and augite syenites) fall between the 700°C and 775°C limits of solid solution. However, as has been found in several other mineral groups (Stephenson, 1972, 1974), the range in composition in SS2 is greater than in the other syenites. Many grains within SS2 show slight zoning with Na and Al increasing and Si decreasing towards the rims, K remaining constant throughout. This was not generally detected in the other syenites, and may be attributed to slightly faster cooling in SS2 against country rocks allowing less time for equilibration with the liquid. Thus, individual grains reflect a temperature range of 900 to 700°C.

Initial nepheline crystallisation may therefore have occurred at about 900°C in the foyaites but in most samples continuous reaction with liquid has resulted in a stabilisation at 775 to 700°C irrespective of magma type. In augite syenites where nepheline is interstitial to feldspar, possible relic high temperatures are recorded in one sample only (127025).

←

Fig. 2. South Qôroq Centre nepheline compositions plotted in terms of molecular weight percent nepheline, kalsilite and excess Si (expressed as SiO_2). Also shown are the experimentally determined limits of solid-solution at 500, 700, 775 and 1068°C of nepheline in equilibrium with alkali feldspar (P_{H_2O} = 1.034 kb) taken from Hamilton (1961); the theoretical Morozewicz composition of rock forming nepheline 'M' ($Na_{6.1}K_{1.52}\square_{0.38}Al_{7.62}Si_{8.38}O_{32}$); and the theoretical Buerger composition 'B' ($Na_3KAl_4Si_4O_{16}$). The two circled groups of analyses from SS5 and SS4b may be showing relic high-temperature compositions, but are more likely to be slightly altered or contain systematic errors in the SiO_2 determination. The three analyses from SS2 with only slight excess SiO_2 are grains completely surrounded by interstitial sodalite and have probably lost SiO_2 to the latter mineral.

A few grains in SS2, which are completely surrounded by interstitial sodalite have virtually no excess SiO_2 and plot near the base line of fig. 2. Other grains in the same slide have normal compositions, so it appears that Si has entered the late sodalite. Nash *et al.* (1969) suggest that coexisting sodalite may invalidate the nepheline geothermometer (in Mt. Suswa lavas with sodalite phenocrysts, Si is higher than expected in nephelines), but in the South Qôroq Centre sodalite crystallises much later, and only appears to have an effect where it is in direct contact with nepheline. No significant compositional differences have been detected in SS4b between the normal nepheline and that exsolved within feldspar.

Nephelines from the recrystallised syenite in SS5 indicate slightly higher temperatures than normal, but this is not noticeable in SS4b. Thus recrystallisation does not appear to have involved re-equilibration at a significantly higher temperature. There does not appear to be a change in the Na:K ratio in such nephelines (cf. increase in Na in pyroxenes from recrystallised rocks; Stephenson, 1972).

The only significant minor elements present in the nephelines are Ca and Fe. As in most plutonic rocks, Ca is very low, being generally between 0.0 and 0.05 wt % in the foyaites, and only slightly higher (0.05–0.30 wt %) in the augite syenites. Fe (probably present as Fe^{3+} substituting for Al) is always present, but is low in the augite syenites (0.20–0.35 wt %) and tends to increase in the foyaites (0.45–0.60 wt %).

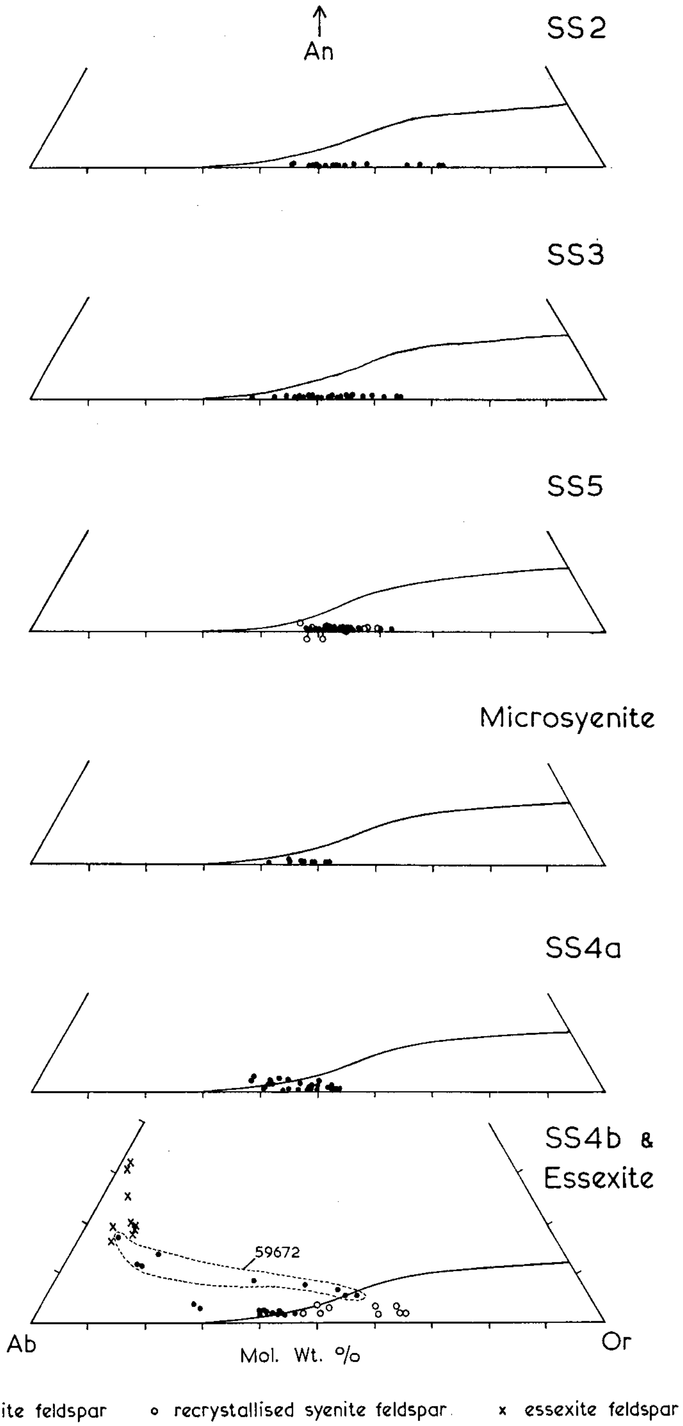
Feldspar

Alkali feldspar is the most abundant mineral in all the South Qôroq Centre rocks, constituting 40–60 % of the foyaites and 50–70 % of the augite syenites, according to the amount of coexisting nepheline. In the foyaites the feldspar usually occurs as tabular crystals, flattened parallel to (010) and reaching up to 30 × 7 × 2 mm in size in SS3 and SS5, where they commonly show a pronounced lamination. Some of the augite syenites also contain tabular feldspar, but commonly a more rhomboid type of habit is indicated by rectangular crystals up to 15 × 5 × 5 mm in size.

Most of the feldspars have perthitic textures, showing varying degrees of subsolidus unmixing even within individual grains. In the foyaites the perthites are generally better developed and the Na and K-rich phases occur in almost equal

→

Fig. 3. South Qôroq Centre feldspar bulk analyses in the system albite–orthoclase–anorthite (molecular weight percent). Also shown is the ternary cotectic at 5 kb (Yoder *et al.*, 1957) which appears to be crossed by the overall feldspar trend. The more calcic feldspars of 59672 are from a mafic band within SS4b. Feldspars from recrystallised rocks all fall on the K-rich side of the cotectic including those of SS4b which retain a higher Ca content than the foyaite feldspars.


An
SS2
SS3
SS5
Microsyenite
SS4a
SS4b & Essexite
59672
Ab
Or
Mol. Wt. %
• syenite feldspar
○ recrystallised syenite feldspar
x essexite feldspar

proportions, but in parts of SS4b the texture is antiperthitic. Thin, irregular rims of albite are found in many samples of both foyaite and augite syenite, but separate grains are not found. Some of the augite syenite feldspars are microperthitic or occasionally cryptoperthitic, and have a characteristic blue schiller in hand specimen, similar to those of the Oslo larvikites (Muir & Smith, 1956). Recrystallised samples of the syenites have particularly coarse perthites.

Twinning is normally of Carlsbad type with simple twins in the augite syenites and frequently multiple twins of up to six individuals in the foyaites. Manebach twins are scarce, but are sometimes seen creating a 'herringbone' effect of perthite lamellae. Albite twinning occurs in the plagioclase rims but is seldom observed in the perthites. Albite–Pericline combinations of the microcline type were not detected.

Bulk electron-probe analyses of the feldspars were obtained by using a broad, defocussed beam (*c.* 50μ) and by concentrating on the less coarsely-exsolved grains. This is not entirely satisfactory since, even with a broad beam, slight fluctuations in Na/K ratio occur, and concentration on microperthitic areas may create a slight bias. However, the analyses give a useful indication of fractionation trends and are shown on fig. 3 plotted in terms of molecular weight percent Or–Ab–An. Representative feldspar analyses are shown in table 3.

The compositions from the 'essexite' dyke and SS4b augite syenites fall on a trend from sodic andesine to a calcium-bearing alkali feldspar of composition $Or_{49}Ab_{49}An_2$. The trend is comparable with other Gardar trends from Kûngnât and Tugtotôq (Upton, 1960, 1964a, b, c) and the SS4b compositions are similar to those from the Oslo larvikites (Muir & Smith, 1956). Feldspars from a mafic band in SS4b (59672) are considerably more calcic than those of the normal augite syenite, and contain 4 per cent or more An.

Without exception, the foyaite feldspars lie on the K-rich side of the 5 kb cotectic (Yoder *et al.*, 1957) and contain no appreciable Ca. Compositions of Or_{38} to Or_{72} occur, but the spread is probably enhanced by analytical uncertainty due to the perthitic nature of some of the grains. There are no significant differences between compositions from individual foyaites. Microsyenites and samples of SS4a having appreciable amounts of nepheline, either interstitially or co-precipitating with feldspar, have feldspar compositions similar to those of the foyaites. However, samples of SS4a with lesser amounts of interstitial nepheline have slightly more calcic feldspars which overlap with and continue the SS4b feldspar trend across the 5 kb cotectic, thus providing evidence for the continuity of the overall feldspar trend.

In many of the feldspar grains, chemical zoning is detected, although the effect is often confused by sub-solidus exsolution. This produces, as would be expected, a trend in 'essexite' and augite syenite feldspars towards the 5 kb cotectic. However, in the foyaites the zoning is also towards K-enrichment, continuing the trend, apparently away from the cotectic.

Table 3. *Representative feldspar analyses from the South Qôroq Centre*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	SS2	SS2	SS3	SS3	SS5	SS5	SS4a	SS4a	SS4b	SS4b	SS4b mafic band	SS4b mafic band	'Essex-ite'	'Essex-ite'	Micro-syenite	SS4b (rexst	SS5 (rexst)
SiO_2	65.68	65.56	66.74	66.93	66.42	66.91	66.51	65.67	66.85	67.30	65.66	65.78	63.36	61.26	66.84	65.02	66.29
Al_2O_3	18.04	18.69	18.02	18.64	18.63	19.05	18.68	19.14	19.13	19.57	19.88	20.76	22.57	24.24	18.56	18.40	18.47
Fe_2O_3	0.36	0.23	0.30	0.20	0.17	0.15	0.19	0.16	0.13	0.06	0.12	0.19	0.13	0.15	0.19	0.29	0.19
CaO	0.01	0.06	0.01	0.04	0.04	0.07	0.10	0.10	0.33	0.71	1.25	2.21	3.68	6.17	0.04	0.39	0.03
Na_2O	3.38	6.10	4.21	6.78	5.24	6.05	5.51	6.70	6.59	7.99	4.82	8.50	8.70	7.88	5.90	4.20	5.26
K_2O	11.96	8.66	10.66	7.09	9.26	7.92	9.12	7.78	7.07	4.40	7.96	2.12	1.53	0.27	8.21	10.98	9.21
	99.43	99.30	99.94	99.68	99.76	100.15	100.11	99.55	100.10	100.03	99.69	99.56	99.97	99.97	99.74	99.28	99.45
Atomic proportions on the basis of 32 oxygen atoms																	
Si	12.036	11.923	12.093	12.018	12.006	11.982	11.986	11.875	11.954	11.924	11.822	11.663	11.254	10.890	12.033	11.928	12.019
Al	3.898	4.007	3.850	3.946	3.970	4.022	3.969	4.081	4.033	4.088	4.220	4.340	4.727	5.081	3.940	3.980	3.948
Fe'''	0.050	0.031	0.041	0.027	0.023	0.020	0.026	0.022	0.017	0.008	0.016	0.025	0.017	0.020	0.026	0.040	0.026
Ca	0.002	0.012	0.002	0.008	0.008	0.013	0.019	0.019	0.063	0.135	0.241	0.420	0.700	1.175	0.008	0.077	0.006
Na	1.202	2.152	1.480	2.362	1.837	2.102	1.926	2.350	2.286	2.746	1.683	2.924	2.998	2.717	2.060	1.495	1.850
K	2.797	2.010	2.465	1.624	2.136	1.810	2.097	1.795	1.613	0.995	1.829	0.480	0.347	0.061	1.886	2.570	2.131
End member composition (molecular weight %)																	
Ab	28.72	49.98	36.02	57.59	44.58	51.96	46.07	54.86	56.14	69.54	43.30	75.34	72.93	67.43	50.52	34.64	44.83
An	0.05	0.29	0.05	0.20	0.20	0.35	0.49	0.48	1.65	3.62	6.58	11.48	18.09	30.95	0.20	1.89	0.15
Or	71.23	49.73	63.93	42.21	55.22	47.68	53.44	44.66	42.21	26.84	50.12	13.17	8.99	1.62	49.28	63.48	55.02

Feldspars from the recrystallised rocks of SS5 show no change in composition compared with unrecrystallised rocks, but in SS4b the change is very apparent. Whereas all normal SS4b feldspars fall on the Na-rich side of the 5 kb cotectic, in the recrystallised samples they fall on the K-rich side and have a similar range to the foyaite feldspars. However, they still retain a higher Ca content. This decrease in Na/K in the feldspars compliments the increased Na found in pyroxenes from recrystallised rocks (Stephenson, 1972).

