# The Tertiary Kærven syenite complex, Kangerdlugssuaq, East Greenland: mineral chemistry and geochemistry

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## Abstract

The Kærven syenite complex, which reflects the hitherto earliest recorded stages in the Tertiary of East Greenland, outcrops in the middle reaches of the Kangerdlugssuaq Fjord as a peripheral intrusion to the Kangerdlugssuaq intrusion. The rocks of the Kærven complex range from syenite through alkali feldspar quartz-syenite to alkali feldspar granite. The general sequence of crystallization of the Kærven magmas was: alkali feldspar ± olivine($Fa_{96-99}$) ± plagioclase($An_{41-11}$), clinopyroxene (augite, ferrosalite, ferrohedenbergite), quartz and amphibole. Whole-rock major and trace-element data show coherent geochemical trends which suggest comagmatism. The data reveal that the Kærven rocks are distinct from the rocks from the adjacent Kangerdlugssuaq intrusion (e.g. higher $TiO_2$, $FeO^T$ in low-$SiO_2$ samples, lower $Na_2O$, approx. constant Zr/Nb). The mineral chemistry supports this conclusion, as the Kærven samples typically have calcic amphiboles and clinopyroxenes with a very limited Na-enrichment in contrast to the sodic trends of the Kangerdlugssuaq intrusion. Normative feldspar compositions plot near to the Ab–Or cotectic in the Q–Ab–Or system and a maximum pressure of crystallization of 3–5 kbar with moderate to low $P_{H_2O}$ is indicated.

Trace elements preferently incorporated in plagioclase and alkali feldspar, i.e. Sr, Ba and Rb, show systematics which are not compatible with an evolution of the rock suite by crystal fractionation of these phases, though possibly alkali feldspar may be partially accumulated in a few very evolved rocks. Numerical calculations do not suggest a magmatic evolution by fractional crystallization of the observed phases. The variation of Sr, Ba and Rb as well as of the incompatible elements Nb, Zr and Th support a derivation of the rock suite mainly by mixing two components, a syenitic and a granitic end-member. It is concluded that magma mixing was the most significant process in the formation of the Kærven rock suite accompanied by some crystal fractionation. Evidence for crustal contamination is detected in a few samples from the outer part of the intrusion but has not affected the main suite of rocks.

KEYWORDS: Kærven syenite complex, Kangerdlugssuaq, East Greenland, mineral chemistry, geochemistry.

## Introduction

THE East Greenland Tertiary Igneous Province is characterized by the extrusion of voluminous flood basalts most notably along the Blosseville Coast, and by a large number of extensive intrusive bodies, the largest concentration of which occur in the Kangerdlugssuaq Fjord area (e.g. Deer, 1976; Brooks and Nielsen, 1982). The Kærven Complex is an early satellite intrusion of the large, *c.* 800 $km^2$, Kangerdlugssuaq syenite intrusion situated near the western shore in the middle reaches of the Kangerdlugssuaq Fjord (Fig. 1). The Kærven syenite complex is of approximately cylindrical form and outcrops over an area of *c.* 10 $km^2$. It is surrounded to the north and east by an outer annulus-shaped layered gabbro intrusion a few hundred metres wide which intrudes the Archean basement (Ojha, 1966). Syenitic rocks were intruded into the gabbro leaving only minor parts intact. Later, during the emplacement of the Kangerdlugssuaq intrusion, the western parts of the Kærven syenite complex were partially removed. The syenitic Kærven complex was emplaced by multiple intrusions. A brief account of some aspects of the Kærven syenite complex has previously been given by Deer and Kempe (1976).

A recent K/Ar and $^{40}Ar/^{39}Ar$ study (Holm, in

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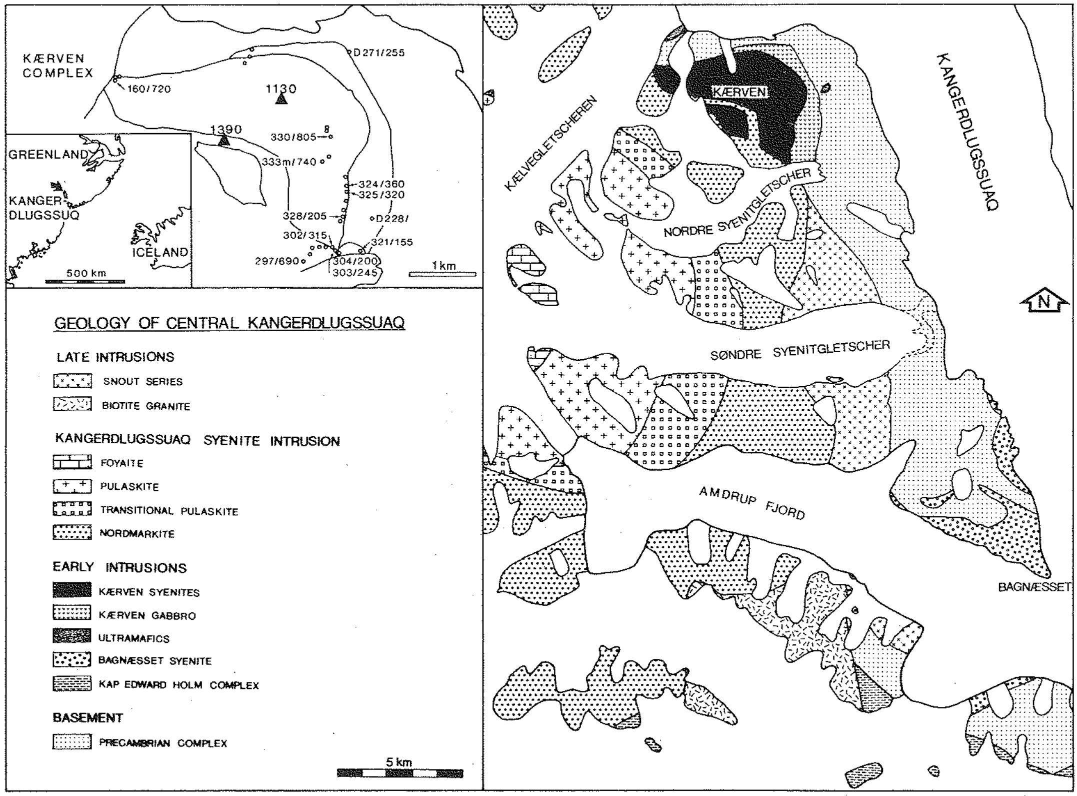

FIG. 1. Geology of the area between the eastern part of the Kangerdlugssuaq intrusion and Kangerdlugssuaq Fjord, after Kempe *et al.* (1970). Insets show the position of the Kangerdlugssuaq region and sample locations from the Kærven syenite complex. Locations of the samples of Table 1 and elevation of site above sea level are indicated.

prep.) has revealed that the Kærven complex was emplaced at *c.* 58 Ma, which is significantly earlier than the syenites of the Kangerdlugssuaq intrusion (Pankhurst *et al.*, 1976) and makes the Kærven complex the oldest Tertiary intrusion in the province established so far. Consequently, the Kærven Syenite Complex may retain information on the first manifestations of the still active Icelandic Hot Spot and the initial magmatism in the lower Tertiary triple junction of the Kangerdlugssuaq area (Brooks, 1973; Brooks and Nielsen, 1982) associated with continental break-up in this part of the North Atlantic.

This paper is concerned with the petrology and geochemistry of the Kærven syenite complex. Although the sample collection of this study is based only on reconnaissance field work, the results are nevertheless thought pertinent for discussion and allow some constraints to be placed on the petrogenesis. Additional sampling and detailed mapping must await further opportunities to visit this rather inaccessible area. The main issues of discussion are the petrogenetic importance of crystal fractionation, crustal assimilation, magma mixing and the mantle in the evolution of the Kærven rocks. An attempt is also made to evaluate the source rocks from which the magmas were derived and the relation of the Kærven rocks to those of the Kangerdlugssuaq intrusion.

## Field relations

In the field the complex appears to be a multiple intrusion with units arranged subparallel to the margins and displaced successively towards the west with all units being pre-nordmarkite. A general stratigraphic decrease in age from the gabbro through the syenitic Kærven rocks to the Kangerdlugssuaq nordmarkites is apparent. However, approximately N–S-trending felsic dyke-like bodies of 10–50 m width, of uncertain age, also cut the syenite and indicate that the geology is not simple. In places the syenites are loaded with fragments of basaltic rocks resembling intrusion breccia. Other types include apparently two-component rocks of felsic granitic and more mafic syenitic components indicating magma mixing. Syenitic veins, a few cm wide, are found in the basement along the gabbro contact and appear to be related to the intrusion of the Kærven syenites. Related syenitic dykes intrude the Kærven gabbro and the basement to the north and east. The Kærven gabbro is a separate intrusion with sharp contacts to the Kærven Syenite Complex. It is not included in this study.

