Sapphirine-bearing granulites from Labwor, Uganda

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SUMMARY. The structural setting of a refoliated belt of sapphirine granulites in northern Uganda and petrography of two selected rocks are described. Electron-probe analyses of the following minerals are given: ilmenite, titanian hematite, rutile, magnetite, sapphirine, hypersthene, brown and green biotite, garnet, and cordierite. Field and experimental data suggest the following paragenesis: deposition of ferruginous shales with siliceous bands, followed by burial and regional metamorphism under granulite facies conditions, and finally rapid unloading associated with refoliation and shearing and crystallization of sapphirine and cordierite.

THE Labwor Hills of northern Uganda consist of Precambrian metamorphic rocks of amphibolite and granulite facies. In 1963–4 the Uganda Geological Survey recognized the presence of sapphirine-bearing granulites that contain a wide mineralogical range of iron magnesium alumino-silicates. Of particular additional interest is the structural setting of these intriguing assemblages. The sapphirine-bearing rocks are restricted to a zone of NW-trending refoliation, 2·5 miles wide and 8 miles long, that forms a conspicuous photogeological feature truncating a zone of easterly-trending foliation (fig. 1). The relationship of these two trends of foliation is particularly well displayed in the SE where banded pyroxene granulites become increasingly tightly folded along NW-trending axes in a westward direction; the end product of this refolding is the development of NW-trending isoclinal folds that have steeply dipping axial planes, and in which the original E-W folds only occur as crescentic-shaped attenuated closures with sheared-out limbs.

Petrography

Sapphirine is most conspicuous in ferruginous rocks containing ilmenite, garnet, hypersthene, and cordierite, and representative specimens, AR39 and AR51, were selected for detailed petrographic study and a third, PHN 1069, for electron probe mineral analysis. In hand specimen, AR39 and AR51 show a lenticular gneissose interbanding of orange garnet-bearing aggregates, with coarse leucocratic minerals. These are silica-deficient and silica-rich bands respectively; the mineral composition, in wt %, determined from heavy liquid and magnetic separations, is:

	AR39	AR51*		AR39	AR51		AR39	AR51
Sapphirine	4	1	Garnet	21	38	Corundum	1	1
Ilmenite	8	7	Sillimanite	15	13	Biotite	4	4
Magnetite	25	8	Cordierite	3	1	Feldspar	10	8
and spinel			Hypersthene	8	1	Quartz	1	18

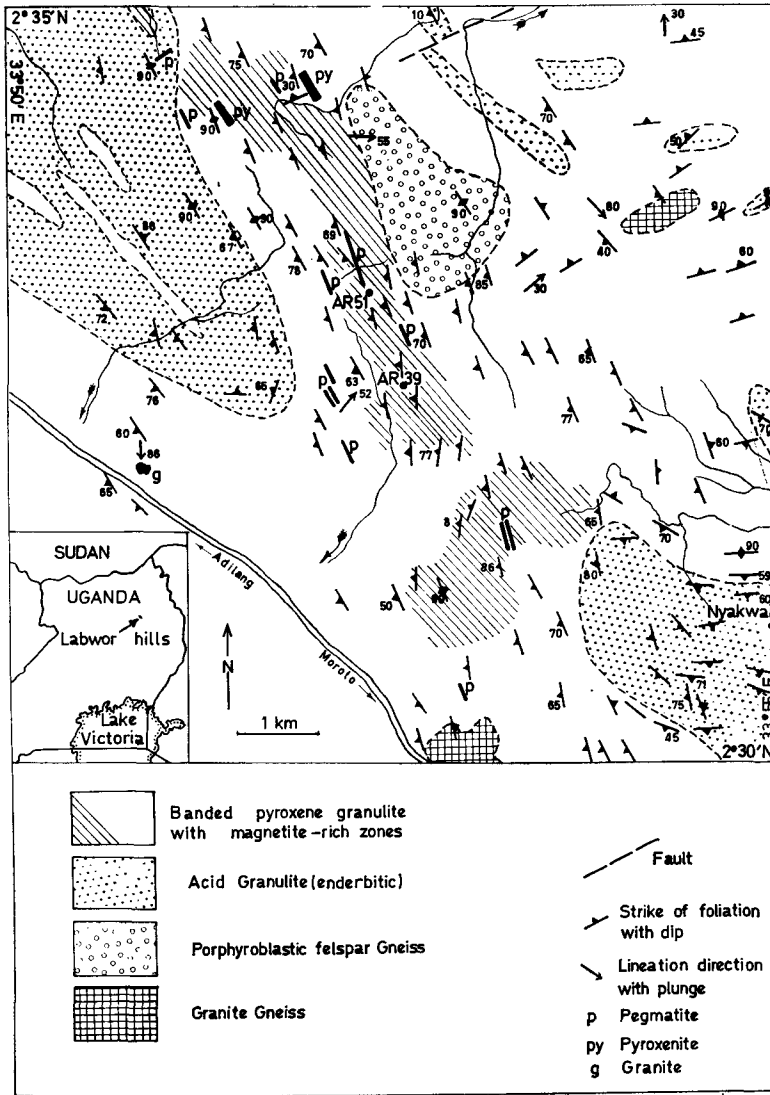* AR51 also contains traces of copper mineralization (chrysocolla).