The only significant minor element present in the feldspars is Fe, which from the formula balance appears to be present as Fe^{3+} substituting for Al. There is little variation between feldspars from different rock types, and values range from 0.1 to 0.2 wt % Fe. However, feldspars from the mafic band (59672) have a very low Fe content. Ba was not detected in any of the samples.

Universal stage measurements of $2V_\alpha$ plotted against the average feldspar

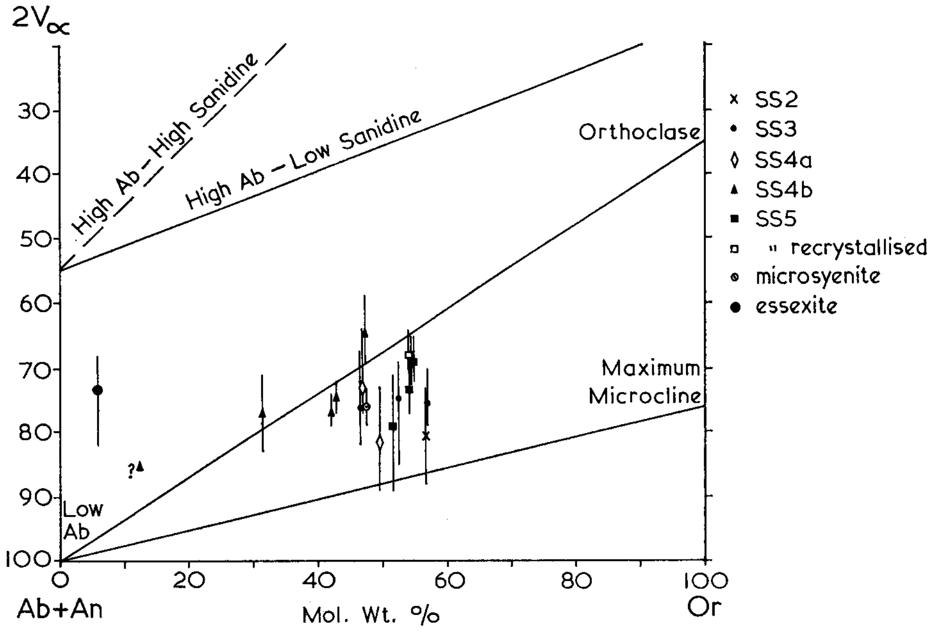


Fig. 4. Average $2V_\alpha$ values for unmixed feldspars as a function of the mean bulk feldspar composition in each electron-probe slide. The vertical lines indicate the range of 2V values obtained in each sample. The foyaite feldspars lie in a field between the low albite – orthoclase and low albite – maximum microcline joins and thus correspond to type (e) in the cooling sequence of MacKenzie & Smith (1962). The augite syenite feldspars lie nearer to the low albite – orthoclase join indicating a lower degree of Al–Si ordering, type (d) of MacKenzie & Smith (op. cit.). Increased Ca content in the 'essexite' and SS4b mafic band feldspars has probably increased the 2V, and these samples should lie nearer the high albite – sanidine join. (Diagram constructed as in Emeleus & Smith, 1959).

compositions of the probe samples are shown in fig. 4. The 2V values represent the average for the two-phase feldspar within the field of the objective, since measurement of individual phases is impracticable. Limitations of the method are outlined by Parsons (1965), and in the South Qôroq samples 2V values were unobtainable from very coarsely perthitic feldspars which may produce a slight bias towards higher structural states. From fig. 4 it can be seen that the foyaite feldspars lie in a field between the low albite–orthoclase and the low albite–maximum microcline joins, and thus correspond to type (e) in the cooling sequence of MacKenzie & Smith (1962), as do most of the Kûngnât and Tugtutôq feldspars investigated by these authors. The augite syenite feldspars plot closer to the low albite–orthoclase join (type (d) of MacKenzie & Smith, op. cit.), indicating a lower degree of Al–Si ordering. The 'essexite' and SS4b mafic band feldspars are difficult to evaluate since their high Ca content will increase the 2V, but they probably belong to the high albite (anorthoclase)–sanidine series.

Textural and mineralogical evidence suggests that the South Qôroq Centre magmas were below their liquidus temperatures on emplacement and that feldspar fractionation had already occurred giving a range of compositions in the various rock types (see next section). Since all the rocks contained essentially one feldspar phase, which has subsequently unmixed to a greater or lesser extent, the crystallisation must have been hypersolvus and may be outlined as follows:

The early stages of fractionation from andesine, through progressively more K-rich oligoclase and anorthoclase are seen in the 'essexite' and in SS4b mafic bands. In the augite syenites, however, the bulk compositions suggest soda-sanidine rather than anorthoclase. The rectangular habit of these feldspars is characteristic of feldspars of a similar composition from Tugtutôq Central Complex (Upton, 1964a). In feldspars of the Hviddal dyke, Tugtutôq (Upton, 1964c) the (010) face becomes increasingly developed throughout an augite syenite–foyaite sequence and eventually very thin, tabular feldspars are produced. This also clearly occurs in the South Qôroq Centre in the more fractionated, Ca-free, K-rich alkali feldspars of the foyaites. Changes from a rhombic anorthoclase or soda-sanidine to a tabular form with fractionation are also recorded from the Kangerdlugssuaq Intrusion (Kempe & Deer, 1970), and the lavas of Mount Suswa (Nash *et al.*, 1969). MacKenzie & Smith (1961) note that the very flat, tabular habit is particularly characteristic of feldspars crystallising from nepheline syenite magmas, and suggest that it is due to the metastable crystallisation of sanidine cryptoperthite with subsequent preservation of the sanidine habit. Thus it would appear from their composition and habit that the foyaite feldspars first crystallised as sanidine.

In order that K-rich alkali feldspars can be precipitated in the foyaites it would appear to be necessary for feldspar compositions to cross the ternary cotectic (fig. 3) and, as is seen from the zoning, fractionation then proceeds in the direction of further K-enrichment. The only published explanation of this phenomenon is that of Carmichael (1965) in which co-precipitation of Na-rich plagioclase with an alkali feldspar at the cotectic leads to Ca-depletion in the alkali feldspar and prevents Na-enrichment with further fraction. With slow cooling the plagioclase is resorbed at a later stage, but there is no evidence of this in the South Qôroq Centre where crystallisation was clearly hypersolvus with continuous reaction of a single feldspar phase. More appropriately in the South Qôroq magmas, the extended feldspar trend seems to be closely correlated with the co-precipitation of nepheline which becomes an early-crystallising phase at the same stage as feldspar compositions appear to cross the cotectic. Similar K-rich feldspars are found in undersaturated late fractions of the Hviddal dyke, Tugtutôq (Upton, 1964c), the Ilímaussaq Intrusion (Ferguson, 1970), the Kangerdlugssuaq Intrusion (Kempe & Deer, 1970) and in undersaturated lavas from Mount Suswa (Nash *et al.*, 1969). However, feldspars from oversaturated alkaline complexes, with no coexisting feldspathoids, and from augite syenites with only interstitial nepheline are seldom seen to cross the cotectic, although they frequently move down the cotectic curve towards a minimum on the Ab–Or join (Kûngnât, Upton, 1960; Tugtutôq Central Complex, Upton, 1964a; Loch Ailsh, Parsons, 1965).

It is most improbable that feldspar compositions can actually cross a cotectic, yet the overall continuity of the South Qôroq trend clearly demonstrates prolonged K-enrichment. Furthermore, feldspars from individual Mount Suswa lavas are seen to cross the position of the cotectic during fractionation (Nash *et al.*, 1969, fig. 2). Thus it seems likely that under certain circumstances the cotectic is moved by a considerable amount from its position in the theoretical Or–Ab–An system at 5 kg P_{H_2O}. Experimental work by Bowen & Tuttle (1950) and Yoder *et al.* (1957) shows that this is unlikely to be brought about by varying P_{H_2O} so it is necessary to invoke the influence of other solid phases. The addition of a co-precipitating feldspathoid to the system is the obvious factor common to all the published groups of K-rich feldspar analyses. Closer examination of published analyses reveals that the K-enrichment is further extended, in both over- and undersaturated suites, in more peralkaline magma compositions. The latter observation correlates with a general movement of minima and phase boundaries in the undersaturated part of the system Q–ne–ks for more peralkaline compositions which will be discussed in a subsequent section. Thus it is concluded that abnormal K-enrichment in alkali feldspars may be brought about by the addition of normative ne and/or ac to the ternary feldspar system which results in a movement of the cotectic towards the Or corner.

Continued cooling of the feldspars under sub-solidus conditions resulted in unmixing into separate Na and K-rich phases with increased Al–Si ordering and the development of a perthitic texture. Emeleus & Smith (1959) demonstrate that volatile fluxes have a considerable influence on the degree of ordering in feldspars, and Ferguson (1970) indicates marked structural differences between feldspars of

Ilímaussaq augite syenites and agpaites, attributable to higher volatile pressure in the latter. Parsons & Boyd (1971) suggest that ordering is also enhanced by peralkalinity of the magma. In the South Qôroq Centre the augite syenite feldspars are less coarsely perthitic and are of a higher structural state than those of the foyaites, which reflects a higher volatile content and peralkalinity in the foyaites, coupled with lower crystallisation temperatures and slower cooling. The very coarse perthites invariably found in the recrystallised rocks suggest a high volatile pressure due to aqueous alkaline solutions during recrystallisation.

The feldspars of initial soda-sanidine composition in the augite syenites resemble those of the Oslo larvikites in many features, and hence their sub-solidus crystallisation was probably similar to that described by Smith & Muir (1958). However, Widenfalk (1972) has pointed out that in addition to unmixing and ordering of feldspar phases, exsolution of nepheline also occurs, due to the initial feldspars having a slight deficiency of SiO_2. This is also seen in the South Qôroq Centre augite syenites as rounded 'blebs' of nepheline within the feldspar, and appears to have occurred quite early in the sub-solidus crystallisation, since the surrounding feldspar is often quite a fine microperthite. Some of the feldspars do recalculate to give a slight SiO_2 deficiency, but this cannot be correlated with the exsolution features in any regular manner. The restriction of exsolved nepheline to augite syenite feldspars can probably be correlated with their higher Ca content, which reduces the amount of nepheline which can be held in solid solution (Widenfalk, op cit.).

Sodalite

Sodalite is present in all the foyaites and in many samples of SS4a, as grey interstitial areas. The sodalite fluoresces bright orange and is seen to be concentrated in areas up to 5 cm across within individual hand specimens. In SS4b, thin rims of sodalite are occasionally found around nepheline, but no large areas occur. Disseminated blue sodalite occurs in a single pegmatite vein cutting SS3. This variety has a pale purple fluorescence.

Three electron-probe analyses of sodalites (one each from SS2, SS5 and recrystallised SS4b) are given in table 4. The two foyaite analyses are from interstitial areas and the SS4b analysis is of a thin rim around nepheline. All the analyses are rich in Cl but contain little S, and are very similar to those from the Ilímaussaq naujaite (Sørensen, 1962). However, Deer *et al.* (1963) point out that sodalite varies very little in major element composition (apart from volatiles) over a wide range of environments, so few conclusions may be made from the analyses, except that a build up in Cl in the late residua is indicated. There is very slight substitution of Fe^{3+} for Al, and Ca for Na, but no appreciable K is detected.

