OLIVINES FROM THE SKAERGAARD INTRUSION, KANGERDLUGSSUAK, EAST GREENLAND

W. A. Deer, *University of Manchester*

AND

L. R. Wager, *University of Reading, England.*

Four olivines separated from the rocks of the Skaergaard intrusion,[1] Kangerdlugssuak, East Greenland, have been analysed. The olivines occur in a layered gabbro intrusion which shows continuous crystallisation-differentiation from a lower and earlier hypersthene-olivine-gabbro to an upper and later fayalite-quartz-gabbro. Two of the three main constituents of this differentiation series, namely plagioclase and monoclinic pyroxene, show a continuous variation in composition, the plagioclase from medium labradorite to oligoclase-andesine, and the monoclinic pyroxene from a diopside-augite to a member of the hedenbergite-clinoferrosilite solid solution series.[2] Hypersthene is also an important constituent of the earlier rocks of the intrusion and varies from Fs_{41} in the lowest exposed rocks to at least Fs_{60} in rock 2000 m. up; above this it does not occur as separate crystals. Olivine is not found throughout the intrusion being absent for 500 metres at about the middle of the layered series. The olivines in the lower and earlier part of the layered series, of which I is an example, are in equilibrium with labradorite, a common type of pyroxene and hypersthene with about 40% $FeSiO_3$. The olivines of the second crystallisation period, of which II, III and IV are examples, are in equilibrium with andesine, an unusual iron-rich pyroxene, which we have already described, and quartz. In these upper rocks the iron-rich olivine was among the later minerals to crystallise, while in the lower and earlier rocks of the intrusion the more magnesian olivine, as is usual, was an early mineral. Except close to the olivine free horizon the amount of modal olivine in the average rock is never less than 10% and rarely greater than 20%.

The four olivines were first separated with the help of methylene iodide, and clerici solutions. They were further purified by an electromagnet and then by hand picking. Olivines I, II and III were practically free from inclusions, but IV contained a large number of minute orientated crystals of iron ore. These were removed by gelatinising the olivine with dilute hydrochloric acid, separating the solution from the silica and

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[1] Wager, L. R., Geological Investigations in East Greenland, Part I. Meddl. om. Gronland, vol. **105,** no. 2, pp. 36–37, 1934.

[2] Deer, W. A., and Wager, L. R., Two new pyroxenes included in the system clinoenstatite, clinoferrosilite, diopside and hedenbergite: *Min. Mag.*, vol. **25,** pp. 15–22, 1938.

TABLE 1

	Olivine I				Olivine II			
	Wt. %	Mol. %	Atomic ratio to 4 oxygens		Wt. %	Mol. %	Atomic ratio to 4 oxygens	
SiO_2	38.11	0.6345	1.028		33.72	0.5614	1.006	
Al_2O_3	nil	—	—		nil	—	—	
TiO_2	trace	—	—		trace	—	—	
Fe_2O_3	0.15	0.0009	0.003		0.05	0.0003	0.002	
FeO	31.48	0.4382	0.710	1.94	47.91	0.6669	1.190	2.00
MnO	0.22	0.0031	0.004		0.41	0.0058	0.010	
MgO	30.50	0.7564	1.225		18.07	0.4482	0.799	
CaO	0.02	—	—		nil	—	—	
	100.48				100.16			
	(Mg, Fe, Mn)$_2$[SiO$_4$] Fo$_{64}$Fa$_{36}$				(Mg, Fe, Mn)$_2$[SiO$_4$] Fo$_{41}$Fa$_{59}$			

