Boron-Bearing Kornerupine from Fiskenaesset, West Greenland: A Reexamination of Specimens from the Type Locality

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Boron-bearing kornerupine from Fiskenæsset, West Greenland: a re-examination of specimens from the type locality

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Abstract
In 1884, Lorenzen proposed the formula MgAl₂SiO₆ for his new mineral kornerupine from Fiskenæsset and did not suspect it to contain boron. Lacroix and de Gramont (1919) reported boron in Fiskenæsset kornerupine, while Herd (1973) found none. New analyses (ion microprobe mass analyser and spectrophotometric) of kornerupine in three specimens from the type locality, including the specimens analysed by Lorenzen and Herd, indicate the presence of boron in all three, in amounts ranging from 0.50 to 1.44 wt.% B₂O₃, e.g. (Li₀.₀₄ Na₀.₀₁ Ca₀.₀₁) (Mg₃.₄₉ Mn₀.₀₁ Fe₀.₁₇ Ti₀.₀₁ Al₃.₆₄ B₉.₃₁)₂₅ O₂₁ (OH₀.₈₉ F₀.₀₁) for Lorenzen’s specimen. Textures and chemical compositions suggest that kornerupine crystallized in equilibrium in the following assemblages, all with anorthite (An 92–95) and phlogopite (Xᵥₑ = atomic Fe/(Fe + Mg) = 0.028–0.035): (1) kornerupine (0.045)–gedrite (0.067); (2) kornerupine (0.038–0.050)–sapphirine (0.032–0.035); and (3) kornerupine (0.050)–hornblende. Fluorine contents of kornerupine range from 0.01 to 0.06%, of phlogopite, from 0.09 to 0.10%. In the first assemblage, sapphirine (0.040) and corundum are enclosed in radiating bundles of kornerupine; additionally sapphirine, corundum, and/or gedrite occur with chlorite and pinite (cordierite?) as breakdown products of kornerupine. Kornerupine may have formed by reactions such as: gedrite + sapphirine + corundum + B₂O₃ (in solution) + H₂O = kornerupine + anorthite + Na-phlogopite under conditions of the granulite facies. Boron for kornerupine formation was most likely remobilized by hydrous fluids from metasedimentary rocks occurring along the upper contact of the Fiskenæsset gabbro-anorthosite complex with amphibolite.

Keywords: boron, kornerupine, Fiskenæsset, Greenland, ion microprobe, spectrophotometry.

Introduction
In 1884, J. Lorenzen† discovered the mineral kornerupine from Fiskenæsset, West Greenland, for which he proposed a formula MgAl₂SiO₆ (his analysis reproduced here in Table 1). Neither Lorenzen (1886, 1893) nor Ussing (1889), who also analysed material from Fiskenæsset, suspected that appear until 1893. None the less, Lorenzen is credited with the first discovery of kornerupine in 1884 and his name, kornerupine, is given priority over prismatic, the name introduced by Sauer (1886) for kornerupine from Waldheim, Saxony, presently a part of the German Democratic Republic.

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Microprobe analysis was performed on a grain of a probe, but none was detected. Boron was sought with a laser identical to Lorenzen's (1919). Herd's electron probe analysis was performed on a grain of a probe, but none was detected. The only other known locality for boron-free korn erupine is in lenses of metasediment within the Messina layered intrusion in the central part of the Limpopo belt in Zimbabwe (Schreyer and Abraham, 1976a; Windley et al., 1984). All other korn erupines analysed for boron have been found to contain it, including korn erupine at other localities in the Fiskenæset region (Petersen et al., 1980). Ackerm and et al. (1984) reported korn erupine breakdown to tourmaline from Sarfaq, Tasiussa, a locality south-east of Fiskenæset, and concluded that this korn erupine is also boron-bearing.

Because the type locality of Fiskenæset is one of only two world localities from which a boron-free korn erupine has been reported and because boron-bearing korn erupine has also been reported from Fiskenæset, we decided to reanalyse several korn erupines from the type locality, including the sample in which Herd (1973) sought boron. Our new analyses show that these korn erupines contain boron, confirming Lacroix and de Gramont's (1919) report of boron in korn erupine from Fiskenæset. The laser probe analysis cited by Herd (1973) was probably performed on another sample accidently substituted for the korn erupine. In view of our findings, the generally accepted use of the name korn erupine for the boron-bearing material is confirmed to be entirely appropriate.

In the present communication, we report new petrographic and analytical data on three specimens from the type locality, and present a possible reconstruction of the field relations of these specimens. One of the three specimens is of particular interest because it contains an apparently stable assemblage of korn erupine with gedrite. Rocks containing orthoamphibole and korn erupine are not common at other world localities and we are aware of only one well-documented report of an equilibrium gedrite-korn erupine assemblage (Waters and Moore, 1985). In other cases the orthoamphibole (gedrite) and korn erupine are not in equilibrium (Schreyer and Abraham, 1976a; Windley et al., 1984). Unfortunately, little information is available on textural relations between the orthoamphibole (anthophyllite) and korn erupine from other localities (Balasubrahmanyan, 1965; Monchoux, 1972).

**Field relations**

Korn erupine is presently known from about ten localities in the Fiskenæset region, including the type locality near Fiskenæset town (e.g. Herd et al., 1969; Herd, 1973; Walton, 1973; Petersen et al., 1980; Friend, 1982; Ackerm and et al., 1984). At localities other than the type locality, korn erupine is invariably associated with sapphire-bearing rocks, along or near the upper contact of metamorphosed anorthosites of the Fiskenæset layered igneous complex with overlying amphibolites. The korn erupine- and sapphire-bearing rocks are commonly associated with ultramafics such as spinel-bearing peridotite, and/or cordierite-gedrite rocks. Other associated rocks are sillimanite-rich layers, calc-silicate rocks, forsterite marbles, and clinoptilite rocks, which are interpreted to be metamorphosed near-shore marine sediments with associated magnesian ultramafics (Herd, 1973). The Fiskenæset complex, as well as the sedimentary and volcanic rocks it intruded, were subjected to granulite-facies metamorphism and subsequently to amphibolite-facies metamorphism.

