

6-1-1992

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Grew, Edward S.; Yates, Martin G.; Konilov, A. N.; and Marquez, Nicholas, "Kornerupine from the Archean Kola Series at Sholt-Yavr, Kola Peninsula, Russia" (1992). *Earth Science Faculty Scholarship*. 162.
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SHORT COMMUNICATIONS

MINERALOGICAL MAGAZINE, JUNE 1992, VOL 56, PP. 247-251

Kornerupine from the Archaean Kola Series at Sholt-Yavr, Kola Peninsula, Russia

KORNERUPINE, approximately $(\square, \text{Mg}, \text{Fe})(\text{Mg}, \text{Fe}, \text{Al})_9(\text{Si}, \text{Al}, \text{B})_5(\text{O}, \text{OH}, \text{F})_{22}$, is a mineral of Mg-Al-rich rocks and magnesian metapelites in upper amphibolite- and granulite-facies rocks. It is reported from about 50–60 localities worldwide, including six in the former Soviet Union: Ukrainian shield (Kuryleva, 1960; Nalivkina, 1959), Aldan shield at the Usmun and Sutam Rivers (Kitsul *et al.*, 1972; Grew *et al.*, 1989, 1991), the Precambrian crystalline rocks of the southwestern Pamir Mountains at Darai Stazh and Mulvoj (Levitskiy *et al.*, 1988, 1990; Grew *et al.*, 1990a), and the Baltic shield in the Archaean Kola series of the Kola Peninsula (Fonarev *et al.*, 1989). The term Kola series refers to units consisting predominantly of biotite-plagioclase \pm amphibole gneisses, amphibolite, and pelitic gneisses that are exposed over a wide area of the Kola Peninsula; metamorphic grade ranges from the amphibolite to the granulite facies (e.g. Nalivkina *et al.*, 1984). In the present paper, we report chemical analyses and discuss the paragenesis of kornerupine first found by Fonarev *et al.* (1989), who reported the assemblage kornerupine + orthopyroxene + sapphirine + biotite, but provided no chemical or petrologic details.

Kornerupine was found in core from a hole (no. 15) drilled in an iron ore deposit on the west shore of Lake Sholt-Yavr, 35 km south-southwest of Murmansk. The hole at Sholt-Yavr penetrates alternating biotite-hornblende \pm garnet gneiss, garnet-biotite-cordierite gneiss, rare cordierite-orthopyroxene gneiss and pyroxene-magnetite quartzite of the Kola series and numerous bodies of microcline granite. Kornerupine occurs in a lens of aluminous sapphirine-bearing biotite schist at 154.2 m depth; lenses of similar biotite schist, but lacking kornerupine and orthopyroxene, are found at 152.7 and 221.5 depth. These lenses are 0.5–1.5 m thick. The rocks were affected by three events for which Fonarev *et al.*

(1989; in press) calculated the following temperatures and pressures: $670 \pm 20^\circ\text{C}$, 5.0 ± 0.5 kbar; $575 \pm 20^\circ\text{C}$, 3–4 kbar; and $500 \pm 20^\circ\text{C}$, the first corresponding to the granulite facies. On the basis of Rb-Sr isochrons, Avakyan and Buyakayte (1991) and Avakyan *et al.* (1991) have dated the beginning of metamorphic activity at 2880 ± 50 Ma and its conclusion at 2540 ± 15 Ma.

