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SAPPHIRINE-BEARING ROCKS FROM WILSON LAKE, LABRADOR

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ABSTRACT

Sapphirine at Wilson Lake, in the Grenville Province, is a constituent of aluminous layers in paragneiss, and in concordant lenses composed mainly of titaniferous hematite. Typically associated minerals are sillimanite, orthopyroxene, cordierite, biotite, and magnetite. Mineral assemblages indicate granulite facies conditions. Sapphirine displays the highest refractive indices reported for the mineral to date, probably because of high ferric : ferrous ratio. Associated orthopyroxene, spinel, and garnet are highly magnesian. The mineral assemblage is indicative of unusually oxidizing conditions during metamorphism ; the composition of the host rocks is suggestive of lateritic origin.

INTRODUCTION

In the summer of 1966, one of us (L.K.M.), while attached to a party of the Geological Survey of Canada, sampled iron oxide-rich lenses and their enclosing gneisses around Wilson Lake, Labrador. The material became the subject of a thesis investigation (Leong 1967), and many of the samples proved to contain sapphirine. Only two other occurrences of this mineral are known in Canada, both in Quebec ; St. Urbain (Warren 1912 ; Mawdsley 1927) and Mekinac township, Laviolette County (Traill 1970). The Wilson Lake locality was recently the subject of a note by Morse & Talley (1971). This paper provides a more detailed description of the paragenesis, particularly of the oxide minerals, and a different emphasis in its interpretation. Because of the complex and atypical nature of this occurrence, further studies are in order.

Wilson Lake (see Fig. 1) lies within the Grenville Province of the Canadian Shield. Reconnaissance mapping (Stevenson 1969) has shown that the dominant rocks in the vicinity are complexly deformed paragneisses, with subordinate amphibolite. Intrusive into this complex are bodies of anorthosite, gabbro, and related rocks. The rocks at Wilson Lake are aluminous paragneisses containing, in places, lenses of oxide minerals ; the lenses vary in width from 5 cm to at least 7 m, though most are less

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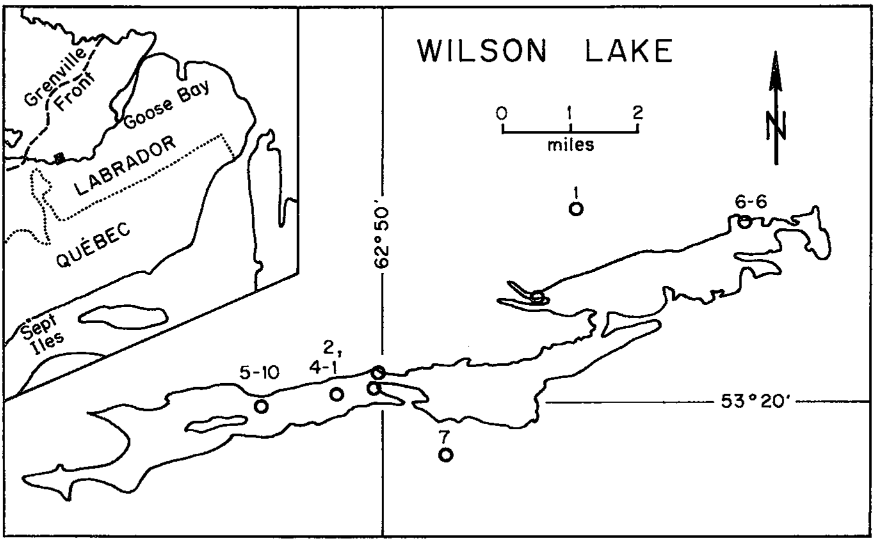

FIG. 1. Map of Wilson Lake area (solid square on inset map), showing sapphirine localities. Numbered localities yielded specimens specifically mentioned in text; specimen numbers in text are preceded by "L".

than 20 cm wide. They are grossly concordant with the foliation of the gneisses; contacts are abrupt to gradational over a few cm, and irregular in detail. In the oxide lenses, most of the silicate minerals of the gneisses are present in amounts up to 40%; oxides compose up to 5% of adjacent gneisses.