## Analytical methods

Major elements were analysed by the Greenland Geological Survey, Copenhagen, by X-ray fluorescence analyses of glass discs prepared with a sodium-tetraborate flux, except for Na and Mg which were analysed by atomic absorption, and volatiles which were analysed by loss on ignition (Sørensen, 1975). Trace elements were analysed directly on pressed powder pellets in the Institute of Petrology, University of Copenhagen (John Bailey), by X-ray fluorescence using a Philips PW1400 instrument and the techniques of Norrish and Chappell (1977). Results were corrected for background and interference from tube and sample spectral lines, and for matrix variation (using the major element composition). USGS standards (G-2, GSP-1, W-1, AGV-1, BCR-1, PCC-1) were used for calibration.

Mineral analyses were performed at the Institute of Mineralogy with a fully automated JEOL JCXA 733 Superprobe using wavelength dispersive methods. Metal standards were used for Mn, Ni and Cr, while natural silicates and oxides were used as references for the other analysed elements. ZAF correction was by the program PACX-M from JEOL.

## Petrography

The main rock types of the Kærven syenite complex are leucocratic medium-grained syenites, alkali feldspar-quartz syenites and alkali feldspar granites (terminology of Streckeisen, 1976). In addition, a few rocks qualify as granites *sensu stricto*. The principal constituents of the rocks are alkali feldspar, quartz, amphibole, clinopyroxene, plagioclase, Fe-Ti oxides, mica and olivine (in approximately decreasing order of abundance); there is also accessory apatite and zircon. In summary the Kærven syenites have modal rock compositions fairly similar to other syenitic complexes in the area, but generally with a less varied accessory paragenesis (Kempe *et al.*, 1970; Deer and Kempe, 1976) and with a more notable granitic component.

The Kærven rocks are similar to the sodic alkaline silica oversaturated trend of Lameyre and Bowden (1982) and Bowden *et al.* (1984). In contrast to the provinces of Niger, Nigeria, Oslo and Corsica, the Kærven suite is not peralkaline. In the system of Lameyre and Bowden (1982) the granite xenoliths of Kærven can be characterized as calc-alkaline or crustally derived.

All granite xenoliths have a similar texture: embayed and resorbed medium-grained plagioclase in a fine-grained matrix of quartz, plagioclase and lesser amounts of alkali feldspar, amphibole and mica. Disequilibrium of the mineral paragenesis at the time of emplacement is indicated for these granites.

Euhedral, phenocrystic microperthite constitutes 40–90 vol. % of the investigated samples, but ranges in a few granites (#40324A and #40327) down to 25 vol. %. Microperthite also sometimes occurs as an interstitial anhedral phase.

Plagioclase has been identified in about half of the investigated samples and in three modes of occurrence: (1) as euhedral–subhedral interstitial grains up to 2 mm across and possibly as phenocrysts in some samples; (2) as albite twinned cores to microperthites and (3) as unmixed constituents of microperthite. The unmixing of the Kærven alkali feldspars is very advanced in most samples ($Ab_{97-99}$ and $Or_{90-97}$) and lamellae showing albite twinning are not uncommon. Plagioclase in occurrence (1) ranges mostly from 5–10 vol. % but in a few granite xenoliths such as #40324A, constitutes about 30 vol. % of the rock.

Amphibole is the most abundant ferromagnesian mineral in the Kærven syenite complex (5–20 vol. %) and invariably displays an anhedral habit interstitial to the main felsic minerals. The amphibole is often poikilitic with numerous inclusions of opaque minerals or clinopyroxene and grain sizes around 0.5–1.5 mm appear typical. The colours in thin section vary according to composition, from yellow–brown magnesian hornblende through dark brown ferrohornblende to light green actinolite.

Clinopyroxene is second in abundance of the ferromagnesian minerals (about 5 vol. %), occurring as euhedral interstitial grains slightly smaller than the amphibole. In contrast to the habit of the clinopyroxene in the Kangerdlugssuaq syenites no adcumulus growth is seen in the Kærven clinopyroxenes. Mica occurs in low abundances (less than 5 vol. %) in most rocks and is generally considered a primary late-stage phase. Olivine is the least abundant Fe–Mg silicate in the Kærven rocks and is present in less than a fifth of the samples, where it occurs as comparatively large (up to 2 mm) rounded fractured grains.

Opaque oxides appear throughout the suite as anhedral interstitial grains.

The crystallization sequence inferred from morphological relations observed in thin section is invariably: alkali feldspar–quartz–amphibole. Occasional olivine is ether earlier than, or contemporaneous with, alkali feldspar. Plagioclase, when present, coprecipitated with alkali feldspar. Clinopyroxene crystallized later than feldspar and earlier than quartz.

## Mineral Chemistry

*Feldspar.* Discrete, interstitial plagioclase occurs in all investigated Kærven rocks with DI less than 81 and shows the range An$_{11-41}$. A few rocks in this group (e.g. #40321) have homogeneous grains of almost pure albite (Ab$_{95}$). In rocks more evolved than DI$_{90}$, plagioclase occurs sporadically and shows a compositional variation of An$_{17-38}$. There is no obvious connection between analysed plagioclase compositions and the degree of differentiation of the respective host rocks and indeed Kærven samples plotting at each end of the bulk rock differentiation trend (#40324*b*: DI$_{77}$ and #40160: DI$_{95}$) show nearly identical plagioclase compositional variation (An$_{19-27}$ and An$_{17-23}$, respectively). Individual crystals display well-developed normal zoning.

Determination of bulk alkali feldspar composition by microprobe is difficult as a consequence of the coarse exolution lamellae. Microprobe traverses suggest a compositional interval of Or$_{26-79}$. The normative feldspar components (see Table 1) plot close to the intersection of the plagioclase–alkali feldspar boundary curve and the Ab–Or join as observed in other syenite complexes, e.g. Klokken (Parsons, 1981). Normative feldspar compositions seem to be the best available approximations to bulk alkali feldspar compositions in the Kærven complex, except for the three samples from which the alkali feldspar has been separated and analysed

Table 1.
Representative analyses from rocks in the Kærven area, Kangerlugssuq.

| | 40228 | 40271 | 40303 | 40328 | 40160 | 40324a | 40297 | 40144 |
|---|---|---|---|---|---|---|---|---|
| | main suite | | | | | granite | Kangerdlugssuaq intrusion nordmark. | basement gneis |
| | Kærven syenite Complex | | | | | | | |
| $SiO_2$ wt % | 62.24 | 64.07 | 67.06 | 69.35 | 71.20 | 71.29 | 63.99 | 67.62 |
| $TiO_2$ | 1.23 | 1.07 | 0.37 | 0.37 | 0.27 | 0.14 | 1.00 | 0.43 |
| $Al_2O_3$ | 16.14 | 15.47 | 15.52 | 14.34 | 13.70 | 16.64 | 16.26 | 15.18 |
| $Fe_2O_3$ | 2.30 | 1.77 | 1.20 | 0.97 | 1.59 | 0.00 | 1.97 | 1.13 |
| FeO | 3.01 | 3.47 | 2.15 | 2.30 | 0.97 | 0.84 | 1.50 | 2.98 |
| MnO | 0.10 | 0.13 | 0.13 | 0.12 | 0.08 | 0.01 | 0.20 | 0.05 |
| MgO | 1.30 | 1.06 | 0.22 | 0.16 | 0.14 | 0.21 | 0.70 | 1.79 |
| CaO | 2.70 | 2.10 | 1.09 | 0.79 | 0.40 | 3.73 | 0.72 | 3.44 |
| $Na_2O$ | 4.40 | 4.59 | 5.34 | 4.74 | 5.39 | 4.62 | 6.96 | 4.11 |
| $K_2O$ | 4.44 | 4.61 | 5.47 | 5.34 | 5.01 | 1.61 | 5.00 | 1.51 |
| Vol. | 0.88 | 0.46 | 0.55 | 0.46 | 0.32 | 0.20 | 0.66 | 0.80 |
| $P_2O_5$ | 0.30 | 0.23 | 0.05 | 0.05 | 0.03 | 0.02 | 0.21 | 0.15 |
| sum | 99.04 | 99.03 | 99.15 | 98.99 | 99.10 | 99.27 | 99.17 | 99.19 |
| CIPW weight norms: | | | | | | | | |
| Q | 12.02 | 12.95 | 11.98 | 18.49 | 20.35 | 29.40 | 3.27 | 26.53 |
| Or | 26.24 | 27.24 | 32.33 | 31.56 | 29.61 | 9.51 | 29.55 | 8.92 |
| Ab | 37.23 | 38.84 | 45.19 | 40.11 | 42.58 | 39.09 | 55.80 | 34.78 |
| An | 11.18 | 7.99 | 2.22 | 2.08 | - | 18.37 | - | 16.09 |
| Ac | - | - | - | - | 2.67 | - | 2.73 | - |
| Di | 0.21 | 0.77 | 2.48 | 1.32 | 1.53 | - | 1.77 | - |
| Hy | 4.92 | 5.64 | 1.85 | 2.74 | 0.50 | 1.85 | 1.52 | 8.38 |
| Mt | 3.33 | 2.57 | 1.74 | 1.41 | 0.97 | - | 1.49 | 1.64 |
| Il | 2.34 | 2.03 | 0.70 | 0.70 | 0.51 | 0.27 | 1.90 | 0.82 |
| Ap | 0.70 | 0.53 | 0.12 | 0.12 | 0.07 | 0.05 | 0.49 | 0.35 |
| C | - | - | - | - | - | 0.56 | - | 0.89 |
| Trace element concentrations: | | | | | | | | |
| Rb ppm | 78 | 61 | 96 | 92 | 130 | 27 | 49 | 46 |
| Ba | 3560 | 1580 | 1100 | 745 | 238 | 1040 | 1380 | 356 |
| Pb | 9 | 15 | 14 | 13 | 12 | 9 | 6 | 9 |
| Sr | 245 | 110 | 87 | 60 | 23 | 493 | 58 | 220 |
| Ce | 70 | 109 | 187 | 188 | 240 | 1 | 186 | 75 |
| Y | 29 | 47 | 52 | 49 | 47 | 2.6 | 30 | 5.8 |
| Th | 3 | 8 | 11 | 13 | 16 | 2 | 4 | 11 |
| Zr | 192 | 485 | 695 | 943 | 797 | 259 | 55 | 96 |
| Nb | 34 | 58 | 99 | 121 | 99 | 1.8 | 71 | 4.4 |
| Ni | 9 | 8 | 5 | 5 | 8 | 3 | 5 | 29 |
| V | 64 | 32 | 9 | 4 | 4 | 6 | 3 | 57 |
| Cr | 5 | 6 | 2 | 4 | 4 | 9 | 5 | 61 |
| Ga | 24 | 28 | 26 | 27 | 38 | 16 | 25 | 16 |

