Sapphirine-bearing rocks from MacRobertson Land, Antarctica.

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Summary. A small isolated outcrop in a large area of charnockites in the Mawson area, MacRobertson Land, Antarctica, consists of enstatite–sapphirine–cordierite rocks. Other highly magnesian outcrops occur in the district and these rocks may be completely recrystallized xenoliths. Analyses of the country rock, the two sapphirine-bearing rocks, and the sapphirine are given; the country rock is very rich in iron and has a high $FeO:MgO$ ratio, while the sapphirine-bearing rocks are very low in iron and high in MgO, approximating to ternary mixtures of MgO, Al_2O_3, and SiO_2.

OF the rock specimens collected by Mr. B. Stinear,[1] geologist for the Australian National Antarctic Research Expeditions during the 1954 operations, several from the Mawson area, MacRobertson Land (fig. 1), were noted to contain irregular blue crystals mixed with a pale bronze mica. Microscopic examination of the blue material proved it to be sapphirine; this mineral was subsequently found to be a regular constituent of one particular group of rocks.

The rocks of the Mawson area are chiefly coarse-grained granitic types carrying hypersthene. The sapphirine-bearing rocks are described by Mr. Stinear as forming an oval-shaped outcrop, some 20 feet by 15 feet, of light coloured rock standing out in low relief from the surrounding dark brown country rock. Over the greater part of the outcrop the rock was of a uniform whitish colour, tinted pink or mauve. In what appeared to be outer concentric zones, it graded into a whiter, more gneissic rock, and then into a dark zone rich in biotite. As is common with rocks from the Antarctic regions, the constituent minerals were fresh and unaltered even on the surfaces that had been exposed to weathering.

Petrography.

The country rock. This is a dark brown quartz-felspathic rock containing many coarser crystals of brown felspar up to an inch in length. Under the microscope, felspars are seen to predominate over quartz, which is

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[1] Mr. Stinear is a geologist of the Commonwealth Bureau of Mineral Resources co-operating with A.N.A.R.E.

rather more finely granular than the felspars. Plagioclase forms larger crystals showing a variety of twin-laws—Carlsbad, Baveno, or pericline combined with albite twinning. The composition suggested by the maximum symmetrical extinction of albite twins is approximately $Ab_{45}An_{55}$—a labradorite. Orthoclase is present in approximately equal amounts, but as larger porphyritic crystals. Hypersthene, rather strongly pleochroic, comprises perhaps 5 % of the rock. From its colour and pleochroism, and the high $FeO:MgO$ ratio in the rock analysis (table I, col. 1), it is evidently a ferriferous variety. With it are associated some apatite and magnetite.
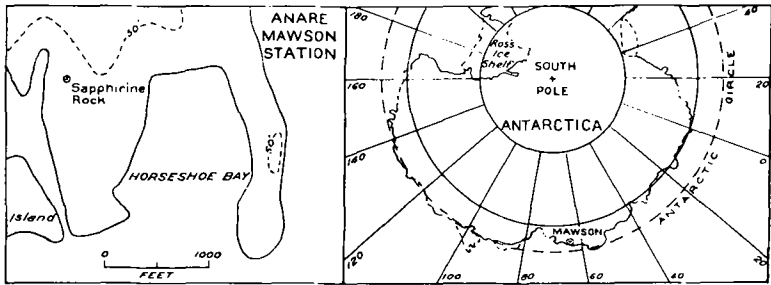

FIG. 1. Antarctica and the Mawson station.

The rock appears to be a characteristic member of the Antarctic charnockites.

Enstatite-sapphirine-spinel rock. This light blue-grey rock of medium grain size is typical of the material making up the greater part of the outcrop. In the hand specimen, especially on the weathered surface, bluish nodules up to 0·5 mm. diameter are clearly distinguishable from the white enstatite. Pale bronze flakes of mica are scattered irregularly through the rock.

Under the microscope the greater part of the rock is seen to be equigranular enstatite (average grain size approximately 0·3 to 0·4 mm. diam.). Of similar appearance, but less abundant and showing no cleavage, is some of the sapphirine; it occasionally forms a myrmekitic intergrowth with the enstatite. More commonly the sapphirine is concentrated in nodules with the spinel, which has almost the same refractive index. They are distinguished only by the weak birefringence of the sapphirine, which also shows a tendency to rim the spinel. The mica is a colourless phlogopite and shows a somewhat irregular distribution

through the sections. A chemical analysis of the rock is given in table I, column 3.

Enstatite–sapphirine–cordierite rock. This occurs as a zone between the spinel-bearing phase of the outcrop and the dark outer band. It is a white rock composed chiefly of enstatite and cordierite, bands rich in phlogopite, and scattered nodules of sapphirine. The cordierite is quite colourless and transparent, nearly always showing parallel multiple twinning. It contains no haloes, is coarsely crystalline, and frequently contains small inclusions of enstatite. The enstatite is similar to that in the spinel-bearing rocks, as is the comparatively small amount of sapphirine. A chemical analysis is given in table I, column 2.