	Olivine III				Olivine IV			
SiO_2	31.85	0.5303	1.008		30.15	0.5019	1.002	
Al_2O_3	trace	—	—		0.07	0.0007	.003	
TiO_2	0.01	—	—		0.20	0.0025	.006	
Fe_2O_3	0.11	0.0007	0.003		0.43	0.0027	.010	
FeO	58.64	0.8162	1.552	1.98	65.02	0.9049	1.807	1.99
MnO	0.85	0.0120	0.023		1.01	0.0149	.030	
MgO	8.49	0.2105	0.400		1.05	0.0260	.052	
CaO	0.18	0.0032	0.006		2.18	0.0389	.078	
	100.13				100.11			
	(Mg, Fe, Mn, Ca)$_2$[SiO$_4$] Fo$_{20}$Fa$_{80}$				(Mg, Fe, Mn, Ca)$_2$[SiO$_4$] Fo$_3$Fa$_{97}$			

inclusions, and finally separating the gelatinous silica from the ore inclusions.

The refractive indices of the olivines were determined by the immersion method using a series of liquids with high dispersion. For those olivines with refractive indices between 1.735 and 1.770 a solution of sulphur in methylene iodide was used, for those between 1.770 and 1.852 two solutions, one of equal parts and one of three parts phenyldi-iodoarsine[3] ($C_6H_5AsI_2$) and one part methylene iodide, and for those above 1.852, pure phenyldi-iodoarsine. The refractive indices of these liquids for varying wave lengths were obtained by placing them in a

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[3] Anderson, B. W., and Payne, C. J., Liquids of high refractive index: *Nature*, London, vol. **133**, pp. 66–67, 1934. Also, The refractometer and other refractive index methods: *Gemnologist*, London, vol. **3**, pp. 216–227, 1934.

small hollow 30° prism on a single circle Fuess goniometer and using the minimum deviation method. As a convenient method of obtaining monochromatic light of varying wave lengths, a monochromatic illuminator designed by Tutton[4] was used, the source of the light being a liliput arc. The monochromator was standardised with yellow sodium light and yellow, green and violet light from a mercury vapour lamp. From a large number of readings, graphs giving the full dispersion of the liquids, were drawn. The measurements of the optic axial angle were made on a universal stage and the specific gravities were determined by suspension in clerici solutions diluted with water, the specific gravity of the solutions being obtained with a hydrostatic balance.

TABLE 2

		I	II	III	IV
2V (negative).[1]		79°	65°	58°	48°
Refractive indices.[2]	α	1.710	1.752	1.788	1.827
	β	1.733	1.781	1.828	1.869
	γ	1.748	1.795	1.840	1.879
	$\gamma-\alpha$	0.038	0.043	0.052	0.052
Colour in thin section.		Faint yellow.	Pale yellowish amber.	Pale yellowish amber.	Yellowish amber.
Pleochroism.		As for IV but less, corresponding to colour.	As for IV but less, corresponding to colour.	As for IV but less, corresponding to colour.	$\alpha=\gamma$ pale yellow. $\beta=$orange yellow.
Colour as small grains.		Lemon yellow.	Deep amber.	Deep amber.	Deep reddish brown.[3]
Specific gravity.		3.69	3.88	4.15	n.d.

[1] Determinations ± 2°.

[2] Determination ± .002.

[3] Partly the result of ore inclusions.

The optical data are given in Table 2 and have been plotted also against chemical composition, and superimposed on the refractive index diagram for the synthetic Mg-Fe olivines of Bowen and Schairer[5] (Fig. 1). For the natural olivines the small amounts of impurities have been disregarded and the analyses recalculated in terms of Mg_2SiO_4 and Fe_2SiO_4. The refractive index of the natural minerals is in every case a little higher than that of the artificial, but the agreement is close. There is also close agreement, except at the fayalite end, with the refractive

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[4] Tutton, A. E. H., Crystallography and Practical Crystal Measurement, *London*, vol. **2**, pp. 959–965, 1922.

[5] Bowen, N. L., and Schairer, J. F., The system, MgO-FeO-SiO_2: *Am. Jour. Sci.*, vol. **29**, p. 197, 1935.

index curves drawn by Winchell[6] from the less complete series of natural minerals previously known.

