

Ford *et al.*, 1983; Takahasi and Kushiro, 1983) have recently argued on experimental grounds that the olivine K_d is pressure-dependent. Whereas there are no comparable experimental data for the opx/liquid K_d relationship, available data (for example, Frey and Prinz, 1978) suggest that the K_d relationships vary sympathetically in these two mineral groups. Therefore, both olivine and orthopyroxene would be expected to become more Mg-rich with reduced pressure. We envisage that the orthopyroxene phenocrysts grew Mg-rich cores zoned to relatively Fe-rich rims at depth, were abruptly transported to a much lower pressure (subvolcanic?) regime, then developed Mg-rich overgrowths which again became zoned to relatively Fe-rich rims. Thus a double-rim is developed in these phenocrysts.

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Kornerupine in a sapphire–spinel granulite from Labwor Hills, Uganda

NIXON *et al.* (1973) report kornerupine in an ore-rich specimen from the Labwor refoliation zone, a belt of granulite-facies rocks where sapphire–quartz and sillimanite–orthopyroxene–quartz assemblages are also found. While kornerupine is known from about thirty-five or forty localities world-wide, only at one other locality, Paderu, India, does kornerupine occur where sapphire–quartz is also reported (Grew, 1982, 1983a). This communication reports mineralogical and chemical details on Nixon *et al.*'s (1973) kornerupine-bearing rock and considers the conditions of kornerupine formation in the Labwor refoliation zone.

The kornerupine-bearing rock (sample No. PHN 984) is an eluvial cobble presumed to represent an iron-rich lens in granulites that contain sapphire, garnet, sillimanite, orthopyroxene, spinel, and cordierite. The cobble consists of a cellular aggregate of green spinel which contains abundant

streaks and fine dust of magnetite. In parts of the cobble, interstices between the spinel aggregate are mostly filled with sillimanite in prisms up to nearly 1 mm across and several millimetres long. This sillimanite is pale yellow in hand specimen and in part chatoyant from fine acicular inclusions. In other parts of the cobble the interstices are largely filled with kornerupine in prisms several millimetres across, having a crude parallel orientation. The kornerupine is distinctly pleochroic: γ -pale brown, β -blue. Sillimanite prisms mostly 0.05 to 0.2 mm across occur sparingly in kornerupine. Sapphire in platelets and irregular grains up to 2 mm across is found throughout the cobble and is best developed along boundaries between spinel and kornerupine grains. Sapphire is markedly pleochroic in brown and blue colours. Oxides besides spinel are magnetite and an ilmenite–hematite intergrowth, which is dominantly hematite with blebs, lamellae, and margins of ilmenite. Biotite flakes 0.1–0.5 mm

across are scattered in kornerupine or less commonly in oxide grains. Traces of K-feldspar(?) and zircon are also present. Seams of secondary Al-hydroxides cut sapphirine and kornerupine.

The constituent minerals were analysed in polished thin sections with the electron microprobes at Bochum and Leeds for elements with atomic number greater than II (Table I). A hand-picked separate of kornerupine was analysed by G. Werding for Li and Be by atomic absorption spectrometry and for B by a spectrophotometric method (see Werding and Schreyer, 1978). Kornerupine composition varies little from grain to grain, and thus the Li, Be, and B values can be added directly to the electron microprobe analyses (Table I). The low totals on the kornerupine analyses

TABLE I. Composition (wt. %) of minerals from the Labwor kornerupine-bearing rock (PHN 984)