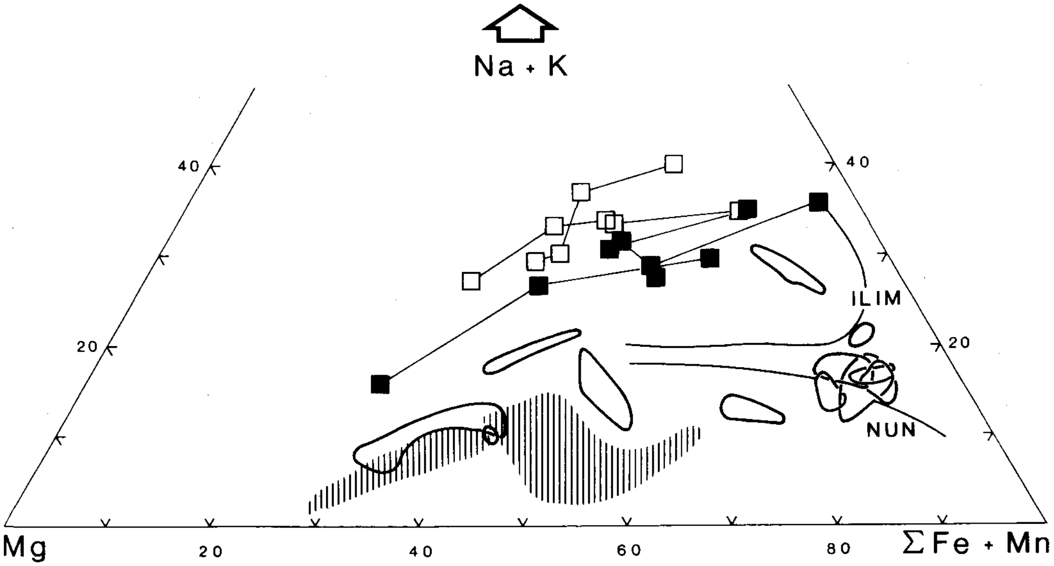

FIG. 2. AFM-diagram showing the compositional ranges of amphiboles in individual Kærven samples (main suite: unshaded areas; plagioclase-rich samples (40324*a* and *b*): shaded areas). Also shown for comparison are amphibole trends in the Ilímaussaq (Larsen, 1976) and Nunarssuit (Stephenson and Upton, 1982) intrusions, as well as amphibole analyses from the Kangerdlugssuaq intrusion (Brooks and Gill, 1982) (filled squares, three nordmarkite samples; unfilled squares, transitional pulaskite and foyaite).

(Table 2). The microperthites contain 0.09–0.40 % FeO.

*Amphibole* is the most abundant ferromagnesian phase in the Kæven suite. The amphiboles are predominantly calcic, but sodic–calcic types also occur (terminology of Leake, 1978).

Amphibole compositions correlate fairly well with host rock compositions since the least fractionated rocks (lowest $FeO^T/MgO$) carry amphiboles of magnesio-hornblende, while rocks with progressively higher $FeO^T/MgO$ have ferro-hornblende and ferroactinolitic hornblende. These more fractionated rocks from Kærven may have amphiboles ranging into the ferroedenite compositional field.

Sodic–calcic amphiboles appear only in more evolved rocks and ferro-richterites are indeed the only amphiboles present in #40160, whereas ferro-baroisite occurs in #40323 alongside the more abundant ferroedenite and ferro-hornblende.

The granite xenoliths (e.g. #40324A and B) contain actinolite and ferro-actinolite which are characteristic minerals in low-grade (greenschist facies) metamorphic rocks (Deer *et al.*, 1963), and #40324B also carries ferro–tschermakitic hornblende. Alkali feldspar syenite #40326B carries magnesian hastingsite, which may indicate either an alkaline host magma or a metamorphic rock (e.g. gneisses and amphibolites; Thomas, 1982).

Individual amphibole grains are invariably slightly zoned with respect to $FeO^T$ and MgO, and $Mg/(Mg+Fe^{2+})$ ratios generally decrease from core to rim.

Representative amphibole analyses are shown in Table 3. In the $Na+K$–Mg–$Fe^T+Mn$ diagram (Fig. 2) comparisons can be made with amphibole compositions from the Kangerdlugssuaq intrusion

Table 2.
Chemical analyses of separated alkali feldspar from the Kærven Complex.

| | | 40228 | 40271 | 40160 |
|---|---|---|---|---|
| $SiO_2$ | wt% | 64.44 | 66.72 | 68.27 |
| $TiO_2$ | | 0.02 | 0.01 | nd |
| $Al_2O_3$ | | 18.66 | 18.33 | 17.45 |
| $Fe_2O_3$ | | 0.08 | 0.08 | 0.49 |
| CaO | | 0.96 | 0.53 | 0.02 |
| $Na_2O$ | | 3.01 | 4.73 | 5.68 |
| $K_2O$ | | 11.18 | 9.33 | 7.71 |
| $H_2O$ | | 0.06 | 0.07 | nd |
| $P_2O_5$ | | 0.09 | 0.03 | nd |
| sum | | 98.20 | 99.52 | 99.22 |
| Rb | ppm | 175 | 127 | 184 |
| Ba | | 6750 | 1920 | 230 |
| Pb | | 25 | 25 | 9 |
| Sr | | 371 | 150 | 27 |
| Ce | | nd | 11 | nd |
| Y | | 3.6 | 3.0 | 2.2 |
| Th | | 5 | 8 | 8 |
| Zr | | 1.4 | 3.7 | 33 |
| Nb | | nd | 0.6 | 2.9 |
| Ga | | 21 | 33 | 45 |

nd: not detected

(Brooks and Gill, 1982) and with amphibole trends from the Ilimaussaq (Larsen, 1976) and Nunarsuit intrusions (Anderson, cf. Stephenson and Upton, 1982). Abundances of K and Na in amphiboles from Kærven increase smoothly with increasing Fe-enrichment and rise sharply only in the most evolved amphiboles (#40160), thus bearing a resemblance to the amphibole trend of the Ilimaussaq intrusion (Larsen, 1976).

*Clinopyroxene.* The Kærven suite clinopyroxenes range from augite through ferroaugite and ferrosalite to ferrohedenbergite (Table 4). Individual grains show only moderate normal zoning and maximum acmite contents, occurring in sample #40160 with the most evolved bulk composition, of *c.* 17%. The Kærven clinopyroxene trend, in the Di-Hd-Ac space, is similar to that displayed by clinopyroxenes from the quartz syenites of the layered series of Kungnat Fjeld (Stephenson and Upton, 1982), where the upper limit of sodium enrichment in clinopyroxenes is $Ac_{19}$.

The Kærven clinopyroxenes are thus chemically distinct with respect to clinopyroxenes from the quartz nordmarkites of the Kangerdlugssuaq intrusion, where Ac contents range as high as 30-80% (Brooks and Gill, 1982).

Clinopyroxenes from individual samples occupy distinct regions in the pyroxene quadrilateral (Fig. 3). The clinopyroxene evolution towards ferrohedenbergite follows relatively closely the differentiation of the respective host rocks as reflected in a negative correlation between $[Mg/(Mg+Fe^T)]_{cpx}$ and $(FeO^T/MgO)_{host\ rock}$. An exception is #40326B which has unusually Fe-rich clinopyroxenes.

The calculated amounts of $Fe^{3+}$ increase regularly with decreasing $Mg/(Mg+Fe^T)$ of the clinopyroxenes. Throughout the compositional range $TiO_2$ and $Al_2O_3$ are significantly lower in Kærven clinopyroxenes than in clinopyroxenes from the Kangerdlugssuaq intrusion (Kempe and Deer, 1970) although Brooks and Gill (1982) reported aegirine from the transitional pulaskite with as little as 0.33% $Al_2O_3$. Augite thermometry suggests subsolidus re-equilibration at lower *T*, 730-850 °C, than magmatic temperatures, 880-930 °C, reported from other syenites (Parsons, 1981).

