

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

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Abstract

In 1884, Lorenzen proposed the formula $MgAl_2SiO_6$ for his new mineral kornerupine from Fiskensæset and did not suspect it to contain boron. Lacroix and de Gramont (1919) reported boron in Fiskensæset 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.% B_2O_3 , e.g. $(Li_{0.04} Na_{0.01} Ca_{0.01}) (Mg_{3.49} Mn_{0.01} Fe_{0.17} Ti_{0.01} Al_{5.64})_{\Sigma 9.30} (Si_{3.67} Al_{1.02} B_{0.31})_{\Sigma 5} O_{21} (OH_{0.99} F_{0.01})$ 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 ($X_{Fe} = \text{atomic Fe}/(\text{Fe} + \text{Mg}) = 0.028\text{--}0.035$): (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 pinitite (cordierite?) as breakdown products of kornerupine. Kornerupine may have formed by reactions such as: gedrite + sapphirine + corundum + B_2O_3 (in solution) + $H_2O = \text{kornerupine} + \text{anorthite} + \text{Na-phlogopite}$ under conditions of the granulite facies. Boron for kornerupine formation was most likely remobilized by hydrous fluids from meta-sedimentary rocks occurring along the upper contact of the Fiskensæset gabbro-anorthosite complex with amphibolite.

KEYWORDS: boron, kornerupine, Fiskensæset, Greenland, ion microprobe, spectrophotometry.

Introduction

IN 1884, J. Lorenzen† discovered the mineral kornerupine from Fiskensæset, West Greenland,

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† According to the summary published in 1886 in *Z. Krystallogr.* **11**, 315, the paper in which Lorenzen first describes the new mineral kornerupine, 'Undersøgelse af Mineralier fra Grønland', was to be published in *Meddelels. Grønland*, 7, in 1884. This issue, however, did not

for which he proposed a formula $MgAl_2SiO_6$ (his analysis reproduced here in Table 1). Neither Lorenzen (1886, 1893) nor Ussing (1889), who also analysed material from Fiskensæset, 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 prismatine, the name introduced by Sauer (1886) for kornerupine from Waldheim, Saxony, presently a part of the German Democratic Republic.

boron was a possible component of the mineral. Lacroix and de Gramont (1919) reported that Fiskeneset kornerupine contained boron, but were not able to analyse it quantitatively. Herd (1973) analysed a kornerupine from the type locality and obtained a composition nearly identical to Lorenzen's (Table 1). Herd's electron microprobe analysis was performed on a grain supplied by H. Sørensen from the material studied by Ussing (1889). Boron was sought with a laser probe, but none was detected.

The only other known locality for boron-free kornerupine 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 kornerupines analysed for boron have been found to contain it, including kornerupine at other localities in the Fiskeneset region (Petersen *et al.*, 1980). Ackermund *et al.* (1984) reported kornerupine breakdown to tourmaline from Sarfaq, Tasiussá, a locality south-east of Fiskeneset, and concluded that this kornerupine is also boron-bearing.

Because the type locality of Fiskeneset is one of only two world localities from which a boron-free kornerupine has been reported and because boron-bearing kornerupine has also been reported from Fiskeneset, we decided to reanalyse several kornerupines from the type locality, including the sample in which Herd (1973) sought boron. Our new analyses show that these kornerupines contain boron, confirming Lacroix and de Gramont's (1919) report of boron in kornerupine from Fiskeneset. The laser probe analysis cited by Herd (1973) was probably performed on another sample accidentally substituted for the kornerupine. In view of our findings, the generally accepted use of the name kornerupine 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 kornerupine with gedrite. Rocks containing orthoamphibole and kornerupine are not common at other world localities and we are aware of only one well-documented report of an equilibrium gedrite-kornerupine assemblage (Waters and Moore, 1985). In other cases the orthoamphibole (gedrite) and kornerupine 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 kornerupine

from other localities (Balasubrahmanyam, 1965; Monchoux, 1972).