K. J. V. Steenstrup (as quoted by Lorenzen, 1893) reports that sapphirene and korn erupine are found in one little spot near Fiskenæset town. The layers here strike approximately EW and dip 60° to 90°. Sapphirene occurs in mica schist and anthophyllite. Steenstrup describes korn erupine as a grayish white radiating mineral reminiscent of kyanite. The exposures described by Steenstrup may be located near the anorthosite contact with pyrolite and ultramafics roughly 30 m north of the main exposure of sapphirene rocks mapped by Herd et al. (1969) on the north shore of the southern harbor at Fiskenæset. Near the shore the contact of the anorthosite trends about N-S. However, further north, near the limit of the town, the trend of the contact becomes E-W due to folding, and this area may be where Steenstrup collected the samples studied by Lorenzen. Despite carrying out detailed mapping (1:200 to 1:20 scale) and collecting in this area, Herd (1972, 1973) had no success in finding korn erupine at what we infer to be Steenstrup's locality. None the less, the physical appearance and mineralogy of Steenstrup's specimens, which one of us (RKH) has examined at the Geologisk Museum ved Københavns Universitet in Copenhagen, are sufficiently distinctive that we have little doubt that these specimens originated from the plagioclase-rich and sapphire-bearing contact zone between Fiskenæset complex anorthosite and adjacent magnesian ultramafics. Sorensen (1955) suggested
that the kornerupine was associated with plagioclase-rich veins cutting the sapphirine-bearing rocks.

Material from the type locality

Steenstrup's collection at the Geologisk Museum presently consists of five specimens, which were registered in the museum in 1883 (nos. 1883.750–4 and 1883.756, O. V. Petersen, pers. comm., 1982, 1986; Petersen et al., 1980, refer to only four specimens). In addition, this museum has two specimens, actually vials with crystals and fragments, that are part of the original material studied by Ussing and possibly, but not certainly, derived from Steenstrup's collection (nos. 1971.683–4, O. V. Petersen, pers. comm., 1982, 1986; Petersen et al., 1980).

The present study concerns three pieces of Steenstrup's material:

(1) Imperial College of Science and Technology no. 32060, a kornerupine-hornblende fragment from the vials of Ussing's material, that is, either no. 1971.683 or 1971.684, which RKH obtained directly from H. Sørensen;

(2) Geologisk Museum no. 1883.754, a kornerupine-gedrite rock that RKH obtained directly from O. V. Petersen. According to the Museum label, no. 1883.754 is the specimen from which Lorenzen obtained material for his chemical analysis, and is thus cotype or even holotype material (Petersen, pers. comm., 1986).

(3) American Museum of Natural History no. 31498, a kornerupine-sapphirine rock, which that museum obtained in 1959 from the Geologisk Museum, very likely from among the material collected by Steenstrup (O. V. Petersen, pers. comm., 1982).

Petrography and mineralogy

Lorenzen (1886, 1893) described kornerupine as forming radiating aggregates with enstatite ('kupferite') and sapphirine and as resembling sillimanite. Ussing (1889) reported that some aggregates constitute an intergrowth with cordierite similar to a micropegmatite. Ussing (1889) included the kornerupine-bearing rocks in his first type of sapphirine rock, which also contains gedrite, hornblende, mica and anorthite, but he did not further specify the kornerupine-bearing assemblages. Vogt (1947) examined a specimen from the type locality and did not find any amphiboles with kornerupine. In addition to the three specimens studied in detail (see below), RKH examined one of Ussing's thin sections at the Geologisk Museum (no. U15, courtesy of H. Sørensen). Kornerupine in U15 occurs in a matrix of plagioclase, cordierite, and phlogopite, without amphibole.

Since the work of Lorenzen (op. cit.), enstatite has not been reported with kornerupine in Steenstrup's material. The only other report of enstatite with kornerupine in the Fiskenesset region is by Petersen et al. (1980) who mentioned it in the kornerupine rocks near Bjørnesund (see below).

Other minerals associated with kornerupine in the Fiskeneset region, namely tourmaline, spinel, garnet, and iron oxides (e.g. Petersen et al., 1980; Ackermand et al., 1984), have not been reported from the material collected by Steenstrup. Although white, brown, green, and blue varieties of kornerupine are known from the Fiskeneset region, only white and pale brown varieties are present in the material from the type locality.

Specimen no. 1883.754 (type material) consists of dominant kornerupine, phlogopite, and anorthite; subordinate gedrite; and traces of clinoamphibole, spinel, corundum, sapphirine, chlorite and pinite (after cordierite?). Four sections were studied, one of which was used for the mineral analyses. The minerals are colourless in thin section except for phlogopite, which is pale brown and gedrite, a paler buff. Subparallel prisms of kornerupine form radiating bundles about a centimetre long and several millimetres across (Fig. 1). Some phlogopite and anorthite are enclosed in the kornerupine bundles, but most of these two minerals, together with gedrite, constitute a matrix for the bundles (Fig. 2). Clinoamphibole forms rare overgrowths on gedrite in one section (Fig. 3). Grain size for phlogopite, anorthite, and gedrite, all of which are in contact with kornerupine, range from a few tenths of a millimetre to nearly 3 mm across. Sapphirine grains, about 0.1 mm to nearly a millimetre long, are enclosed in the kornerupine bundles. Sapphirine, in turn, has inclusions of phlogopite, anorthite, and in one case, spinel, and in another case, corundum (Fig. 4). In the analysed section, corundum occurs only as small grains (to 0.3 mm across) in kornerupine or in anorthite enclosed in kornerupine. In the other sections of 1883.754, corundum also occurs in small grains around the borders of kornerupine and is associated with a pale chlorite and a pinitic material, possibly derived from cordierite (Fig. 5). In two of these sections, sapphirine and gedrite also appear around the margins of kornerupine (Figs. 6–7). Thus breakdown of kornerupine to corundum + chlorite + cordierite (pinite), sapphirine + gedrite + cordierite (pinite), and to sapphirine + cordierite (pinite) + chlorite occurred to a limited extent in this sample.