The kornerupine-bearing rock (15/154.2) consists dominantly of biotite, roughly equal amounts of orthopyroxene and sapphirine, and trace amounts of kornerupine, spinel, monazite, zircon, apatite, calcite, and ferroan magnesite. Grain size of the silicate phases is mostly 0.5–2 mm, with sapphirine somewhat finer and kornerupine somewhat coarser (to 2.5 mm). Biotite flakes are generally randomly oriented relative to one another. Sapphirine grains are equant to tabular and are commonly in aggregates. Spinel is found only as inclusions in sapphirine and is nearly opaque from fine magnetite inclusions, which probably contributed to the high Fe_3O_4 content in the microprobe analysis (Table 1). Kornerupine is pleochroic from colourless to pale blue in thin section. Its grains are typically subhedral to euhedral and contain inclusions of biotite and sapphirine. Kornerupine is locally in direct contact with orthopyroxene. Orthopyroxene also encloses sapphirine, but less commonly than kornerupine does. The equilibrium mineral assemblage is inferred to have been kornerupine + sapphirine + orthopyroxene + biotite, whereby kornerupine was the latest mineral to form, biotite and sapphirine the earliest. Spinel is interpreted as a relic armoured by sapphirine. Late low-temperature alteration affected sapphirine more than the other minerals: it is cut by seams of secondary minerals. Calcite locally fills cracks between cleavage foliae of biotite, whereas ferroan magnesite is associated with spinel.

The biotite schist at 152.7 m (15/152.7) contains

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Table 1. Compositions of minerals in sample 15/154.2 from Sholt-Yavr, Kola Peninsula, USSR.

	Kornerupine 1	2	Sapphirine	Ortho- pyroxene	Biotite	Spinel
Electron Microprobe Analyses-wt %						
SiO ₂	28.98	29.36	13.82	51.21	38.20	b.d.
TiO ₂	0.05	0.04	0.05	0.04	0.75	b.d.
Al ₂ O ₃	44.73	43.96	60.73	7.97	17.86	48.75
Cr ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	0.03
FeO	7.20	7.14	7.80	13.68	6.75	36.21
MnO	0.14	0.24	0.11	0.27	b.d.	0.22
MgO	17.02	16.42	17.61	26.58	19.93	11.49
CaO	0.07	0.07	0.04	0.15	0.02	b.d.
ZnO	b.d.	b.d.	b.d.	b.d.	b.d.	3.31
Na ₂ O	b.d.	b.d.	b.d.	b.d.	0.37	b.d.
K ₂ O	b.d.	b.d.	b.d.	b.d.	10.08	b.d.
Ion Microprobe Analysis-wt %						
Li ₂ O	0.03	0.03	0.004	b.d.	0.002	-
BeO	b.d.	0.001	b.d.	b.d.	b.d.	-
B ₂ O ₃	1.32	1.21	0.16	0.004	b.d.	-
F	0.03	0.02	b.d.	b.d.	0.19	-
BaO	b.d.	b.d.	b.d.	b.d.	0.04	-
Calculated-wt %						
H ₂ O	1.19	1.18	-	-	4.03	-
Total	100.74	99.66	100.32	99.90	98.17 ¹	100.0 ²

O	Formulae					
	21.5	21.5	20	6	22	4
Si	3.619	3.704	1.631	1.829	5.555	0
B	0.285	0.263	0.033	0	0	-
Al	6.583	6.536	8.446	0.335	3.061	1.603
Ti	0.005	0.004	0.004	0.001	0.082	0
Cr	0	0	0	0	0	0.001
Fe ³⁺	-	-	0.253	-	-	0.396
Fe ²⁺	0.752	0.753	0.517	0.409	0.821	0.449
Mn	0.015	0.026	0.011	0.008	0	0.005
Mg	3.168	3.088	3.098	1.415	4.320	0.478
Zn	0	0	0	0	0	0.068
Li	0.015	0.015	0.002	0	0.001	-
Ca	0.009	0.009	0.005	0.006	0.003	0
Na	0	0	0	0	0.104	0
K	0	0	0	0	1.870	0
Ba	-	-	-	-	0.002	-
Total	14.450	14.400	14.000	4.003	15.822 ¹	3.000
Anions						
F	0.012	0.008	-	-	0.087	-
OH	0.988	0.992	-	-	3.913	-
X _{Fe}	0.192	0.196	0.143	0.224	0.160	0.484

Notes: All Fe measured as FeO. Fe³⁺ calculated in sapphirine and spinel assuming stoichiometry and 14 and 3 cations, respectively. H₂O was calculated assuming ideal (OH+F) contents. Totals corrected for F=O. b.d.=below detection. Electron microprobe analyses by M. G. Yates; ion microprobe analyses by N. Marquez.