Besides the physical properties given in Table 2 mention should be made of the cleavage and inclusions. The iron rich olivine II has distinct cleavages parallel to [010]. Tabular inclusions of ore are abundant parallel to [100] and are sporadic parallel to [001]. This olivine is comparable with the Onverwacht hortonolite[7] from the Bushveld Complex in which very distinct [010] and less distinct [001] cleavages are developed. The Bushveld mineral also has two sets of included minute tabular plates lying at right angles to each other and developed in sheets parallel to [100] and [001]. The refractive index β is 1.749 (=$Fo_{52}Fa_{48}$) compared with 1.781 (=$Fo_{41}Fa_{59}$) for the Skaergaard hortonolite. The more iron rich olivines, III and IV, have similar cleavages and more abundant inclusions.

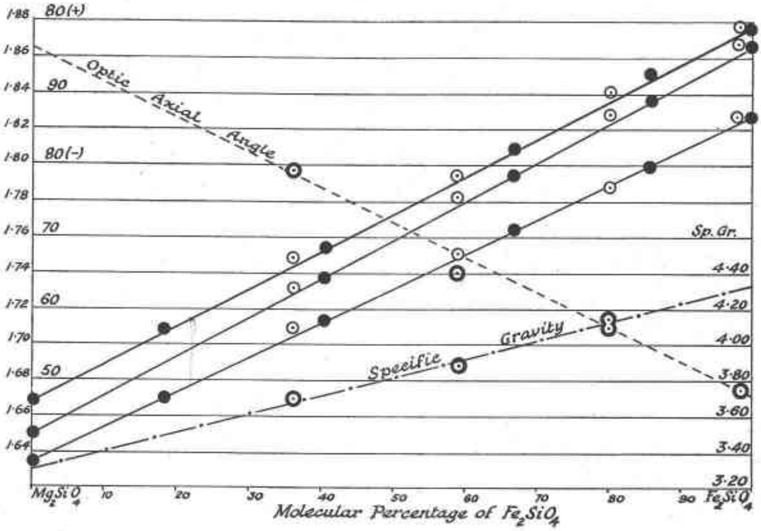

FIG. 1. Variations in composition and optical properties of the olivine series. ● Variation of refractive indices after Bowen and Schairer. ⊙ Date for the olivines of the Skaergaard intrusion.

Olivines containing from 0 to 30 molecular percentage of Fe_2SiO_4 are common in igneous rocks, and olivines with as much as 50% Fa are known and have been described from a number of localities, especially from the Bushveld Complex,[8] the East Greenland basalts north of

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[6] Winchell, A. N., Elements of Optical Mineralogy, *New York*, Pt. 2, p. 191, **1933**.

[7] Wagner, P. A., Platinum Deposits and Mines of South Africa: *London*, pp. 55–59, **1929**.

[8] Wagner, P. A., *op. cit.*, pp. 50–68.

Scoresby Sound,[9] and the Hällefors Dyke.[10] Fayalite is of course well known as a natural mineral. Although recently the complete series of solid solution from Mg_2SiO_4 to Fe_2SiO_4 have been synthesised and described, the complete series had not previously been found to occur naturally. The two iron rich olivines II and III, are therefore, of immediate interest for they extend the range of naturally occurring olivines and, in conjunction with other examples from the Skaergaard intrusion, prove that in natural magmas, as in the laboratory, a complete series of solid solutions may occur. In Table 3 the analyses of the Kangerdlugssuak olivines are compared with analyses of other iron rich olivines. The previously existing gap in our knowledge of natural olivines was between those containing 50% fayalite and almost pure fayalite.