Sample 32060 is similar to 1883.754 in that
kornerupine occurs in a matrix of anorthite, phlogopite, and amphibole. In this sample, however, the amphibole is a green hornblende, and neither sapphirine nor corundum was found.

Sample 31498 consists largely of platy blue sapphirine, phlogopite and a trace of anorthite. Sapphirine and phlogopite have a preferred orientation. Kornerupine occurs in limpid, colourless, columnar aggregates of parallel prisms. In thin section, kornerupine prisms up to 0.5 mm across and 3 mm long contain inclusions of sapphirine, but sapphirine tablets also cut across kornerupine grain boundaries. Sapphirine tablets are riddled with inclusions of phlogopite; anorthite and rarely kornerupine are also enclosed in sapphirine. There are localized patches of alteration with fine-grained corundum.

Chemical composition

Minerals in sample 32060 were analysed by RKH with a Geoscan electron microprobe at Imperial College, London (see Herd, 1973) and in 1883.754 and 31498 by ESG with a CAMEBAX instrument equipped with wavelength dispersive spectrometers at the Ruhr-Universität, Bochum (for method, see Schreyer et al., 1984). The following materials were used as standards in the electron microprobe analyses: at Imperial College; wollastonite (Ca, Si), rhodonite (Mn), jadeite (Na), syn-
BORON-BEARING KORNERUPINE

Figs. 5 and 6, Fig. 5 (left). Alteration patch in a concentration of kornerupine. The high relief corundum (Cdm) is set in a matrix of chlorite (Chl) and pinitized cordierite (?). No. 1883.754 (fourth section). Plane light. Fig. 6 (right). Kornerupine grains (Krn) with inclusions (dark) of sapphirine (Sap) in plagioclase matrix (Pig) abut a phlogopite-rich area (top of photograph). Kornerupine has been locally replaced by gedrite + sapphirine (Ged and Sap), and there is chlorite (Chl) and pinitite among the fine-grained phyllosilicates. No. 1883.754 (third section). Crossed polars.

thetic TiO₂ (Ti), synthetic spinel (Mg, Al), synthetic Y–Fe garnet (Fe), synthetic potassium tantalate (K); and at the Ruhr Universität; synthetic pyrope (Mg, Al, Si), orthoclase (K), synthetic magnetite (Fe), jadeite (Na), wollastonite (Ca), metal (Mn), synthetic TiO₂ (Ti), and synthetic Cr₂O₃ (Cr). Precision of the microprobe analyses at Imperial College was calculated to be ±3% for major element values by using an internal standard with each analysis set. Standard deviations for the microprobe analyses at the Ruhr-Universität are ≤ 1.5% of the given average value for oxides constituting > 18% of the mineral, ≤ 2.2% for oxides in the 8–14% range, ≤ 12% for oxides in the 0.5–4% range, and > 12% for oxides constituting < 0.5%. An exception is CaO in anorthite of sample 31498, for which the standard deviation exceeds 2% in one grain due to compositional heterogeneity.

The electron microprobe compositions in Tables 1–4 are averages of 6 to 19 analytical spots per mineral (1 to 7 analytical spots per grain over 2 to 7 grains) in 1883.754 and of 5 element readings per element per mineral at 1 to 3 spots per grain in 32060. In both sections minerals vary little in composition from grain to grain. However, in sample 31498, compositions are given for selected individual grains (3 to 10 analytical spots each), which differ to some extent from one another in composition.

Li, B, F, and Ba were analysed in kornerupine, sapphirine, and phlogopite by ESG and NM at one spot per mineral in each sample, except for three spots on kornerupine in 1883.754 and two on kornerupine in 31498, with the ARL ion microprobe mass analyser (IMMA) at the Aerospace Corporation in Los Angeles (method of Grew and Hinthorne, 1983; Grew et al., 1986). Raw IMMA count ratios were corrected by mineral standards, namely grandidierite (B/Si), spodumene (Li/Si), and biotite (F/Si, Ba/Si), by applying a working curve. Estimated precision is about ±20% of the given values of B and Li in most kornerupines and Ba in phlogopite and is poorer than ±20% for other IMMA values listed in the tables. In the absence of standards, the amounts of Sr and Rb can be

Fig. 7. Subidioblastic kornerupine grains (Krn), intergrown with phlogopite (Phl), and with inclusions of sapphirine (Sap). The kornerupine has been locally replaced along grain margins by sapphirine, chlorite and cordierite (?) (pinitite) (Chl and Crd). No. 1883.754 (third section). Crossed polars.
Table 1. Analyses of kornerupine in specimens from the type locality, Fiskenaesset, West Greenland.

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<td></td>
<td>Wet Chemistry</td>
<td>Electron Microprobe (weight %)</td>
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<td>SiO₂</td>
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<td>30.3</td>
<td>29.80</td>
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<td>1.8</td>
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<td>FeO</td>
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<td>19.1</td>
<td>18.96</td>
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<td>MgO</td>
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<tr>
<td>H₂O</td>
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<td>(1.22)</td>
<td>(1.21)</td>
<td>(1.17)</td>
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<td>B₂O₃</td>
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<td>1.44</td>
<td>0.50</td>
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<td>Li₂O</td>
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<td>0.08</td>
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<tr>
<td>F</td>
<td>0.01</td>
<td>0.01</td>
<td>0.06</td>
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<td>Total</td>
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<td>99.17</td>
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Cations per 21.5 Oxygens

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<td>Si</td>
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<td>3.711</td>
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<td>Al</td>
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<td>1.075</td>
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<tr>
<td>B</td>
<td>0.214</td>
<td>0.306</td>
<td>0.108</td>
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<td>5.000</td>
<td>5.000</td>
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<tr>
<td>Al</td>
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<td>5.623</td>
<td>5.642</td>
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<td>Ti</td>
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<td>Fe</td>
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<td>0.184</td>
<td>0.165</td>
<td>0.143</td>
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<tr>
<td>Mn</td>
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<td>0.005</td>
<td>0.003</td>
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<tr>
<td>Mg</td>
<td>2.483</td>
<td>2.487</td>
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<td>2.419</td>
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<td>Ca</td>
<td>0.007</td>
<td>0.009</td>
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<tr>
<td>Li</td>
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<td>Na</td>
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<td>0.010</td>
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Anions

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<td>F</td>
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<td>0.019</td>
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<tr>
<td>OH</td>
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<td>0.994</td>
<td>0.995</td>
<td>0.977</td>
<td>0.981</td>
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<tr>
<td>Fe/(Fe-Mg)</td>
<td>0.050</td>
<td>0.050</td>
<td>0.045</td>
<td>0.040</td>
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</table>

Totals corrected for F = 0. Dash: Not analyzed or not calculated. All Fe as FeO. b.d.: below detection. For 2-5, H₂O values (in brackets) were calculated assuming ideal anion composition.