1. Totals for biotite include 0.02 wt % Rb₂O and 0.001 wt % SrO; 0.002 Rb per formula unit; Cs₂O<0.001 wt% from ion microprobe analyses.

2. Spinel analysis is a quantitative EDS analysis with normalization to 100 wt %; remaining analyses are WDS. $X_{Fe} = Fe^{2+} / (Fe^{2+} + Mg)$

cordierite, sapphirine, spinel, apatite, monazite, zircon, and sericite. Sapphirine grains are 0.1–1 mm, the larger ones are cored by spinel. The cordierite is extensively altered, but the sericite appears to have formed from another mineral, possibly calcic plagioclase (microprobe analyses of some patches correspond to muscovite, others, to a phase rich in Ca, Al, and Si).

The biotite schist at 221.5 m (15/221.5) contains minor K-feldspar, sillimanite and corundum in addition to the minerals in the schist at 152.7 m. However, the sericitic patches are absent and cordierite is largely fresh. Most sapphirine forms elongated symplectites with cordierite, perthitic K-feldspar, and fine sillimanite. A few grains (to 1.5 mm) of sapphirine in biotite may also be in this symplectite where the symplectite lies nearly perpendicular to the plane of the thin section. Sillimanite also forms prisms in cordierite and in biotite adjacent to sapphirine. Corundum forms grains less than 1 mm across in biotite and cordierite.

At the University of Maine (UM), the silicate minerals in 15/154.2 were analysed with a wavelength-dispersive (WDS) MAC 400s electron microprobe (20 nA specimen current on quartz at 15 kV), whereas spinel in 15/154.2 was analysed with an energy-dispersive (EDS) Link AN 10000 system (Table 1). The Link system was also used to search for constituents with $Z > 10$; only those given in Table 1 were detected. Each mineral was analysed at one spot (kornorupine at two spots on one grain) within an area 2 mm across; the analysed spinel was located about 1.5 cm from this area. At the Institute of Experimental Mineralogy (IEM), minerals in all three samples were analysed with an EDS on a Camebax electron microprobe equipped with a Link detector; a few minerals in 15/221.5 were analysed by EDS on the scanning electron microscope Tesla BS-301 with an Ortec detector (selected analyses are listed in Table 2). The IEM analyses have been normalised to a specified total. The tabulated data are averages (except spinel and K-feldspar) of analyses at several points on one or several grains. The EDS analyses of silicate minerals in 15/154.2 done at IEM are in good agreement with the WDS analyses done at UM.

The silicate minerals in 15/154.2 were analysed at the same spots as the WDS with an ARL ion microprobe mass analyser at the Aerospace Corporation (method given in Grew *et al.*, 1990b). Kornorupine in sample B.M. 1940,39 was analysed concurrently as an internal standard, resulting in the following values (in weight percent): Li_2O 0.20, BeO 0.035, B_2O_3 3.72, and F 0.66, in fair (BeO) to good agreement with the

wet chemical and ion microprobe data reported by Grew *et al.* (1990b).

Compared to the 31 kornorupine samples discussed by Grew *et al.* (1990b), the Kola kornorupine is poor in boron and fluorine and intermediate in Fe/Mg ratio. Total Al + B = 6.80–6.87 atoms per formula unit, which is at the upper limit for kornorupine associated with orthopyroxene. Idealised F–OH distribution between kornorupine and biotite, which is $(\text{F}/\text{OH})^{\text{Krn}}/(\text{F}/\text{OH})^{\text{Bt}} = 0.36\text{--}0.54$, overlaps the range of values for kornorupine associated with Ti-poor biotite. The relatively high $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratios calculated for sapphirine suggest that Fe^{3+} could also be present in kornorupine, but we have no way to analyse for it.