PETROGRAPHY

Study of thin and polished sections reveals the mineral assemblages listed in Table 1. Recognition of compatible assemblages is difficult owing to the complex textures of the rocks. For purposes of description, we may distinguish gneisses and oxide-rich rocks.

Gneisses. This group comprises: quartzo-feldspathic biotite gneisses bearing combinations of sillimanite, garnet, cordierite, orthopyroxene, and green hornblende; amphibolite; and feldspathic, sapphirine-bearing gneisses with sillimanite, bronzite, cordierite, little quartz or garnet, minor biotite, and no amphibole. In some specimens, quartzo-feldspathic layers alternate with aluminous, sapphirine-bearing bands, but quartz and sapphirine are nowhere in contact, being separated by sillimanite and/or bronzite. Accessory constituents are hematite, with or without magnetite; rutile; apatite and zircon.

TABLE 1. MINERAL ASSEMBLAGES OF ROCKS AT WILSON LAKE

Without Sapphirine	With Sapphirine
+ *qz-bi;* ± *pl, or:*	+ *pl-sa;* ± *or, bi:*
si	si-opx
si-ga	opx-sp
si-opx	si-opx-sp
si-cd-opx	si-opx-cd
opx-ga-hb	si-cd-sp
hb	si-ga-sp
	+ *sa;* ± *bi:*
	si-sp-co
+ *pl-or:*	si-cd
si-cd-opx	opx-cd

Symbols: qz: quartz; bi: biotite; pl: andesine, antiperthite; or: microperthite; si: sillimanite; ga: garnet; opx: hypersthene or bronzite; cd: cordierite; hb: hornblende; sa: sapphirine sp: spinel co: corundum. Most assemblages include hematite and rutile; many, magnetite.

Oxide-rich rocks. Titaniferous hematite is the major oxide mineral; magnetite and green spinel are subordinate. Corundum was seen in one sample. Sapphirine is the most abundant silicate, being accompanied by sillimanite, bronzite, cordierite, and minor biotite, rutile, apatite and zircon. Cordierite was detected only at localities L2 and L4.

Mineral assemblages are indicative of the granulite facies of regional metamorphism, and in many respects are typical of sapphirine occurrences (Sørensen 1955). Distinctive features of the sapphirine-bearing rocks at Wilson Lake are the abundance of hematite, absence of amphibole, and the common association of orthopyroxene with sillimanite.

MINERALOGY

Sapphirine

Optical properties of the sapphirine are summarized in Table 2. It is greenish-blue in hand specimen; in thin section some of the crystals exhibit local colour variation, γ varying between bluish-green and blue. Under crossed polarizers many crystals have an anomalous purple tint, generally concentrated in the core. Some grains are multiply twinned on (010); oriented inclusions of hematite and magnetite are common. Altera-

TABLE 2. OPTICAL DATA FOR SAPPHIRINE

Refractive Index (± .002)	Sample			Pleochroic Formula
	L1-1e	L2-1c	L7-3	
α	1.726	1.726	1.725	greenish yellow
β	1.730	1.731	1.730	light green
γ	1.733	1.733	1.733	bluish green
$\gamma \wedge c$	6°-9°			
$2V\alpha$	82 ± 2° (5 measurements)			

Mineral assemblages: L1-1e : sa-si-bpx-sp-hm-mt
L2-1c : pl-sa-si-cd-sp-hm
(qz and opx in specimen, but not with sa)
L7-3 : sa-si-hm-co-sp-bi