The dark border phase. From the appearance of the specimens this is probably rather a narrow band, perhaps only a few inches wide. It is a dark gneissic rock, rich in dark mica, and frequently shows patches of dark blue mineral on weathered surfaces. Some of the specimens also show a gradation into material resembling the country rock.

Microscopically, the predominant mineral is a light brown biotite. Mixed with this is a plagioclase of similar composition to that in the country rock, and a pale hypersthene. The dark blue mineral of the hand specimens is largely an iron-rich sapphirine associated with a little spinel; they are identical in appearance. In the specimens available there is some segregation of the ferromagnesian minerals. The biotite is more abundant on the inside of many of the specimens, and the hypersthene more abundant on the side that grades, rather sharply, into the country rock.

Mineralogy.

Sapphirine occurs in most of the rocks in mauve-coloured aggregates with spinel, a few millimetres in diameter. In certain cases it occurs pure as sky-blue grains 2 to 3 mm. across mixed with phlogopite on the surface of the specimen. This surface appears to have been part of a vein or vug. The mineral was originally identified from such material by its optical properties, which are: $\alpha = 1.703$, $\gamma = 1.710$, 2V near 80°, positive. No cleavages were seen. The identity of the mineral was confirmed by X-ray powder photographs taken by Dr. B. J. Skinner. A chemical analysis of the sky-blue material is included in table I.

Enstatite is white or pale grey in colour, and is common to all the light coloured rocks. Its iron content is very low, probably of the order of 2 % FeO. This is indicated partly by the low iron content of the rocks as a whole, and also by its low refractive indices: $\alpha = 1.655$, $\gamma = 1.665$.

Spinel is common in all the specimens from the centre of the outcrop.

It is very similar in appearance to the sapphirine, both in the hand specimen and in thin section. Its refractive index is 1·717, which suggests a practically pure magnesium spinel.

Cordierite is quite colourless, with refractive indices $\alpha = 1·532$, $\gamma = 1·540$, 2V close to 70°, positive. Commonly it is twinned on a

Table I. Chemical analyses of three rocks and of sapphirine from Mawson, Antarctica.

	1.	2.	3.	4.
SiO_2	63·12	46·34	38·00	16·71
Al_2O_3	14·29	23·21	23·58	54·77
Fe_2O_3	0·97	0·77	1·03 ⎫	
FeO	6·12	0·66	1·03 ⎭	3·16
MgO	2·07	24·00	32·57	19·89
CaO	4·32	0·36	0·16	1·13
Na_2O	2·96	1·24	1·72	0·20
K_2O	4·14	2·42	1·70	0·95
TiO_2	1·48	0·34	0·32	0·67
P_2O_5	0·41	—	0·02	—
SO_3	0·02	0·03	0·03	—
Cl	0·03	0·04	nil	—
MnO	trace	—	—	—
H_2O at 100° C. ...	0·17	0·08	0·07	0·21
H_2O over 100° C.	0·26	1·19	0·35	—
Ign.	—	—	—	1·90
Less O equiv. ...	0·01	0·01	—	—
Total	100·35	100·67	100·58	99·59

1. Charnockitic country rock, Mawson area.
2. Enstatite–sapphirine–cordierite rock.
3. Enstatite–sapphirine–spinel rock.
4. Sapphirine.

Analyses undertaken through the courtesy and co-operation of the South Australian Department of Mines. Analysts P. C. Hemingway and R. N. Lewis of the Geological Survey Laboratories.

parallel law. Occasionally it occurs in small veinlets one or two millimetres across, when it is quite colourless and transparent. The refractive indices of the mineral and the low iron content of the rock suggest that it is an almost pure magnesium cordierite.

Phlogopite is a pale bronze colour, uniaxial negative, with refractive indices $\beta = \gamma = 1·570$; α was not measured.

Chemistry.

Chemical analyses of the country rock, the enstatite–sapphirine–spinel rock, the enstatite–sapphirine–cordierite rock, and sapphirine separated from a small vein are given in table I.

The most notable features of the analyses are the high iron content and high $FeO:MgO$ ratio in the country rock, and the very high magnesia and low iron content of the sapphirine rocks. The latter, in fact, approximate to ternary mixtures of the system $MgO–Al_2O_3–SiO_2$, these three constituents making up some 95 % of the rocks.

The sapphirine analysis gives almost exactly the formula $Mg_2Al_4SiO_{10}$, or $2MgO.2Al_2O_3.SiO_2$. Other published analyses of sapphirine give, in most instances, compositions ranging from this to $Mg_4Al_{10}Si_2O_{23}$, or

TABLE II.