Orthopyroxene Al_2O_3 content is mostly 5.4–6.9 wt.%, but locally reaches 8 wt.% (e.g. Table 1). The other minerals in 154.2 are relatively homogeneous, and, in general, the compositions tabulated in Table 2 are representative of the analysed points in this sample and in the other two samples. For example, in a second section of 15/154.2, biotite TiO_2 and Al_2O_3 contents average 0.73 and 17.79 wt.%, respectively, and sapphirine SiO_2 and Al_2O_3 average 14.24 and 60.69 wt.%, respectively, although orthopyroxene ($X_{\text{Fe}} = 0.21$) and biotite ($X_{\text{Fe}} = 0.14$) are slightly more magnesian (cf. Table 2). On the other hand, sapphirine in 15/221.5 is heterogeneous; some spots in the symplectite contain less than 60 wt.% Al_2O_3 , the difference being made up by Fe or Cr. K-feldspar varies in Na_2O and BaO contents.

Comparison of the compositions from the three rocks shows that the most important difference is the extent of Tschermak substitution, (Mg,Fe)- SiAl_2 (Table 2). Al_2O_3 contents of sapphirine and biotite increase systematically from the least aluminous assemblage with orthopyroxene + kornorupine in 15/154.2 to the most aluminous assemblage with sillimanite + corundum in 15/221.5. Decrease in Fe^{2+}/Mg ratio of this sequence is less marked.

Temperatures calculated from coexisting biotite and orthopyroxene in 15/154.2 (Tables 1–2 and Konilov, unpublished data on a second section) are 693–749°C and 706–728°C (for pressures of 4–5 kbar) from the calibrations of Aranovich *et al.* (1988) and Sengupta *et al.* (1990), respectively. These estimates, although reasonable for granulite-facies metamorphism, are higher than the value of $670 \pm 20^\circ\text{C}$, which Fonarev *et al.* (1989; in press) reported as the peak conditions for the region as a whole on the basis of several geothermometers.

The Sholt-Yavr biotite schist has several

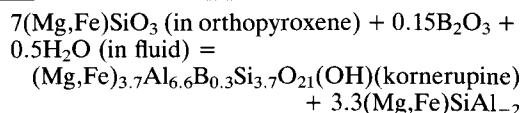
Table 2. Electron microprobe analyses of minerals in sapphirine-bearing rocks from Sholt-Yavr, Kola Peninsula, USSR.

15/	Sapphirine			Spinel	Opx	Biotite			Cordierite		K-feldspar
	154.2	152.7	221.5	152.7	154.2	154.2	152.7	221.5	152.7	221.5	221.5
	wt%										
SiO ₂	13.90	12.49	11.86	0	51.40	38.80	38.12	37.64	49.99	50.58	64.75
TiO ₂	0.02	0.02	0.02	0.05	0.04	0.83	1.23	1.06	0.03	0.02	0.16
Al ₂ O ₃	59.92	62.40	64.78	64.11	6.28	17.53	18.72	19.44	34.45	34.10	19.05
Cr ₂ O ₃	0.02	0.05	0.04	0	-	0.02	0.05	0.03	0.02	0.01	-
FeO	7.85	6.93	5.12	16.18	14.07	6.73	6.93	6.05	2.02	1.77	0.09
MnO	0.15	0.11	0.15	0.20	0.36	0.04	0.06	0.04	0.08	0.09	-
MgO	17.74	17.83	17.74	17.13	27.34	20.85	20.26	20.10	13.26	12.99	-
CaO	0.08	0.03	0.03	0.05	0.15	0.02	0.04	0.09	0.08	0.04	0.19
Na ₂ O	0.28	0.11	0.16	0.72	0.32	0.30	-	0.31	-	0.36	1.27
K ₂ O	0.03	0.03	0.10	0.03	0.04	9.88	9.59	10.25	0.07	0.04	13.86
Other	-	-	-	1.55 ¹	-	-	-	-	-	-	0.63 ²
Total	100.00	100.00	100.00	100.00	100.00	95.00	95.00	95.01	100.00	100.00	100.00