Field relations

Kornerupine is presently known from about ten localities in the Fiskeneset region, including the type locality near Fiskeneset town (e.g. Herd *et al.*, 1969; Herd, 1973; Walton, 1973; Petersen *et al.*, 1980; Friend, 1982; Ackermund *et al.*, 1984). At localities other than the type locality, kornerupine is invariably associated with sapphirine-bearing rocks, along or near the upper contact of metamorphosed anorthosites of the Fiskeneset layered igneous complex with overlying amphibolites. The kornerupine- and sapphirine-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 clintonite rocks, which are interpreted to be metamorphosed near-shore marine sediments with associated magnesian ultramafics (Herd, 1973). The Fiskeneset 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 sapphirine and kornerupine are found in one little spot near Fiskeneset town. The layers here strike approximately EW and dip 60° to 90°. Sapphirine occurs in mica schist and anthophyllite. Steenstrup describes kornerupine as a grayish white radiating mineral reminiscent of kyanite. The exposures described by Steenstrup may be located near the anorthosite contact with pyribolite and ultramafics roughly 30 m north of the main exposure of sapphirine rocks mapped by Herd *et al.* (1969) on the north shore of the southern harbor at Fiskeneset. 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 kornerupine 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 sapphirine-bearing contact zone between Fiskeneset complex anorthosite and adjacent magnesian ultramafics. Sørensen (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 ('kupfferite') 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,

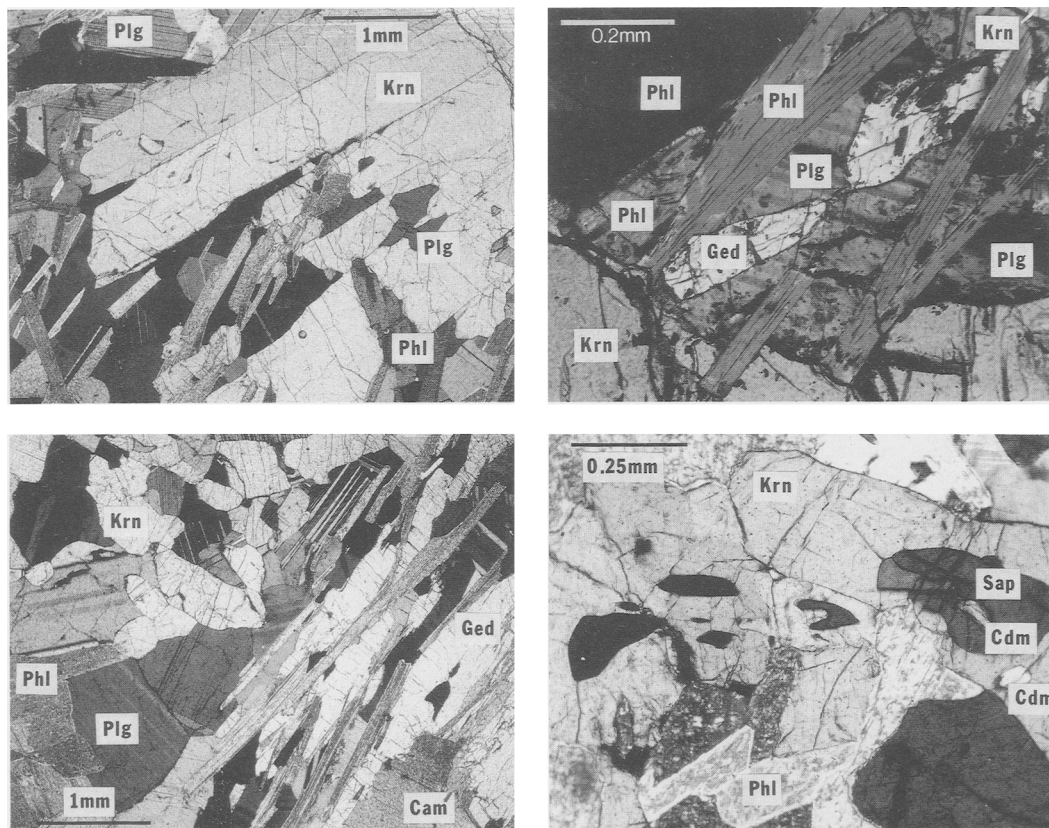
courtesy of H. Sørensen). Kornerupine in U15 occurs in a matrix of plagioclase, cordierite, and phlogopite, without amphibole.

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 Fiskeneset 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; Ackermund *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



FIGS. 1-4. FIG. 1 (*top left*). Radiating kornerupine prisms (Krn) lie in matrix of plagioclase (Plg) and phlogopite (Phl). Kornerupine contains xenoblastic inclusions of plagioclase, and is cut by phlogopite. No. 1883.754 (second section). FIG. 2 (*top right*). Gedrite (Ged), phlogopite (Phl), in flakes parallel to plane of section, black, and perpendicular to it, and plagioclase (Plg) in band between two kornerupine aggregates (Krn). No. 1883.754 (analysed section). FIG. 3 (*bottom left*). Gedrite prisms (Ged), intergrown with and overgrown by phlogopite, in a matrix of plagioclase (Plg), phlogopite (Phl) and kornerupine (Krn). Minor clinoamphibole (Cam-leader points to clinoamphibole between phlogopite and gedrite) overgrows gedrite at one margin. No. 1883.754 (second section). FIG. 4 (*bottom right*). Prisms of kornerupine (Krn), contain xenoblastic inclusions of sapphirine (Sap). Both the sapphirine and the kornerupine contain corundum (Cdm-white) inclusions. No. 1883.754 (third section). All under crossed polars.