FIG. 1. Geological sketch map of part of the southern Labwor Hills based on mapping by Baldock
et al. (1964) with later additions.

Aggregates of ore minerals are concentrated in the garnet-rich bands and consist
of ilmenite, green spinel (striped and dusted with magnetite), and accessory corundum
(see fig. 2A). Of these, the *green spinel* in AR39 has a refractive index, 1.775 ± 0.003
indicating a magnesian hercynite composition. The *magnetite* analysis (Table I) con-
tains a very limited amount of hercynite in solid solution indicated by 1.4% Al_2O_3.
The *ilmenite* has a high proportion of Fe_2O_3 in solid solution but a low percentage of

MgO (0·91 %) for granulites. Associated small amounts of hematite are titaniferous and could be an oxidation product. A third titanium mineral, *rutile*, occurring with the ilmenite and magnetite, was detected with the electron probe in PHN 1069.

The ore aggregates have discontinuous reaction rims of striking *blue sapphirine* (fig. 3A and B) with no discernible cleavage: β c. 1·732; pleochroism α pale yellow-

TABLE I. *Electron probe analyses of minerals from sapphirine garnet cordierite gneiss, PHN 1069, from Labwor, Northern Uganda*

	Ilmenite	Ti-Hematite	Rutile	Magnetite
TiO_2	43·8	16·8	97·6	0·01
Al_2O_3	0·78	0·90	0·75	1·40
Cr_2O_3	0·02	0·19	0·02	0·02
Fe_2O_3*	13·72	62·68	1·50	66·83
FeO	37·85	16·50	—	31·09
MnO	0·31	0·02	0·00	—
MgO	0·91	0·30	0·13	—
ZnO	0·03	0·02	0·05	0·02
Total	97·42	97·41	100·05	99·37

	Sapphirine	Hypersthene	Biotite Brown	Biotite Green	Garnet	Cordierite
SiO_2	11·6	[45·4]	37·4	38·3	[39·4]	47·5
TiO_2	0·03	0·16	5·2	1·8	0·02	0·00
Al_2O_3	65·0	9·0	15·1	14·6	22·8	34·9
FeO	9·0	24·0	10·6	8·9	22·2	4·0
MnO	0·10	0·29	0·06	0·04	0·96	0·06
MgO	15·1	21·0	17·9	21·4	13·5	11·4
CaO	—	0·18	0·08	0·01	1·09	—
Na_2O	—	—	0·12	0·05	—	0·08
K_2O	—	—	10·0	10·1	—	0·08
Total	100·8	[100·0]	96·46†	95·20†	[100·0]	98·02†

Analyst: L. K. Burns.

* FeO/Fe_2O_3 calculated by the method in Carmichael (1967*a*).

† Totals do not include water.

Analytical Methods: Mineral analyses were carried out with an ARL electron microprobe at the Department of Geology and Geophysics, University of California, Berkeley. The cordierite analyses for the major elements were made using a series of analysed natural cordierites as standards. The techniques used in the analyses and corrections of the other minerals have been described in detail by Carmichael (1967*a*, 1967*b*) and by Evans and Moore (1968).

brown, β green-blue, γ deep blue-green; variable negative 2V (10 to 30°); dispersion of the optic axes $v < r$; and incomplete extinction, γ:[001] c. 5°.