Madagascar (Lacroix and de Gramont, 1921) ...	$Mg_{2.00}Al_{4.16}Si_{1.00}O_{10}$
India (Muthuswami, 1949)　　...　　...　　...	$Mg_{2.00}Al_{4.04}Si_{1.00}O_{10}$
Quebec (Warren, 1912) ...　　...　　...　　...	$Mg_{2.00}Al_{4.00}Si_{1.00}O_{10}$
Mawson (this paper)　　...　　...　　...　　...	$Mg_{2.06}Al_{3.93}Si_{1.00}O_{10}$
Italy (Cornelius and Dittler, 1929)　　...　　...	$Mg_{3.83}Al_{10.00}Si_{2.08}O_{23}$
Transvaal (Mountain, 1939)　　...　　...　　...	$Mg_{3.76}Al_{10.16}Si_{2.00}O_{23}$
Western Australia (Prider, 1945)　　...　　...	$Mg_{3.99}Al_{9.90}Si_{2.07}O_{23}$
Greenland (Ussing, 1889)　　...　　...　　...	$Mg_{4.03}Al_{10.08}Si_{2.00}O_{23}$

$4MgO.5Al_2O_3.2SiO_2$. Table II gives the approximate formulae (reduced to $Mg:Al:Si:O$ ratios) of sapphirine from eight localities, calculated from the various published analyses.

Foster (1950) found the best synthetic composition for sapphirine to be $Mg_4Al_{10}Si_2O_{23}$. Gössner and Mussgnug (1928) found the crystal structure to correspond to $Mg_2Al_4SiO_{10}$ in which MgSi is indefinitely replaced by AlAl. This appears to be confirmed by the natural occurrences; many of these correspond closely to $Mg_2Al_4SiO_{10}$, but by replacement of (Mg,Fe)Si by AlAl grade into $Mg_4Al_{10}Si_2O_{23}$, which appears to be the limiting composition of the mineral, at least in nature.

Discussion.

The genesis of these rocks must remain in some doubt. They form a small isolated outcrop in a large rather flat area of charnockites. No clear relation can be seen between the composition of the main part of the outcrop and that of the charnockite, except for the magnesium contents. It may be of significance that at least two other small isolated outcrops of magnesia-rich rocks occur in the Mawson area. One of these is largely composed of a diopside–spinel rock, and the other is a forsterite marble. It is possible that these outcrops represent the remains of large xenoliths of magnesia-rich sedimentary rocks, which have been included in the charnockite and completely recrystallized.

The system $MgO–Al_2O_3–SiO_2$, both with and without water, has

been investigated intensively. In the original work on the dry system (Rankin and Merwin, 1918) sapphirine was not recorded. Foster (1950) predicted, and Kieth and Schairer (1952) confirmed the presence of a small field for this compound on the liquidus of the dry system. Yoder (1952) determined assemblages stable in the presence of an excess of water vapour at 15 000 lb. per sq. in. up to 990° C. and Roy and Roy (1955) covered the field at 10 000 lb. per sq. in. up to 780° C. In neither of these cases was sapphirine recorded. Yoder also gives a diagram for probable assemblages stable in water-deficient regions at approximately 600° C. and 15 000 lb. per sq. in. Again, sapphirine is not included in this diagram.

In the work on the hydrous system, less attention was paid to the alumina–spinel–silica part of the diagram, so that it is possible that sapphirine may still occur under those experimental conditions. It seems more likely, however, that sapphirine enters the assemblages under conditions of undersaturation with water.[1] This is in line with its natural occurrences. The two notable assemblages at Mawson are enstatite–sapphirine–spinel and enstatite–sapphirine–cordierite. These two assemblages are known from a number of localities, as is the corundum–sapphirine assemblage (fig. 2). Assemblages in the area cordierite–corundum–sapphirine are much more in doubt. Vogt (1947) discusses mineral assemblages with sapphirine, but leaves this area of his diagram open. He notes, however, that sapphirine and sillimanite have yet to be found together, even in areas where sillimanite occurs in associated rocks. Furthermore, cordierite–corundum is of such widespread occurrence under a variety of conditions that it may not be unreasonable to expect it to be a stable assemblage under the conditions for the formation of sapphirine. Therefore, it seems reasonable to accept the assemblages of fig. 2 for sapphirine-bearing facies of the type described here.

The approximate compositions, recalculated to mol. %, of the enstatite–sapphirine–spinel rock, the enstatite–sapphirine–cordierite rock, and the charnockite (substituting MgO for FeO) have also been plotted on fig. 2. They lie almost on a line, so that it seems reasonable to suppose that the cordierite-bearing phase is the result of reaction between the highly magnesian rock and the charnockitic country rock. The iron-rich investment of the outcrop is a well-known feature of the reaction between basic or acid xenoliths and host rock of the opposite nature. This, together with the occasional occurrence of other highly magnesian outcrops in the locality, suggests that these rocks may be isolated large xenoliths of siliceous magnesian sedimentary rocks, which

[1] See Appendix.

have been caught up in the original granitic magma and undergone complete recrystallization and partial reaction with the host, under conditions of moderately high pressure and temperature and little water.