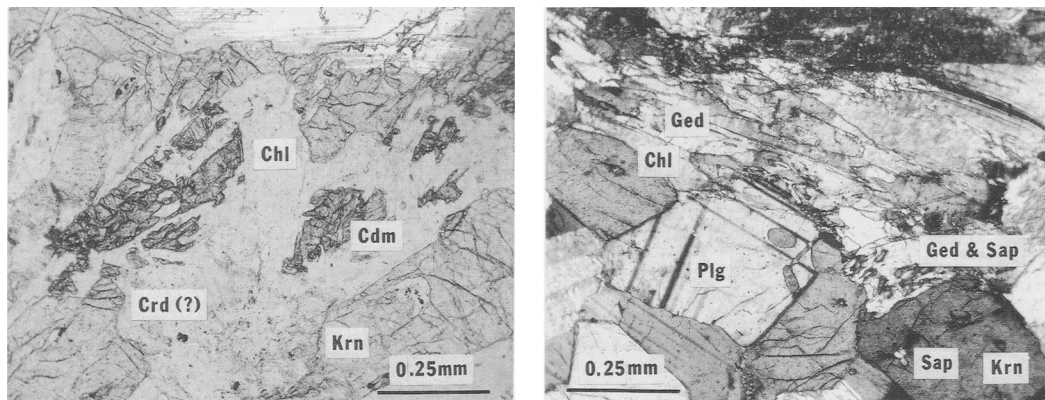
kornerupine occurs in a matrix of anorthite, phlogopite, and amphibole. In this sample, however, the amphibole is a green hornblende, and neither sapphirine nor corundum was found.

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-



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 (Crd) (?). No. 1883.754 (fourth section). Plane light. FIG. 6 (right). Kornerupine grains (Krn) with inclusions (dark) of sapphire (Sap) in plagioclase matrix (Plg) about a phlogopite-rich area (top of photograph). Kornerupine has been locally replaced by gedrite + sapphire (Ged and Sap), and there is chlorite (Chl) and pinite among the fine-grained phyllosilicates. No. 1883.754 (third section). Crossed polars.

thetic TiO_2 (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 TiO_2 (Ti), and synthetic Cr_2O_3 (Cr). Precision of the microprobe analyses at Imperial College was calculated to be $\pm 3\%$ for major element values by using an internal standard with each analysis set. Standard deviations for the microprobe analyses at the Ruhr-Universität are

$\leq 1.5\%$ of the given average value for oxides constituting $> 18\%$ of the mineral, $\leq 2.2\%$ for oxides in the 8–14% range, $\leq 12\%$ 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, sapphire, 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 grandierite (B/Si), spodumene (Li/Si), and biotite (F/Si, Ba/Si), by applying a working curve. Estimated precision is about $\pm 20\%$ of the given values of B and Li in most kornerupines and Ba in phlogopite and is poorer than $\pm 20\%$ for other IMMA values listed in the tables. In the absence of standards, the amounts of Sr and Rb can be

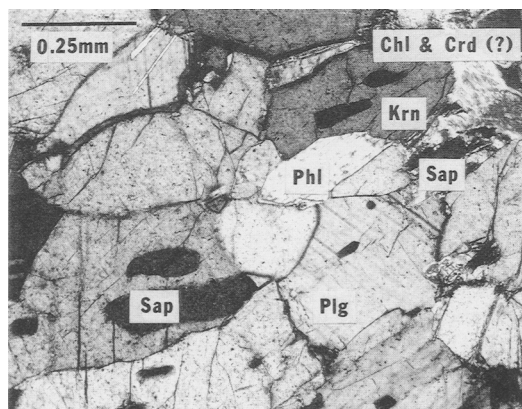


FIG. 7. Subidioblastic kornerupine grains (Krn), intergrown with phlogopite (Phl), and with inclusions of sapphire (Sap). The kornerupine has been locally replaced along grain margins by sapphire, chlorite and cordierite(?) (pinite) (Chl and Crd). No. 1883.754 (third section). Crossed polars.

Table 1. Analyses of kornerupine in specimens from the type locality, Fiskenaeset, West Greenland.