These properties are somewhat different from typical sapphirine (Deer, Howie, and Zussman, 1962), due to an unusually high iron content (Table I). The analysis shows it to be high in Al and low in Si reflecting appreciable $2Al \rightleftharpoons SiMg$ substitution. It corresponds to a formula: $(Fe,Mg)_{3·6}Al_{9·1}Si_{1·4}O_{20}$. However, differences in colour

intensity and magnetic susceptibility (observed during magnetic separation) suggest that there is a slight variation in composition within a single specimen.

The high iron content is unusual but is similar to a sapphirine from Madura, India (Muthuswami, in Deer, Howie, and Zussman, 1962, **1**, 179). A blue sapphirine with β 1·734 and similar iron content, but lower Al and higher Si, is recorded in granulites of the Anabar massif, U.S.S.R. (Lutts and Kopaneva, 1968).

Sillimanite, in part replaced by sapphirine, rims the ore aggregates (figs. 2A and 3A), and is seen in contact with all other minerals present. In zonal sequence away from the ore, sillimanite is usually in contact with garnet and hypersthene (fig. 3C) containing sillimanite rods and fibres. These minerals are partially replaced by sapphirine. Idioblastic sillimanite may be of a later generation.

Hypersthene shows conspicuous red-green pleochroism; 2V is negative, medium, with γ 1·715±0·003 indicating 45 to 65 % $FeSiO_3$ according to the content of alumina (Winchell, 1951, p. 406). The hypersthene from PHN 1069 (Table I) is highly aluminous and contains 60 % $FeSiO_3$. Alteration to *yellowish-green biotite* occurs along cleavages and marginally. This is less titaniferous and ferriferous than the primary *brown biotite* (Table I). Neither is a major constituent.

The orange *garnet* shows a moderate development of crystal faces and has a refractive index of 1·773±0·003, reflecting the approximately equal amounts of pyrope and almandine and confirmed by the garnet analysis of PHN 1069 (Table I); the grossular component is small. Where the garnet is in contact with cordierite a small amount of brown biotite may be present.

Cordierite, although scarce in specimens AR39 and AR51, is abundant in other specimens from the refoliation zone where it occurs in monomineralic lenses up to 20 cm across. It also occupies interstices between idioblastic garnets and may contain exsolved sapphirine (fig. 3D). The optical properties are variable (2V negative ranges from nearly uniaxial to 30°) indicating a range in the distortion index (Myashiro, 1957).

Two cordierite porphyroblasts in specimen PHN 1069 were analysed in 88 different places with the electron probe and no chemical zoning was detected. The composition, shown in Table I, is an average of the 88 determinations. However, more deeply coloured, iron rich, varieties were observed in other rocks. Nevertheless, it is the most magnesian mineral of the granulite assemblages as is shown below:

PHN 1069	Cordierite	Biotite green	brown	Sapphirine	Hypersthene	Garnet
Mg/(Mg+Fe) %	84	81	75	75	61	53

Kornerupine was identified from an ore-rich specimen from the Labwor refoliation zone. The X-ray data are similar to those given by Girault (1952). *Olivine* is rare but was noted in rocks rich in opaque minerals and sillimanite.

Of the feldspars present in these suites *sanidine* (small 2V negative, γ 1·627±0·002) has been identified by X-ray diffraction.[1] It occurs as late-formed blebs and myrmekitic patches within quartz, garnet, and cordierite, or in eutectic intergrowths with sapphirine. Fine perthites are occasionally present.

[1] Courtesy of Dr. H. S. Yoder of the Geophysical Laboratory, Carnegie Institution of Washington.

Andesine is present in the leucocratic lenses. The range of compositions of the feldspars from electron probe analyses are given below:

	CaO	Na$_2$O	K$_2$O	An	Ab	Or
Alkali feldspar	0·25–0·44	0·82–0·85	15·19–15·44	1·24–2·18	6·93–7·19	89·80–91·28
Plagioclase	8·23–8·45	6·62–6·64	0·48–0·52	40·83–41·92	56·01–56·18	2·83–3·07

Quartz is associated with the feldspars and cordierite in the leucocratic lenticles; it is criss-crossed by threads of a highly birefringent mineral (? rutile).