*Biotite.* Three analyses are presented in Table 4, with structural formulae calculated to 22 O and assuming all Fe as $Fe^{2+}$. Overall, Kærven biotites display a large range of Mg/Fe ratios ($Ann_{9.5-44.1}$) with partial overlap with the Kangerdlugssuaq intrusion micas (Kempe and Deer, 1970; Brooks and Gill, 1982). Individual samples have biotites with a restricted Mg/Fe variation (Fig. 3). Fe/Mg ratios of biotites show a well-marked correlation with coexisting clinopyroxenes. MnO concentrations correlate with FeO, in the most Fe-rich biotite analysed, $Ann_{95.9}$, having 1.04% MnO.

Kempe and Deer (1970) presented two biotite analyses from the transitional pulaskite and the pulaskite of the Kangerdlugssuaq intrusion. These biotites are $Ann_{53.2}$ and $Ann_{59.1}$, respectively, calculating all Fe as divalent. Kærven biotites with similar annite contents have lower abundances of $SiO_2$, MnO, CaO and $Na_2O$ and higher concentrations of $TiO_2$ and $Al_2O_3$ compared to the Kangerdlugssuaq types. Biotite much richer in Mg ($An_{18}$) was reported from the pulaskite of the Kangerdlugssuaq intrusion by Brooks and Gill (1982) as an average of five analyses.

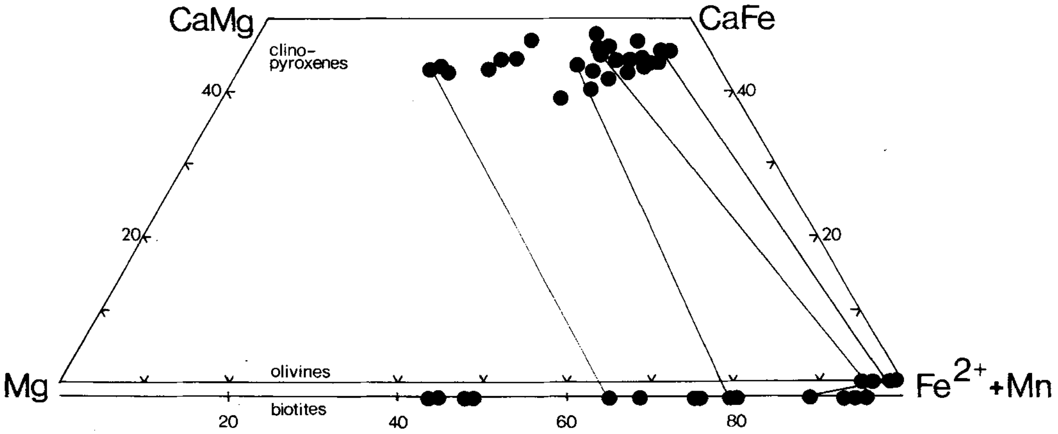

FIG. 3. Ca-Mg-$Fe^{2+}$+Mn diagram showing clinopyroxene, olivine and mica compositional fields in individual samples from the Kærven syenites. Olivine is plotted on the base line, while mica is shown below. Tie-lines join the cores of most Mg-rich coexisting species.

TABLE 3.
Representative amphibole analyses from the Kærven syenite complex.

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | wt% | 47.61 | 45.16 | 38.35 | 51.68 | 44.71 | 46.77 | 44.39 | 45.78 |
| $TiO_2$ | | 0.55 | 1.65 | 1.34 | 0.34 | 1.49 | 1.23 | 1.30 | 1.79 |
| $Al_2O_3$ | | 5.99 | 6.33 | 15.75 | 2.49 | 5.71 | 3.54 | 4.90 | 2.11 |
| FeO* | | 15.11 | 16.86 | 18.07 | 20.95 | 26.15 | 32.13 | 32.92 | 29.92 |
| MnO | | 0.27 | 0.61 | 0.20 | 0.85 | 1.01 | 0.97 | 1.29 | 1.73 |
| MgO | | 14.19 | 11.82 | 7.79 | 11.20 | 5.92 | 2.61 | 1.90 | 2.66 |
| CaO | | 11.97 | 11.18 | 11.55 | 10.50 | 9.55 | 8.15 | 8.94 | 5.42 |
| $Na_2O$ | | 0.95 | 1.90 | 3.09 | 0.50 | 1.93 | 2.81 | 2.55 | 5.46 |
| $K_2O$ | | 0.71 | 0.76 | 1.03 | 0.27 | 0.87 | 0.95 | 0.95 | 1.21 |
| sum | | 97.35 | 96.27 | 97.17 | 98.78 | 97.34 | 99.16 | 99.14 | 96.08 |
| $Fe_2O_3$ | | 5.00 | 10.37 | 1.08 | 9.99 | 5.81 | 5.01 | 5.59 | 9.28 |
| FeO | | 10.61 | 7.53 | 17.09 | 11.96 | 20.93 | 27.61 | 27.89 | 21.57 |
| recalc.sum | | 97.85 | 97.31 | 97.27 | 99.78 | 97.93 | 99.65 | 99.70 | 97.01 |
| Formula based on 23 anions and according to Leake (1978): | | | | | | | | | |
| | Si | 6.946 | 7.027 | 5.880 | 7.648 | 6.909 | 7.287 | 6.926 | 7.635 |
| T | Al | 1.030 | 0.973 | 2.120 | 0.352 | 1.041 | 0.649 | 0.909 | 0.365 |
| | $Fe^{3+}$ | 0.024 | | | | 0.050 | 0.064 | 0.105 | |
| | Al | | 0.116 | 0.725 | 0.081 | | | | 0.022 |
| | Ti | 0.060 | 0.180 | 0.154 | 0.038 | 0.174 | 0.144 | 0.154 | 0.210 |
| C | $Fe^{3+}$ | 0.757 | 1.139 | 0.132 | 0.097 | 0.794 | 0.620 | 0.676 | 1.093 |
| | $Fe^{2+}$ | 1.062 | 0.919 | 2.184 | 2.314 | 2.536 | 3.502 | 3.551 | 2.824 |
| | Mn | 0.034 | 0.075 | 0.026 | 0.104 | 0.133 | 0.127 | 0.172 | 0.230 |
| | Mg | 3.087 | 2.571 | 1.779 | 2.469 | 1.364 | 0.606 | 0.446 | 0.621 |
| B | Ca | 1.870 | 1.748 | 1.898 | 1.952 | 1.580 | 1.361 | 1.507 | 0.907 |
| | Na | 0.130 | 0.252 | 0.102 | 0.048 | 0.420 | 0.639 | 0.493 | 1.093 |
| A | Na | 0.141 | 0.286 | 0.815 | 0.095 | 0.157 | 0.211 | 0.285 | 0.563 |
| | K | 0.133 | 0.142 | 0.202 | 0.051 | 0.171 | 0.189 | 0.190 | 0.242 |

1: Magnesio-hornblende core in 40324a, contaminated granite.
2: Magnesio-hornblende core in 40228, syenite.
3: Edenitic hornblende in 40326b, alkali feldspar syenite.
4: Actinolitic core in 40324b, contaminated granite.
5: Ferro-hornblende core in 40321, alkali feldspar granite.
6: Ferro-hornblende core in 40329, alkali feldspar syenite.
7: Ferro-hornblende core in 40323, alkali feldspar granite.
8: Ferro-richterite core in 40160, alkali feldspar granite.

*Olivine* has been petrographically identified in four alkali feldspar syenites from Kærven, and Table 4 presents representative analyses.

The analysed olivines range from $Fe_{99.1-95.8}$ (Fig. 3) and Fa-contents correlate negatively with $Mg/(Mg+Fe^T)$ of the host rocks. The olivines are characterized by high and varying Mn concentrations (3.7–4.8% MnO) which are correlated with Fe. They have low CaO (0.09% CaO), in the expected range for plutonic olivines (Simkin and Smith, 1970), and resemble those in similar silica-oversaturated syenites elsewhere (e.g. Stephenson and Upton, 1982; Brown and Becker, 1986).

*Fe–Ti oxides* occur exsolved throughout the Kærven Syenite Complex and representative analyses are presented in Table 4. Titanomagnetites have 0.1–48.1% ulvøspinel calculated from the relation given by Powell and Powell (1977), with the least exsolution-affected grain in sample #40326A. Ilmenite in the same sample has 2.6–2.8% hematite calculated according to Anderson (1968). These compositions give a temperature around 600 °C and $\log f_{O_2} = -21.7$ (Spencer and Lindsley, 1981) for #40326A which is close to the QFM-buffer. The conditions are, however, not considered to reflect those during the original crystallization, but rather the conditions at which exsolution in this sample stopped. For samples #40228 and #40160, Fe–Ti oxides yield equilibration conditions of 580 °C, $\log f_{O_2} = -20.8$ and 550 °C, $\log f_{O_2} = -23.5$, respectively. These values are consistently lower than those reported from the peralkaline Mulanje complex, Malawi (Platt and Woolley, 1986), the Coldwell complex (Mitchell and Platt, 1978 and 1982) and the Klokken intrusion (Parsons, 1981) for which $\log f_{O_2}$ in the range $-13$ to $-14$ was reported. Similar low $f_{O_2}$ hav been reported from the Skærgaard intrusion (Buddington and Lindsley, 1964).