TABLE 3. PARTIAL CHEMICAL AND OPTICAL DATA FOR SAPPHIRINE

Sample No.	1	2	3	4	5	6	7	8	9	10
Fe_2O_3	0.93	3.16	3.74	1.69	1.27	1.2	—	—	—	2.72
FeO	0.65		1.73	3.09	5.43	5.6	6.61	7.65	9.08	8.35
MgO	19.78	19.89	20.87	15.22	18.75	18.0	15.61	17.13	15.28	17.16
MnO	—	—	0.43	tr.	0.02	0.10	0.21	—	n.d.	0.02
$\frac{Mg \times 100}{Mg + Fe^{2+} + Fe^{3+} + Mn}$	96	92	87	85	84	82	80	80	75	74
$\frac{Fe^{3+} \times 100}{Fe^{3+} + Fe^{2+}}$	55	44*	66	33	11	16	0	0	0	23
α	1.7055	1.703	1.725	1.714	1.720	1.720	—	1.714	1.729	1.717
β	1.7088	—	—	1.719	1.723	1.724	1.720	1.718	—	—
γ	1.7112	1.710	1.732	1.720	1.725	1.727	—	1.720	—	1.724
$2V_{\alpha}$	81 (calc.)	100	114	50.5	48	52	50	—	—	64

* Fe partitioned so $Al + Fe^{3+} = 4.00$
1. Fiskernaes, Greenland (quoted by Bøggild 1954)
2. Mawson area, Antarctica (Segnit 1957)
3. Mautia Hill, Tanzania (McKie 1963)
4. Blinkwater, Transvaal (Mountain 1939)
5. Razor Hill, Central Australia (Wilson & Hudson 1967)
6. Val Codera, Italy (Barker 1964)
7. Dangin, W. Australia (Prider 1945)
8. Vizagapatam, S. India (Walker & Collins 1907)
9. St. Urbain, Québec (Warren 1912)
10. Madura, S. India (Muthuswami 1949)

tion to a fine, oriented aggregate of boehmite and a mineral of the chlorite group is locally evident. The textural relations of sapphirine are complex. It is seen as:

a) Discrete grains up to 1–2 mm (Figures 2, 3), enclosing bronzite and spinel in places;

b) A rim between bronzite and spinel, or bronzite and hematite;

c) Inclusions in bronzite and sillimanite;

d) A symplectite with hematite (Figure 4) or cordierite.

Partial electron probe analyses of sapphirines from L1-1e and L2-1b yield molar Mg : Mg + Fe (total) in the range of 0.75–0.80. Comparison of available analyses of sapphirine with accompanying optical data (Table 3) shows that the Mg : Mg + Fe + Mn ratio varies in the range 0.74–0.96 (which includes all published analyses), and that refractive indices are least for the most magnesian members of the series. A marked exception to the general pattern is the sapphirine from Mautia Hill, Tanzania

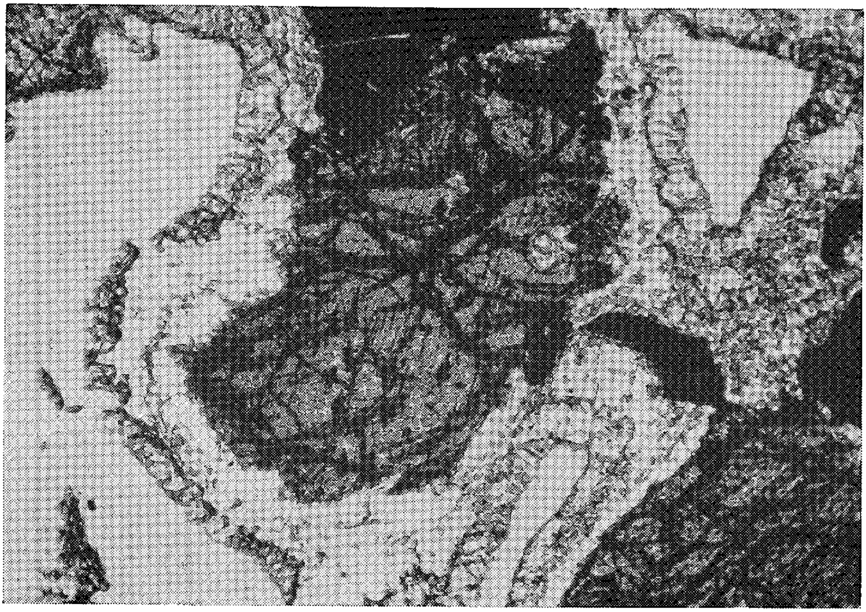

FIG. 2. Sapphirine, mantled successively by sillimanite and orthopyroxene, in matrix of quartz, plagioclase and cordierite. Opaque grains and inclusions in sapphirine are hematite. Cordierite and plagioclase partly separate sillimanite from orthopyroxene. L2-1c, plane light, × 50.