Qu, Quartz
Cord, Cordierite
Sil, Sillimanite
Hy, Hypersthene
Gt, Garnet (pyrope-alm.)
Sa, Sapphirine
Sp, Spinel with magnetite inclusions
Il, Ilmenite
Cor, Corundum

A   B
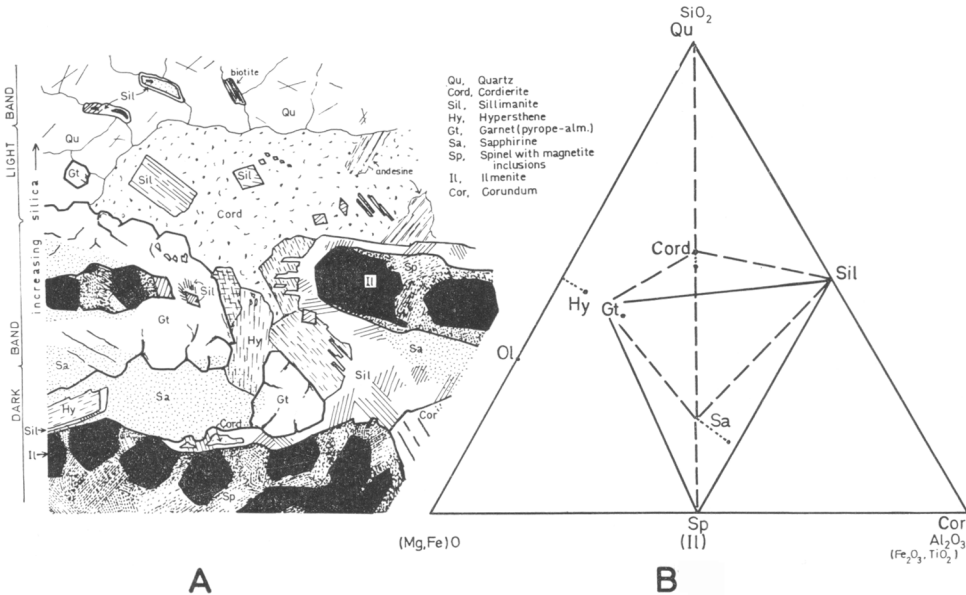
FIG. 2. A: Sketch of idealized rock thin section, 1 cm wide, showing mineral relationships. B: Calc-alkali deficient argillites tentatively showing phases in equilibrium for granulite facies. The phases present at lower pressure (sapphirine and cordierite) are joined by dashed lines.

Paragenetical conclusions

By combining the mineral analyses with the mode it can be shown that the Labwor sapphirine granulite rocks are rich in Fe, Mg, Al, and Si, having $(FeO+MgO)/Al_2O_3 \leqslant 1$ and $100\ Mg/(Mg+Fe) = c.\ 40$. Compared with other granulites of the northern Uganda basement they are deficient in Na, Ca, and OH; and chemical inhomogeneity, represented by alternating saturated (quartz) and undersaturated (corundum) bands, may be due to paucity of OH, which inhibited ionic migration as a whole.

In Central Australia, similar sapphirine granulites appear to be the result of thermal metamorphism under granulite facies conditions (Prof. A. E. Wilson, written communication). The highly magnesian sapphirine rocks of MacRobertson Land, Antarctica, are thought to represent sedimentary xenoliths caught up in a granitic magma and subsequently recrystallized under moderately high *PT* conditions (Segnit, 1957).