## Geochemistry

Representative major and trace element analyses are summarized in Table 1. Harker diagrams (Fig. 4) for all major elements, except $Na_2O$ and $K_2O$, display an overall monotonous decrease in concentration with increasing silica. Ba and Sr also decrease with increasing silica content. For $Na_2O$,

TABLE 4.
Representative analyses of olivine, clinopyroxene, mica and Fe-Ti-oxides in the Kærven syenite complex.

|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |  | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 30.54 | 30.80 | 52.82 | 50.25 | 49.81 | 50.68 | 35.63 | 36.30 | 36.98 |  | 0.16 | 0.01 |
| $TiO_2$ | 0.08 | 0.00 | 0.15 | 0.25 | 0.24 | 0.07 | 4.44 | 4.95 | 2.40 |  | 17.18 | 51.17 |
| $Al_2O_3$ | 0.01 | 0.00 | 0.48 | 0.63 | 0.43 | 0.15 | 12.45 | 13.04 | 9.60 |  | 0.11 | 0.03 |
| $Cr_2O_3$ | 0.00 | 0.00 | 0.04 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |  | 0.00 | 0.01 |
| FeO* | 64.61 | 64.62 | 14.25 | 21.20 | 23.02 | 27.99 | 18.16 | 25.59 | 35.88 |  | 78.64 | 42.24 |
| MnO | 3.66 | 4.67 | 0.54 | 1.21 | 1.18 | 1.42 | 0.29 | 0.21 | 0.35 |  | 1.79 | 5.85 |
| MgO | 1.66 | 0.44 | 11.42 | 6.35 | 5.11 | 1.42 | 12.90 | 4.80 | 2.45 |  | 0.00 | 0.05 |
| CaO | 0.07 | 0.04 | 20.82 | 17.00 | 18.57 | 19.03 | 0.01 | 0.02 | 0.04 |  | 0.03 | 0.08 |
| $Na_2O$ | 0.05 | 0.06 | 0.32 | 1.02 | 1.11 | 1.41 | 0.16 | 0.02 | 0.00 |  | 0.04 | 0.00 |
| $K_2O$ | 0.00 | 0.00 | 0.01 | 0.10 | 0.10 | 0.03 | 9.78 | 9.67 | 9.53 |  | 0.01 | 0.03 |
|  | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |  | ----- | ----- |
| sum | 100.68 | 100.63 | 100.95 | 98.02 | 99.67 | 102.20 | 93.83 | 97.60 | 97.23 |  | 98.06 | 99.47 |
| Formulas calculated for number of anions: | 4 | 4 | 6 | 6 | 6 | 6 | 22 | 22 | 22 |  | 4 | 4 |
| Oxidation state of iron corrected assuming stochiometry: | - | - | + | + | + | + | - | - | - |  | + | + |
| Si | 1.014 | 1.031 | 1.995 | 2.017 | 1.980 | 2.010 | 5.556 | 5.604 | 6.044 |  | 0.006 | 0.000 |
| Ti | 0.002 | 0.000 | 0.004 | 0.008 | 0.007 | 0.002 | 0.521 | 0.521 | 0.294 |  | 0.480 | 0.974 |
| $Al^{iv}$ |  |  | 0.005 | 0.000 | 0.004 | 0.000 |  |  |  |  |  |  |
| $Al^{vi}$ | 0.000 | 0.000 | 0.017 | 0.030 | 0.016 | 0.007 | 2.289 | 2.373 | 1.849 |  | 0.005 | 0.001 |
| $Fe^{2+}$ | 1.794 | 1.808 | 0.446 | 0.706 | 0.673 | 0.851 |  |  |  |  | 1.420 | 0.840 |
| $Fe^{3+}$ |  |  | 0.004 | 0.006 | 0.093 | 0.077 | 2.368 | 3.304 | 4.904 |  | 1.025 | 0.054 |
| Mn | 0.103 | 0.133 | 0.017 | 0.041 | 0.040 | 0.048 | 0.038 | 0.027 | 0.049 |  | 0.057 | 0.125 |
| Mg | 0.081 | 0.022 | 0.643 | 0.380 | 0.303 | 0.085 | 2.999 | 1.796 | 0.596 |  | 0.000 | 0.002 |
| Ca | 0.003 | 0.002 | 0.843 | 0.731 | 0.792 | 0.809 | 0.002 | 0.004 | 0.007 |  | 0.001 | 0.002 |
| Na | 0.003 | 0.004 | 0.023 | 0.079 | 0.085 | 0.109 | 0.049 | 0.006 | 0.000 |  | 0.003 | 0.000 |
| K | 0.000 | 0.000 | 0.000 | 0.005 | 0.005 | 0.002 | 1.946 | 1.904 | 1.986 |  | 0.001 | 0.001 |
| $Mg/(Mg+Fe^{2+}+Mn)$ | 0.041 | 0.011 | 0.581 | 0.337 | 0.298 | 0.086 | 0.555 | 0.350 | 0.107 | FeO | 45.67 | 39.69 |
|  |  |  |  |  |  |  |  |  |  | Fe2O3 | 36.64 | 2.84 |
|  |  |  |  |  |  |  |  |  |  | Usp% | 46.7 |  |
|  |  |  |  |  |  |  |  |  |  | Hem% |  | 2.8 |

1: olivine core in 40329, alkali feldspar syenite.
2: olivine core in 40332, alkali feldspar syenite.
3: clinopyroxene core in 40324b, contaminated granite.
4: clinopyroxene core in 40325, alkali feldspar granite.
5: clinopyroxene core in 40328, alkali feldspar syenite.
6: clinopyroxene core in 40329, alkali feldspar syenite.
7: mica core in 40228, granite.
8: mica core in 40324b, contaminated granite.
9: mica core in 40329, alkali feldspar syenite.
10: titanomagnetite in 40326a, alkali feldspar granite.
11: ilmenite in 40326a.

a positive correlation with silica at low $SiO_2$ is succeeded at *c.* 66 wt. % $SiO_2$ by a negative correlation. For $K_2O$ a rather similar increasing trend is followed at higher silica by approximately constant concentrations. Also the trends of $SiO_2$ versus $TiO_2$, MgO, CaO and $P_2O_5$ show marked kinks at around 66 wt. % $SiO_2$. In the low-silica range the decline in these elements is very steep. The concentrations of compatible elements such as Cr, Ni, V and Sc are all low. In the Kærven Syenite Complex rocks the oxides of the compatible elements Ti, Fe, Mg and Ca display a greater range than that seen in the adjacent Kangerdlugssuaq intrusion (Kempe *et al.*, 1970). The coherent trends

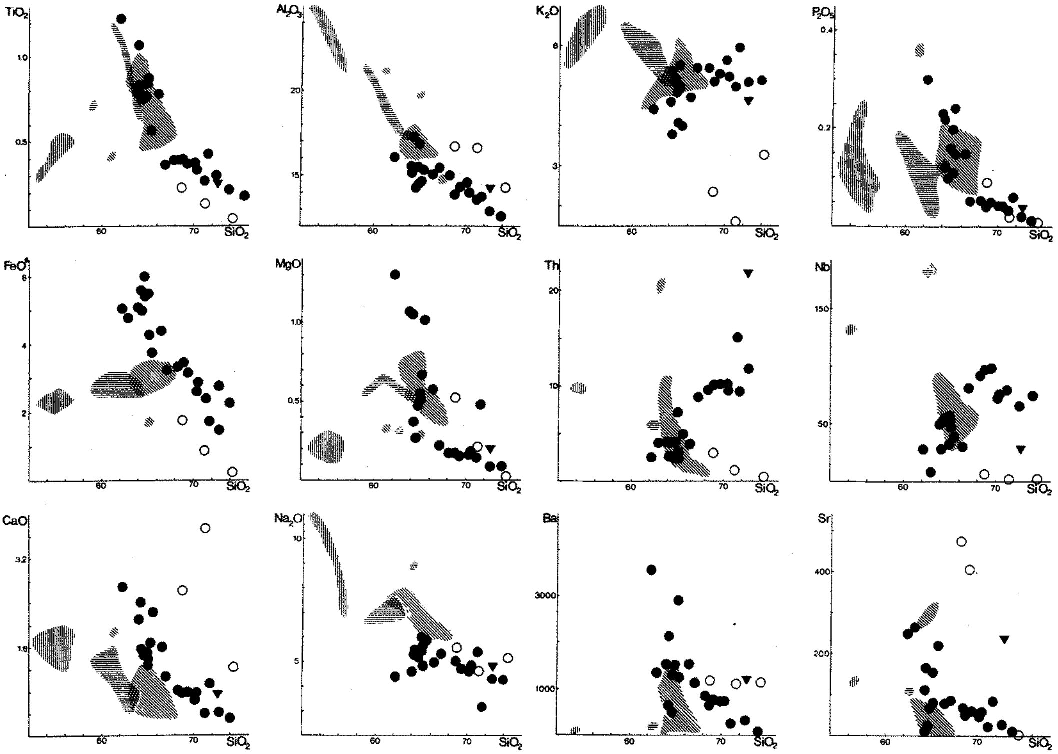

FIG. 4. Harker variation diagrams for major (wt. %) and selected trace elements (ppm) in analysed samples of the Kærven syenite complex (this study) and the adjacent Kangerdlugssuaq intrusion (Kempe *et al.*, 1970; Brooks and Gill, 1982; Brooks and Nielsen, 1982 and this study). Filled circles, main Kærven suite; open circles, plagioclase-rich Kærven granites; vertical shaded areas, Kangerdlugssuaq foyaites; horizontally shaded areas, Kangerdlugssuaq pulaskites; diagonally shaded areas, Kangerdlugssuaq quartz nordmarkites, nordmarkites and transitional pulaskites; triangle, biotite granite from late satellite intrusion.

displayed in the Harker diagrams contrasts with the heterogeneity of the Kangerdlugssuaq intrusion and suggests that the Kærven rocks belong to a single suite related through processes such as fractional crystallization or magma mixing. Exceptions to these trends are the corundum and highly quartz-normative samples of the granite xenoliths. These samples can also be distinguished by low $TiO_2$, $FeO^T$, $K_2O$ and high CaO relative to $SiO_2$.