	Kornerupine		Sapphirine 3	Sillimanite 4	Spinel 5
	1	2			
SiO ₂	29.34	29.07	13.28	36.60	0.25
TiO ₂	0.18	0.15	0.03	0.02	0.02
Al ₂ O ₃	42.36	42.37	57.37	61.37	60.55
Fe ₂ O ₃	—	—	4.39	1.58	—
FeO	8.61	8.56	8.89	—	26.84
MnO	0.39	0.36	0.28	< 0.01	0.51
MgO	15.10	15.12	14.68	0.06	11.37
CaO	0.03	≤ 0.01	≤ 0.02	< 0.01	0.01
Na ₂ O	0.04	0.09	≤ 0.02	≤ 0.01	—
K ₂ O	< 0.01	≤ 0.01	< 0.01	< 0.01	—
Cr ₂ O ₃	< 0.01	≤ 0.01	0.06	≤ 0.01	0.10
ZnO	—	≤ 0.01	≤ 0.03	≤ 0.04	—
B ₂ O ₃	2.04	2.04	—	—	—
Li ₂ O	0.02	0.02	—	—	—
BeO	c. 0.005	c. 0.005	—	—	—
Total	98.11*	97.78	98.98	99.63	99.65*
Cations					
Si	3.682	3.656	1.633	0.996	—
Ti	0.017	0.014	0.003	0.000	—
Al	6.265	6.281	8.316	1.969	—
Fe ³⁺	—	—	0.406	0.032	—
Fe ²⁺	0.903	0.900	0.915	—	—
Mn	0.042	0.038	0.029	0.000	—
Mg	2.825	2.834	2.692	0.002	—
Ca	0.004	0.000	0.000	0.000	—
Na	0.010	0.022	0.000	0.000	—
Cr	0.000	0.000	0.006	0.000	—
B	0.442	0.443	—	—	—
Li	0.010	0.010	—	—	—
Be	~ 0.002	~ 0.002	—	—	—
Total cations normalized to	14.2		14.0	3.0	

Dash: Not analysed. All Fe as FeO (kornerupine, spinel) or Fe₂O₃ (sillimanite); sapphirine Fe³⁺ estimated from stoichiometry (Higgins *et al.*, 1979). Compositions are averages of 2 to 3 grains, except spinel. Spinel, average of 9 grains (compositional range: SiO₂ 0.00–0.44; TiO₂ 0.00–0.09; Al₂O₃ 59.27–61.55; FeO 25.97–28.35; MnO 0.38–0.76; MgO 10.85–11.85; CaO 0.00–0.06; Cr₂O₃ 0.06–0.23). ZnO in spinels, determined by E. Grew, range from 0.1–0.2 wt. %.

* 0.08 wt. % NiO in 1 kornerupine grain, and 0.04% NiO in 1 spinel grain.

Analysts: 1, 5—E. Condiliffe; 2, 3, and 4—E. Grey; B₂O₃, Li₂O, and BeO—G. Werding; average of two determinations.

suggest water is also present. Compared to other kornerupines, such as the suite studied by Grew (1983b), the Labwor kornerupine is intermediate in boron and aluminum contents and is relatively iron rich. As atomic Si is less than atomic Fe + Mn + Mg, this kornerupine composition projected on to the (Mg, Fe, Mn)O–Al₂O₃–SiO₂ plane plots below the line joining the theoretical compositions of 1:1:1 and 4:3:4 (see Werding and Schreyer, 1978). The composition of sapphirine associated with kornerupine also varies little from grain to grain. This sapphirine is rich in iron and slightly richer in SiO₂ than the theoretical 7:9:3 composition (for divalent, trivalent, and quadrivalent cations, respectively). A third of the iron is estimated from stoichiometry (see Higgins *et al.*, 1979) to be ferric, which is consistent with the marked brown and blue pleochroism, colours characteristic of Fe³⁺-rich sapphirine (e.g. Caporuscio and Morse, 1978). Sillimanite associated with kornerupine is also relatively rich in ferric iron (Table I). The MgO content (0.06 wt. %) may be coupled with boron as in other granulite sillimanites (Grew and Hinthorne, 1983). The boron content is estimated from their data to be 0.004 B per formula unit or 0.09% wt. % B₂O₃ on the basis of this MgO content. The green spinel is largely hercynite–spinel solid solution, for Cr₂O₃ and ZnO contents are only 0.06–0.23% (Table I). The variation of Al₂O₃ and FeO contents from one analytical spot to another appears to reflect variation in Fe³⁺ content of the spinel. Most of the Fe³⁺ originally dissolved in the spinel has since exsolved as magnetite streaks and dust. Hematite is titaniferous (12.4, 14.0 wt. % TiO₂), and exsolved ilmenite contains minor MnO (1.4, 1.8%) and MgO (1.4, 1.1%). Biotite composition varies from grain to grain, e.g. in FeO (6.5, 8.7 wt. %) and TiO₂ (2.9, 5.0 wt. %). The chemical composition of spinel, sapphirine, and sillimanite are typical of these minerals in other rocks from the Labwor Hills, notably in the low ZnO and Cr₂O₃ contents of spinel and relatively high Fe³⁺ contents of sapphirine and sillimanite (Nixon *et al.*, 1973; Grew, 1980; Neall, 1981).