FIG. 3. Aggregate of sapphirine (dark grey, with plagioclase inclusions), orthopyroxene (light grey) and sillimanite (white) with hematite and minor plagioclase. L4-3, plane light, × 145.

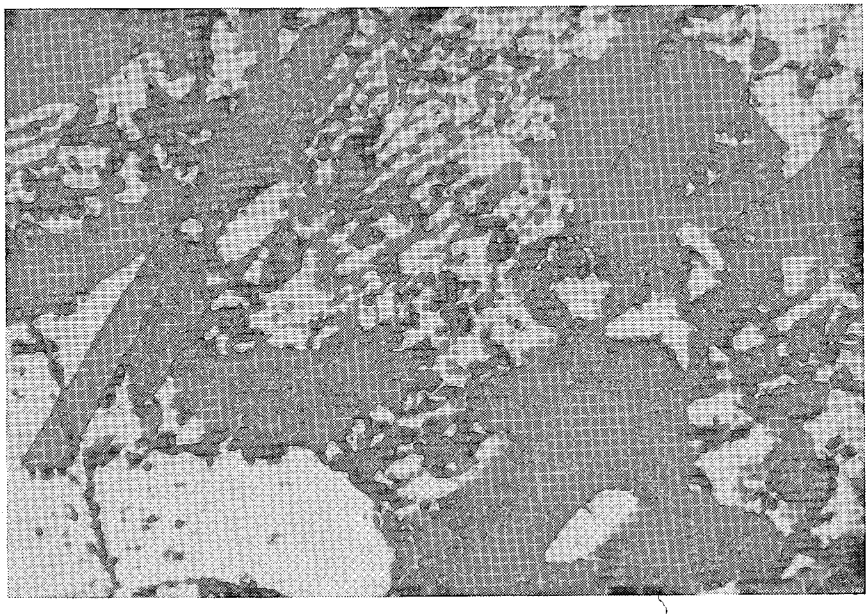

FIG. 4. Intergrowth of sapphirine (grey) and hematite (white). Sharp prism is sillimanite. L1-1e, reflected light, × 240.

(McKie 1963) which is seen to have a high ferric : ferrous ratio and relatively high Mn content. The indices of the Wilson Lake sapphirine are the highest complete set on record, and compare closely with those of the Mautia Hill specimen. Most sapphirines exhibit the pleochroic formula α : pale yellow ; β : blue ; γ : dark blue, whereas the Wilson Lake material is distinctive by virtue of its green tint. The *x*-ray data of Table 4 demonstrate that our material has a larger cell than sapphirines from Greenland and Australia (the Strangways specimen in Table 4 has similar physical properties to that of Razor Hill, 5, Table 3). This expansion, as well as the high refractive indices, could result either from the substitution of Fe^{2+} for Mg (as shown by the two sapphirines from Australia and Greenland), or of Fe^{3+} for Al.

The Mg : Mg + Fe ratios determined are too high to support simple substitution of Fe^{2+} for Mg as the cause of the high refractive indices. The association with hematite makes it likely that the Fe^{3+} content is high, as in the case of the Mautia Hill occurrence. Other elements could also be involved ; preliminary electron probe study of L1-1e by R. K. Herd (personal communication) reveals unusually high content of Mn, Cr, Ni, Ti and V. Resolution of these uncertainties awaits satisfactory mineral separation, a goal which has so far proven unattainable.