Most samples are quartz-normative (7–28% Q) and metaluminous, exceptions are the granite xenoliths which have high Q and normative corundum ($C \leqslant 0.6\%$) and the most evolved alkali feldspar granite which is peralkaline with Ac = 2.7%. The nordmarkites of the Kangerdlugssuaq intrusion along the contact with the Kærven Intrusion are peralkaline (1.7–4–6% Ac) and have virtually silica-saturated compositions.

Normative components of Q, Ab and Or constitute 75–93% of the normative mineralogy. The An component is below 10% in all and below 3% in most samples of the main suite. Thus, the ternary system Q–Ab–Or, Fig. 5, may be expected to give a good representation of the magmatic phase relations. Except for the granite xenoliths all Kærven samples plot in the ternary system Q–Ab–Or on a linear trend parallel to the general trend of two-feldspar cotectic from *c.* 35% Or on the Ab–Or join towards the Q apex, ending at approximately 30% Q. In contrast the granites plot in the typical tonalite field.

Except for Ba and Sr most LIL and HFS trace elements correlate positively with $SiO_2$. However, the degree of correlation is very variable being highest for Rb and Th. Yttrium, niobium (Fig. 4) and in particular zirconium possibly show a decreasing trend at $SiO_2 > 70$ wt. %.

The good correlation between several incompatible elements such as Zr and Nb (constant ratio) (Fig. 6), and Th and Ce (Fig. 7), is consistent with a

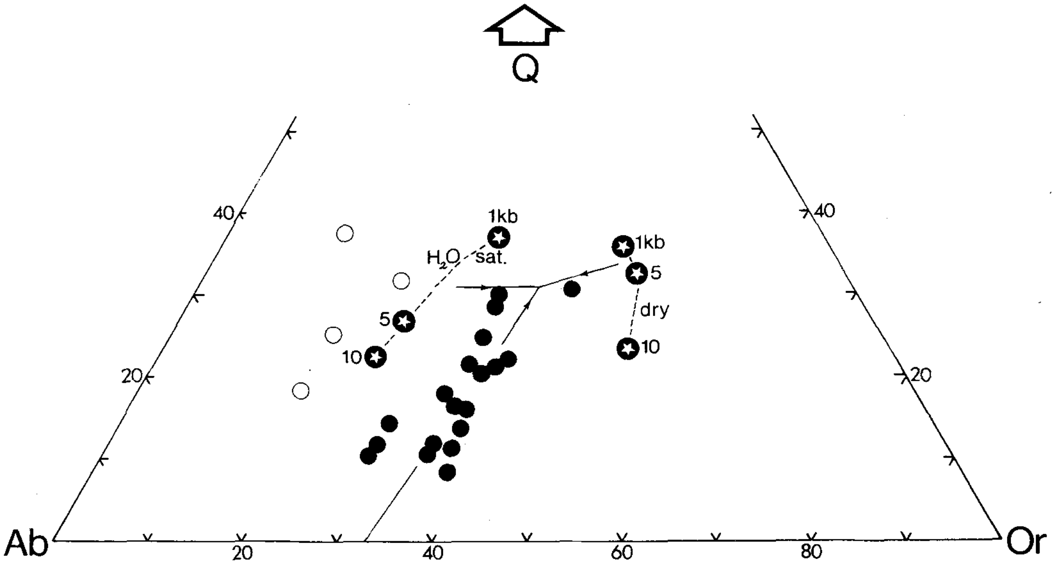

FIG. 5. Q–Ab–Or plot showing the normative compositions of the Kærven rock samples. Also shown are the positions of the invariant point at various pressures during experiments carried out under dry and water-saturated conditions as indicated (Tuttle and Bowen, 1958; Luth *et al.*, 1964; Luth, 1969). The feldspar cotectic is for $An_3$ (James and Hamilton, 1969). Filled circles, main Kærven suite; open circles, plagioclase-rich granites.

comagmatic origin for most rocks of the complex and also indicates that in general these elements were incompatible in any possible fractionation scheme. According to Leat *et al.* (1986) Zr concentrations higher than *c.* 500 ppm in subalkaline granitic rocks are very rare and occurrences are limited to Iceland (Wood, 1978) and the Galapagos Islands (McBirney and Williams, 1969; Baitis and Lindstrom, 1980).

Most Kærven samples have Zr/Nb ratios in the narrow interval of 6–9 (Fig. 6). This is in contrast to the ratios of 1–4 for the Kangerdlugssuaq intrusion samples. The granite xenoliths and a syenitic vein in the basement have higher Zr/Nb ratios and in Fig. 6 largely plot in the field defined by the basement samples, which have ratios in the range 17–62.

Compared to the Kangerdlugssuaq intrusion (Holm, unpubl. analyses), the Kærven Intrusion has higher maximum values for Zr (943 ppm), Ba (3560 ppm) and, except for one Kangerdlugssuaq quartz nordmarkite, Th (16 ppm). Major elements distinguish the Kærven Intrusion by reaching both higher silica and by having as much as 3.5–6.0 wt. %, FeO in the low silica samples. Also, Na is lower in the samples from Kærven. In conjunction, these geochemical features clearly set the Kærven complex apart from the Kangerdlugssuaq intrusion.

Another striking feature of the Kærven suite is the correlation of Sr and Ba (Fig. 8). The Ba/Sr ratio of *c.* 16 (range 12–25) is high compared to most other grantitic rocks. Of the rocks from the Kangerdlugssuaq intrusion only the nordmarkites plot on the Ba–Sr trend of the Kærven suite.

Covariance of Ba and Sr (Fig. 8) is not uncommon in peralkaline magma suites (Imeokparia, 1983; Whalen, 1983; MacDonald and Edge, 1970; Noble and Parker, 1974; Villari, 1974). However, the very high Ba/Sr ratio and absolute Ba concentrations are not matched by other subalkaline or peralkaline oversaturated occurrences. Very high Ba/Sr is also seen in the Loch Ainort epigranite, Western Red Hills complex, the British Tertiary centre of Skye (J. C. Bailey, pers. com.).

The relative positions of the samples in the Rb/Ba *vs.* Nb/Ba plot (Fig. 9), resemble those in the silica variation diagrams and most samples have Rb/Nb ratios around 0.9. The Kangerdlugssuaq syenites generally have slightly lower Rb/Nb ratios of 0.7 to 0.9, but some nordmarkites have higher ratios and as a group the nordmarkites display no well-defined trend.

Ratios of perfectly incompatible elements are expected to be constant for all samples derived from one magma. In a two-dimensional plot of such ratios such as Nb/Zr *vs.* Y/Zr (Fig. 10) comagmatic rocks should ideally be represented by one point. An inclined oblong trend for most Kærven samples

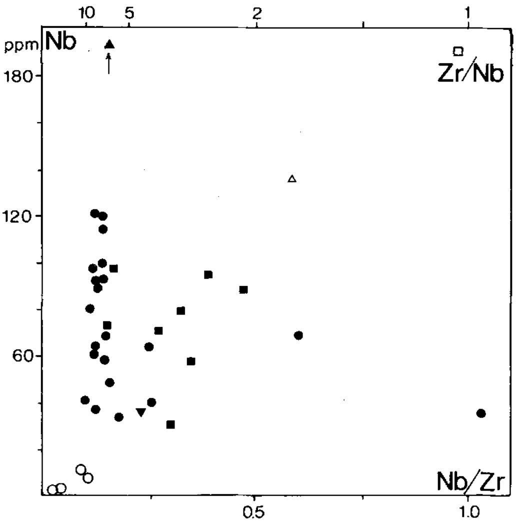

FIG. 6. Nb *vs.* Nb/Zr. The diagram shows the main Kærven suite (filled circles), the plagioclase-rich granites (open circles); Kangerdlugssuaq intrusion: nordmarkites/quartz nordmarkites/transitional pulaskites (filled squares), pulaskite (open squares) and foyaite (open triangle). From late satellite intrusions: biotite granite (inverted triangle); alkali granite (filled triangle). Outside diagram: alkali granite (0.159, 1453).

is displayed. Mostly Nb, Zr and Y are incompatible as illustrated by their positive correlation with silica, e.g. Fig. 4 (Nb *vs.* $SiO_2$). In Fig. 10 only two samples #40329 and #40332 show a large deviation from the main trend and two more deviate somewhat (#40304 and #40330).