Table 4. South Qôroq sodalite analyses

	127075 SS2		58230 SS5		58164 SS4b (recrystallised)	
SiO_2	37.50		38.00		37.04	
Al_2O_3	30.58		34.41		32.50	
Fe_2O_3	0.60		0.53		0.40	
CaO	0.13		0.19		0.27	
Na_2O	26.36		22.75		24.75	
K_2O	–		–		0.06	
S	0.08		0.06		–	
Cl	6.62		6.76		6.53	
	101.87		102.70		101.55	
O=S, Cl	1.52		1.54		1.48	
	100.35		101.16		100.07	
Cations to 26 (O, S, Cl)						
Si	5.054	11.946	5.973	12.411	5.951	12.154
Al	5.819		6.376		6.154	
Fe^{3+}	0.073		0.062		0.048	
Ca	0.022	8.277	0.031	6.963	0.047	7.872
Na	8.255		6.932		7.709	
K			–		0.116	
S	0.025	1.834	0.017	1.817	–	1.776
Cl	1.809		1.800		1.776	

GEOCHEMISTRY

Samples from all units of the South Qôroq Centre were analysed by X-ray fluorescence techniques for 10 major elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, P) and 14 trace elements (Ba, Nb, Zr, Y, Sr, Rb, Pb, Zn, Cu, Ni, La, Th, U, V). A total of 128 analyses were made including 90 representative samples analysed for FeO (method of Wilson, 1955) and H_2O^-, H_2O^+, CO_2 (method of Riley, 1958). Representative analyses are listed in table 5 and the complete data are lodged in the data bank of Gardar province analyses (Anderson, 1974).

The rocks are all silica-undersaturated, containing both normative and modal nepheline. The peralkalinity index (atomic ratio [Na + K]/Al) is between 0.7–0.95 in the augite syenites but rises to values close to unity (0.95–1.10) in the foyaites (fig. 5). The centre is thus only mildly peralkaline and lacks the agpaitic geochemical and petrographic features of the nearby Ilímaussaq Intrusion (Sø-

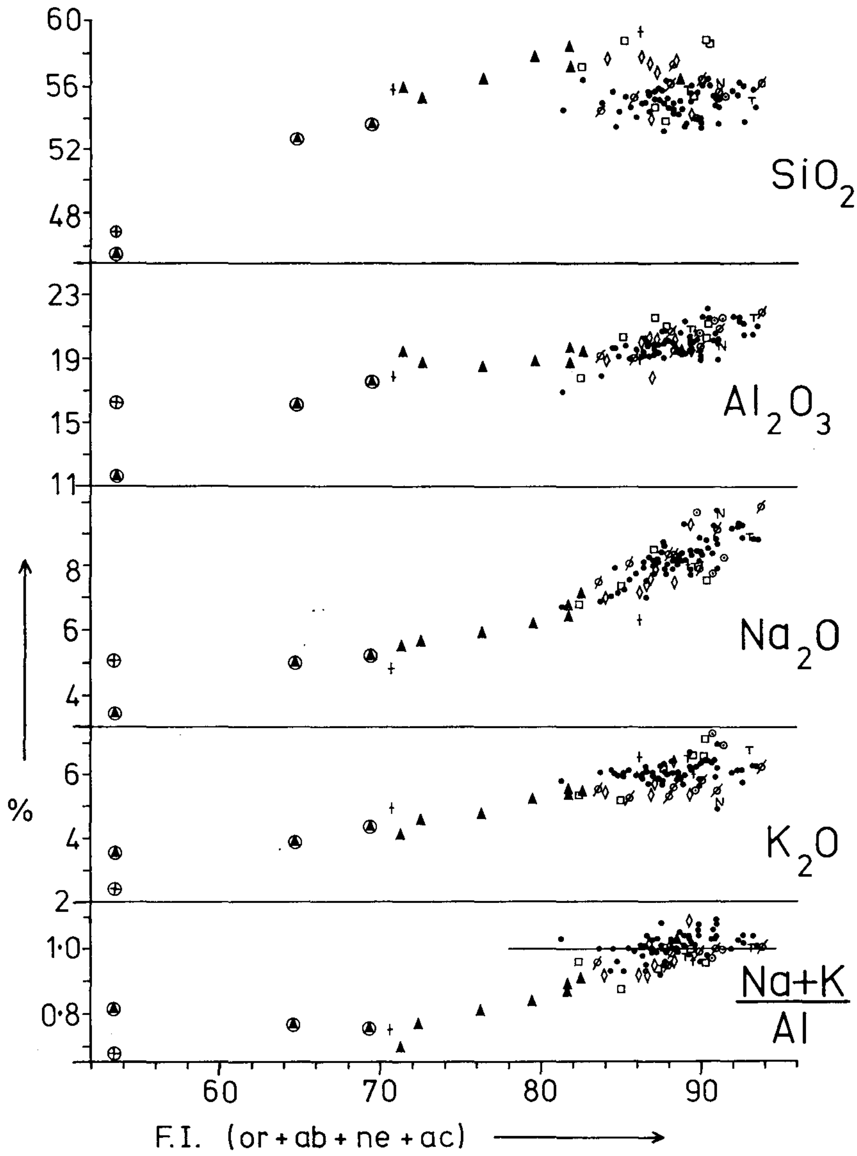


Fig. 5. Variation of major elements and major element ratios with the 'Fractionation Index' (F.I.) of MacDonald (1969), i.e. F.I. = or + ab + ne + ac (see text).

●	Foyaites SS2, SS3 & SS5	*N*	Narssarssuaq Syenite
◊	SS4a	T	Tunugdliarfik Syenite
▲	Augite syenites of SS4b	Ø	Østfjordsdal Syenite
+	'Essexite'	☐	Recrystallised syenites near to the Igdlerfigssalik Centre
⊙	Microsyenite Sheets		
†	SS1	⊕ ◬	Accumulative rocks

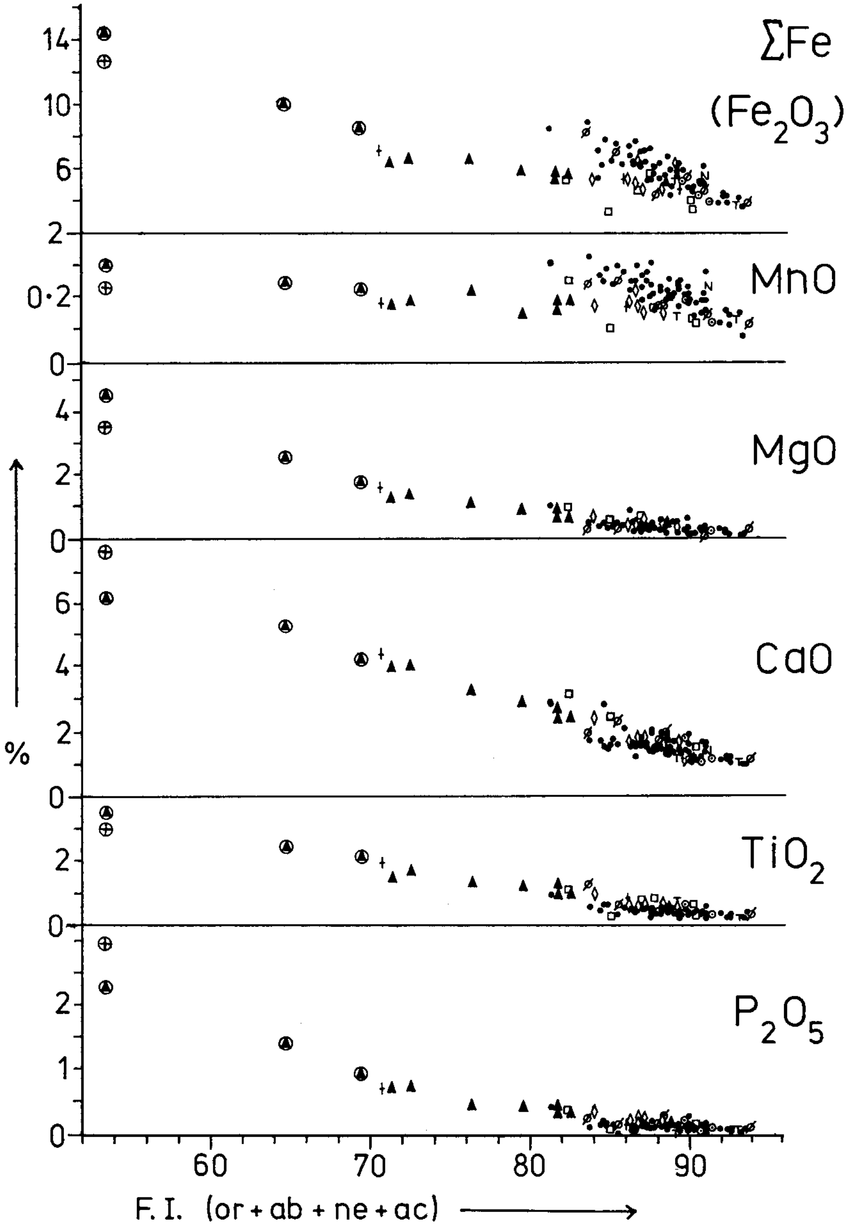

ΣFe
(Fe$_2$O$_3$)
14
10
6
2
MnO
0·2
0
MgO
4
2
0
CaO
6
4
2
%
0
TiO$_2$
2
0
P$_2$O$_5$
2
1
0
60
70
80
90
F. I. (or + ab + ne + ac)
N
T

Fig. 5 *cont.*

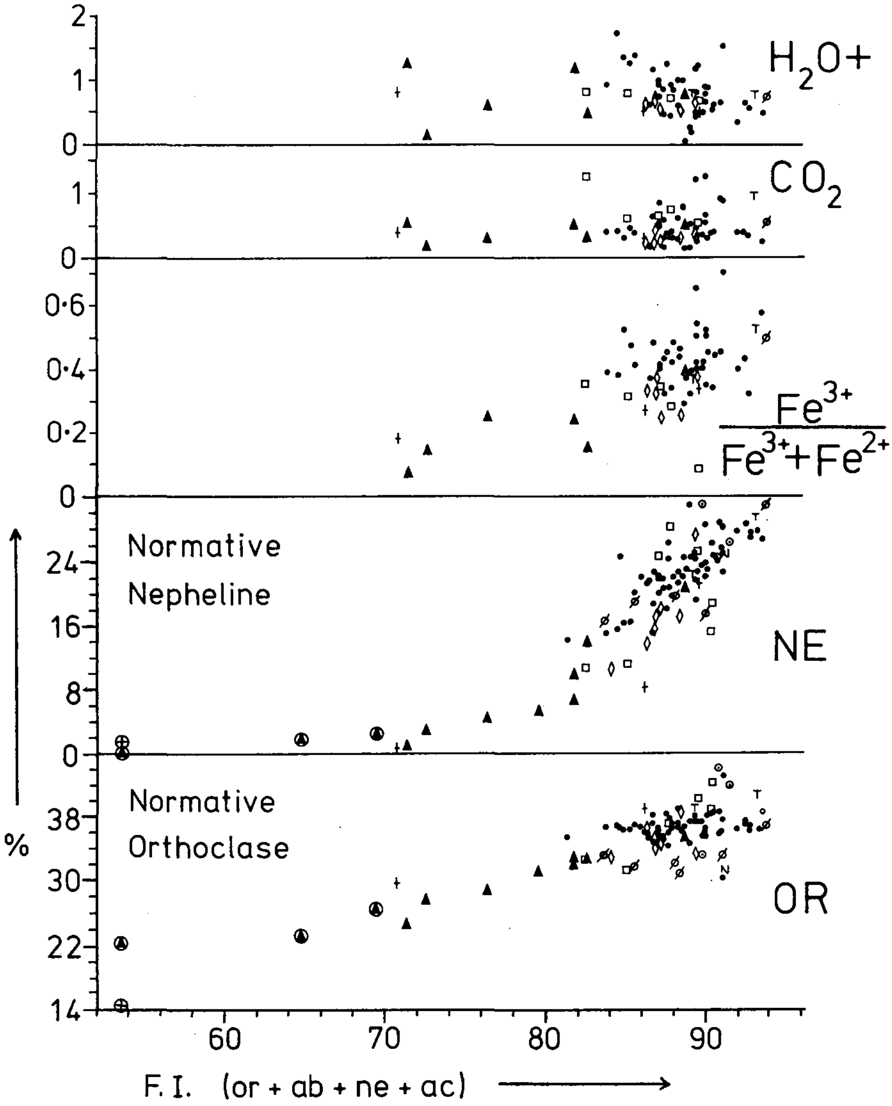

H_2O+
CO_2
$\frac{Fe^{3+}}{Fe^{3+}+Fe^{2+}}$
Normative Nepheline
NE
Normative Orthoclase
OR
%
2
1
0
1
0
0·6
0·4
0·2
0
24
16
8
0
38
30
22
14
60
70
80
90
F.I. (or + ab + ne + ac)