Textures and compositional homogeneity suggest that the equilibrium assemblage in the Labwor rock is spinel–kornerupine–sapphirine–magnetite–titaniferous hematite. Sillimanite appears to be a stable part of the assemblage only in the kornerupine-free parts of the rock. In the kornerupine-bearing parts, the status of sillimanite, as well as of biotite, is less clear; possibly these formed during a later stage in the metamorphic cycle. Of the kornerupine parageneses described in the literature, the Labwor kornerupine-bearing rock resembles most the kornerupine–sapphirine rocks from Paderu

and Ganguvarpatti in India, which are characterized by relatively iron-rich, dark coloured sapphirine and kornerupine and high Fe^{3+} contents (Grew, 1982). The Labwor paragenesis differs from the Indian rocks in that spinel is the dominant mineral in the rock and hematite is more abundant than ilmenite in the rhombohedral oxide phase.

By analogy with the Indian rocks, we suggest that the Labwor kornerupine-bearing rock formed by metamorphism of a boron-rich sedimentary precursor, an origin that is consistent with the sedimentary origin (ferruginous shales) proposed for other sapphirine rocks from Labwor (Nixon *et al.*, 1973).

Nixon *et al.* (1973) suggested that cordierite, sapphirine, and second generation sillimanite in the Labwor rocks developed from assemblages of first generation sillimanite, garnet, iron oxides, orthopyroxene, and corundum at temperatures of 1050 °C and pressures below 9 kbar during unloading. Neall (1981) proposed that the sapphirine-bearing assemblages represented peak temperature and pressure conditions of 1100 °C and 10 kbar. Neall (1981) based her estimates largely on Seifert's (1974) experimental data for sapphirine + mullite in the $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2$ system and Hensen and Green's (1973) petrogenetic grid. On the basis of Nixon *et al.*'s (1973) compositions, Harley and Green (1982) calculated a metamorphic temperature and pressure of 1000 °C and 10 kbar, and Bohlen *et al.* (1983) calculated a pressure of 6.5 kbar (assumed temperature of 950 °C). The present authors accept Neall's (1981) interpretation that the sapphirine-bearing assemblages formed at the peak metamorphic conditions. However, the effect of Fe^{2+} and Fe^{3+} on lowering the temperatures needed to stabilize sapphirine-quartz, spinel-quartz, and sapphirine-sillimanite may be substantial (e.g. Seifert, 1974; Caporuscio and Morse, 1978) and temperatures in the range of 800–900 °C could have been sufficient to produce the mineral assemblages in the Labwor rocks. A metamorphic temperature of 900 °C is also suggested by the extent of Fe-Mg fractionation between sapphirine and garnet, which is the same for Labwor as for an Antarctic terrane metamorphosed at 900 °C (Grew, 1983c). Moreover, Harley and Green's (1982) pressure estimate of 10 kbar is based on an inappropriate application of their experimentally calibrated geobarometer to the Labwor rocks. Harley and Green's (1982) geobarometer is derived

from synthetic garnet-orthopyroxene assemblages, whereas the Labwor rock used to calculate the pressure contains garnet, orthopyroxene, and sapphirine. Variation of orthopyroxene Al_2O_3 content as a function of orthopyroxene Fe:Mg ratio depends on the mineral assemblage and this variation would be different for sapphirine-free and sapphirine-bearing rocks. Pressures as low as 6 kbar are sufficient for sapphirine + quartz to react with decreasing temperature to form orthopyroxene + sillimanite (see Grew, 1982, fig. 14), a textural relation characteristic of the Labwor sapphirine granulites (Neall, 1981). Thus Bohlen *et al.*'s (1983) 6.5 kbar value, which was calculated from coexisting orthopyroxene, plagioclase, garnet, and quartz, is a plausible estimate for metamorphic pressures at Labwor.

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