## Discussion

*Fractional crystallization.* Geochemical diversification of the Kærven suite solely through fractional crystallization is unlikely as evident from the following observations:

(1) The steep trends for Ti, Fe, Mg, Ca and P in the interval 62-66% $SiO_2$ (Fig. 4) would suggest fractional control by mafic phases; yet the textural relationships indicate that a model of *in situ* fractional crystallization should be dominated by alkali feldspar through the entire range of rock types. Moreover, the apparently compatible behaviour of Sr and Ba in the low silica range excludes a major role for fractionation of mafic phases.

(2) Nb is expected to be more incompatible than Rb during crystallization of felsic magmas (e.g. Arth, 1976; Lopez-Escobar *et al.*, 1977; Pearce and Norry, 1979). The incompatibility of Nb is also indicated from its good correlation with Zr (Fig. 6). Thus, the enrichment of Rb relative to Nb in the low-Ba samples and rather constant ratio of Rb/Nb ratios in most other samples (Fig. 9) indicate that alkali feldspar was not fractionated out of the magmas to any significant extent.

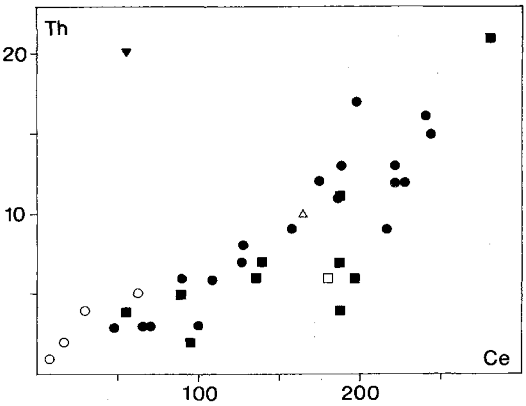

FIG. 7. Th *vs.* Ce symbols as in Fig. 6. Outside diagram: alkali granite (518, 147).

(3) Decreasing Sr and Ba abundances—the covariance of Sr and Ba and the relatively narrow range of Ba/Sr ratios are consistent with alkali feldspar control. Significant plagioclase control of the Sr variation is ruled out by the scarcity of plagioclase and the good correlation of CaO and Ba. For only high values of $K_D$, such as the 20-30

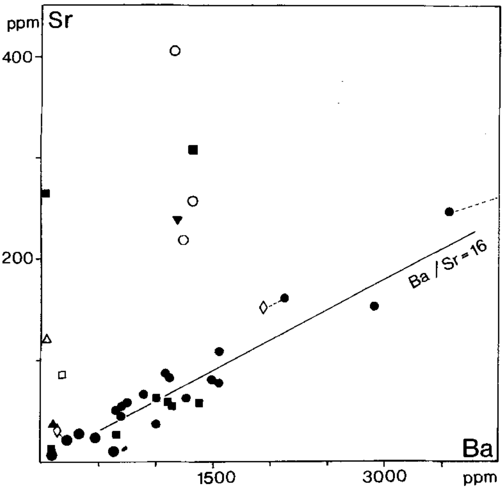

FIG. 8. Sr *vs.* Ba. Symbols as in Fig. 6 except unfilled diamonds: alkali feldspars connected with host rock analysis. Outside diagram: alkali feldspar of 40228 (see Table 2).

reported by Leeman and Phelps (1981), the observed variation of Sr and Ba could have been achieved by fractionation of alkali feldspar (calculated: *c.* 15%) in the relatively small amounts required by the Rb–Nb systematics. However, such limited fractionation would not explain the total geochemical variation, in particular the compatible behaviour of Ti, Ca and Mg. Whether such high partition coefficients are indicated by the Kærven rocks was investigated. Unfortunately, the partition coefficients for the Kærven magmas can only be poorly estimated (3 to > 10) from (*a*) the measured concentrations of Ba and Sr in separated alkali feldspars and whole rocks (Tables 1 and 2) and (*b*) a best guess of the proportion of crystals relatve to magma at the time of feldspar growth.

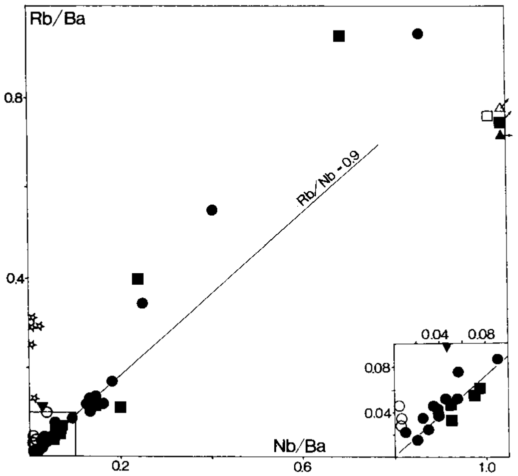

FIG. 9. Rb/Ba *vs.* Nb/Ba. Symbols as in Fig. 6 except for basement compositions, stars. Outside diagram: nordmarkite (7.31, 5.15), foyaite (2.78, 2.02) and alkali granite (11.1, 7.63).

(4) In order to recognize a possible component in the Ba–Sr systematics caused by crystal accumulation, analysed alkali feldspar separates and whole rocks have been compared (Tables 1, 2 and Fig. 8). The alkali feldspars of the two rocks #40228 and #40271 have very different Ba and Sr contents which most likely reflect variation between liquids. Furthermore, the concentration of alkali feldspar in #40228 is much less than in #40271 and thus the high Ba and Sr content of the former rock is not a consequence of accumulation of alkali feldspar. The alkali feldspar from the most evolved rock, #40160, accordingly show very low Ba and Sr concentration. Moreover, no cumulative textures are seen in any members of the suite. It is thus thought most likely that both these samples and in general the rocks of the Kærven suite do represent liquids.

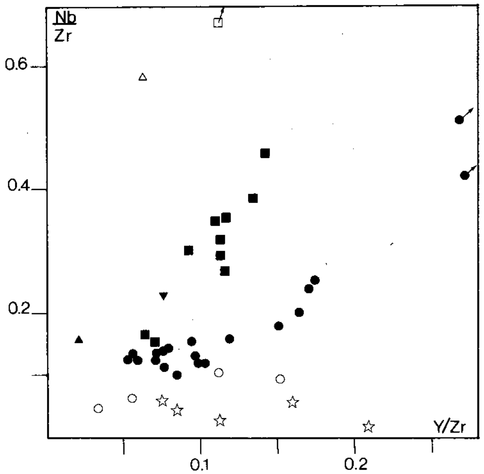

FIG. 10. Nb/Zr *vs.* Y/Zr. Symbols as in Fig. 6 except for basement compositions, stars. Outside diagram: Kærven samples (1.03, 0.68) and (0.60, 0.32), pulaskite (0.16, 0.97).

(5) Attempts were made to model numerically the geochemical variation within the main suite by least squares methods using Kærven whole rock and mineral analyses. The calculations did not yield any acceptable results which would relate the observed whole rock variation to addition or substraction of a combination of the mineral phases present in the rocks. We consider this a strong indication that crystal fractionation was not the dominating process in the generation of the Kærven magmas at upper crustal levels.

(6) The variation expected from thermogravitational diffusion (Hildreth, 1981) was compared to that of the syenites. Much of the variation seen among the trace elements is rather similar to the expected behaviour but notable exceptions are the *LREE* and Zr which, in contrast to their positive correlation with differentiation index, would be expected to decrease. Also the large range in silica is not in favour of this evolutionary mechanism.

*Crustal contamination.* For the main syenitic suite no indication is seen of significant crustal contamination. This is most clearly demonstrated by the striking geochemical difference between the main Kærven suite samples and the granite xenoliths, which from petrographical evidence are seen to be highly contaminated. In Figs. 4, 6, 8 and 9 the granite xenoliths show deviations from the main trend attributable to crustal contamination, such as low Nb and Y and high Ba/Sr and Rb/Nb. Furthermore, the spikes in the elemental patterns of crustal rocks from the Kangerdlugssuaq area are present only in the xenoliths, except for the Ba-anomalies (Fig. 11). Thus, crustal contamination had only an insignificant effect on the geochemistry of the main Kærven suite.

*Mixing processes.* The overall geochemical variation of the Kærven syenitic suite is in many respects compatible with an origin by the mixing of magmas: (1) The variation displayed in several element–element plots is linear, e.g. the Harker diagrams for Al, Fe and Ca, and the plot of Sr *vs.* Ba; (2) Plots of the type A/C *vs.* B/C also display linear arrays, e.g. Rb/Ba *vs.* Nb/Ba and Zr/Nb *vs.* 1/Nb. Furthermore, the relative position of the samples are largely consistent with a model of two-component mixing. We are also inclined to interpret the trend in the Nb/Zr *vs.* Y/Zr diagram (Fig. 10) as one of mixing between the end-members exemplified by samples #40228 and #40160.