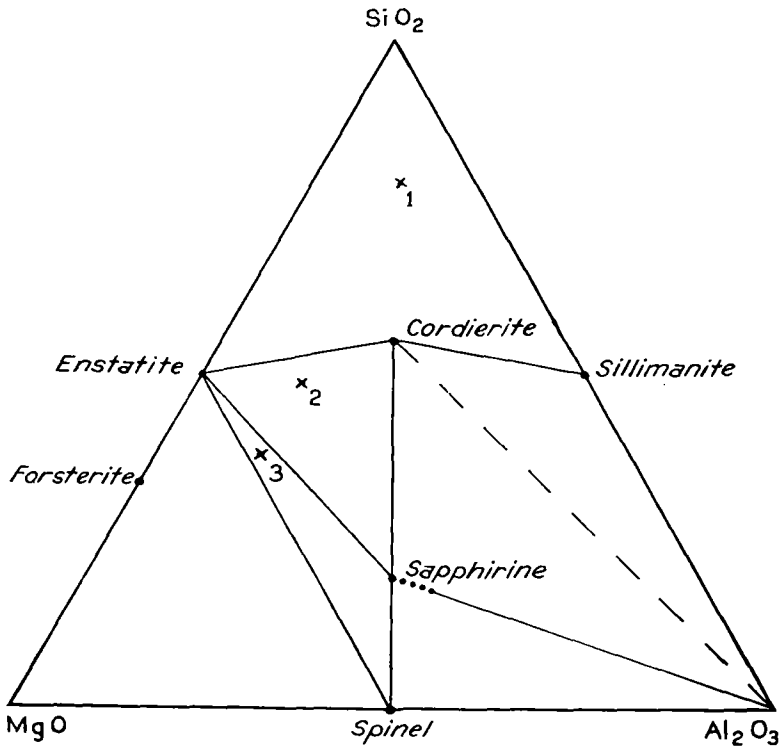Finally, it may be noted that further synthetic work on the system

Fig. 2. Mineral assemblages in the system $MgO-Al_2O_3-SiO_2$. Crosses indicate approximate positions of rocks described in text. Mols. per cent.

$MgO-Al_2O_3-SiO_2-H_2O$ under conditions of undersaturation with water, especially in the regions of the system where sapphirine assemblages might be expected to form, may give some precise information as to the temperature–pressure conditions under which these unusual rocks were formed, and, as a corollary, as to the conditions under which the surrounding charnockites have formed.

References.

CORNELIUS (H. P.) and DITTLER (E.), 1929. Neues Jahrb. Min., Abt. A., Beil.-Bd. 59, p. 27.

FOSTER (W. R.), 1950. Journ. Geol., Chicago, vol. 58, p. 135.

GÖSSNER (B.) and MUSSGNUG (F.), 1928. Neues Jahrb. Min., Abt. A, Beil.-Bd. 58, p. 213.

KIETH (M. L.) and SCHAIRER (J. F.), 1952. Journ. Geol., Chicago, vol. 60, p. 181.

LACROIX (A.) and DE GRAMONT (A.), 1921. Bull. Soc. franç. Min., vol. 44, p. 67.

MOUNTAIN (E. D.), 1939. Min. Mag., vol. 25, p. 277.

MUTHUSWAMI (T. N.), 1949. Proc. Indian Acad. Sci., Sect. A, vol. 30, p. 295.

PRIDER (R. T.), 1945. Geol. Mag., vol. 82, p. 49.

RANKIN (G. A.) and MERWIN (H. E.), 1918. Amer. Journ. Sci., ser. 4, vol. 45, p. 301.

ROY (Della M.) and ROY (Rustum), 1955. Amer. Min., vol. 40, p. 147.

USSING (N. V.), 1889. Zeits. Kryst. Min., vol. 15, p. 596.

VOGT (T.), 1947. Compt. Rend. Soc. Géol. Finlande, vol. 20 (Eskola volume), p. 15.

WARREN (C. H.), 1912. Amer. Journ. Sci., ser. 4, vol. 33, p. 263.

YODER (H. S.), 1952. Ibid., Bowen volume, p. 600.

APPENDIX (see p. 695)

Discussion with Dr. G. C. Kennedy of the Institute of Geophysics, University of California, Los Angeles, suggests that this is an erroneous premise. Water vapour pressures lower than total pressure may give rise to different assemblages. The mineral associations recorded in this paper may have been formed under such conditions, or may have been formed in a pressure range higher than has been yet investigated for this system.