Although olivines II, III and IV have crystallised from a magma comparatively rich in lime, they have remained almost pure members of the simple solid solution series Mg_2SiO_4-Fe_2SiO_4 being with the exception of IV practically free from Ca_2SiO_4. In this respect they resemble fayalites from syenites which are also apparently free from Ca_2SiO_4 although there is plenty of lime in the rocks from which they come. The fayalites from lithophysae and acid lavas are also lime free but this is to be expected as they have crystallised from a magma poor in both lime and magnesia. It is interesting to find that these natural iron rich olivines are also free from lime in view of the results from the synthetic melt system CaO-FeO-SiO_2.[11] Olivine IV is in equilibrium with a monoclinic pyroxene of the hedenbergite-clinoferrosilite solid solution series, close to ($Wo_{30}En_1Fe_{69}$) in composition, with plagioclase, Ab_{70}, and quartz. The data from the synthetic system suggest that olivine in equilibrium with a similar monoclinic pyroxene, excluding the 1% of $MgSiO_3$, would contain between 6 and 7% Ca_2SiO_4. As we have stated above there is no lack of lime in the rock and we can offer no definite explanation of this difference from the experimentally determined system. The percentage of Mn_2SiO_4 is also low but this is to be expected as the rocks are relatively poor in manganese. It is, however, significant that as the manganese content of the rocks increases the manganese in the olivines also increases.

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[9] Backlund, H. G., and Malmquist, D., Zur Geologie und Petrographie der Nordostgronlandischen Basaltformation. Part 1, Die Basische Reiche. Meddel om Gronland, vol. **87,** part 5, pp. 1–61, 1932.

[10] Krokström, T., The Hällefors dolerite dyke and some problems of basaltic rocks: *Bull. Geol. Instit. Upsala*, vol. **26,** pp. 115–258, 1936.

[11] Bowen, N. L., Schairer, J. F., and Posnjak, E., The system, CaO-FeO-SiO_2: *Am. Jour. Sci.*, vol. **26,** p. 233, 1933.

The four analysed olivines form a comparatively pure mineral series thus contrasting with the variations found in the pyroxene series (Deer and Wager 1938). This may be related to the simpler unit cell of the olivines giving less possibilities for variation. As there is no replacement of silicon by aluminium in the independent SiO_4 tetrahedra, the replacement of divalent Mg, Fe and Mn by trivalent iron and alumina or tetravalent titania does not take place and the olivines have a relatively simple composition.

TABLE 3. ANALYSES OF IRON-RICH OLIVINES AND DUNITES

	A	B	I	C	D	E	II	F	III	IV	G
SiO_2	37.92	36.72	38.11	34.00	34.38	33.94	33.72	33.27	31.85	30.15	29.60
Al_2O_3	—	—	nil	—	1.46	—	nil	—	trace	0.07	—
TiO_2	—	—	trace	nil	0.05	—	trace	trace	0.01	0.20	—
Fe_2O_3	—	—	0.15	—	0.03	—	0.05	0.37	0.11	0.43	—
FeO	25.96	29.96	31.48	37.80	38.30	47.32	47.91	49.32	58.64	65.02	68.73
MnO	—	—	0.22	—	0.40	4.32	0.41	1.50	0.85	1.01	—
MgO	34.47	31.99	30.50	23.60	22.09	13.74	18.07	16.08	8.49	1.05	1.78
CaO	nil	nil	0.02	—	2.36	—	nil	—	0.18	2.18	—
H_2O	—	—	—	—	0.55	0.48	—	—	—	—	—
	98.35	98.67	100.48	95.40	99.62	99.80	100.16	100.54	100.13	100.11	100.11