Notes:
1 - Sample 1883.754, Lorenzen (1886, 1893). 2.02% Fe₂O₃ recalculated as FeO. H₂O value is loss of ignition.
3 - Sample 1883.754, average of 5 grains.
4 - Sample 31498, grain 1.
5 - Sample 31498, grain 2. For 3-5, b.d. means Cr₂O₃ and K₂O ≤ 0.01%.

Boron was found in every kornerupine grain analysed with the IMMA (Table 1). The value of 1.44% B₂O₃ for 1883.754 is an average of four analyses at three points (range 1.19-1.61%). The IMMA boron contents of kornerupine in 31498 are less than the 1.01 wt. % which G. Werding (pers. comm., 1983) obtained by a spectrophotometric method (see Werding and Schreyer, 1978) on a 40 mg hand-picked separate. (which may have had about a 15% anorthite impurity). The kornerupine in this sample appears to vary somewhat in boron content from grain to grain (Table 1) and this variation could explain the discrepancy between the IMMA and spectrophotometric analyses. On the other hand, the IMMA Li₂O values on both grains in 31498 are in good agreement with G. Werding's (pers. comm., 1983) atomic absorption value of 0.06% Li₂O on the hand-picked separate. The composition listed in Table 1, column 4, for 31498 is representative of three of the four prisms analysed. The major element compositions of two of the other prisms are: SiO₂ 28.45, 29.12%; Al₂O₃ estimated from theoretical relative sensitivity factors of Sr/Sr = 3.7 (Grew et al., 1986) and Rb/Si = 3.3 (J. Hinthorne, pers. comm., 1984). Be was sought but not detected (that is, < 0.005% BeO present).
FIG. 8. Compositional variations of Fiskenæsset korne-
rupines in cations per formula unit of $21 O^+(OH, F)$. 
Numbers refer to the columns in Table 1. $\Sigma R^{3+} = Al + B 
(+ Fe^{3+}), \Sigma R^{2+} = Mg + Fe + Mn$. For no. 5, solid symbol 
refers to all Fe = Fe$^{2+}$; open symbol refers to the assumed 
values of Fe$^{3+}$ = 0.1 and Fe$^{2+}$ = 0.082.

The kornerupine $H_2O$ contents that were cal-
culated assuming an anion composition of $21 O + (OH, F)$ (Moore and Araki, 1979) are consistent 
with the weight losses on ignition reported by 
Lorenzen (1886, 1893) and Ussing (1889) (Table 1) 
and attributed by Ussing (1889) to essential water.

Sapphirine contains minor B$_2$O$_3$, Li$_2$O, and F 
(Table 2). Fe$^{3+}$ contents of sapphirine estimated 
from stoichiometry by normalizing to 14 cations 
and 20 oxygens (cf. Higgins et al., 1979) are mostly 9 
to 12% of the total iron (Table 2). These low values 
for Fe$^{3+}$ are negligible given the uncertainties in 
stoichiometric estimates. In a third grain analysed 
in 31498 (Table 2, column 3), the estimated Fe$^{3+}$ 
content is 38% of the total Fe and could be 
significant. The presence of fluorine in sapphire 
of sample 31498 is surprising, particularly as the 
associated phlogopite is fluorine-poor (Table 3). 
The fluorine was detected during two separate 
sessions on the IMMA; an earlier analysis of the 
same grain in 31498 yielded 0.07 wt.% F, but the 
count rate was 19 counts per second (cps), 
compared to 99 cps for the 0.17% value listed in Table 2.

The phlogopites contain minor Ba and F, and 
only traces of B and Li (Table 3). Their F contents 
are surprisingly low given their low FeO contents. 
Their Li$_2$O contents are among the lowest for 
phlogopite and biotite associated with kornerupine 
and sapphirine (0.001–0.1 wt. % Li$_2$O, Grew 1985, 
1986a, b; Grew et al., 1985, 1986 and unpublished 
data) and are lower than most Li$_2$O values reported 
for phlogopite and biotite from amphibolite-facies 
metapelites (0 to 0.43% Li$_2$O, Hietanen, 1969; 
Dutrow et al., 1986) and from granites, pegmatites, 
and other rocks, such as marble (0.04 to over 2% 
Stevens and Schaller, 1942; Foster, 1960; Wilson 
and Long, 1983). Rb$_2$O contents are estimated to be 
0.04–0.06 wt. %, and the SrO content of 1883.754, 
0.002 wt. %. Moreover, the phlogopites are among 
the most sodic reported and their $X_{Na}$ (= atomic 
Na/(Na + K) ratios) are comparable to K-phlogo-
mites associated with Na-phlogopite ($X_{Na} = 0.05$–
0.28, Schreyer et al., 1980) and wonesite (0.07–0.17, 
Spear et al., 1981). Moreover, the Fiskenæsset
phlogopites contain significant Al$_2$O$_3$ and have nearly full occupancy of the interlayer site (87-88%), a combination not reported from the K-phlogopites associated with sodium phlogopite and wonesite. This combination of compositional features is also characteristic of nearly iron-free phlogopite associated with kornerupine in Blaise and Cesbron’s (1966) specimen from Sar-e-Sang, Afghanistan (X$_{Na} = $ atomic Mg/(Mg + Fe) = 0.995, X$_{Na} = $ 0.26, Na + K = 1.89, 17.3% Al$_2$O$_3$; Grew, 1986a). On the other hand, the more iron-rich

| Table 2. Analyses of sapphire in kornerupine-bearing specimens from the type locality, Fiskenæsset, west Greenland. |
|---|---|---|
| 1 | 2 | 3 |
| **Electron Microprobe (weight %)** | | |
| SiO$_2$ | 13.48 | 13.54 | 12.79 |
| Al$_2$O$_3$ | 64.39 | 64.01 | 64.29 |
| Cr$_2$O$_3$ | b.d. | 0.06 | 0.05 |
| FeO | 1.46 | 1.27 | 1.17 |
| MgO | 19.77 | 19.98 | 19.05 |
| Total: | 99.16 | 98.92 | 97.05 |