Fig. 5 *cont.*

Table 5. Representative whole rock analyses from the South Qôroq Centre

Unit	SS2	SS2	SS3	SS3	SS5	SS.5	SS4a	SS4a	SS4b	SS4b	SS4b (mafic band)	'Essex-ite'	Microsy	SS3 (rexst)	SS5 (rexst)	SS4b (rexst)	SS2 (alte-red)	SS4a (alte-red)
GGU No	58231	127021	52297	127015	46243	58222	58150	58228	58220	58259	59672	58130	127027	58328	58154	58165	58256	58149
SiO_2	55.84	55.72	55.02	55.35	56.42	54.77	57.58	57.35	56.03	56.52	52.71	48.64	54.00	58.67	53.75	54.66	55.31	54.94
TiO_2	0.51	0.47	0.56	0.30	0.48	0.51	0.62	0.59	1.50	0.97	2.48	2.95	0.61	0.65	0.85	0.79	0.46	0.22
Al_2O_3	19.30	19.63	17.92	20.02	20.84	19.03	20.13	20.31	19.39	19.36	16.20	15.93	20.52	20.17	20.94	21.52	20.29	22.49
Fe_2O_3	3.03	2.65	3.51	3.39	1.77	3.11	1.14	1.63	0.42	0.83	(10.05)	0.34	(5.13)	(3.95)	1.60	1.56	3.46	2.47
FeO	3.64	3.97	4.85	2.62	3.13	4.05	3.08	3.05	5.36	4.40	(–)	9.97	(–)	(–)	3.71	2.77	3.25	2.43
MnO	0.28	0.27	0.33	0.25	0.21	0.30	0.15	0.17	0.18	0.19	0.25	0.21	0.19	0.13	0.16	0.16	0.29	0.20
MgO	0.35	0.38	0.48	0.28	0.32	0.47	0.41	0.40	1.24	0.65	2.55	3.47	0.54	0.20	0.44	0.64	0.61	0.12
CaO	1.69	1.74	1.75	1.34	1.56	1.67	1.59	1.71	3.96	2.48	5.32	7.52	1.86	1.54	1.58	1.70	1.51	0.91
Na_2O	8.19	7.04	6.89	8.33	7.92	7.58	7.49	7.53	5.51	7.18	5.03	4.69	9.70	7.53	8.64	8.52	5.43	6.54
K_2O	5.89	6.13	6.06	6.22	6.34	6.11	6.46	5.91	4.14	5.44	3.94	2.50	5.50	6.55	6.17	5.76	6.22	6.25
P_2O_5	0.14	0.16	0.12	0.07	0.14	0.02	0.21	0.19	0.74	0.34	1.43	2.95	0.22	0.13	0.23	0.30	0.10	0.03
H_2O+	0.86	1.75	0.94	1.22	0.44	1.42	0.48	0.65	1.28	0.49	–	–	–	–	0.72	0.66	2.35	2.23
CO_2	0.60	0.42	0.42	0.31	0.32	0.40	0.31	0.24	0.56	0.33	–	–	–	–	0.75	0.67	0.56	0.42
	100.32	100.33	98.85	99.70	99.89	99.44	99.65	99.73	100.31	99.18	99.96	99.17	98.27	99.52	99.54	99.71	99.84	99.25
Trace elements (ppm)																		
Ba	191	170	136	125	242	179	823	977	4470	2048	3205	3071	849	768	337	659	245	153
Sr	138	124	237	100	234	102	289	375	1698	744	1286	1741	334	399	157	349	596	249
Rb	233	230	279	276	216	210	190	174	62	150	78	36	173	153	230	72	383	335
Nb	228	240	443	264	113	283	94	126	71	132	126	59	191	58	96	34	248	246

Zr	954	774	1297	957	261	1012	297	443	259	460	447	218	666	125	191	89	792	1252
Y	50	55	37	47	20	66	23	33	26	35	48	35	50	73	20	18	41	37
Pb	23	23	38	23	0	27	14	19	21	28	86	0	27	0	8	9	20	18
Zn	181	186	234	191	100	190	86	105	90	107	133	115	123	52	91	51	253	160
Cu	12	13	13	5	8	9	9	9	11	11	21	22	7	4	9	9	8	0
La	97	97	77	74	40	89	43	55	49	62	88	72	78	139	47	38	68	50
Th	13	12	15	16	0	22	0	8	2	9	11	5	13	24	10	4	12	7
U	6	9	9	11	8	11	5	7	2	4	0	0	8	0	7	4	7	3
Norms																		
C	–	–	–	–	–	–	–	–	0.4	–	–	–	–	–	–	–	2.2	3.5
or	35.2	36.9	36.7	37.4	37.8	37.0	38.6	35.3	24.8	32.7	23.4	14.9	33.2	39.0	37.2	34.6	37.9	38.2
ab	28.8	31.9	31.9	26.9	29.0	28.1	32.6	35.8	45.4	35.8	39.4	37.0	19.3	35.9	22.2	27.7	38.1	35.8
an	–	3.9	0.1	–	2.6	–	2.3	4.2	15.0	4.6	10.1	15.1	–	1.9	0.1	3.5	7.1	4.5
ne	20.8	15.6	15.1	23.1	20.9	20.2	17.1	15.5	1.0	14.1	1.9	1.6	31.0	15.3	28.3	24.7	5.1	11.7
ac	2.5	–	–	1.9	–	0.2	–	–	–	–	–	–	6.2	–	–	–	–	–
di	6.6	3.3	7.0	5.4	3.7	7.2	3.7	2.7	–	4.9	5.9	2.5	6.8	3.1	5.5	2.6	–	–
ol	1.6	3.2	2.6	0.4	2.1	1.7	2.4	2.5	8.0	4.1	7.3	15.7	1.7	–	2.1	2.4	3.4	2.2
mt	3.2	3.9	5.2	4.0	2.6	4.5	1.7	2.4	0.6	1.2	3.9	0.5	–	2.7	2.4	2.3	5.2	3.7
il	1.0	0.9	1.1	0.6	0.9	1.0	1.2	1.1	2.9	1.9	4.7	5.6	1.2	1.2	1.6	1.5	0.9	0.4
ap	0.3	0.4	0.3	0.2	0.3	–	0.5	0.5	1.8	0.8	3.4	7.0	0.5	0.3	0.6	0.7	0.2	0.1
H_2O	0.9	1.8	0.9	1.2	0.4	1.4	0.5	0.6	1.3	0.5	–	–	–	–	0.7	0.7	2.3	2.2
F.I.	87.3	84.4	83.7	89.4	87.7	85.5	88.3	86.7	71.3	82.5	64.7	53.5	89.7	90.2	87.7	87.0	81.0	85.7
$\frac{(Na + K)}{Al}$	1.03	0.93	1.00	1.02	0.95	1.00	0.96	0.92	0.70	0.91	0.77	0.65	1.07	0.97	1.00	0.94	0.77	0.78

XRF. FeO_2, H_2O and CO_2 determined chemically.

rensen, 1960). In variation diagrams (figs 5, 7, 8) the analyses form a smooth, continuous trend from the 'essexite', through mafic bands in the augite syenites, to the augite syenites and foyaites.

Major element variation

The major element variation diagrams are shown in fig. 5 using the 'Fractionation Index' (F.I.) of Macdonald (1969) as an abcissa. This index is a modification of the 'Differentiation Index' of Thornton & Tuttle (1960) and consists of the sum of all the normative components in the 'residua system' + ac + ns (i.e. in the South Qôroq Centre, F.I. = or + ab + ne + ac). The modification is essential in peralkaline rocks, since the appearance of ac in the norm tends to progressively decrease the 'Differentiation Index' of Thornton & Tuttle with progressive fractionation. Since in most cases it is impossible to distinguish between individual foyaites from their geochemical features, SS2, SS3 and SS5 are plotted with the same symbol for clarity.

The analyses include a group in which the nepheline is pseudomorphed by aggregates of micaceous material (probably gieseckite). Such rocks have a reduced content of Na_2O and slightly higher Al_2O_3 compared with unaltered equivalents, with the result that they have anomalously low values of 'Fractionation Index' and peralkalinity, and frequently show normative corundum. The loss in Na_2O is accompanied by a considerable increase in H_2O^+ (2.0–2.5 % as opposed to 0.5–1.5 % in unaltered rocks) and hence appears to be due to hydrothermal alteration of nepheline. Many of the altered samples are from the vicinity of faults or marginal areas of intrusions, but are also found elsewhere. These analyses cause considerable distortion in the variation diagrams and hence have been omitted.

In fig. 5 most elements are seen to follow a smooth, continuous trend through the augite syenites and foyaites, with the exception of SiO_2. The latter shows an increase with fractionation in the least fractionated augite syenites, followed by scattering and vague decrease in the more fractionated augite syenites and foyaites. Al_2O_3 and K_2O increase steadily through the series, but Na_2O shows an increase with a pronounced kink towards the end of the augite syenite part of the trend, followed by a steep rise in the foyaites. This is even more pronounced in the normative nepheline content and reflects the point at which nepheline appears with alkali feldspar as a cumulus phase, rather than interstitially. CaO, MgO, TiO_2 and P_2O_5 decrease steadily through the series but total iron (as Fe_2O_3) and MnO, although decreasing, show a slight suggestion of a separate, convergent trend in the foyaites. The iron oxidation ration ($Fe^{3+}/[Fe^{3+}+Fe^{2+}]$) shows a general increase with fractionation. H_2O^+ and CO_2 show a considerable scatter, but there is a suggestion that H_2O^+ increases throughout the augite syenites but decreases in the later stages of foyaite fractionation.

The three analyses from mafic bands in SS4b, and the 'essexite' dyke, all of which show accumulation of olivine, iron-titanium oxides and possibly clinopyroxene, lie on backward extensions of the trends for all elements. Extreme late fractionates such as pegmatite veins have not been analysed.

Analyses from the microsyenite sheets and satellitic intrusions are also plotted on fig. 5. In general they are seen to fall on the same trends as the larger intrusive units. However, the Østfjordsdal Syenite, which conforms to the foyaite part of the trend in most elements, has a lower K_2O content and slightly higher Na_2O.

Since a vertical section of almost 1,000 m is represented in the centre, the possibility of cryptic, geochemical variation was investigated by plotting the analyses against height above sea level. No systematic variation in a vertical sense was detected.

Slight variations in a horizontal sense, across the outcrops of the syenites, are detectable and are best seen in the outer syenite SS2 and the ring-dyke rocks of SS4a and SS4b (fig. 6). Although SS5 is the most complete separate intrusion, mafic bands and igneous lamination are usually developed and probably mask any slight horizontal variations. For many elements the scatter masks the systematic variation, but representative elements from SS2 and SS4 are shown on fig. 6, where slight trends outwards towards more fractionated rocks are seen. Normal centripetal cooling,

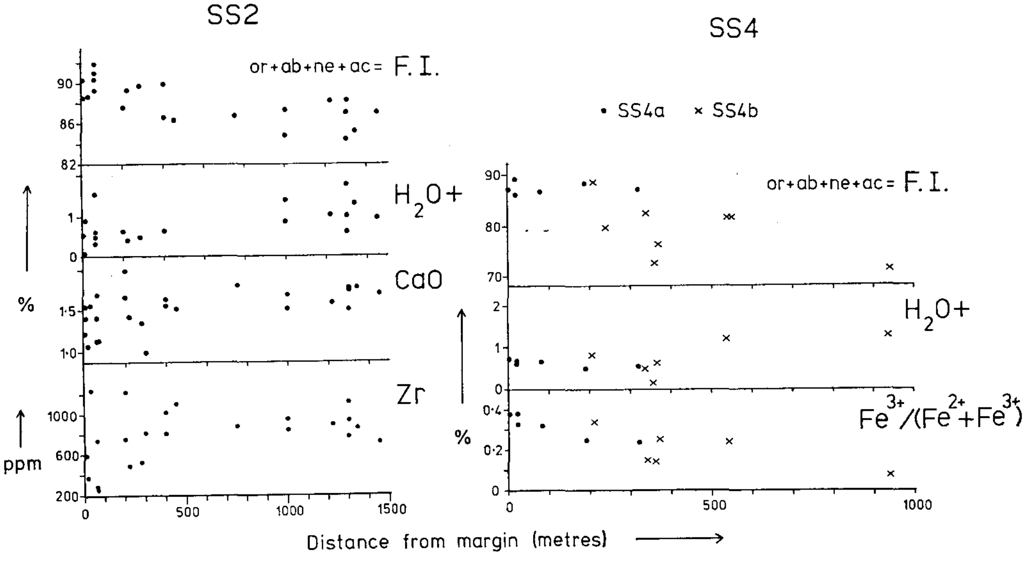


Fig. 6. Variations in selected element concentrations horizontally across the outcrops of SS2 and SS4. Only the most instructive elements are shown, plotted against distance from the outer contacts of the respective units. In the case of SS4, both SS4a and SS4b are plotted against distance from the outer contact of SS4a. Despite considerable scatter the rocks are seen to generally become more fractioned outwards with an increase in F.I. and iron oxidation ratio, and a decrease in CaO, TiO_2, P_2O_5 etc.

as described by Kempe *et al.* (1970) for the Kangerdlugssuaq Intrusion, would result in a trend inwards to more fractionated rocks. Kogarko (1974) has pointed out the high solubility of volatiles, in particular water, in alkaline magmas, forming aqueous alkaline solutions in the late stages of crystallisation. Hence in the South Qôroq Centre the variation is possibly due to volatile transfer of alkali elements outwards along a thermal diffusion gradient during cooling. Alkali elements would thus be concentrated towards the margins producing more fractionated rocks. H_2O^+ is plotted on fig. 6, but if anything shows a decrease towards the margins, probably reflecting loss into country rock. Accumulation of volatiles probably accounts for marginal pegmatite patches and also for some of the slight variations in composition and fractionation state seen on the variation diagrams in other areas of the intrusions.