	1	2	3	4	5
	Wet Chemistry		Electron Microprobe (weight %)		
SiO ₂	30.90	30.3	29.80	28.68	28.73
TiO ₂	-	0.07	0.06	0.10	0.10
Al ₂ O ₃	46.79	46.4	45.85	47.68	46.50
FeO	1.82	1.8	1.60	1.36	1.74
MnO	-	0.01	0.05	0.03	0.03
MgO	19.46	19.1	18.96	18.33	18.74
CaO	-	0.05	0.07	0.07	0.10
Na ₂ O	-	0.02	0.04	0.03	b.d.
H ₂ O	1.30	(1.22)	(1.21)	(1.17)	(1.17)
	Ion Microprobe (weight %)				
B ₂ O ₃	-	1.01	1.44	0.50	0.87
Li ₂ O	-	0.06	0.08	0.07	0.07
F	-	0.01	0.01	0.06	0.05
Total	100.27	100.05	99.17	98.06	98.08
	Cations per 21.5 Oxygens				
Si	3.774	3.711	3.674	3.588	3.597
Al	1.226	1.075	1.020	1.304	1.216
B	-	0.214	0.306	0.108	0.187
Total	5.000	5.000	5.000	5.000	5.000
Al	5.509	5.623	5.642	5.728	5.645
Ti	-	0.006	0.006	0.009	0.009
Fe	0.186	0.184	0.165	0.143	0.182
Mn	-	0.001	0.005	0.003	0.003
Mg	3.543	3.487	3.485	3.419	3.498
Total	9.238	9.301	9.303	9.302	9.337
Ca	-	0.007	0.009	0.010	0.013
Li	-	0.030	0.038	0.037	0.036
Na	-	0.005	0.010	0.007	0.000
Total Cations	14.238	14.343	14.360	14.356	14.386
	Anions				
F	-	0.006	0.005	0.023	0.019
OH	1.059	0.994	0.995	0.977	0.981
Fe/(Fe+Mg)	0.050	0.050	0.045	0.040	0.050

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.

2 - Sample 32060. Electron microprobe data from Herd (1973).

Cr₂O₃ and

K₂O ² < 0.01%.

3 - Sample 1883.754, average of 5 grains.

4 - Sample 31498, grain 1.

5 - Sample 31498, grain 2. For 3-5, b.d. means

Na₂O ≤ 0.02%, also Cr₂O₃ and
K₂O ≤ 0.02%.

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).

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

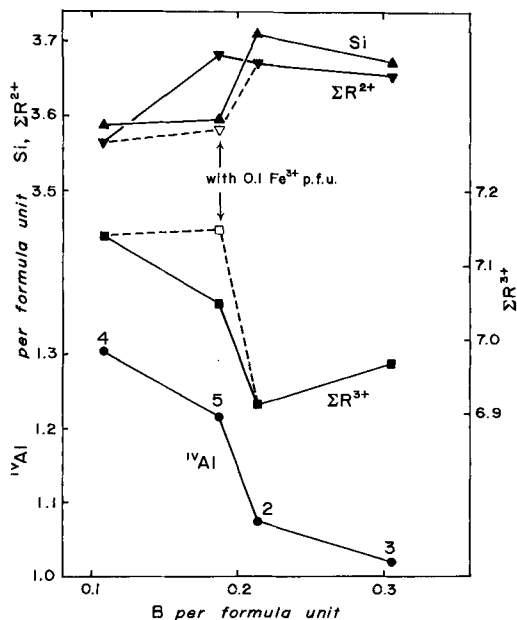


FIG. 8. Compositional variations of Fiskensæset kornerupines in cations per formula unit of 21 O+(OH, F). Numbers refer to the columns in Table 1. $\Sigma R^{3+} = \text{Al} + \text{B} (+\text{Fe}^{3+})$. $\Sigma R^{2+} = \text{Mg} + \text{Fe} + \text{Mn}$. For no. 5, solid symbol refers to all $\text{Fe} = \text{Fe}^{2+}$; open symbol refers to the assumed values of $\text{Fe}^{3+} = 0.1$ and $\text{Fe}^{2+} = 0.082$.

46.97, 47.20%; FeO 1.33, 1.30%; and MgO 18.44, 18.59%. The composition of a fourth prism is different (Table 1, column 5).