TABLE 4. X-RAY POWDER DATA FOR SAPPHIRINE *

L1-1e	L2-1c	I/I_1	Strangways	I/I_1	Fiskernaes	I/I_1
3.290	3.285	10	3.272	40	3.26	10
3.002	3.001	60	2.996	65	2.97	70
2.851	2.843	50	2.842	65	2.83	40
2.778	2.775	5	2.764	20	2.75	20
2.712	2.706	5	2.700	10	2.68	10
2.579	2.569	25	2.579	30	2.56	30
2.459	2.456	80	2.453	100	2.44	50
2.355	2.351	20	2.348	60	2.34	30
2.139	2.135	15	2.129	30	2.12	20
2.026	2.020	100	2.019	90	2.01	100
1.904	1.898	15	1.897	30	1.89	20
1.554	1.553	5	1.552	10	1.549	50
1.546	1.544	10	1.543	25	1.538	40
1.446	1.441	70	1.441	80	1.438	90
1.426	1.426	60	1.422	70	1.420	60
1.415	1.411	30	1.410	60	1.408	30

* *d*-values in Å. ; determined for Wilson Lake sapphirine by measurement of films from Siemens 114.6 mm Debye-Scherrer camera, corrected for shrinkage. Cu$K\alpha$ radiation, Ni filter. Data for Strangways Range specimen from Hudson & Wilson (1966) (PDF 19-750). Data for sapphirine from Fiskernaes, Greenland (PDF 11-607). Intensities are visual estimates.

Oxide minerals

In all specimens from Wilson Lake, the principal oxide mineral is *hematite*, with up to 30% by volume of ilmenite lamellae (Figure 5). In the sapphirine-bearing rocks, the content of ilmenite lamellae never exceeds 5%. Inclusions of spinel and rutile (?) are locally present. *Magnetite*, absent in some specimens, has a reciprocal abundance relation with sapphirine, and commonly contains a few inclusions of spinel. Green *spinel* is present in many specimens as discrete grains but abundant only in those lacking sapphirine. Most of the spinel is included in, or forms rims around, hematite. Spinel coexisting with magnetite contains magnetite lamellae, oriented in two or three orthogonal directions (Figure 5). Hexagonal plates of hematite, with or without magnetite, are similarly orientated in spinel.

Partial *x*-ray diffraction data for hematite are given in Table 5. All specimens save L1-1d also contain sapphirine; in all, hematite has similar cell dimensions. On the basis of the approximately linear variation of cell constants with composition in the hematite-ilmenite series (Lindsley

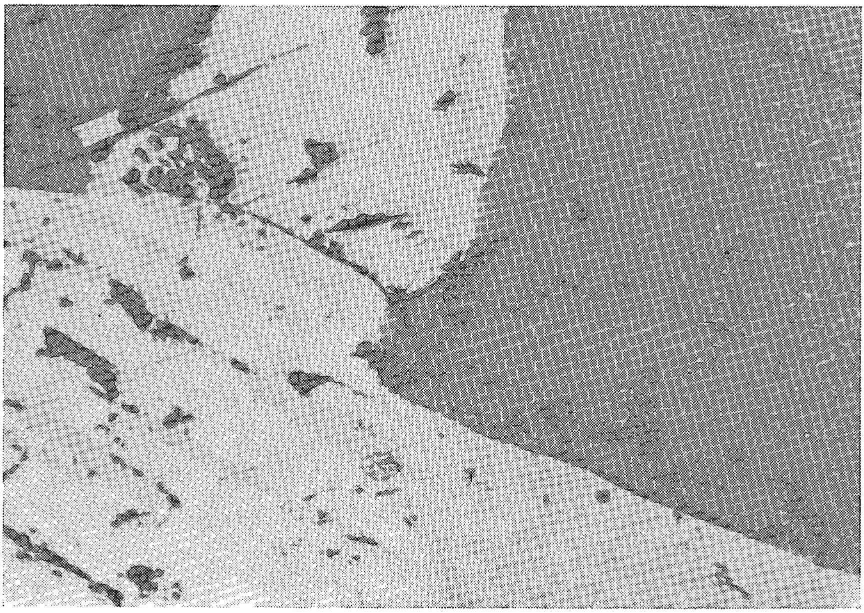

FIG. 5. Lamellar intergrowth of ilmenite in hematite, in contact with magnetite (medium grey) and spinel (dark grey, with minute magnetite inclusions). L1-1d, reflected light, × 300.