Trace element variation

Trace element variation is shown in fig. 7. The ranges of most elements are similar to those found in highly fractionated rocks elsewhere in the Gardar province (Upton 1960, 1964c; Macdonald & Edge, 1970; Gill, 1972) but do not reach the extreme values found in the Ilímaussaq Intrusion (Hamilton, 1964; Ferguson, 1970). The variation patterns are generally typical of highly differentiated magmas of alkaline affinities (Nockolds & Allen, 1954; Gerasimovsky, 1974). Correlation coefficients for the trace elements are given in table 6.

Barium and strontium

These two elements have a strong positive correlation (table 6) and both show a rapid depletion through the augite syenites of SS4b and SS4a, so that low concentrations with a slight spread are found in the foyaites. Slight variations can be detected between individual foyaites, with SS5 having generally higher values and SS2 having low values. Ba and Sr usually concentrate with fractionation in more basic magmas until the point where alkali feldspar begins to crystallise, but then decreases rapidly in late differentiates due to fractionation of the alkali feldspar (Taylor, 1965). Alkali feldspar fractionation is thus strongly implicated during the evolution of the South Qôroq Centre. The 'essexite' and mafic cumulates from SS4b fall below the normal trend as would be expected with a lower proportion of felsic phases.

Rubidium

Rubidium shows a steady increase through the series, having a negative correlation with Ba and Sr. The K/Rb ratio drops considerably with increasing F.I. from 550 in the most basic augite syenite, to 150 in some of the foyaites. This behaviour is usual in alkaline complexes where fractionation is dominated by alkali feldspar crystallisation, since size differences lead to an enrichment of Rb (1.47Å)

Table 6. Correlation coefficients between trace elements in the South Qôroq Centre syenites

	Ba	Sr	Rb	Zr	Nb	Y	La	Zn	Pb	Th	U	V	Cu	Ni
Ba	–													
Sr	*0.603*	–												
Rb	*–0.719*	–0.478	–											
Zr	–0.247	–0.161	0.260	–										
Nb	–0.341	–0.238	0.325	*0.917*	–									
Y	–0.154	–0.111	0.097	*0.759*	*0.730*	–								
La	–0.187	–0.132	0.082	*0.630*	*0.647*	*0.773*	–							
Zn	–0.246	–0.146	0.215	*0.725*	*0.788*	*0.682*	0.579	–						
Pb	0.025	–0.032	0.044	0.473	0.460	0.432	0.365	0.457	–					
Th	–0.202	–0.240	0.090	0.499	0.560	*0.758*	0.562	*0.671*	0.439	–				
U	–0.274	–0.393	0.294	0.521	0.562	0.430	0.382	0.531	0.297	0.378	–			
V	–0.362	–0.233	0.309	0.241	0.325	0.005	0.033	0.230	0.215	0.154	0.248	–		
Cu	0.432	0.294	–0.432	–0.026	–0.040	–0.003	0.081	0.169	0.074	–0.067	0.030	–0.128	–	
Ni	0.120	0.086	–0.071	–0.015	–0.019	–0.006	–0.016	–0.035	–0.029	–0.053	–0.014	–0.013	–0.026	–

The values include hydrothermally altered rocks, accumulative rocks and recrystallised rocks. Values greater than 0.600 are italicised. The enclosed area includes all elements which appear to behave in a 'residual' manner and hence show reasonably high correlation.

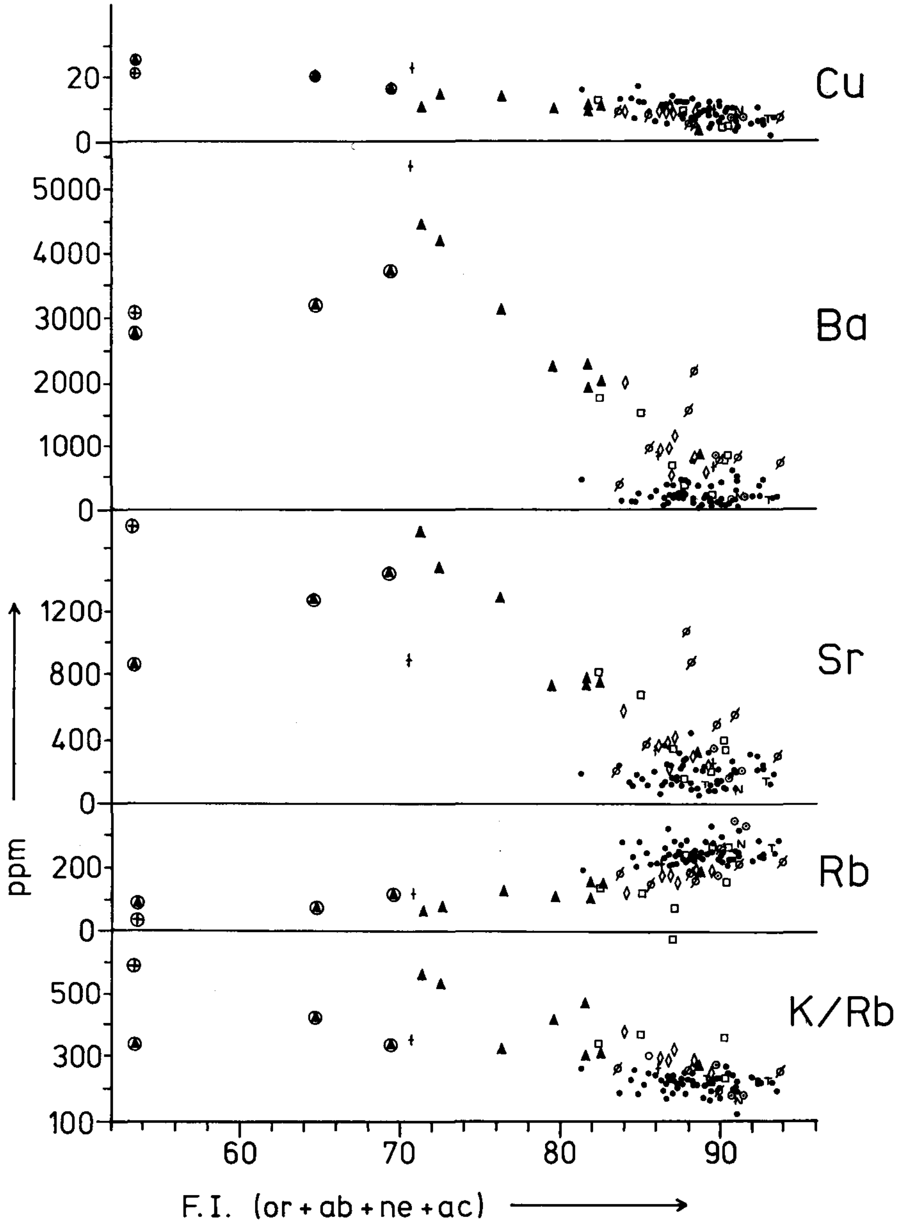
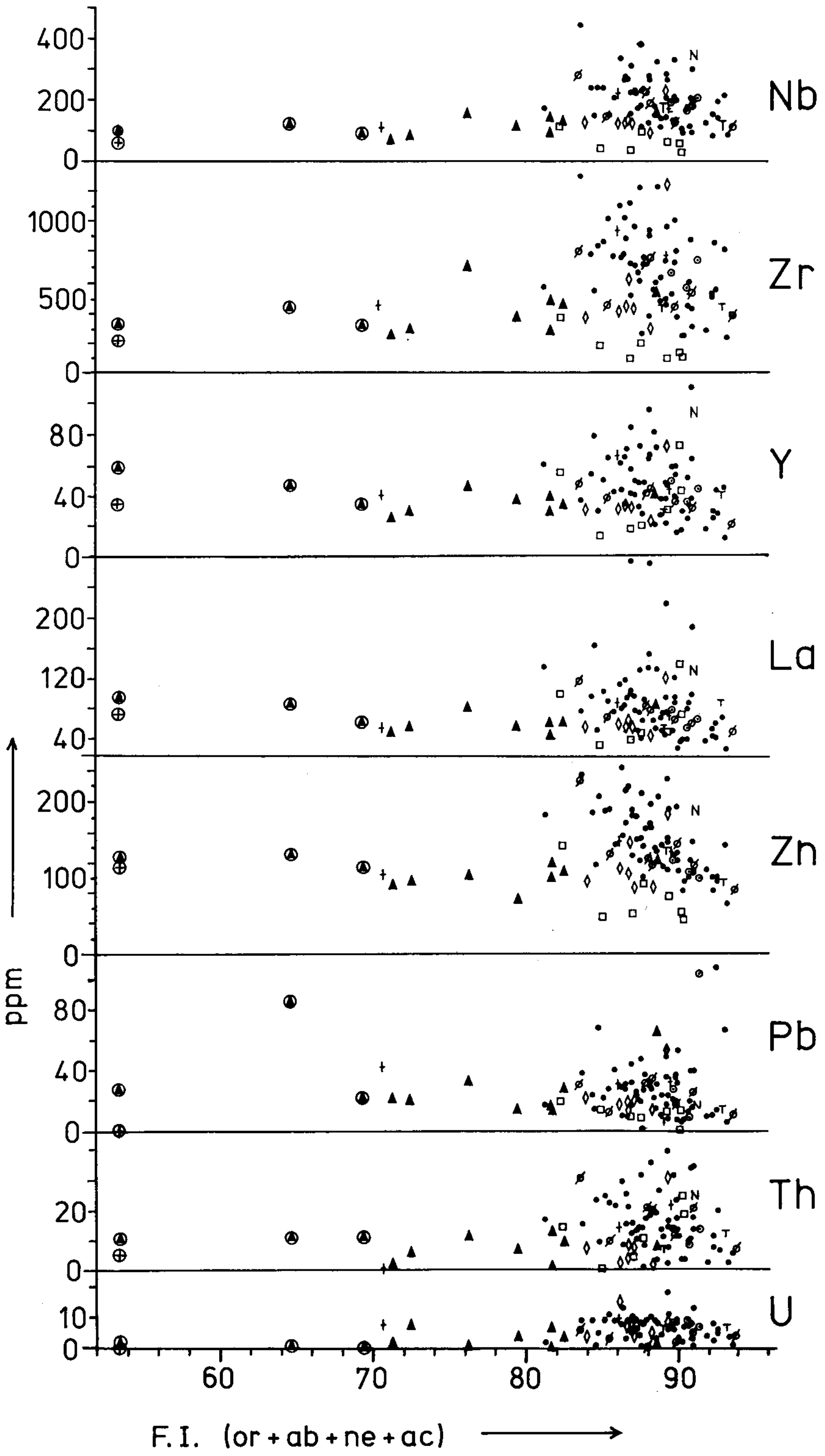


Fig. 7. Trace element variation in the South Qôroq Centre rocks. 'Fractionation Index' (F.I.) and symbols as for fig. 5.



Nb
Zr
Y
La
Zn
Pb
Th
U
400
200
0
1000
500
0
80
40
0
200
120
40
200
100
0
80
40
0
20
0
10
0
60
70
80
90
ppm
F.I. (or + ab + ne + ac)
N
T

Fig. 7 *cont.*

relative to K (1.33Å) in the liquid (Taylor, 1965). The strong Rb-enrichment is evident from the K–Rb diagram (fig. 8) in which the South Qôroq trend is very oblique to the average K:Rb curve of Ahrens *et al.* (1952). Differences between individual syenites can be recognised on this trend, and the more differentiated nature of SS3 is particularly well seen. The 'essexite' and two of the augite syenites lie outside the normal limits of scatter (Ahrens *et al.*, op. cit.) on the Rb-deficient side. Rb-deficiency also occurs in several less fractionated rocks from the Kûngnât Complex (Upton, 1960) and is correlated with an increased Ca and/or Ba content in the crystallising feldspar restricting the entry of Rb (Heier & Taylor, 1959).