Three substitutions relate the kornerupine compositions: (1) $\text{Mg} = \text{Fe}^{2+}$; (2) $\text{Al} = \text{B}$; and (3) $(\text{Mg}, \text{Fe}^{2+}, \text{Mn}) + \text{Si} = 2(\text{Al}, \text{B})$ (Figs. 8-9), which are characteristic of kornerupine (Seifert, 1975; Grew *et al.*, 1984; Waters and Moore, 1985). In addition, a fourth substitution, $\text{Fe}^{3+} = \text{Al}$, may relate the unusual kornerupine composition in 31498 (Table 1, column 5) to the compositions of the other analysed kornerupines. The formula for this kornerupine is distinct in that $\text{Fe} + \text{Mg} + \text{Mn}$ exceeds Si. If 0.1 Fe per formula unit is assumed to be ferric (that is, 55% of the Fe), the composition of this grain would lie on the trends for the other Fiskensæset kornerupines (Figs. 8-9).

The kornerupine H_2O contents that were calculated assuming an anion composition of 21 O + 1 (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_2O_3 , Li_2O , 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 sapphirine 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.

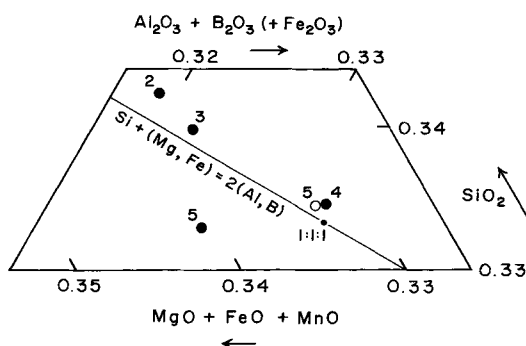


FIG. 9. Plot of Fiskensæset kornerupine composition on $\text{MgO} + \text{FeO} + \text{MnO} - \text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3 (+\text{Fe}_2\text{O}_3) - \text{SiO}_2$ (mole proportions) diagram. Numbers refer to the columns in Table 1. Open symbol for no. 5 refers to the assumed values of $\text{Fe}^{3+} = 0.1$ and $\text{Fe}^{2+} = 0.082$.

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_2O contents are among the lowest for phlogopite and biotite associated with kornerupine and sapphirine (0.001-0.1 wt. % Li_2O , Grew 1985, 1986a, b; Grew *et al.*, 1985, 1986 and unpublished data) and are lower than most Li_2O values reported for phlogopite and biotite from amphibolite-facies metapelites (0 to 0.43% Li_2O , 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_2O 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 $\text{Na}/(\text{Na} + \text{K})$ ratios) are comparable to K-phlogopites associated with Na-phlogopite ($X_{\text{Na}} = 0.05-0.28$, Schreyer *et al.*, 1980) and wonesite (0.07-0.17, Spear *et al.*, 1981). Moreover, the Fiskensæset

phlogopites contain significant Al_2O_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_{Mg} = atomic Mg/(Mg + Fe) = 0.995, X_{Na} = 0.26, Na + K = 1.89, 17.3% Al_2O_3 ; Grew, 1986a). On the other hand, the more iron-rich

Table 2. Analyses of sapphirine in kornerupine-bearing specimens from the type locality, Fiskenaeset, West Greenland.

	1	2	3
Electron Microprobe (weight %)			
SiO_2	13.48	13.54	12.79
Al_2O_3	64.39	64.01	64.29
Cr_2O_3	b.d.	0.06	0.05
FeO	1.46	1.27	1.17
MgO	19.77	19.88	19.55
Ion Microprobe (weight %)			
B_2O_3	0.05	0.05	—
Li_2O	0.01	0.01	—
F	b.d.	0.17	—
Total	99.16	98.92	97.85
Cations normalized to 14 cations and 20 Oxygens			
Si	1.570	1.582	1.508
Al	4.419	4.408	4.492
B	0.011	0.010	—
Total	6.000	6.000	6.000
Al	4.420	4.405	4.443
Cr	—	0.006	0.005
Fe 3+	0.015	0.011	0.044
Fe 2+	0.128	0.113	0.071
Mg	3.433	3.462	3.437
Li	0.005	0.003	—
Total	8.001	8.000	8.000
Anions			
F	0.000	0.062	—
Fe/(Fe+Mg)	0.040	0.035	0.032
Fe ²⁺ /(Fe ²⁺ +Mg)	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, average of 3 grains.
2 - Sample 31498, grain 1.
3 - Sample 31498, grain 3. Na_2O , K_2O , MnO and TiO_2 are $\leq 0.02\%$; $\text{Cr}_2\text{O}_3 \leq 0.04\%$.

phlogopite (X_{Mg} = 0.780–0.789) associated with kornerupine at Sarfaq is not unusually sodic (0.29–0.36% Na_2O , Ackermann *et al.*, 1984). Guidotti (1984) suggested that iron-poor phlogopites would be able to accommodate more Na than iron-rich biotites because the Mg octahedral sheet is smaller than the Fe octahedral sheet. We thus conclude that the relatively high Na_2O contents of the Fiskenaeset phlogopites are a result of their very low Fe content. Moreover, the interlayer site in Fe-poor phlogopite appears to incorporate more