1965), the hematite contains about 20 mole percent ilmenite in solid solution (the iron content of three hematite grains from locality L1, determined by microprobe, varies from 63.6 to 64.0 weight percent, in good agreement). Using the solvus of Carmichael (1961), a temperature of formation for the oxide assemblage of greater than 650°C may be inferred. Up to 30% of ilmenite lamellae may be present in hematite of this composition (e.g. L1-1d), implying a higher temperature of formation of the rhombohedral oxide before exsolution.[1]

In specimen L1-1d, spinel, magnetite, and intergrown hematite-ilmenite coexist (Figure 5). Physical data for the spinel are :

$$a = 8.126 \text{ Å}$$
$$D = 3.900 \pm .005$$
$$n = 1.780 \pm .002$$

Using the curves of Deer, Howie and Zussman (1962), the cell edge and refractive index values yield the composition :

$$Sp_{88}Hc_6Mt_6$$

To reconcile the density value, it is necessary to invoke the presence of about 10 mole percent magnetite in the form of inclusions, a value in reasonable accord with visual estimation. Even if larger errors in the a and n were to be admitted, and magnetite inclusions were negligible, the spinel could not be more iron-rich than Hc_{80}.

Orthopyroxene is strongly pleochroic : α = rose pink, β = light yellow, γ = light green. Bronzite from L1-1e is En_{77-79} by probe ; that from L5-10 (assemblage Sa–Opx–Sp–An_{45}–Hm–Mt) has $\gamma = 1.684$, $2V_\alpha = 84°$, cor-

TABLE 5. X-RAY POWDER DATA FOR HEMATITE

L1-1d	L2-1c	L4-1d	L5-10	L7	I/I_1	hem[1]	I/I_1	ilm[2]	I/I_1	*hkl*
3.678	3.686	3.676	3.678	3.689	35	3.66	25	3.73	50	01.2
2.701	2.701	2.701	2.701	2.702	100	2.69	100	2.74	100	10.4
2.518	2.518	2.519	2.518	2.518	60	2.51	50	2.54	85	11.0
2.206	2.207	2.205	2.206	2.207	30	2.201	30	2.23	70	11.3
1.843	1.839	1.843	1.840	1.842	40	1.838	40	1.86	85	02.4
1.696	1.695	1.697	1.696	1.695	70	1.690	60	1.72	100	11.6
1.600	1.599	1.600	1.600	1.600	10	1.595	16	1.63	50	01.8

Data for Wilson Lake hematite obtained as indicated in Table 4; *d*-values in Å.
[1] hematite, PDF 13-534; [2] ilmenite, PDF 3-0781.

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[1] Studies by Rumble and Lindsley (Rumble 1971) show that natural and synthetic hematites may dissolve 30% $FeTiO_3$ at temperatures not exceeding 600°C. Temperature estimates using Carmichael's solvus thus appear to be excessive.