Iron-rich sapphirine granulites are relatively rare, but a rock from the Anabar massif, U.S.S.R. (Lutts and Kopaneva, 1968) is similar to those from Labwor. The rock is composed of a coarse grained aggregate of sillimanite, biotite, cordierite, and
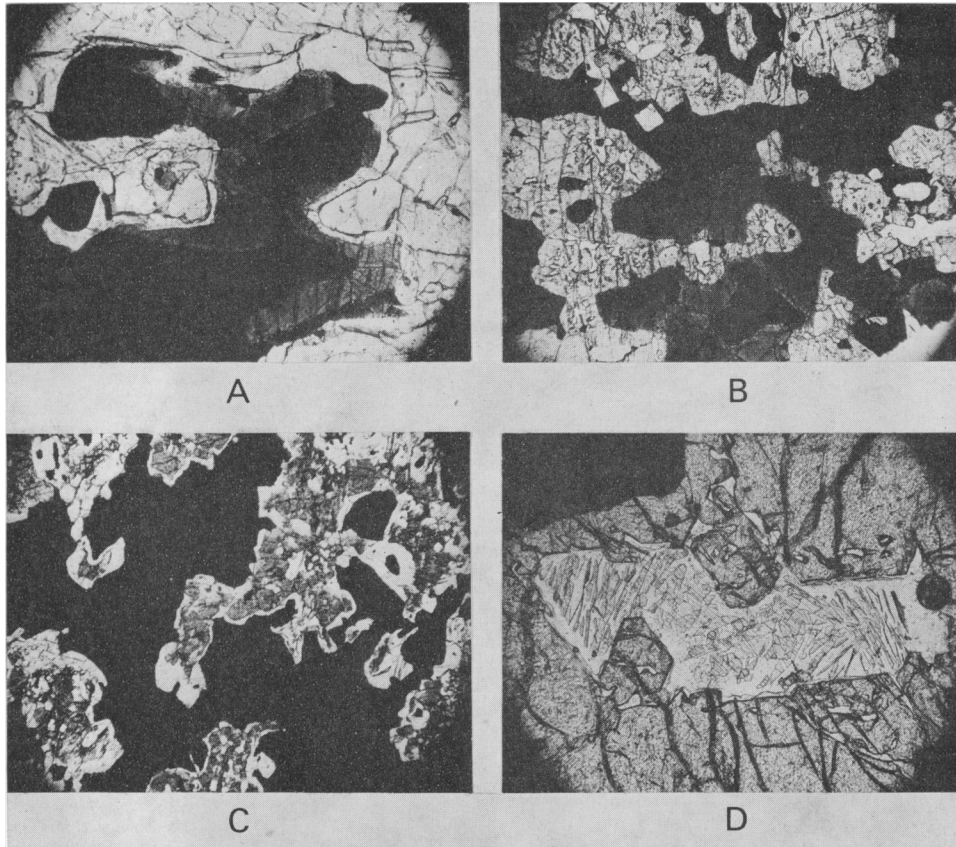

FIG. 3. A: Ore (black) with sapphirine (dark grey) forming within sillimanite rind. Pegs of sillimanite probably of a later generation protrude into interstitial cordierite. AR 39, ordinary light, X50. B: Sapphirine (dark grey) pseudomorphing poekilitic garnet with inclusions of cordierite. Cracks in the garnet survive the replacement. Two square-sectioned sillimanite crystals are conspicuous within the ore aggregate. AR 39, ordinary light, ×16. C: Corona of sillimanite (white) around ore (black) separating hypersthene (grey). AR51, ordinary light, ×16. D: Exsolution lamellae of sapphirine in small cordierite enclave surrounded by idioblastic pyrope–almandine, which is lined by a film of quartz (?). AR51, ordinary light, ×40.

hypersthene with coarse porphyroblasts of garnet and dark blue sapphirine. Based on experimental data, the rock is thought to have arisen under conditions of metamorphism of 12 kb and 950°. Aluminous granulites in the Kola peninsula contain kyanite but this gives way to a low-pressure–high-temperature assemblage, which includes sapphirine, at the same estimated *PT* conditions (Bondarenko, 1972).
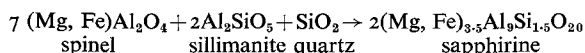
In Labwor, the presence of *magnetite* dust in the *green spinel* suggests that, formerly,

the two were in solid solution at a temperature above 858 °C, according to the experimental data of Turnock (1959) on the magnetite–hercynite system. The high Fe_2O_3 content in *ilmenite* and high TiO_2 in *hematite* (Table I) can also be regarded as high temperature features (Deer, Howie, and Zussman, 1962, **5**, 22). Similar amounts of Fe_2O_3 are present in kimberlitic ilmenites formed at elevated pressure but these are also rich in MgO, which is lacking in ilmenites of the Labwor granulites.

Sapphirine is a replacement mineral. It formed largely at the expense of spinel and adjacent garnet, which, by extrapolation of the pyrope and almandine stability data of Boyd and England (1962) and Yoder and Chinner (1960), suggests a pressure drop over intermediate ranges at high temperatures. Experimental work of Henson and Green (1970) on a system with $(FeO+MgO)/Al_2O_3 < 1$ and $100\ Mg/(Mg+Fe) = 70$ shows that at an optimum pressure of 9 kb sapphirine was not stable below 1050 °C. With decreasing Mg/Fe ratios, as in the Labwor granulites, the sapphirine is stable at lower pressures at that temperature, but in iron-rich assemblages an iron-rich spinel becomes stable in place of sapphirine.