Cations normalized to 14 cations and 20 Oxigens

| **Silica** | 1.570 | 1.582 | 1.508 |
| **Al** | 4.419 | 4.498 | 4.492 |
| **Na** | 0.011 | 0.010 | --- |
| **Total** | 6.000 | 6.000 | 6.000 |

| **Titanate** | 4.420 | 4.405 | 4.443 |
| **Cr** | 0.015 | 0.011 | 0.009 |
| **Fe** | 0.126 | 0.113 | 0.071 |
| **Mg** | 3.433 | 3.463 | 3.457 |
| **Li** | 0.005 | 0.003 | --- |
| **Total** | 8.001 | 8.000 | 8.000 |

| **F** | 0.000 | 0.002 | 0.002 |
| **F/(Fe+Mg)** | 0.040 | 0.035 | 0.032 |
| **Fe$_2$O$_3$/Cr** | 0.036 | 0.032 | 0.020 |

Totals corrected for F = 0. Dash: not analyzed or not calculated.

All Fe as FeO in analyses. b.d.: below detection.

Notes:
1 - Sample 1883.754, electron microprobe data from Herd (1972).
2 - Sample 31495, average of 3 grains.
3 - Sample 31495, grain 1.
4 - Sample 31495, grain 2.

The ferromagnesian silicates are highly magnesian and increase in X$_{Fe}^2+$ (atomic Fe/(Fe + Mg) assuming all Fe is Fe$^{2+}$) as follows: (1) 36020—phlogopite (0.035) < kornerupine (0.050); (2) 1883.754—phlogopite (0.034) < sapphire (0.040) < kornerupine (0.045) < gedrite (0.067); Na than the alkali site in associated anorthite (An 92-95, Table 4), possibly because of a miscibility gap in the plagioclases at these compositions (see Smith, 1983, Fig. 2).
and (3) 31498—phlogopite (0.028–0.031) < sapphire (0.032–0.035) < kornerupine (0.038–0.050).

If the proportions of ferric iron estimated from stoichiometry in sapphire (grain 3) and kornerupine (grain 2) of 31498 are assumed, then $X_{Fe^{3+}}$ increases as follows for these two grains: sapphire (0.020) < kornerupine (0.023). The equilibrium sequence for Fiskenæsset thus appears to be phlogopite < sapphire < kornerupine < gedrite, which has been reported for the Limpopo belt where kornerupines contain 0 to 0.6% B$_2$O$_3$ (Schreyer and Abraham, 1976a; Windley et al., 1984). On the other hand, in a Waldheim, G.D.R., paragenesis, where kornerupine contains 3.4% B$_2$O$_3$ and Fe$^{3+}$ contents are negligible, the equilibrium sequence is biotite (0.19) < kornerupine (0.19–0.20) < sapphire (0.22) (Grew, 1985, 1986b). The Fe$^{2+}$–Mg fractionation between kornerupine and sapphire in the Waldheim rock is reversed by comparison with the fractionation in the Fiskenæsset and Limpopo rocks, while the fractionation between biotite and sapphire is about the same. This difference suggests that boron in kornerupine may affect the partitioning of Fe$^{2+}$ and Mg between kornerupine and associated minerals: as kornerupine boron content increases, kornerupine becomes more magnesian relative to associated minerals.

The distribution coefficients for fluorine and hydroxyl ($K_D = (F/OH)_{Krn}/(F/OH)_{Phl}$) are 0.46 and 0.50 for 1883.754 and 32060, respectively, but are 1.8 and 2.2 for 31498. As the $K_D$ values for other kornerupine–biotite (phlogopite) pairs analysed by Grew et al. (1985 and unpublished data) are mostly 0.5 to 1.0, the relatively high $K_D$ values for 31498 may not represent an equilibrium F–OH distribution. Regarding the other light elements, kornerupine is enriched both in B and Li relative to sapphire and phlogopite such that (in wt. %), for B$_2$O$_3$, kornerupine >> sapphire > phlogopite, and for Li$_2$O, kornerupine > sapphire > phlogopite. This confirms the general observation that trioctahedral micas incorporate little boron (e.g. Harder, 1959; Grew et al., 1986).

**Conditions of kornerupine formation**

The experimental results of Seifert (1975) on the stability of B-free kornerupine in the model MgO-Al$_2$O$_3$-SiO$_2$-H$_2$O system provide a framework for inferring pressures and temperatures of kornerupine formation at the type locality in Fiskenæsset. In the model system, the assemblages kornerupine–sapphire and kornerupine–corundum, which are present in samples 31498 and 1883.754 (see below), have a narrower stability field than kornerupine overall (Fig. 10). According to Seifert (1975), these two assemblages would be stable at pressures of at least 5 kbar, and at temperatures of at least 740°C. The boron in the Fiskenæsset rocks would have extended the range of conditions for kornerupine formation.

![Fig. 10. Partial Seifert's (1975, Fig. 6) pressure-temperature grid for boron-free kornerupine in the system MgO-Al$_2$O$_3$-SiO$_2$-H$_2$O system provide a framework for inferring pressures and temperatures of kornerupine formation at the type locality in Fiskenæsset.](image-url)
stability to lower pressures and temperatures, while the small iron contents of the Fiskenaesset minerals would have had a negligible effect. Moreover, Seifert's (1975) experiments were carried out at $P_{H_2O} = P_{total}$. Thus water partial pressures lower than total pressure in the metamorphic fluids would have shifted the reactions (except for the corundum-absent breakdown of kornerupine) to lower temperatures relative to Seifert's experiments.