Zirconium, niobium, yttrium, lanthanum and zinc

These elements do not substitute readily for major elements in the rock forming minerals and are concentrated in residual liquids (Taylor, 1965). In strongly differentiated series they therefore increase with fractionation. In the South Qôroq Centre values tend to be fairly constantly low, or increase sligtly with F.I. in the augite syenites, but show a wide scatter over much higher values in the foyaites and related rocks. Within the scatter the five elements behave almost identically as is demonstrated by their high correlation coefficients given in table 6. In some elements there is a suggestion, particularly within individual intrusions that values are highest in foyaites with a lower F.I. and that there is then a rapid decrease with fractionation. Zircon and other zirconium silicates are not common in the rocks, but it has been shown that Zr can enter aegirine and alkali amphibole to a large extent substituting isomor-

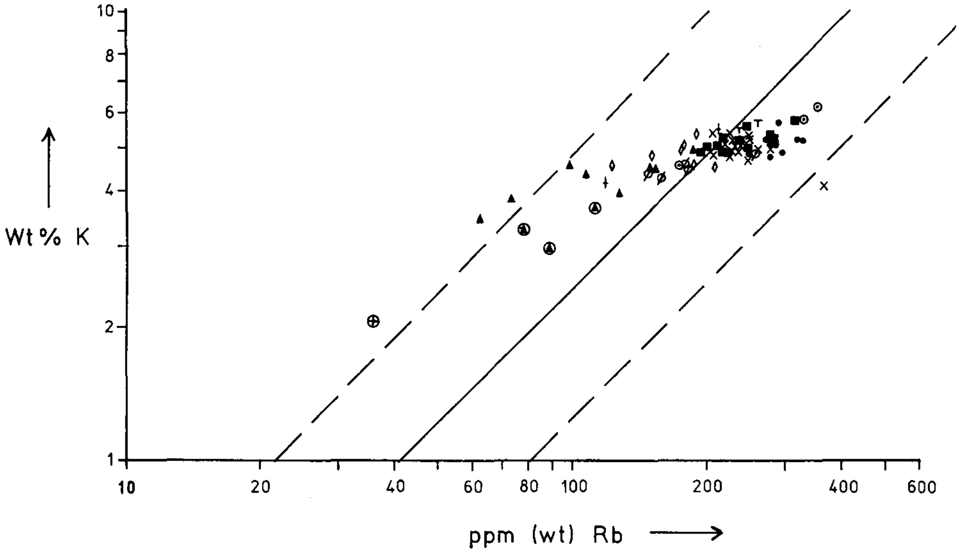


Fig. 8. Potassium (cation wt %) versus rubidium (wt ppm) diagram for the South Qôroq Centre rocks. Average K:Rb curve and normal limits of scattering taken from Ahrens *et. al.* (1952). × SS2, ● SS3, ■ SS5. Other symbols as in fig. 5.

phously for Ti (Degenhardt, 1957; Bowden, 1966; Gerasimovsky, 1974). It is therefore possible that the residual elements may enter late-crystallising sodic clinopyroxene and/or alkali amphibole and are thus subsequently reduced during the final stages of crystallisation. However, Macdonald & Parker (1969) found that Zr concentrations in aegirine and alkali amphibole are unable to account for whole rock content in Tugtutôq alkaline dykes, and tentatively suggest the presence of sub-microscopic, Zr-rich accessory minerals.

The wide scatter of values observed in the 'residual' elements of the foyaites probably reflects the ease with which these elements are removed by hydrous solutions in the final stages of crystallisation. This will be discussed more fully in relation to the aureole of the Igdlerfigssalik Centre where rocks show a drastic depletion in 'residual' elements.

Lead, thorium and uranium

The heavy elements appear from fig. 7 to have a similar residual behaviour to the previous group, although they do not show such strong correlations (table 6). Radioactive minerals are not detected in the syenites and (Th + U) never exceeds 60 ppm. In many samples they are near or below the detection limits.

Copper, nickle and vanadium

Copper shows a steady decrease from the 'essexite' through augite syenites to the foyaites, where concentrations are less than 10 ppm. Ni and V values are close to or below the detection limits and are thus not included in fig. 7.

Microsyenite sheets and satellitic syenites generally conform to the trends as in the major elements. However, the Østfjordsdal Syenite, having a lower K_2O content, is correspondingly depleted in Rb and enriched in Ba and Sr relative to the other rocks.

Variations with height in the intrusion are not detected, and trace elements show less systematic variation towards the edges of intrusions than the major elements due to scattering, probably acquired during the late stages of crystallisation. However, some elements have fairly constant values in the centres of intrusions, but show increased scatter towards the margins. This is demonstrated in fig. 6 by the Zr content of SS2.

Normative mineralogy and comparisons with experimental systems

With the exception of mafic cumulates and two less fractionated samples from SS4b, all the unaltered South Qôroq Centre rocks have normative (ab+or+ne) greater than 80 per cent and have been plotted in 'Petrogeny's Residua System' (Q–ne–ks) (Bowen, 1937). The peralkalinity index is very close to 1.0 for most

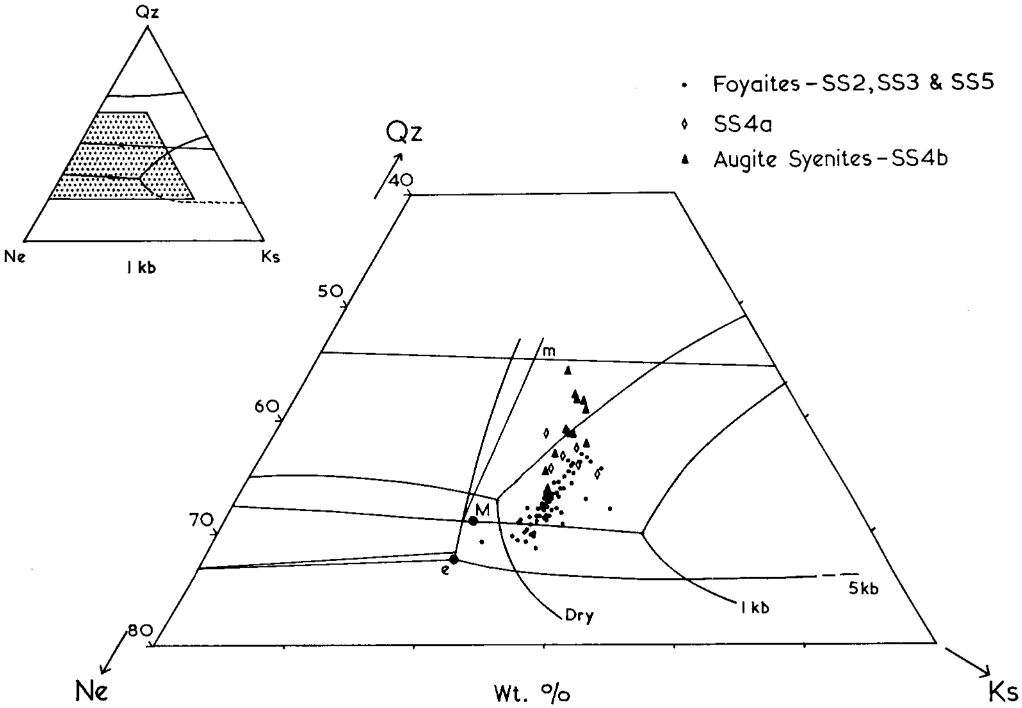


Fig. 9. Analyses from the main units of the South Qôroq Centre plotted in the Q–ne–ks 'residua system'. Phase equilibria relationships at 1 atm, 1kb P_{H_2O}, and 5kb P_{H_2O}: 1 atm after Schairer (1950); 1 kb after Hamilton & MacKenzie (1965); 5 kb after Morse (1969). m = feldspar binary minimum at 1 kb, M = 'nepheline syenite' ternary minimum at 1 kb, e = 5kb eutectic. Unique fractionation paths at 1 and 5 kb are also shown.

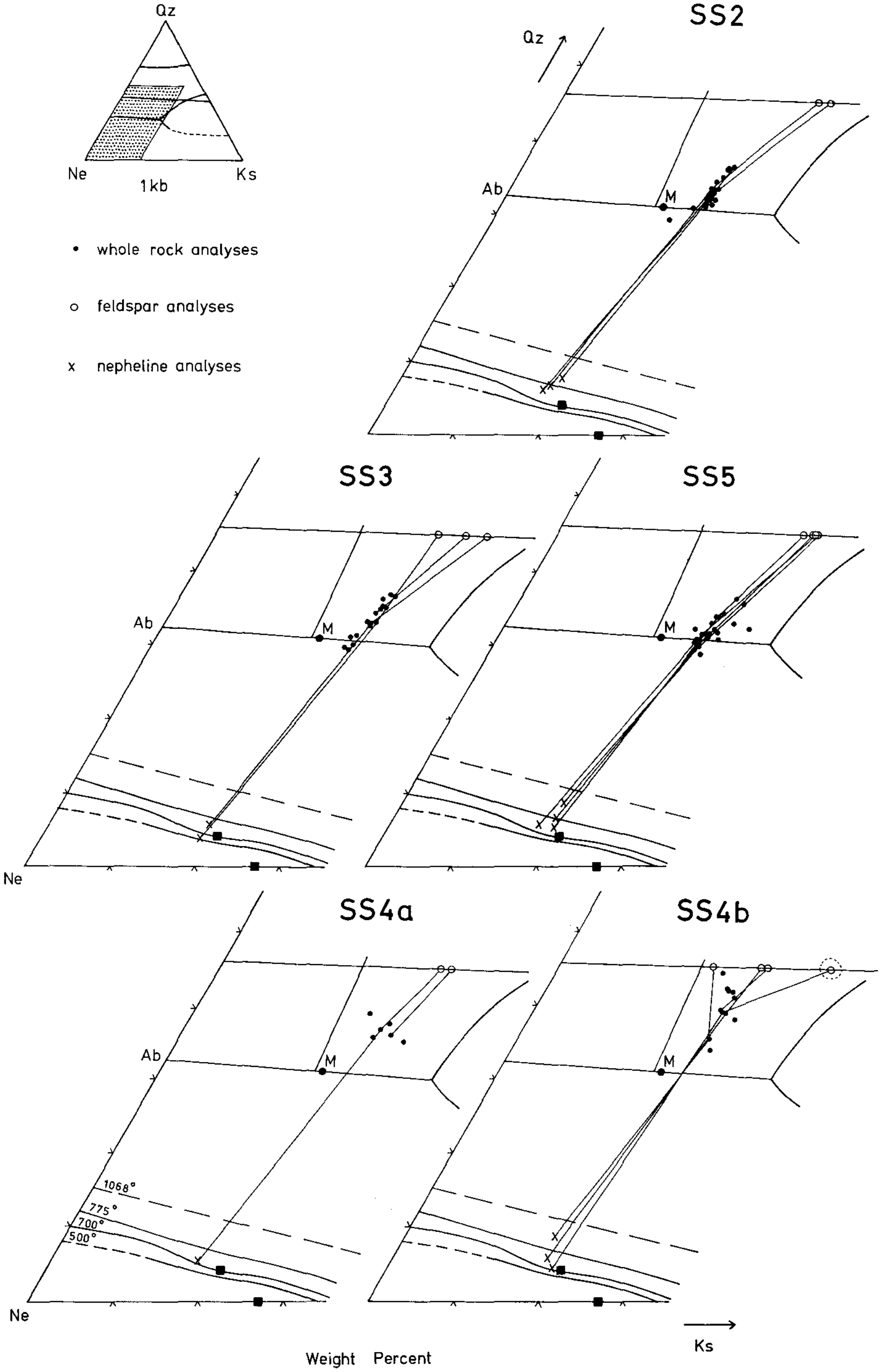
of the foyaites and only the more fractionated rocks are peralkaline. Hence the analyses lie close to the Q–ne–ks plane, and distortions due to the normative allocation of the excess alkalis over aluminium are only significant in the most fractionated samples (Bailey & Schairer, 1964; Thompson & MacKenzie, 1967). Rocks from the main intrusive units (with the exception of hydrothermally altered rocks) are shown in fig. 9 in relation to phase equilibrium relationships in the Q–ne–ks system at 1atm (Schairer, 1950); at 1 kb P_{H_2O} (Hamilton & MacKenzie, 1965); and at 5 kb P_{H_2O} (Morse, 1969).

The rocks lie on a curving trend (concave towards the ne–Q join) from the least fractionated augite syenites of SS4b near to the or–ab thermal divide, through SS4a and the foyaites, to a minimum in the region of the feldspar–nepheline phase boundary. Several analyses fall just inside the nepheline field at 1 kb, but are well within the feldspar field at 5 kb. By comparison with the experimentally-derived fractionation curves at 1kb (Hamilton & MacKenzie, 1965), the foyaites would appear to lie along a line parallel to the unique fractionation curve in the low temperature thermal trough, and are derived via the augite syenites from the sodic side of the trough. Although the shape of the fractionation curve conforms to that of experimental equivalents, there is a considerable overall displacement towards ks in the South Qôroq rocks compared with both the experimental data and the density distribution of natural rocks from Washington's tables (Hamilton & MacKenzie, op. cit.). It is not unusual for such a displacement to occur in natural rock series, due to the presence of other phases (such as an and ac) not represented in the 'Residua System' and the trend is similar to natural fractionation curves derived by Nash *et al.* (1969) for Mt. Suswa lavas. Peralkaline rocks (with normative acmite) are particularly prone to displacement; and the true South Qôroq minimum is probably approaching that of the 'Peralkaline Residua System' Na_2O–Fe_2O_3–Al_2O_3–SiO_2 described by Bailey & Schairer (1966). Engell (1973) has related rocks of the Ilímaussaq Complex to this system, in which they are seen to be fractionating towards a eutectic at which ab, ne, ac, ds and liquid coexist. Phase relations in this system are significantly affected by P_{H_2O}, P_{O_2} and the amount of diopside component in the clinopyroxene. The latter factor is even more significant in the South Qôroq Centre which is more Mg-rich than Ilímaussaq, resulting in a considerable expansion of the ac field (Nolan, 1966). Thus, although the South Qôroq rocks show a similar pattern to those of Ilímaussaq (Engell, 1973, figs 3 & 6), there is a considerable displacement relative to the theoretical phase boundaries.

In fig. 10 analyses from the various units of the centre are plotted with tie lines to average feldspar and nepheline compositions from individual samples (where available from microprobe analyses). Regular relationships between whole rock analyses and the felsic phases conform to those expected from experimental investigations and suggest that the rock compositions are little modified by accumulation of the felsics. The trends seen in figs 9 & 10 are thus considered to be close approximations to liquid lines of descent derived by alkali feldspar fractionation.