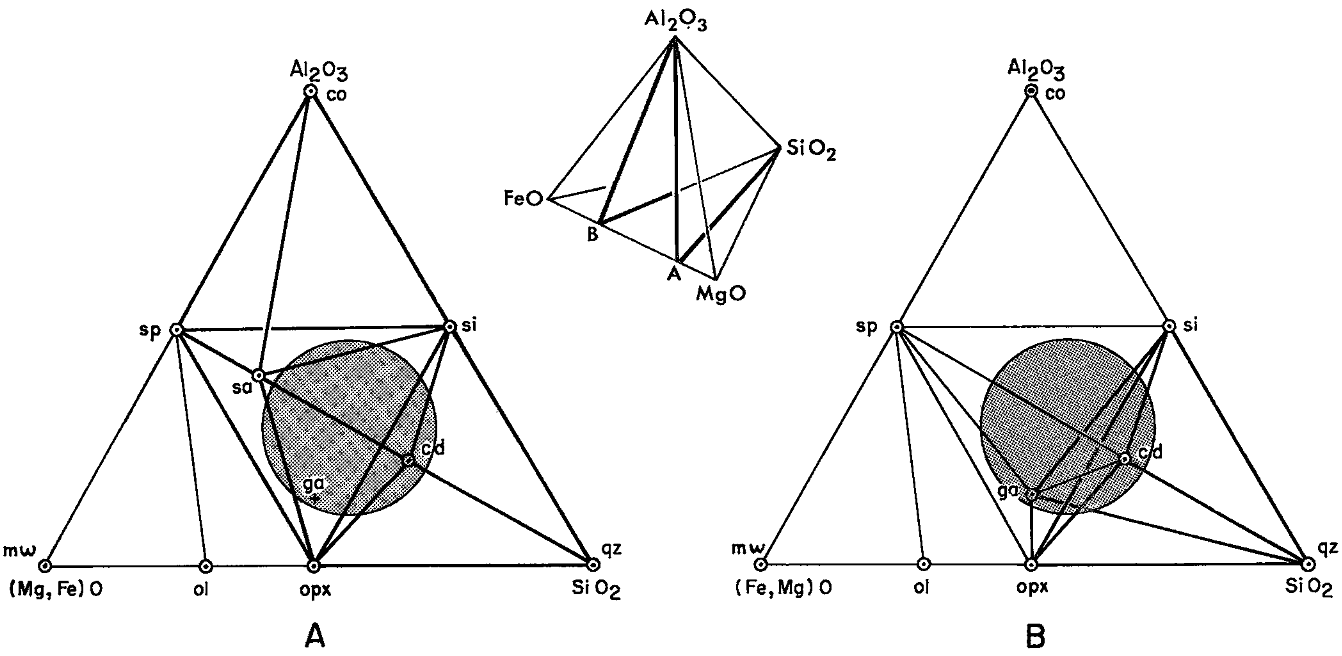

FIG. 6. Mineral assemblages in a portion of the system FeO-MgO-Al$_2$O$_3$-SiO$_2$. A: with high Mg : Fe^{2+} ratio; B: with Fe^{2+} in excess of Mg. Heavy tie lines represent associations at Wilson Lake. Symbols as in Table 1, plus mw: magnesiowustites; ol: olivine. Minerals present in both A and B have higher Mg : Fe ratios in A.

responding to En_{88}. The Mg : Fe ratio is thus close to that of the sapphirine, and it is probable that the pyroxenes are aluminous. In one of the few examples of garnet coexisting with sapphirine (L6-6b), the garnet has $n = 1.755 \pm .002$, and density $3.940 \pm .005$, appropriate to a member of the almandine-pyrope series with Fe : Mg ~ 1 : 1. Sillimanite is pleochroic (γ = light brown) in patches, suggesting unusually high Fe^{3+} content. Cordierite occurs in grains 0.5-1 mm, with tapering polysynthetic twins and pleochroic haloes, and in symplectites with sapphirine or feldspar. Cordierite in L2-1b, analysed by probe, is more magnesian than the coexisting sapphirine, with Mg : Mg + Fe (total) = 0.92. Plagioclase from several sapphirine-bearing rocks lies in the composition range $An_{35\text{-}45}$.

PETROGENESIS

The textural complexity of the rocks renders hazardous the inference of reactions among the associated minerals.

Only biotite, as fine fringes on other iron-bearing minerals, appears to be consistently retrograde. Although orthopyroxene and sillimanite are associated in symplectites and coronas in some examples, elsewhere they coexist in megascopic dimensions. Sapphirine and quartz are invariably separated by other minerals, save in the case of a few inclusions of quartz (optically identified) at L1, where intervening shells of orthopyroxene are incomplete or lacking.