Temperatures and pressures estimated for the high-grade metamorphism in a nearby area of the Fiskenaesset region are 730 °C and 7 kbar (Weaver et al., 1982), and at Fiskenaesset Harbour, 700-800 °C and 5-8 kbar (Dymek and Stocking, 1985). We calculated temperatures of 723 and 726 °C from the garnet and clinopyroxene compositions of Weaver et al. (1982) and the calibration of Ellis and Green (1979), a geothermometer not used by Weaver et al. (1982). Dymek and Stocking's estimates overlap with the stability field predicted by Seifert (1975) for boron-free kornerupine with sapphirine and corundum (Fig. 10). Addition of $B_2O_3$ or decreased $P_{H_2O}$ relative to total pressure would shift the kornerupine–sapphirine–corundum field to lower temperatures, so that overlap with the estimates of Weaver et al. would also be possible. We conclude that kornerupine in the rocks presently exposed at Fiskenaesset must have crystallized at 700–800 °C and at 5 kbar or more. A similar conclusion was also reached by Ackermand et al. (1984) for kornerupine at Sarfaq.

Temperatures of 700–800 °C at pressures above 5 kbar are characteristic of the granulite facies. Thus kornerupine is properly a granulite-facies mineral in the Fiskenaesset complex and must have formed during the earlier of the two regional metamorphic events to affect the Fiskenaesset region after emplacement of the anorthosite complex (see Herd et al., 1969; Herd, 1973).

We attribute the localized breakdown of kornerupine in sample 1883.754 to the later metamorphic event in the amphibolite facies, which has retrograded a large portion of the high-grade rocks in the Fiskenaesset region (e.g. Herd et al., 1969). According to Seifert's (1975) results, the breakdown assemblage corundum + cordierite + chlorite is stable up to 740–748 °C at $P_{H_2O} = 5–7$ kbar and, sapphirine + chlorite + cordierite, to 5 kbar at 740–760 °C in the boron-free system (Fig. 10). Temperatures and pressures for kornerupine breakdown in the boron-bearing system are 730 °C and 7 kbar (Weaver et al., 1985). The presence of the two breakdown assemblages suggests a drop in pressure (uplift) accompanied the temperature decrease, for the sapphirine-forming breakdown reaction is nearly temperature independent (Fig. 10). The breakdown reactions involving tourmaline that Ackermand et al. (1984) described may also be related to the amphibolite-facies event, for these authors concluded that the breakdown products formed during retrogression from the granulite-facies conditions cited above.

**Petrologic interpretation**

Textural relations suggest equilibrium crystallization of the assemblages kornerupine–hornblende–phlogopite–anorthite (32060), kornerupine–gedrite–phlogopite–anorthite (1883.754), and sapphirine–kornerupine–phlogopite–anorthite (31498). In 1883.754, sapphirine and corundum appear to be in equilibrium with kornerupine, but not with the entire 4-phase assemblage. Other assemblages from the type locality are kornerupine–cordierite–phlogopite–anorthite ± sapphirine (sample No. U15 and Vogt, 1947). Uniform mineral compositions in 32060 and 1883.754 are consistent with chemical equilibrium. The small variations found in mineral compositions from grain to grain of no. 31498 probably represent slight departures from chemical equilibrium, possibly the result of incomplete reaction with Na- and B-bearing fluids (see below) and to variations in the oxidation state of iron.

Inclusions of biotite and plagioclase in sapphirine in 1883.754 and 31498 imply that these two minerals were present during the early metamorphic history of the rocks and subsequently equilibrated with kornerupine (see also Ackermand et al., 1984). Sapphirine appears to have formed before kornerupine in 1883.754 while in 31498, sapphirine developed coevally with kornerupine. In 1883.754, the sapphirine and corundum enclosed in kornerupine are interpreted to be relics of an earlier metamorphic assemblage. Sapphirine and corundum occurring along the margins of the kornerupine appear to have formed from kornerupine breakdown during a later event.

Of the three samples, 1883.754 provides the most information on kornerupine petrogenesis, for more phases are present. Textures and chemographic relations in this sample suggest that kornerupine formed from sapphirine, corundum, and gedrite. However, the source of the boron is problematic, for there is no evidence for a boron-bearing precursor. Two alternatives are viable: (1) a tourmaline precursor in the rock itself that was subsequently consumed during kornerupine formation and (2) metasomatizing boron-bearing fluids. Tourmaline has been suggested as a precursor to kornerupine at Waldheim, G.D.R. (Schreyer et al., 1975; Grew, 1985, 1986b).

In the Fiskenaesset region, we are aware of tourmaline–kornerupine associations from only two localities: Sarfaq (Ackermand et al., 1984), and...
near Bjørnesund (Petersen et al., 1980). Ackermann et al. reported that tourmaline developed from the breakdown of kornerupine.

In two samples from the Bjørnesund locality provided by O. V. Petersen and in U.S. National Museum sample no. 133771, collected by Brian Mason (1982, pers. comm. to E. Grew) at the same locality, textures also suggest later formation of tourmaline. Kornerupine in these samples consists largely of dense aggregates of relatively coarse prisms. A few tourmalines are included in the kornerupine or included in hornblende itself included in kornerupine. However, most are found with chlorite, cordierite, phlogopite, hornblende, and corundum interstitially to the kornerupine prisms. A few tourmalines enclose kornerupine or penetrate it. These relations, together with the common subhedral to euhedral outlines of the tourmaline, suggest that tourmaline formed from the breakdown of kornerupine. Possibly the tourmaline 'inclusions' are related to tourmaline penetration along cracks that are outside the plane of the thin sections. A possible breakdown reaction in the Bjørnesund rocks is:

Kornerupine = chlorite + tourmaline + cordierite + corundum.

This reaction is similar to that inferred for 1883.754 except that boron remains fixed in tourmaline. Hornblende and phlogopite formed where Na$_2$O, CaO, and K$_2$O were introduced. Minor sapphirine is present in the Bjørnesund rocks. Some grains appear to have formed prior to the kornerupine, but others appeared to have formed from kornerupine breakdown (see also Herd, 1973). In sum, we have no clear-cut evidence for a tourmaline precursor to kornerupine in rocks from the Fiskeneset area.