Fractionation of a relatively sodic alkali feldspar is seen in SS4b and feldspar compositions become more potassic as the liquid moves towards the thermal trough defined in fig. 9. Eventually, liquids in the trough precipitate feldspars having compositions at the intersection of the trough with the feldspar join. At this stage, which is particularly well seen in SS4a and SS5, tie lines between feldspar, rock and nepheline are straight and are parallel to the unique fractionation curve (Hamilton & MacKenzie, 1965). By analogy with the experimental phase boundaries, the intersection of the trough with the feldspar join should approximately indicate the position of the feldspar binary minimum at this stage. However, in SS2 and SS3 several samples have feldspars on the potassic side of the projected minimum. Such samples are all seen to have peralkaline bulk compositions (i.e. the liquid has moved out of the Q–ne–ks plane) and the feldspar, rock and nepheline compositions form a three-phase triangle.

Hypothetical phase relations and crystallisation paths for peralkaline under-


Qz
Ne
Ks
1 kb
• whole rock analyses
o feldspar analyses
x nepheline analyses
SS2
Qz
Ab
M
SS3
SS5
Ne
SS4a
SS4b
1068°
775°
700°
500°
Weight Percent
Ks

saturated liquids within the SiO_2–Al_2O_3–Na_2O–K_2O system have been suggested by Nash *et al.* (1969, figs 11 & 12) based upon Mt. Suswa lavas. Owing to the curvature of the 'low temperature surface' (the surface extending the thermal trough from the Q–ne–ks plane) concave towards ab, peralkaline liquids approaching from the sodic side of the surface precipitate feldspars which become increasingly more potassic. This is well demonstrated by several of the Mt. Suswa peralkine lavas and also by the more peralkine South Qôroq rocks. Consequently, to enable this to occur the feldspar minimum must move considerably towards Or from its original position on the projection of the thermal trough as the liquid becomes more peralkaline. Not all of the South Qôroq foyaites have peralkaline bulk compositions, but they are clearly fractionating towards a peralkaline final residuum, manifested in the rocks by interstitial sodalite and cancrinite. Thus, even in rocks with non-peralkaline bulk compositons, the outer zones of feldspars may be K-enriched due to the above effect.

EFFECTS OF RECRYSTALLISATION AROUND THE IGDLERFIGSSALIK CENTRE

Marked textural and mineralogical changes occur in the South Qôroq Centre rocks in a wide zone around the later Igdlerfigssalik Centre, and in certain areas remobilisation has occurred. On the west side of Qôroq progessive alteration can be traced southwards along the coast section in the foyaites. Fayalite, the first mineral to react, is pseudomorphed by chlorite and iron-oxides and finally disappears. Aegirine-augite and biotite begin to show a clearly recrystallised, poikilitic texture; and very near to the contact the mafics are completely made over to 'knots' of iron oxide and decussate biotite flakes. Iron-titanium oxides recrystallise into discrete phases of magnetite and ilmenite with associated sphene. The alkali feldspars become irregular in shape with lobate or interlocking margins and are coarsely perthitic. In extreme cases the nepheline is highly altered with much development of interstitial cancrinite and calcite. Similar effects are observed in SS4b and SS4a with coarsely perthitic feldspar and altered nepheline. Some samples also have additional fresh nepheline which may have been developed during recrystallisation. The pyroxene becomes a more sodic, green aegirine-augite (Stephenson,

←
Fig. 10. Analyses from individual units of the South Qôroq Centre together with coexisting average feldspar and nepheline analyses, where available, plotted in the 'residua system' Q–ne–ks. Phase relationships at 1 kb P_{H_2O} after Hamilton & MacKenzie (1965). Limits of nepheline solid solution after Hamilton (1961). N.B. extreme potassium enrichment in the feldspar from a recrystallised rock in SS4b (circled).

1972), but some retain cores of titanaugite. Olivine is unstable; and amphibole, where present, is often a blue-green variety.

Recrystallised rocks near to the Igdlerfigssalik Centre show little deviation from normal values in most major elements (fig. 5). Where the recrystallisation is most intense, samples of SS3 and SS4 have a slight depletion in total Fe, and some samples of SS4b have a slightly increased iron oxidation ratio. It has been shown (Stephenson, 1972) that clinopyroxenes from recrystallised rocks are more sodic than those from unrecrystallised equivalents. This is particularly noticeable in SS4b where there is a corresponding decrease in Na/K in the alkali feldspars. However, there is no apparent increase in the whole-rock content of Na_2O and K_2O, and some samples of SS3 and SS4a actually show a depletion.

The most apparent chemical feature of the recrystallised rocks is their depletion in the 'residual' trace elements (fig. 7). Such elements may have been concentrated in late-crystallising amphibole which is usually replaced by biotite during recrystallisation. This could have led to a release of those elements which were unable to be accommodated in any available lattice after the disappearence of amphibole. Whatever the mechanism of release, the removal was probably enhanced considerably by the presence of aqueous solutions during reheating (see below).

Increased oxidation and high diffusion rates in recrystallised rocks are suggested by the fact that, in more extreme examples, ilmenite and magnetite occur as discrete phase instead of in the normal exsolution relationship. The clinopyroxene trends of such rocks suggest some form of constant fo_2 buffering, at least during part of their crystallisation (Stephenson, 1972). Fayalite is absent from the recrystallised zone and the hydrous mafic mineral tends to be biotite rather than amphibole. These features suggest that fo_2 had been raised above the appropriate FMQ buffer (Stephenson, 1974).

The relative increase in fo_2 is associated with the incorporation of more Na-Fe^{3+} in the pyroxenes, and in the SS4b sample investigated there is a corresponding decrease in Na/K in the alkali feldspars. The alkali feldspars themselves are very coarsely exsolved perthites, indicating a high degree of sub-solidus ordering. Emeleus & Smith (1959) have shown that this is favoured by a fairly high P_{H_2O} and slow cooling rates. Temperatures of crystallisation deduced from the nepheline compositions (Hamilton, 1961) do not indicate any significant rise in temperature during recrystallisation, so it is suggested that temperatures were sustained for a longer period in the recrystallised rocks under hydrous conditions, thus contributing to the increased feldspar ordering.

It therefore seems highly likely that the recrystallisation took place under increased P_{H_2O} conditions due to aqueous solutions emanating from the Igdlerfigssalik magmas. These solutions were probably CO_2-bearing as is implied by the increase of calcite and cancrinite in the recrystallised zone. Dissociation of the H_2O and loss of H_2 could increase relative oxygen fugacity at any given temperature as is observed from the mafic mineralogy. The increased P_{H_2O} and sustained temperatures led to increased sub-solidus ordering in the feldspars and the solutions were probably responsible for the removal of 'residual' trace elements from the zone of recrystallisation. Unfortunately, there is insufficient evidence to determine whether these elements are concentrated around the edge of the zone, but it seems likely that they were ultimately removed upwards and lost to the surface. These effects cast doubt upon the validity of using elements such as Zr as differentiation indices in rock suites, since their 'residual' behaviour is so easily disrupted. However, they do give a valuable insight into the behaviour of trace elements during reheating of a magmatic rock under aqueous conditions and the earliest stages of partial melting.

SOURCE AND EVOLUTION OF THE SOUTH QÔROQ CENTRE MAGMAS

Field relationships show that the South Qôroq Centre is made up of a series of concentric, high-level intrusions emplaced in fairly rapid succession. The trend towards successively less fractionated magmas with time can be seen from the petrography and geochemistry, but is particularly well demonstrated by the clinopyroxene trends.

Upton *et al.* (1971) describe similar situations in the Gardar silica-oversaturated syenite complexes of Kûngnât and Central Tugtutôq. At Kûngnât, later intrusions become successively less fractionated, crystallising under conditions of slow cooling to give accumulative sequences with considerable cryptic layering. At Central Tugtutôq, which is a higher-level intrusion, a succession of magma batches already below their liquidus temperatures were intruded in rapid succession. Cooling was faster than at Kûngnât and *in situ* fractionation was negligible, although deeper levels may have similar accumulative sequences to those at Kûngnât. In both cases Upton *et al.* (op. cit.) consider that the complexes were derived from a deeper magma chamber which had already differentiated giving trachytic compositions overlying more basic magma at depth. It is suggested that the South Qôroq Centre is analogous to the Central Tugtutôq Complex and that separate intrusions were derived from some form of differentiated chamber at depth, from which progressively deeper fractions worked up to the surface separated by short time intervals.

Objections may be raised to a model invoking tapping of a differentiated magma chamber on the grounds that lower levels would be largely crystalline long before they could be emplaced. The syenites were emplaced over a short time interval, and it could be significant that there is very little material more basic than augite syenite in all the Gardar major intrusions. Thus it is possible that the higher levels of the magma chambers were tapped off, forming intrusions of syenite, nepheline syenite and augite syenite, but that the lower, more basic levels were too highly-crystallised to rise to higher levels. However, there is no direct evidence to support this such as less fractionated (deeper origin) rocks being more porphyritic.

Liquid fractionation

Alternatively a residual magma of augite syenite composition may have become compositionally zoned through some form of liquid fractionation, to act as a largely liquid parent body for the higher level intrusions.

Liquid fractionation involving a vertical column of magma, progressively more salic in composition at higher levels, is envisaged by Bridgwater in Bridgwater & Harry (1968) as the principal source of high-level Gardar dykes involving pulses of magma with widely varying composition. Thus the primary compositions of the feldspars and other minerals in each magma batch would reflect the composition of the liquid at the depth of origin. A similar mechanism is proposed by Lipman *et al.* (1966) and Lipman (1967) for the source of compositionally zoned salic ash-flow sheets in southern Nevada and south-western Japan. It is also implied by Gibson (1970) for welded ash-flows from Fantale volcano, Ethiopia.

Although this hypothesis is perhaps the simplest way of explaining compositional differences in successive magma pulses, and particularly such mineralogical variations as are seen in the South Qôroq clinopyroxenes (Stephenson, 1972), it is difficult to envisage a mechanism whereby such a column of liquid may be generated and perpetuated on such a large scale. A certain amount of crystallisation is bound to occur, and it is clear that many Gardar intrusions were in fact partly crystalline on emplacement.

The most likely mechanism of liquid fractionation is an upward diffusion of alkalis in the liquid, aided by volatile transfer (Kennedy, 1955) and such a process is envisaged by Sørensen (1958, 1960) as having operated during the evolution of the Ilímaussaq agpaitic magma. Increased solubility of volatiles in peralkaline magmas is demonstrated by Kogarko (1974) and hence volatile transfer is possible without the separation of an aqueous vapour phase considered necessary in silicate melts by Burnham (1967). The South Qôroq magmas are seen to have a reasonably high volatile content, and outward volatile transfer under a thermal diffusion gradient after emplacement has been suggested. At relatively low pressure a gradual transition is possible from alkali–silicate melt into aqueous liquid solution (Kogarko, 1974) and such solutions were probably responsible for much of the alteration of South Qôroq Centre rocks around the Igdlerfigssalik Centre.

Thus, although large-scale liquid fractionation processes prior to emplacement seem unlikely in the South Qôroq Centre, volatile transfer of alkalis can be suggested as a mechanism for the modification of interstitial, residual liquids in the later stages of magma evolution.

Fractional melting or fractional crystallisation?

In recent years several authors (Bailey, 1964, 1970; Bailey & Schairer, 1966; Wright, 1971) have presented convincing evidence for the derivation of trachytic and phonolitic magmas by melting of mantle material in areas of high geothermal gradients such as are found in rift environments. Therefore an alternative hypothesis is that successive intrusions in the South Qôroq Centre were produced by successive stages in partial melting of crustal or upper mantle material. Major and trace elements of the early-melting mineral phases would form the first low-temperature melts, probably with some diffusion out of intergranular areas. Immediate removal of earlier-formed magma to higher crystal levels would result in later batches being more basic in composition (fractional melting). Since there is little material of more basic composition than augite syenite in the central complexes, it may be that temperatures seldom rose above the augite syenite liquidus. This apparent lack of basic material at present erosion levels would tend to favour a fractional melting hypothesis, but it is highly likely that large volumes of basic material are present at greater depths beneath the complexes (see below).

The continuous major element trends from augite syenite to foyaite in the South Qôroq Centre are suggestive of fractional crystallisation of a common magma source. Curves having pronounced kinks which correlate with the appearance of a new cumulus phase (e.g. Na_2O with nepheline) are particularly characteristic of crystal fractionation trends. Such an origin is also implicated by liquid trends in the system Q–ne–ks and definite crystallisation trends in individual mineral phases. In particular the alkali feldspars exhibit regular crystal/liquid relationships suggesting that they constitute a major fractionating phase. Liquids derived by fractional melting would be expected to show much more irregular trends, probably with compositional breaks corresponding to temperature intervals during which addition of heat caused no melting (Presnall, 1969; Roeder, 1974).