Table 3. Analyses of phlogopite and gedrite in kornerupine-bearing specimens from the type locality, Fiskenaeset, west Greenland

	1	2	3	4
Phlogopite				
Gedrite				
Electron Microprobe Analysis (weight %)				
SiO_2	39.9	39.59	38.96	45.66
TiO_2	0.66	0.64	0.78	0.11
Al_2O_3	18.4	18.59	18.59	19.11
FeO	1.6	1.53	1.34	3.26
MnO	b.d.	b.d.	b.d.	0.12
MgO	24.4	24.06	23.79	25.33
CaO	0.07	b.d.	b.d.	0.64
Na_2O	0.93	1.03	0.90	2.08
K_2O	8.2	8.13	8.18	b.d.
H_2O	(4.24)	(4.22)	(4.17)	(2.20)
Ion Microprobe Analysis (weight %)				
B_2O_3	0.005	b.d.	0.001	—
Li_2O	0.005	0.002	0.004	—
BaO	0.32	0.22	0.19	—
F	0.10	0.09	0.10	—
Total	98.79	98.06	96.97	98.51
Cations				
Oxygens	22	22	22	23
Si	5.577	5.568	5.540	6.230
Al	2.422	2.432	2.460	1.770
B	0.001	0.000	0.000	—
Total	8.000	8.000	8.000	8.000
Ti	0.069	0.068	0.083	0.011
Al	0.609	0.649	0.655	1.304
Fe	0.187	0.180	0.159	0.372
Mn	0.000	0.000	0.000	0.014
Mg	5.084	5.044	5.043	5.152
Li	0.003	0.001	0.002	—
Total	5.952	5.942	5.942	6.853
Ca	0.010	0.000	0.000	0.093
Ba	0.018	0.012	0.011	—
Na	0.252	0.281	0.248	0.550
K	1.462	1.459	1.484	0.000
Total	1.742	1.752	1.743	0.643
Total Cations	15.694	15.694	15.685	15.496
Anions				
F	0.044	0.042	0.043	—
OH	3.956	3.958	3.957	2.000
Fe/(Fe+Mg)	0.035	0.034	0.031	0.067
Na/(Na+K)	0.15	0.16	0.14	—

Totals corrected for F = 0. Dash: not analyzed or not calculated. All Fe as FeO. b.d.: below detection. H_2O values (in brackets) were calculated assuming ideal anion composition.

Notes: 1 - Sample 32060. Electron microprobe data from Herd (1972). b.d. means $< 0.01\%$.
2 - Sample 1883,754, average of 14 grains.
3 - Sample 31498, grain one.
4 - Sample 1883,754, average of 2 grains. For 2–4, b.d. means CaO, MnO, Cr_2O_3 , and $\text{K}_2\text{O} \leq 0.02$.

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).

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) < sapphirine (0.040) < kornerupine (0.045) < gedrite (0.067);

Table 4. Analyses of anorthite in kornerupine-bearing specimens from the type locality, Fiskenesstet, west Greenland (electron microprobe)

	1	2	3
	Weight %		
SiO ₂	45.2	44.00	43.42
Al ₂ O ₃	34.6	34.96	35.01
FeO	0.01	0.03	0.03
CaO	18.8	19.31	19.16
Na ₂ O	0.87	0.73	0.60
K ₂ O	0.01	b.d.	b.d.
Total	99.5	99.03	98.22
	Cations per 8 oxygens		
Si	2.095	2.056	2.045
Al	1.890	1.925	1.943
Fe	0.000	0.001	0.001
Ca	0.934	0.967	0.967
Na	0.078	0.066	0.055
K	0.001	0.000	0.000
Total	4.998	5.015	5.011
An	92	94	95

All Fe as FeO b.d.: below detection

Notes: 1 - Sample 32060, Electron microprobe data from Herd (1972)
 2 - Sample 1883.754, average of 9 grains
 3 - Sample 31498, grain one
 Cr₂O₃, K₂O, MnO, MgO, and TiO₂ ≤ 0.02.