In contrast, there is abundant evidence for metasomatism through fluid activity in the Fiskeneset complex, most notably the coarse-grained, pegmatitic appearance of several of the kornerupine-bearing rocks in which crystals exceed 0.5 m in length (Herd, 1973). Fluids may have removed boron from the metasedimentary rocks found locally along the anorthosite-amphibolite contact. Subsequently, through interaction with the highly magnesian sapphirine-phlogopite rocks (or the more iron-rich spinel-biotite rock at Sarfaq), the boron was removed from the fluid and fixed in kornerupine, as suggested by Grew (1982a).

According to our interpretation, the kornerupine-bearing rocks did not have boron-bearing precursors. None the less, the boron may not have been transported more than a few tens or hundreds of metres along the anorthosite-amphibolite contact.

We are now in a position to propose a kornerupine-forming reaction on the basis of the minerals and their compositions. Initially, we will assume that the bulk chemistry is unchanged by the reaction except for H$_2$O and B$_2$O$_3$. By combining Fe with Mg and neglecting Ti, Mn, and F, the mineral compositions in 1883.754 have been simplified as follows:

Kornerupine (Krn): Mg$_{3.65}$Al$_{6.66}$B$_{0.30}$Si$_{3.67}$O$_{21}$(OH)

Sapphirine (Sap): Mg$_{3.58}$Al$_{8.84}$Si$_{1.57}$O$_{20}$

Gedrite (Ged): Na$_{0.55}$Ca$_{0.09}$Mg$_{5.52}$Al$_{3.07}$Si$_{6.23}$O$_{22}$(OH)$_2$

Na-phlogopite end member (Na-Phl): Na$_{1.80}$Mg$_{5.22}$Al$_{3.08}$Si$_{5.56}$O$_{20}$(OH)$_4$

Anorthite (An 94): Na$_{0.06}$Ca$_{0.94}$Al$_{1.94}$Si$_{2.06}$O$_8$

Corundum (Cdm): Al$_2$O$_3$

The calculated reaction is:

3.31Ged + 0.62Sap + 7.96Cdm + 0.63B$_2$O$_3$ + 0.78H$_2$O → 4.18Krn + 1Na-Phl + 0.33An 94 (1)

The Na-phlogopite presumably would be incorporated in the K-phlogopite. Alternatively, we could assume that Na released by gedrite breakdown is lost to the system, resulting in the following reaction:

2.87Ged + 0.67Sap + 9.55Cdm + 0.75B$_2$O$_3$ + 0.78H$_2$O → 5Krn + 0.28An 94 + 0.37Na$_2$O (2)

Most likely, the actual reaction was a combination of the two, in which some of the Na$_2$O was held in the phlogopite and the remainder, lost. This kornerupine formation would probably involve a hydration, consistent with the suggested high fluid activity. This reaction proceeded until one of the reactants was consumed, or was armoured from further reaction by kornerupine. An analogous reaction involving pargasite instead of gedrite may explain kornerupine formation in 32060.

Because kornerupine occurs also with cordierite, Vogt (1947) proposed the following reaction for kornerupine formation at the type locality:

Sapphirine + gedrite + cordierite + B$_2$O$_3$ = kornerupine + albite + H$_2$O (3)

We noted above that Na is at least as extensively accommodated in phlogopite as it is in anorthite. By analogy with reactions (1) and (2), possible alternatives to Vogt's (1947) reaction are (for the compositions of minerals in 1883.754 and an ideal cordierite (Crd), Mg$_5$Al$_4$Si$_5$O$_{18}$·0.5H$_2$O):

2.72Sap + 1.31Gedrite + 1.68Crd + 0.75B$_2$O$_3$ + 1.15H$_2$O = 5Krn + 0.13An 94 + 0.40Na-Phl (4)

and

2.70Sap + 0.95Gedrite + 1.68Crd + 0.75B$_2$O$_3$ + 0.71H$_2$O = 5Krn + 0.09An 94 + 0.26Na$_2$O (5)
In 31498, kornerupine could have formed either by the reactions involving corundum or by those involving cordierite. We presume that there was an excess of sapphireine, which remained in stable equilibrium with kornerupine after all the gedrite and corundum or cordierite were consumed.

**Kornerupine–gedrite assemblage**

The kornerupine–gedrite–phlogopite–anorthite assemblage in 1883.754 is interpreted to be an equilibrium one, in which gedrite remained in the rock after sapphireine and corundum had been isolated by kornerupine. These two minerals are preserved only as armoured relics in kornerupine and are not part of the gedrite-bearing assemblage. Other than Fiskenaeset, kornerupine-gedrite assemblages have been reported only from the Limpopo belt, Zimbabwe (Schreyer and Abraham, 1976a; Windley et al., 1984), Namaqualand complex, South Africa (Waters and Moore, 1985) and from north-west India (Sharma et al., 1985). The textures of the Limpopo and Indian kornerupine-gedrite rocks are complex and there is no evidence for a stable kornerupine-gedrite association. Kornerupine-anthophyllite assemblages are reported from southern India (Balasubrahmanyam, 1965) and from Lherz, in south-western France (Monchoux, 1972). Unfortunately, Balasubrahmanyan did not specify the textural relations between the minerals. In the Lherz rocks, the textural relations were largely destroyed by cataclasis and by extensive alteration, such as phlogopite (?) to vermiculite (Monchoux, 1972).

Detailed descriptions of the textural relations between gedrite and kornerupine are available for the Limpopo and Namaqualand rocks. In the Limpopo samples gedrite occurs as part of symplectic intergrowth with cordierite and sapphireine resulting from breakdown of kornerupine (Schreyer and Abraham, 1976a; Windley et al., 1984). Only boron-free kornerupine was affected. Boron-bearing kornerupine was replaced by sapphireine-cordierite-chlorite symplectites and gedrite was not found with the boron-bearing kornerupine (Windley et al., 1984). In one Namaqualand sample, kornerupine and gedrite form a coarse intergrowth in which grains of orthopyroxene and cordierite are dispersed (Waters and Moore, 1985).