A. Dunite composed of iron-rich olivine, approaching hyalosiderite, from Upper Quarry, Driekop Mine. Anal. A. MacJohnson (Wagner, **1929,** p. 84).
B. Hyalosiderite. Kaiserstuhl (Doelter, vol. **2,** p. 1, p. 300).
I. Hyalosiderite. E.G.4077, from hypersthene-hyalosiderite-gabbro, Kangerdlugssuak, E. Greenland.
C. Honey-brown, coarse-grained hortonolite-dunite 200 ft. level, Onverwacht Mine. Anal. R. A. Cooper (Wagner, **1929,** p. 60) (incomplete analysis).
D. Hortonolite-dunite from outcrop, Onverwacht Mine, Lydenberg District, Transvaal. Anal. H. G. Weall (Wagner, **1929.** p. 60). Recalculated analysis which showed 2.90% Fe_2O_3 on assumption that all ferric oxide except 0.05% of magnetite, originally present as ferrous oxide. Analysis includes Cr_2O_3, 0.10; Na_2O, 0.20; P_2O_5, 0.05.
E. Hortonolite, Munroe, Orange Co., N. J. (Penfield and Forbes, **1896,** p. 211).
II. Hortonolite, E.G.1907, from quartz-hortonolite-gabbro. Kangerdlugssuak, E. Greenland.
F. Hortonolite. Cumberland (Rhode Island). (Anal. C. H. Warren, 1908.)
III. Ferrohortonolite, E.G.4146, from quartz-ferrohortonolite-gabbro. Kangerdlugssuak, E. Greenland.
IV. Fayalite, E.G.4139, from quartz-fayalite-gabbro. Kangerdlugssuak, E. Greenland.
G. Fayalite from pegmatite, Mourne Mts., Ireland. Quoted from Doelter, vol. **2,** pt. 1, p. 716.
Analyst for olivines I–IV, W. A. Deer.

At present the classification of the olivine series is somewhat confused and there is a considerable lack of agreement about the subdivisions and their names. Wagner [12] has stated: "the term olivine, by general consent, is applied to mixtures of forsterite and fayalite having the constitution $n Mg_2SiO_4 + Fe_2SiO_4$ where n varies from 12 to 2." In using the name olivine for a definite part of the series Wagner followed Dana[13] and Iddings,[14] although the latter (p. 46) states that in common olivines the FeO% may reach 12 (i.e. $= Fo_{87}Fa_{13}$) and in another place[15] he uses

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[12] Wagner, *op. cit.*, pp. 50–51.

[13] Dana, E. S., A Textbook of Mineralogy, *New York*, pp. 510–13, **1922.**

[14] Iddings, J. P., Igneous Rocks, *New York*, vol. 1, pp. 44, 46, **1909.**

[15] Iddings, J. P., Rock Minerals, *New York*, pp. 379–86, **1911.**

olivine as the group name and both olivine and chrysolite for compositions between forsterite and hortonolite. Mügge[16] in his revision of Rosenbusch, Miers,[17] Niggli,[18] Winchell[19] and Alling[20] and many others use olivine as the group name. No agreement exists moreover, in the names of the subdivisions of the series. Winchell[21] restricts the name chrysolite to minerals containing between 5 and 25% Fe_2SiO_4, and Alling to minerals between 15 and 35% Mg_2SiO_4. Wagner uses the name hyalosiderite, following Hintz[22] and Doelter,[23] for minerals "in which the ratio of Mg_2SiO_4 to Fe_2SiO_4 is approximately as 2:1," and he states that the name should only be applied to varieties of the mineral having that composition. Alling proposes 65 to 40% Mg_2SiO_4 as the limits for hyalosiderite and thus encroaches on Wagner's definition of the term hortonolite.

The authors consider that if separate names are to be used for various parts of the continuous series of solid solutions of Mg_2SiO_4 and Fe_2SiO_4 that the subdivision should be systematic. At present the names commonly accepted, in order of increasing richness in the fayalite molecule are forsterite, chrysolite, hyalosiderite, hortonolite and fayalite. Although Winchell uses these terms he refrains from defining the limits of hortonolite. Wagner accepted all these names except chrysolite, and Alling in dealing recently with the classification of the olivines used all the names. The two latter authors suggested definite limits but the range of their subdivisions is different. The end members, forsterite and fayalite have been variously defined, from 5 to 15%, leaving 90 or 70% of the series to be covered by three names, and in each case an unequal subdivision of the middle of the series was made. In view of the fact that naturally occurring olivines have now been shown to range over the whole series it is important that the nomenclature should be standardised. This we believe can be done without undue modification of the previous schemes and yet in a way which will systematise the subdivision. Thus if the names forsterite and fayalite are limited to olivines having from between 0 to 10, and 90 to 100 molecular per cent of Fe_2SiO_4, respectively, then the series may be divided systematically into units