O	Formulae										
	20	20	20	4	6	22	22	22	18	18	8
Si	1.652	1.475	1.394	0	1.844	5.571	5.465	5.403	4.928	4.980	2.976
[⁴]Al	4.348	4.525	4.606	1.955	0.156	2.429	2.535	2.597	4.002	3.957	1.032
[⁶]Al	4.046	4.158	4.366	-	0.109	0.537	0.628	0.692	-	-	-
Ti	0.002	0.002	0.002	0.001	0.001	0.090	0.133	0.114	0.002	0.001	0.006
Cr	0.002	0.005	0.004	-	-	0.002	0.006	0.003	0.002	0.001	-
Fe ³⁺	0.296	0.356	0.232	0.044	-	-	-	-	-	-	0.003
Fe ²⁺	0.485	0.328	0.271	0.306	0.422	0.808	0.831	0.726	0.167	0.146	-
Mn	0.015	0.011	0.015	0.004	0.011	0.005	0.007	0.005	0.007	0.008	-
Mg	3.144	3.138	3.108	0.661	1.462	4.463	4.330	4.301	1.949	1.907	-
Ca	0.010	0.004	0.004	-	0.006	0.003	0.006	0.014	0.008	0.004	0.009
Na	-	-	-	-	0.023	0.084	-	0.086	-	0.069	0.113
K	-	-	-	-	0.002	1.810	1.754	1.877	0.009	0.005	0.813
Other	-	-	-	0.030 ¹	-	-	-	-	-	-	0.011 ²
Total	14.000	14.002	14.001	3.000	4.035	15.802	15.695	15.818	11.070	11.077	4.964
X _{Fe}	0.134	0.095	0.080	0.316	0.224	0.153	0.161	0.144	0.079	0.071	-

Note: All Fe measured as FeO. Analyses normalized to 100 wt% for all minerals except biotite, for which normalization is 95%. Fe³⁺/Fe²⁺ ratio calculated from stoichiometry, assuming cations total 14 in sapphirine, 3 in spinel. Na and K contents of sapphirine and spinel and Ca in spinel are assumed to be negligible. Analyses by A. N. Konilov. 1. ZnO and Zn. 2. BaO and Ba. X_{Fe}=Fe²⁺/(Fe²⁺+Mg)

features in common with silica-undersaturated, kornerupine-bearing rocks elsewhere; for example, kornerupine overgrowths on sapphirine are characteristic of similar rocks from the Namaqualand complex in South Africa (Waters and Moore, 1985) and the Usmun River, Aldan shield, Russia (Grew *et al.*, 1989, 1991). Formation of these overgrowths in the Namaqualand rocks was attributed to introduction of fluids, whereas its formation in the Aldan rocks was attributed to partial melting and breakdown of tourmaline. The Sholt-Yavr kornerupine could be associated with the metasomatic reworking that Fonarev *et al.* (1989) inferred had accompanied the high-grade metamorphism. In this case, a much simplified reaction for kornerupine formation with introduction of aqueous fluids could be:



The kornerupine composition has been simplified from the analyses, in which (Mg + Fe + Mn) > Si (Table 1). Thus an SiO₂-poor phase such as sapphirine would also be needed as a reactant to balance the equation. (Mg,Fe)SiAl₋₂ represents the Tschermak substitution and implies a shift to less aluminous compositions in orthopyroxene, sapphirine, and biotite. Waters (1986) proposed an analogous equation for sapphirine formation from cordierite and spinel, which accompanied a shift to less aluminous compositions in phlogopite. This shift need not have been large because kornerupine is so much less abundant than

sapphirine, phlogopite, and orthopyroxene in the Sholt-Yavr rock. Boron could have been introduced with the aqueous fluid. However, a more likely source is sapphirine, which contains enough B₂O₃ for kornerupine to form given the abundance of sapphirine relative to kornerupine.

Acknowledgements. Financial support from the U.S. National Science Foundation Grant DPP-8815863 to the University of Maine is acknowledged. We thank V. I. Fonarev and K. Kh. Avakyan for their assistance and P. C. Grew for comments on an earlier draft.

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[Manuscript received 8 July 1991:
revised 27 August 1991]

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KEYWORDS: kornerupine, sapphirine, orthopyroxene, biotite, spinel, Kola Peninsula, Russia.

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