Figure 6 is an attempt to show, graphically, the principal associations in sapphirine-bearing and sapphirine-free rocks at Wilson Lake. Graphical simplifications necessarily exclude feldspars and Fe-Ti oxides. The two triangles A and B may be regarded respectively as projections of parts of the tetrahedron $FeO–MgO–Al_2O_3–SiO_2$ with high and low ratios of magnesium to ferrous iron. They share the edge $Al_2O_3–SiO_2$. In A, the mineral associations of the Wilson Lake rocks are shown by heavy tie lines. In view of the rarity of garnet with sapphirine, tie lines to garnet have not been drawn. The associations Sa-Cd and Si-Opx are not exclusive ; all four coexist in several specimens. In view of the probable differences in Mg : Fe ratio between sapphirine and cordierite, the four-mineral association is to be expected. This association was also reported from Madras State, India (Walker & Collins 1907) and Val Codera, but at Val Codera orthopyroxene and sillimanite are inferred to be incompatible (Cornelius & Dittler 1929 ; Barker 1964). In the Wilson Lake samples, there is no textural evidence for incompatibility of these two minerals.

It is significant that the highly magnesian suite of silicates and spinel is associated with abundant hematite. The coexistence of silicate minerals with high Mg : Fe ratio, with oxides of high ferric : ferrous ratio, is characteristic of the products of recrystallization under relatively oxidizing conditions, as demonstrated in other localities (Chinner 1960; Mueller 1960; Hounslow & Moore 1967) and by experiment (Wones & Eugster 1965). The ferric : ferrous ratio in the silicates of such assemblages is also relatively high; the physical properties of sapphirine at Wilson Lake are in accord with this observation.

In Figure 6B are shown several mineral associations in quartz-bearing sapphirine-free rocks at Wilson Lake. These are similar to granulite facies assemblages of normal pelites, which have lower bulk ferric : ferrous ratios and more iron-rich silicate assemblages. The most magnesian members of the almandine-pyrope series stable under these conditions coexist with sapphirine, in the absence of quartz. More iron-rich almandines are stable with quartz. The field of bulk composition represented by the sapphirine rocks is approximately shown in Figure 2A, and reproduced in B. It may be seen that an increase in the ratio of magnesium to ferrous iron may correspond to a transition from a quartz-almandine-bearing assemblage to a quartz-free, sapphirine-bearing rock. This difference might simply reflect variation in the ferric : ferrous ratio of rocks having similar total iron contents, with appropriate changes in the oxide : silicate ratios. It is probable that the ferric : ferrous ratio is an inherited feature of the parent rock. That this ratio was, alternatively, imposed during metamorphism, the oxides being derived by decomposition of ferrous silicates of lower grade (Ramberg 1948b), cannot however be excluded.

Pending more complete information on mineral compositions, application of existing experimental data to infer conditions of formation is unwarranted. The experiments of Hensen & Green (1970) limit coexistence of sillimanite and orthopyroxene with quartz, to pressures in excess of 9.3 kilobars, but both high- and low-pressure sides of their limiting reaction:

$$\text{cordierite} \rightleftharpoons \text{silimanite} + \text{orthopyroxene} + \text{quartz}$$

may be found in the Wilson Lake rocks, allowing a substantial uncertainty. Similarly, although there is an indication that sapphirine might have been stable with quartz at some stage in the evolution of the rocks, the compositional characteristics of the Wilson Lake sapphirine may render unnecessary the extremely high temperatures (in excess of 1060°C) ascribed to this assemblage by Hensen & Green (1970). The association of sillimanite, rather than kyanite, with the oxide phases described indicates that, at least when these phases were quenched, the rocks were at a pressure below 7 kilobars (Richardson *et al.* 1968).

The origin of sapphirine in various localities has been ascribed to:

a) Reaction between orthopyroxene and spinel during metamorphism of mafic and ultramafic rocks and anorthosite (Sørensen 1955; Herd *et al.* 1969),
b) Contact reaction between mafic or ultramafic rocks, and granitic or aluminous rocks, during regional metamorphism (Walker & Collins 1907; Ramberg 1948b; Prider 1945),
c) Contact metamorphism of laterite (Agrell, *vide* Sørensen 1955),
d) Reaction between spinel and vein quartz in desilicated (?) hornfels near a contact with norite (Friedman 1952).

The relations at Wilson Lake demand a different explanation. The interlayering of incompatible assemblages in the gneisses, together with the small, dispersed, lenticular character of the oxide bodies, implies that the rocks were originally aluminous, ferruginous sediments, possibly of lateritic origin.

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