The scarcity of gedrite-kornerupine assemblages is probably due to the relatively limited range of bulk compositions over which both minerals may be stable together. In many cases, either gedrite or kornerupine appears, but not both, or one of the minerals associated with kornerupine seems to exclude gedrite. For example, sillimanite commonly occurs with kornerupine. Because the assemblage gedrite–sillimanite is relatively rare, we would expect the assemblage gedrite–sillimanite–kornerupine to be even rarer. Thus it is no surprise that the sillimanite-cordierite–sapphirine rocks of the Ellamankovilpatti–Kiranur area of southern India contain orthoamphibole (gedrite or anthophyllite) or kornerupine, but rarely, if ever, both (Balasubrahmanyam, 1965; Grew, 1982b; Lal et al., 1984; Grew et al., 1987). Moreover, gedrite is absent from the sillimanite–boron kornerupine assemblages of the Limpopo belt reported by Windley et al. (1984). Kornerupine-bearing rocks lacking sillimanite are less common and many contain hornblende or orthopyroxene. We would not expect gedrite to be common in these rocks, particularly in rocks with orthopyroxene, as the gedrite-orthopyroxene assemblage is by itself not common, as, for example, in the Fiskenaeset region (Herd et al., 1969). Because gedrite itself is more restricted in its paragenesis than either sillimanite, hornblende, or orthopyroxene, kornerupine-gedrite would be more restricted than either kornerupine-sillimanite, kornerupine-hornblende or kornerupine-orthopyroxene.

The final question regarding the Fiskenaeset kornerupine-bearing rocks concerns the composition of the fluids involved in kornerupine formation. We have already shown that boron is an essential constituent of kornerupine and thus these fluids undoubtedly transported boron. Moreover, the compositions of the kornerupine-bearing rocks are unusual in their very high Mg/Fe ratio, high Mg, Al, Ca, and K, and relatively low Si and Na, leading to the rare kornerupine-gedrite as well as the more usual kornerupine-sillimanite, kornerupine-cordierite, and kornerupine-hornblende assemblages. In addition, F contents of the hydrous minerals are low, despite the high temperatures of crystallization and the high Mg/Fe ratios of the minerals. We further suggested that the fluids probably removed Na; K may also have been mobile (Herd et al., 1969; Herd, 1973). Consequently, we are left with the final question as to whether the fluids were H₂O-rich or CO₂-rich.

The association of three hydrous phases, gedrite or hornblende, F-poor phlogopite, and F-poor kornerupine suggests relatively high water activities, particularly at the high temperatures (700–800°C) indicated for metamorphism. On the other hand, CO₂-rich fluid inclusions in kornerupine and corundum at Sarfaq are reported by A. H. Rankin (pers. comm. to Ackerman et al., 1984). These may be interpreted as evidence for a CO₂-rich fluid being present during kornerupine formation. Given this contradictory evidence, we have taken a closer look at the mineral assemblages, which could reveal some constraints on possible fluid compositions.
Again, we note the similarity of the Fiskenæsset assemblage to a magnesite-enstatite-phlogopite-kornerupine ± sapphirine (largely enclosed in kornerupine) assemblage in the sample from the Sar-e-Sang lapis lazuli deposit, Afghanistan (Blaise and Cesbron, 1966; Grew, 1986a). Assemblages with primary carbonate, but without kornerupine, are also known from Fiskenæsset.

This Sar-e-Sang assemblage is remarkably magnesian, for example, orthopyroxene is 98.7–98.8% aluminous enstatite (1.8–3.2% Al₂O₃) and the carbonate is 98.6% MgCO₃. Consequently, experimental data on the model MgO-SiO₂-CO₂-H₂O system are applicable. Johannes (1969) experimentally determined that at 2 kbar and 550 °C enstatite-magnesite is stable for XCO₂ = molecular CO₂/(CO₂ + H₂O) ≥ 0.88. However, Schreyer et al. (1972) and Ohnmacht (1974) calculated that the minimum XCO₂ required to stabilize this assemblage decreases with increasing total fluid pressure and temperature. For example, at 650 °C and 7 kbar, conditions close to those estimated for Sar-e-Sang (Schreyer and Abraham, 1976b; Grew, 1986a) and Fiskenæsset, this minimum XCO₂ value is 0.55. Moreover, Ohnmacht (1974) estimated that anthophyllite appears at XCO₂ ≤ 0.16 and temperatures above 750 °C (P = 7 kbar), a marked contrast to the situation at 2 kbar, where anthophyllite is stable at XCO₂ ≤ 0.98 and temperatures down 510 °C (Johannes, 1969). Thus the Sar-e-Sang and Fiskenæsset carbonate-bearing assemblages probably crystallized at XCO₂ ≥ 0.55.

However, the carbonate-free, amphibole-bearing kornerupine assemblages from Fiskenæsset undoubtedly crystallized at XCO₂ significantly less than 0.5. If the fluid inclusion compositions cited by Ackermann et al. (1984) are taken to represent the composition of the metamorphic fluid during the granulite-facies event, the Sarfaq kornerupine assemblage must have formed at XCO₂ significantly higher than that inferred for the amphibole-bearing assemblages at the type locality. On the other hand, the CO₂-rich fluid inclusions in the Sarfaq rocks may not be representative of the metamorphic fluid at the time of recrystallization. Instead, they may be a residue enriched in CO₂ after extraction of H₂O as Crawford and Hollister (1986) proposed for granulite-facies rocks in general. In their review Crawford and Hollister (1986) concluded that an anatectic melt may have extracted H₂O in most terrains. A viable alternative is the proposal of Lamb et al. (1986) for late entrainment of CO₂ based on their studies of granulite-facies rocks in the Adirondack Mountains (USA). Thus the CO₂-rich fluids may not represent fluid compositions during kornerupine formation. Pending a detailed study of fluid inclusions, which is beyond the scope of the present paper, we suggest that kornerupine at the type locality, and possibly also at other localities in the Fiskenæsset complex, formed in association with water-rich metatorphic fluids.

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