In view of the high-Al/low-Si nature of the sapphirine, its formation cannot involve the simple reaction of free silica with spinel that has commonly taken place elsewhere (Deer, Howie, and Zussman, 1962, **1**, 181).

By employing a sapphirine formula close to that determined analytically, it is necessary to involve an aluminous mineral, in this instance sillimanite:

$$7\ (Mg,\ Fe)Al_2O_4 + 2Al_2SiO_5 + SiO_2 \rightarrow 2(Mg,\ Fe)_{3.5}Al_9Si_{1.5}O_{20}$$
$$\text{spinel} \qquad \text{sillimanite} \quad \text{quartz} \qquad \text{sapphirine}$$

In the absence of quartz in the lenticular ore zones, the silica balance is seen to be provided by the small quantities of hypersthene and garnet, which are now pseudomorphed by the sapphirine product. Calculations suggest that in these reactions the ratio of spinel to garnet or hypersthene is greater than 10 to 1 and the amount of spinel is thus a limiting factor in the formation of sapphirine. The presence of spinel, albeit heavily occluded by magnetite, indicates that the reaction is incomplete, presumably due to rapid pressure or temperature changes.

Sapphirine was not observed breaking down into other minerals even in contact with quartz or corundum. This may be due to sluggish reaction behaviour or, in the latter case, sapphirine and corundum could approach a stable association.

Sillimanite is common and reflects the aluminous character of the rocks. In low alumina rocks, i.e. $(MgO+FeO)/Al_2O_3 \gg 1$, it does not occur under any experimental conditions (Henson and Green, 1970). Its occurrence in the Labwor granulites as a primary constituent, and as later crystallized rods and spicules, is significant since the experimental data show that it forms under a wide range of pressure conditions at 800 °C. However, kyanite was not observed although it is commonly developed in rocks of similar chemical composition to the north-east of Labwor.

In the present study *pyrope–almandine* and *aluminous hypersthene* appear to be compatible; possibly components of a 'sliding reaction' (Henson and Green, 1970) in which solid–solid reactant and product coexist over a limited pressure–temperature

interval. The increasing order of $Mg/(Mg+Fe^{2+})$ ratios in garnet, hypersthene, and cordierite (p. 423) is similar to that observed experimentally by these authors.

Provided the garnet is a variety rich in almandine, it can coexist with *cordierite* (Hirschberg and Winkler, 1968). However, the interstitial nature of the Labwor cordierite indicates that it was one of the last minerals to crystallize, probably at pressures less than 10 kb (Schreyer and Yoder, 1961; Boyd and England, 1963). The range in the distortion index suggests that high-temperature or rapidly crystallized forms are represented (Myashiro, 1957).

Further evidence for a low-pressure or high-temperature influence or both can be argued from the presence of sanidine, kornerupine, and olivine.

A tentative paragenesis based on the textural relations and experimental data of the Labwor sapphirine granulites is:

Deposition of ferruginous shales with siliceous bands, followed by burial and regional metamorphism under high-temperature and high-pressure (granulite) conditions, during which water and alkalis were removed as anatectic granitic liquid, pegmatites, etc. (fig. 1 shows several such intrusions). Crystallization of sillimanite, garnet, ore/spinel, hypersthene, and corundum occurred during this stage. Finally, there was unloading and crystallization of cordierite, sapphirine, and second generation sillimanite at high temperature (the formation of this assemblage is indicated in fig. 2B by dashed lines). Experimental data indicates that the pressure must have fallen below 9 kb but that elevated temperatures of greater than 1050 °C were maintained.

This latter stage is envisaged as taking place during refoliation in the roots of large shear zones several miles in width, which at higher levels are represented by belts of mylonites and shear gneisses; compare the nearby Aswa fault (Almond, 1962). The high-temperature mineralogy is essentially a granulite facies legacy, imprinted upon the rocks under sharply reduced pressure.

The sapphirine granulites may, therefore, be regarded as transitional to pyroxene hornfels facies.

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