and (3) 31498—phlogopite (0.028–0.031) < sapphirine (0.032–0.035) < kornerupine (0.038–0.050). If the proportions of ferric iron estimated from stoichiometry in sapphirine (grain 3) and kornerupine (grain 2) of 31498 are assumed, then $X_{Fe^{2+}}$ increases as follows for these two grains: sapphirine (0.020) < kornerupine (0.023). The equilibrium sequence for Fiskenesstet thus appears to be phlogopite < sapphirine < kornerupine < gedrite, which has been reported for the Limpopo belt where kornerupines contain 0 to 0.60% B₂O₃ (Schreyer and Abraham, 1976a; Windley *et al.*, 1984). On the other hand, in a Waldheim, G.D.R., paragenesis, where kornerupine contains 3.4% B₂O₃ and Fe³⁺ contents are negligible, the equilibrium sequence is biotite < kornerupine (0.19–0.20) < sapphirine (0.22) (Grew, 1985, 1986b). The Fe²⁺–Mg fractionation between kornerupine and sapphirine in the Waldheim rock is reversed by comparison with the fractionation in the Fiskenesstet and Limpopo rocks, while the fractionation between biotite and sapphirine is about the same. This difference suggests that boron in kornerupine may affect the partitioning of Fe²⁺ 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 sapphirine and phlogopite such that (in wt. %), for B₂O₃, kornerupine >> sapphirine > phlogopite, and for Li₂O, kornerupine > sapphirine > 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–Al₂O₃–SiO₂–H₂O system provide a framework for inferring pressures and temperatures of kornerupine formation at the type locality in Fiskenesstet. In the model system, the assemblages kornerupine–sapphirine 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 Fiskenesstet rocks would have extended the range of conditions for kornerupine

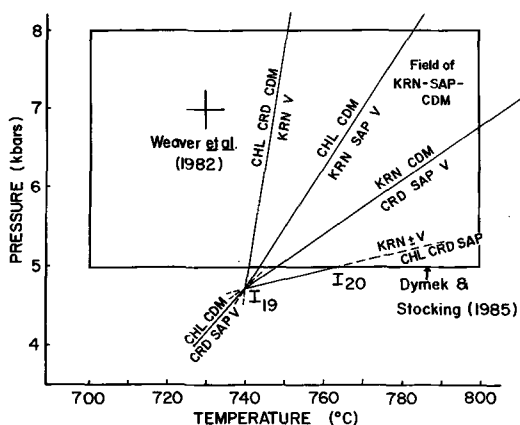


FIG. 10. Portion of Seifert's (1975, Fig. 6) pressure-temperature grid for boron-free kornerupine in the system MgO–Al₂O₃–SiO₂–H₂O. Box is range of pressures and temperatures estimated by Dymek and Stocking (1985) for Fiskenesstet. Cross indicates 'preferred' conditions estimated by Weaver *et al.* (1982, p. 2205) for nearby Qeqertarsuaq (size of cross does not indicate uncertainties in the estimate). Mineral abbreviations: chl—chlorite, crd—cordierite, cdm—corundum, krn—kornerupine, sap—sapphirine, and V—vapour. I₁₉ and I₂₀ are Seifert's invariant points.

stability to lower pressures and temperatures, while the small iron contents of the Fiskensæset minerals would have had a negligible effect. Moreover, Seifert's (1975) experiments were carried out at $P_{\text{H}_2\text{O}} = P_{\text{total}}$. 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 Fiskensæset region are 730 °C and 7 kbar (Weaver *et al.*, 1982), and at Fiskensæset 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 $P_{\text{H}_2\text{O}}$ 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 Fiskensæset must have crystallized at 700–800 °C and at 5 kbar or more. A similar conclusion was also reached by Ackermann *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 Fiskensæset complex and must have formed during the earlier of the two regional metamorphic events to affect the Fiskensæset region after emplacement of the anorthositic 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 Fiskensæset 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 $P_{\text{H}_2\text{O}} = 5\text{--}7$ 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 undoubtedly lower. 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 in-

volving tourmaline that Ackermann *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 Ackermann *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 Fiskensæset region, we are aware of tourmaline–kornerupine associations from only two localities: Sarfaq (Ackermann *et al.*, 1984), and

near Bjørnesund (Petersen *et al.*, 1980). Ackermand *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.

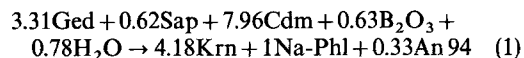
This reaction is similar to that inferred for 1883.754 except that boron remains fixed in tourmaline. Hornblende and phlogopite formed where Na₂O, CaO, and K₂O were introduced. Minor sapphirine is present in the Bjørnesund rocks. Some grains appear to have formed prior to the kornerupine, but others 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 Fiskensættet area.

In contrast, there is abundant evidence for metasomatism through fluid activity in the Fiskensættet 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.