However, the kink on some Harker diagrams (e.g. Mg and Na, Fig. 4) as well as deviations of samples in other diagrams, indicate that magma mixing was not solely responsible for the geochemical evolution of the Kærven suite. The kinks cannot be easily explained even by superposing crystal fractionation or cumulation on a mixing trend.

*Source characteristics.* Several authors have suggested that A-type granitic suites are derived from monzonitic magmas which were derived by anatexis in the lower crust probably related to the injection of basic magmas (Collins *et al.*, 1982; Imeokparia, 1983; O'Halloran, 1985), while other workers favour derivation from a (hydrated) mantle (Harris, 1985; Pearce *et al.*, 1985). Although no conclusive evidence is presented, many indications point towards a derivation of the Kærven magmas from the mantle: the value of the Zr/Nb ratios; the element patterns and the lack of crustal signature in the magmas. We, therefore, favour a mantle origin of these syenites. There are, however, no indications of high $P_{H_2O}$.

Elemental spectra (spidergrams) for the samples compared to ocean ridge granites (Pearce *et al.*,

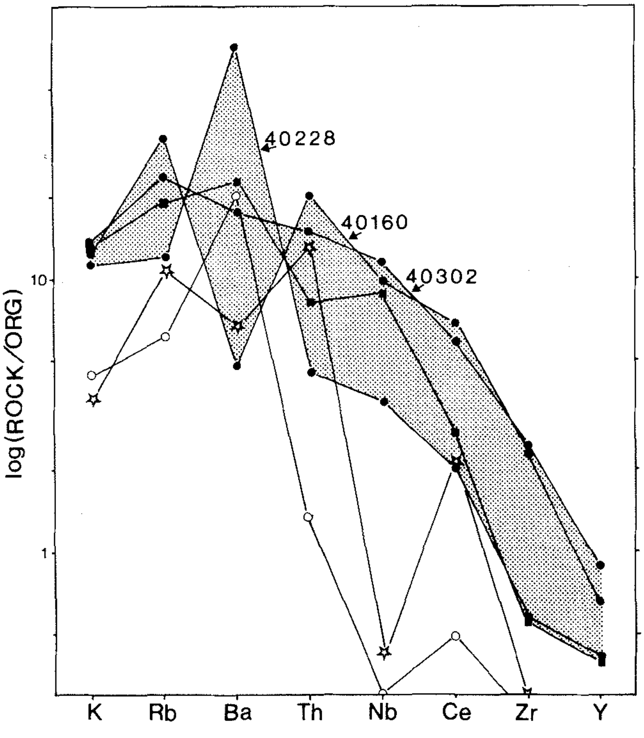

FIG. 11. Multi-element Ocean Ridge Granite-normalized spectra (after Pearce *et al.*, 1985) for three samples of the Kærven main suite (filled circles, 40228, 40302 and 40160) which encompass the shaded area, one Kangerdlugssuaq nordmarkite near the Kærven complex (filled squares, 40297), one sample of typical basement near the Kærven complex (stars, 40144) and one plagioclase-rich granite (unfilled circle, 40324*a*).

1985) are presented in Fig. 11. Except for Ba and $K_2O$ the spectra are in general smooth and increasing from Y to $K_2O$. Barium displays a marked variation between a large positive (max: 70 times ORG) and a large negative anomaly (min: 2 times ORG) the size of which is negatively correlated with an increase in silica. Potassium shows a total variation of only 40% whereas Zr ranges from 4 to 20 times ORG.

Except for Ba and $K_2O$ the ORG normalized element spectra of the main Kærven suite generally rise smoothly from Y to $K_2O$, similar to the patterns of within-plate granites from the Oslo rift and Ascension Island, and contrast to within-plate granites of attenuated continental crust. Pearce *et al.* (1985) consider this pattern to be dominantly mantle-derived in the absence of crustally induced anomalies of low Nb and Zr. The negative Ba anomaly, which is also displayed by some samples in their study, was not explained. Positive Ba anomalies, such as in the less evolved rock types of Kærven, were not presented. It should be noted, however, that we compare felsic rocks of a rather large interval of silica concentrations to ORG, whereas Pearce *et al.* (1985) presented only granites of around 70% $SiO_2$. A nordmarkite sample from the Kangerdlugssuaq intrusion near Kærven shows an element pattern not unlike that of the Kærven samples. However, the nordmarkite is relatively less enriched in Ce, Zr and Y than in the more incompatible elements. This results in a relatively low Zr/Nb ratio.

The roughly constant ratio of the Zr/Nb for most samples of the Kærven suite indicate that the value of Zr/Nb = *c.* 7.5 may be characteristic of the source region, a T-type MORB source (le Roex *et al.*, 1983), for the parental Kærven magmas. More enriched sources are indicated for the Kangerdlugssuaq intrusion: P-type MORB for the nordmarkites and still more enriched for the pulaskites and foyaite.

The unusually high Zr levels in these subalkaline rocks may be related to a hot spot origin (Pearce *et al.*, 1985; Leat *et al.*, 1986).

In the Rb *vs.* Y + Nb discrimination diagram (not shown) of Pearce *et al.* (1985) both the Kærven and Kangerdlugssuaq intrusion samples fall in the field of within-plate granites.

Summing up, a two-stage model is suggested for the Kærven syenites: (1) generation of basaltic liquids in the mantle followed by (2) mixing of monsonitic or syenitic magmas and still more evolved alkali feldspar granite derived from the basaltic melts.

*P,T conditions of crystallization.* The trend of all uncontaminated samples models the cotectic crystallization of Or and Ab in a liquid evolving from the syenite minimum (saddle point) towards the granite minimum (Fig. 5). As solely hypersolvus alkali feldspar crystallized from the melts, they were probably relatively dry or the pressure relatively low with $P_{H_2O} < c.$ 5 kbar $< P_{tot}$ at the time of alkali feldspar crystallization. If it is assumed that the evolution of the Kærven rocks took place in one magma or similar magmas at constant depths, a maximum pressure may be indicated from Fig. 5. The trend of the Kærven suite is intermediate between the cotectics for dry and water saturated compositions, irrespectable of the 0–5% An component. The Q-rich end of the trend define the maximum pressure, 3–5 kbar, at which the suite could have evolved at constant pressure. If it is further assumed that the end of the trend is situated at the invariant point, 3–5 kbar is the pressure indicated at which the melt evolved. However, it must be noted that there is nothing to show that magmatic diversification took place at the site of the final crystallization. The position of the apparent feldspar cotectic, both in Fig. 5 and in the system Ab–An–Or, indicate an approximate An component of 3% which agrees with both normative and measured contents. In accord with the trend towards the granite minimum, a trend in the system $CaO–Na_2O–K_2O$ towards lower CaO is accompanied by a slight increase in the $K_2O/Na_2O$ ratio.

The temperatures indicated from pyroxene thermometers are considered to be magmatic. It is interesting to note that in spite of its higher clinopyroxene Mg/Fe ratio, the crystallization temperature for granite xenolith #40324a (an assumed partial basement melt) is lower than the temperature calculated for samples #40325 and #40328 which are syenites with low Mg/Fe ratios. It is thus probable that the Mg/Fe ratio of sample #40324a was inherited from the basement, which has often quite high Mg/Fe (e.g. # 40144, Table 1).

The oxygen fugacities of the Kærven rocks are very low compared with peralkaline and alkaline A-type syenite-granite complexes. This is thought to indicate that the primary magma had close affinities to tholeiitic magma types.

## Summary of the main conclusions

(1) The syenitic to granitic rocks of the Kærven Complex constitute a cogmagmatic suite, which is clearly distinguished from the rocks of the Kangerdlugssuaq intrusion. The rock types are: quartz syenite, alkali feldspar quartz syenite and alkali feldspar granite.

(2) The petrography suggests a general sequence of crystallization in the rock suite: (1) alkali feldspar ± olivine ± plagioclase, (2) clinopyroxene, (3) quartz and (4) amphibole.

(3) Mineralogy of alkali feldspar, Fe-Ti oxides and modal compositions suggest cotectic crystallization along the feldspar minimum in the residual system at a maximum pressure of the final crystallization 3-5 kbar with moderately to low $P_{H_2O}$.

(4) Geochemical consideration and mass balance calculations indicate that the suite evolved dominantly by mixing, possibly with some superposed fractional crystallization. The end members of the mixing were magmas that evolved at depth. The parental magmas were genetically closely related. Crustal contamination by assimilation was insignificant, except for a few samples. Some geochemical featues remain unexplained, most notably the kinks on some Harker diagrams.

(5) The elemental pattern and some elemental ratios confirm the large scale tectonic setting as intra-plate rifting similar for example to the Oslo rift. Further, a hot spot origin is indicated.

(6) Mantle sources are indicated for the main suite. Source characteristics are weakly alkaline with rather low Zr/Nb compared to MORB-types, but high compared to the pulaskites and foyaites of the Kangerdlugssuaq intrusion. A two-stage model is tentatively suggested in which basaltic mantle derived magmas after evolution by fractional crystallization mixed to form the Kærven suite, which crystallized at high crustal levels.

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