Similarly the trace element distribution observed in the South Qôroq Centre is unlikely to have been produced by fractional melting, the highly ordered enrichment and depletion of elements being more consistent with fractional crystallisation (Taylor, 1965; Taylor *et al.*, 1968). Ba and Sr decrease rapidly to low levels of concentration as is usually observed in the late stages of evolution of a magma in which alkali feldspar fractionation has played a major part. K enters preferentially over Rb into alkali feldspar, and hence in successive liquids the K/Rb ratio is progressively reduced (Taylor, 1965). These features are well illustrated in the centre, implying a considerable amount of alkali feldspar fractionation. Crystal fractionation would also lead to a build up in residual elements (Zr, Nb, Y, La, Zn, Pb, Th, U) in late liquids and this too is seen.

Elsewhere in the Gardar province continuous gradations of rock type within individual field units suggest fractionation *in situ*. In the giant dykes of Isortoq gradations are observed from olivine dolerite to quartz syenite (Bridgwater & Coe, 1970; Watt, 1966), and in the Hviddal dyke there is a gradation from augite syenite to nepheline syenite, both rock types being similar to those of the South Qôroq Centre (Upton, 1964c). Thus, although it is recognised that comparative data are unavailable for magma series with a proven origin by fractional melting, the evidence strongly suggests evolution of the South Qôroq Centre by fractional crystallisation of an augite syenite magma. This magma was itself most likely derived by fractional crystallisation of a more basic source which, by analogy with exposed basic rocks in the province, is considered to be alkali olivine basaltic in composition (Upton, 1974). Isotopic work on a wide range of rocks from the Gardar Province has shown that low initial Sr^{87}/Sr^{86} ratios are consistent with a lower crustal or upper mantle origin (van Breemen & Upton, 1972; Blaxland *et al.*, in press). These values include a ratio of 0.7029 ± 0.0004 from the South Qôroq Centre.

Mechanisms of fractional crystallisation

Bridgwater & Harry (1968) and Upton (1964b) present evidence for the presence of large anorthositic bodies beneath much of the Gardar province, locally associated with layered, anorthositic gabbros. Fragments of these rocks are incorporated as xenoliths in a suite of differentiated Gardar dykes (the 'Big Feldspar Dykes' or 'BFDs') and are seen to consist of labradorite with varying amounts of olivine, iron-titanium oxides, ortho- and clinopyroxene. Thus it is probable that removal of early-formed plagioclase in such anorthositic bodies gave rise to liquid residua of trachytic composition. These were emplaced as augite syenite magmas which appear to fulfil a parental role in most of the Gardar major intrusions.

Continued plagioclase feldspar fractionation and removal of Ca + Al results in a trend towards increasing peralkalinity of successive residua. In the South Qôroq Centre microprobe analyses of the feldspars show a range from a sodic oligoclase, through Ca-bearing anorthoclase in the augite syenites, to K-rich alkali feldspars in the foyaites. On reaching the feldspar–nepheline phase-boundary, nepheline began to co-precipitate with alkali feldspar. Marked changes in the chemical trends of the rocks are seen at this point, and feldspar compositions become enriched in potassium.

The South Qôroq element variation cannot be entirely explained by feldspar fractionation, and a considerable contribution must also have been made by fractionating mafic phases. Fayalitic olivine, iron-titanium oxide, apatite and titanaugite usually crystallise relatively early, particularly in the less differentiated augite syenites and are also found as cumulus phases in mafic bands. The reductions in Mg, Ti and P in the augite syenites and low concentrations in the foyaites can be attributed to fractionation of these phases. Continued fractionation of an alkali clinopyroxene would further deplete the liquid in Fe and Ca, although these elements are still present in the intercumulus which consists largely of alkali amphibole and/or biotite.

The importance of fractionating mafic minerals, particularly in the earlier evolution of the augite syenite magma, is emphasised by the few available analyses from SS4b mafic bands which lie on backwards extensions of the major element trends. Slight deviations in the Fe and Mn content of several foyaite samples suggest that mafic accumulation probably also occurred in the foyaites, particularly in SS5 where definite mafic bands are observed.

In order that the fractionation processes should be effective, it is necessary that some of the early-formed crystals be removed from the liquid by crystal settling. It is therefore possible that a series of layered cumulates is present below the South Qôroq Centre in a situation analogous to the Kûngnât and Central Tugtutôq relationship (Upton *et al.*, 1971). Cryptic layering is present in unit SI4 and possibly other units of the Igdlerfigssalik Centre, but has not yet been recognised in the other Igaliko intrusions.

Magmatic development and sequence of intrusion

It has already been suggested that the South Qôroq magmas were below their liquidus on emplacement. Feldspar and in some cases possibly nepheline were the principal phases at the liquidus, but it is also likely that small amounts of magnetite and clinopyroxene had started to nucleate. Clinopyroxene in particular commonly occurs as phenocrysts in the associated Igaliko trachytic dykes. Melting experiments on similar undersaturated rocks from the province by Piotrowski & Edgar (1970) and Sood & Edgar (1970) have shown that under most conditions of P_{H_2O} and P_{O_2}, clinopyroxene is either the primary liquidus phase or appears within 20°C of the liquidus after feldspar and/or nepheline. Thus, in each of the South Qôroq intrusions, the starting point of the respective pyroxene trend probably reflects the composition of the pyroxene on intrusion, and hence the depth of origin in the underlying magma chamber (Stephenson, 1972).

The earliest syenite (SS2) has a trend which starts fairly early in the pyroxene series, probably due to intrusion before much differentiation had taken place at depth. Pyroxenes from this syenite also show considerable zoning which reflects the relatively rapid cooling against country rock, preventing continuous reaction with liquid. (This is also seen in several other minerals). The next syenite (SS3) contains the most fractionated pyroxenes, with a considerably advanced starting point, indicating an origin near the top of the differentiated chamber which had now formed. Successive intrusions (SS5, SS4a, SS4b) then show a continuous regression of starting point due to tapping from deeper levels.

The satellitic syenite stocks around the periphery of SS2 would in general appear to be derived from the same or a similar source to the rest of the centre. They lie, on the same major and trace element trends with the exception of the Østfjordsdal Syenite which is slightly less potassic and is correspondingly depleted in Rb and enriched in Ba and Sr relative to the other syenites. All the satellites were emplaced earlier than the main centre and hence may represent small batches of magma which separated at an early stage and subsequently evolved along slightly different lines.

TEMPERATURE AND PRESSURE OF CRYSTALLISATION OF THE SOUTH QÔROQ CENTRE MAGMAS

Estimates of liquidus temperatures of natural magmas from experimental phase equilibria are usually unreliable due to the presence of additional components; inaccuracies in estimating P_{H_2O} and P_{O_2} in the magma; and the inability to take into account variations of P_{H_2O} and P_{O_2} during crystallisation. However, in the South Qôroq Centre data are available on alkali feldspar and nepheline, both of which appeared at or close to liquidus temperatures and together constitute about 80 per cent of the rocks.

Consideration of the experimental data in the system Ab–Or (Bowen & Tuttle, 1950; Yoder *et al.*, 1957; Tuttle & Bowen, 1958) enables broad estimates of crystallisation temperature and pressure to be made. Since the feldspars are all hypersolvus, they must have crystallised at a P_{H_2O} of less than 4.2 kb, since at this pressure in the Ca-free system the solidus and solvus intersect resulting in two separate feldspar phases (Morse, 1970). In the South Qôroq Centre, however, it seems likely that most of the crystallisation took place under a P_{H_2O} of about 1 kb since the maximum observed cover of basalt and sandstone in the area is known to be 3 km, and there is no evidence such as vesicular pegmatites to suggest that hydrostatic pressure was exceeded. This is supported by a good correlation between normative rock compositions and the 1 kb phase equilibria in the Q–ne–ks system. Crystal fractionation probably resulted in a build-up in P_{H_2O} during the later stages of crystallisation, particularly in the foyaites, but this could not have exceeded 4.2 kb.

The temperature of crystallisation of the feldspars may be determined from the feldspar minimum in the system Or–Ab–H_2O. The maximum possible value is 1063°C in the dry system (1 atm), but this reduces to 840°C at 1 kb which is the approximate pressure estimated in the South Qôroq Centre. The lowest possible temperature is governed by the temperature at which the solidus and solvus intersect. This is considered to be 750°C at 2 kb P_{H_2O} with 1 per cent An by Parsons (1965), but the low Ca content of the South Qôroq foyaite feldspars could make this as low as 715°C (the temperature of the intersection at 4.2 kb in the Ca-free system (Morse, 1970)). Augite syenite feldspars, having an appreciable Ca content, may have commenced crystallisation at temperatures somewhat above 840°C. However, the relatively flat nature of the solidus in the Ab–Or system over the range of foyaite feldspar compositions suggests that these feldspars completed crystallisation within 20° of 840°C unless P_{H_2O} rose significantly during their crystallisation.

A more reliable geothermometer is provided by nepheline (assuming no subsolidus adjustments), since compositions are almost independent of other variables (Hamilton, 1961). Cores of zoned nepheline in SS2 suggest that the phase commenced crystallisation between 900 and 850°C which is a reasonable correlation with the 840°C suggested by foyaite feldspars (augite syenite feldspars slightly higher). Whereas the feldspars probably completed crystallisation within 20°C, most nepheline grains appear to have stabilised between 775 and 700°C irrespective of magma type (augite syenite or foyaite). This shows good agreement with the undersaturated minimum in the 1 kb 'residua system' which is at 750°C.

LATE-STAGE CRYSTALLISATION CONDITIONS

A build-up of P_{H_2O} in the later stages of crystallisation of all the rocks of the centre is seen by the appearance of interstitial hydrous phases. Alkali amphibole becomes stable in place of clinopyroxene and in many samples biotite forms a second hydrous phase. The stability of both phases is enhanced by the gradually decreasing oxygen fugacity which, by this stage, is above any fayalite–magnetite–quartz (FMQ) type of buffer and is probably decreasing along a buffer of the biotite–magnetite–alkali feldspar type (Stephenson, 1974).

Other volatiles were also exerting an influence on the final stages of crystallisation. Interstitial sodalite is common in most foyaite samples and is seen to be rich in Cl with no detectable SO_4. Calcite is also occasionally present in interstitial patches and a CO_2-rich residuum is implicated by the common reaction rims of cancrinite around nepheline grains and the presence of carbonate-rich veins within and around the syenites. Alkali amphibole analyses show appreciable amounts of F and occasional fluorite is seen. Outward migration of these volatiles under a thermal diffusion gradient as aqueous alkaline solutions has been suggested and local concentrations towards the margins of intrusions are seen as areas of coarser crystallisation ('patch pegmatites').

The presence of volatile fluxes in the later stages of cooling would be conducive to sub-solidus unmixing and structural ordering in the alkali feldspar (Emeleus & Smith, 1959). This is well demonstrated in the South Qôroq Centre where ordering is more pronounced in foyaite feldspars than in those of the augite syenites. The coarseness of perthites increases from augite syenites, through foyaites to a maximum in patch pegmatites and in rocks affected by recrystallisation under aqueous alkaline conditions.

SUMMARY

The interpretations on the magmatic and structural evolution of the South Qôroq Centre add considerable support to the conclusions of many workers in the Gardar province that the differentiated alkaline complexes can be derived from alkali olivine basalt via liquids of augite syenite composition largely by processes of fractional crystallisation (Engell, 1973; Upton, 1974). Fractional melting and removal of early melts to higher levels seems to be an unlikely mechanism, particularly in view of continuous major element trends, feldspar–liquid relationships, and trace element evidence. Large bodies of anorthositic gabbro postulated by Bridgwater & Harry (1968) probably gave rise to residua of augite syenite composition by fractionation and subsequent removal of plagioclase feldspar. Further fractionation of feldspar and mafic phases produced stratified magma chambers with an upward increase in salic constituents. Liquid fractionation through upward volatile transfer of alkalis may have contributed slightly to this stratification but such an effect is more noticeable in post-emplacement modification of residua. Tapping of a stratified magma chamber from successively lower levels produced a series of concentric, high level stocks of foyaite and a later ring-dyke of augite syenite to form the South Qôroq Centre.

Since the South Qôroq Centre is composed of batches of magma which were already below their liquidus temperatures and highly differentiated on emplacement into a fairly cool, high structural level, further differentiation after emplacement has been minimal (cf. Central Tugtutôq, Upton *et al.*, 1971). Occasional mafic bands, concordant with igneous lamination, have produced local variations. However, the main effect has been the volatile transfer of alkalis outwards under a thermal diffusion gradient established during cooling. This is seen as slight variations in element content across the intrusion with an increase in differentiation outwards. Marginal pegmatites, suggesting local accumulation of trapped volatiles, are common and there is often a zone of alkali metasomatism in the country rocks around the centre. Pegmatite veins representing the final magmatic residuum rich in volatiles (H_2O, CO_2 with Cl and F) and composed essentially of the low temperature phases albite, aegirine and calcite cut the outer syenite SS2.

Hydrothermal alteration of the rocks (particularly affecting nepheline) occurred in several areas, but was particularly active in the vicinity of faults, in shear zones and in marginal areas. Recrystallisation and slight remelting near to later Igdlerfigssalik magmas occurred under conditions of increased P_{H_2O} due to residual aqueous solutions emanating from these magmas. Although no metasomatic transfer of major elements can be demonstrated, the solutions seem to have been responsible for the removal of the 'residual' trace elements from the recrystallised zone.

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