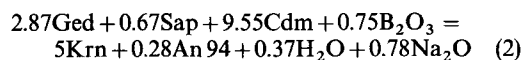
We are now in a position to propose a kornerupine-forming reaction on the basis of the minerals and their compositions. Initially, we will assume that the bulk chemistry is unchanged by the reaction except for H₂O and B₂O₃. By combining Fe with Mg and neglecting Ti, Mn, and F, the mineral compositions in 1883.754 have been simplified as follows:

Kornerupine (Krn): Mg_{3.65}Al_{6.66}B_{0.30}Si_{3.67}O₂₁(OH)
Sapphirine (Sap): Mg_{3.58}Al_{8.84}Si_{1.57}O₂₀
Gedrite (Ged): Na_{0.55}Ca_{0.093}Mg_{5.52}Al_{3.07}Si_{6.23}O₂₂(OH)₂
Na-phlogopite end member (Na-Phl): Na_{1.80}Mg_{5.22}Al_{3.08}Si_{5.56}O₂₀(OH)₄
Anorthite (An 94): Na_{0.06}Ca_{0.94}Al_{1.94}Si_{2.06}O₈
Corundum (Cdm): Al₂O₃

The calculated reaction is:

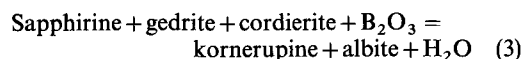


The Na-phlogopite presumably would be incorporated in the K-phlogopite. Alternatively, we could assume that Na released by gedrite breakdown is lost to the system, resulting in the following reaction:

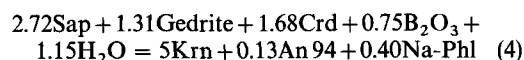


Most likely, the actual reaction was a combination of the two, in which some of the Na₂O was held in the phlogopite and the remainder, lost. This kornerupine formation would probably involve a hydration, consistent with the suggested high fluid activity. This reaction proceeded until one of the reactants was consumed, or was armoured from further reaction by kornerupine. An analogous reaction involving pargasite instead of gedrite may explain kornerupine formation in 32060.

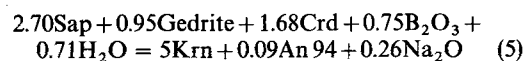
Because kornerupine occurs also with cordierite, Vogt (1947) proposed the following reaction for kornerupine formation at the type locality:



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), Mg₂Al₄Si₅O₁₈ · 0.5H₂O):



and



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 sapphirine, 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 sapphirine 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 Fiskensæset, 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, Balasubrahmanyam 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 symplectitic intergrowth with cordierite and sapphirine 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 sapphirine–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 Ellammankovilpatti–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 Fiskensæset 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 Fiskensæset 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–sapphirine, 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 Ackermann *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 Fiskensæset 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 Fiskensæset.

This Sar-e-Sang assemblage is remarkably magnesian, for example, orthopyroxene is 98.7–98.8% aluminous enstatite (1.8–3.2% Al_2O_3) and the carbonate is 98.6% MgCO_3 . Consequently, experimental data on the model $\text{MgO-SiO}_2\text{-CO}_2\text{-H}_2\text{O}$ system are applicable. Johannes (1969) experimentally determined that at 2 kbar and 550 °C enstatite–magnesite is stable for X_{CO_2} = molecular $\text{CO}_2/(\text{CO}_2 + \text{H}_2\text{O}) \geq 0.88$. However, Schreyer *et al.* (1972) and Ohnmacht (1974) calculated that the minimum X_{CO_2} 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 Fiskensæset, this minimum X_{CO_2} value is 0.55. Moreover, Ohnmacht (1974) estimated that anthophyllite appears at $X_{\text{CO}_2} \leq 0.16$ and temperatures above 750 °C ($P = 7$ kbar), a marked contrast to the situation at 2 kbar, where anthophyllite is stable at $X_{\text{CO}_2} \leq 0.98$ and temperatures down 510 °C (Johannes, 1969). Thus the Sar-e-Sang and Fiskensæset carbonate-bearing assemblages probably crystallized at $X_{\text{CO}_2} \geq 0.55$.

However, the carbonate-free, amphibole-bearing kornerupine assemblages from Fiskensæset undoubtedly crystallized at X_{CO_2} significantly less than 0.5. If the fluid inclusion compositions cited by Ackermund *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 X_{CO_2} significantly higher than that inferred for the amphibole-bearing assemblages at the type locality. On the other hand, the CO_2 -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 CO_2 after extraction of H_2O 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 H_2O in most terrains. A viable alternative is the proposal of Lamb *et al.* (1986) for late entrapment of CO_2 based on their studies of granulite-facies rocks in the Adirondack Mountains (USA). Thus the CO_2 -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 Fiskensæset complex, formed in association with water-rich metamorphic fluids.

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