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[16] Mügge, O., Mikroskopische Physiographie der Petrographisch Wichtigen Mineralien by H. Rosenbusch, vol. **1**, part 11, pp. 354–67, 1927.

[17] Miers, A. A., Mineralogy, *London*, pp. 414–16, **1902.**

[18] Niggli, P., Lehrbuch der Mineralogie, *Berlin*, vol. **11**, pp. 521–26, 1926.

[19] Winchell, A. N., *op. cit.*, pp. 186–94.

[20] Alling, H. L., Interpretative Petrology of the Igneous Rocks, *New York*, p. 105, **1936.**

[21] Winchell, A. N., The Microscopic Characters of Artificial Minerals, *New York*, p. 291, **1931.**

[22] Hintze, Handbuch der Mineralogie, vol. **2**, p. 22, 1897.

[23] Doelter, Handbuch der Mineralchemie, vol. **2**, pl. 1, pp. 289–313, 1914.

with a range of 20%. Such a subdivision which is like that of the plagioclase series is compared with some of the previously suggested classifications in Fig. 2. The existing names can satisfactorily be adapted for these subdivisions except that from 70 to 90% Fa is without any name. For this we suggest the compound name ferrohortonolite.

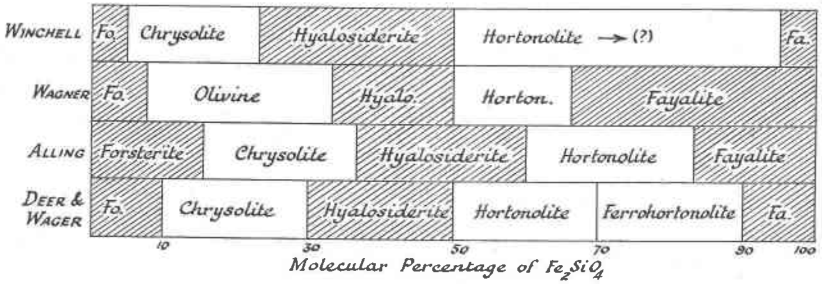

FIG. 2. Proposed classification of the Mg_2SiO_4-Fe_2SiO_4 olivines compared with the subdivisions of Winchell, Wagner and Alling.

The new data from these Kangerdlugssuak olivines show that the composition of natural olivines may be estimated from measurement of the refractive indices or of 2V. If more accurate determinations be made of the composition of olivines than has been the practice of most petrologists in the past, a far greater range than at present suspected may well be found among the common igneous rocks.

		Fayalite %	
2E	2V	Mol.	Wt.
94	94	0	0
93	92	8	11
92	90	13	18
91	88½	17	23
90	87½	20	27
89	86½	23	30
88	84½	27	35
87	83	30	38
86	82	33	42
85	81	35	44
84	79½	38	47
83	78½	41	50
82	77	44	53
81	75½	46	55
80	74½	48	57
79	73½	51	60
78	72½	53	62
77	71	56	65
76	70	58	67
75	68½	60	69
74	67½	62	70
73	66½	64	72
72	65½	66	74
71	64½	68	75
70	63½	70	77
69	62½	72	79
68	61½	74	80
67	60½	76	82
66	59½	78	84
65	58½	80	85
64	57½	81	86
63	56½	83	87
62	55½	85	89
61	54	87	91
60	53	89	92
59	52	91	94
58	51	93	95
57	50	95	96
56	49	96	97
55	48	98	98
54	47	100	100