An unusual cordierite-rock from Upington, Cape Province.

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Introduction.

SAMPLES of an unusual cordierite-rich rock from near Upington, Cape Province, were collected by Dr. A. Poldervaart who kindly passed them to me for further study. This paper presents the results of the petrographic examination together with chemical analyses of the rock and of cordierite and biotite, which are two of the constituent minerals.

The rock has a most striking appearance. The major constituent is deep-brown cordierite occurring as porphyroblasts measuring up to an inch in size. Occasional flakes of biotite are present, while the interstitial matter appears to consist principally of quartz with some felspar and white mica. The rock has not the typical banded structure of a gneiss nor does it possess the characteristic fabric of a hornfels.

It was first mentioned by E. J. Dunn in 1872 (Rogers and du Toit, 1910). Dunn called the small hill which makes the entire outcrop 'Tourmaline Kop'. The rock was identified by Drs. A. W. Rogers and A. L. du Toit (1910) as a cordierite-bearing rock. Rogers (1910) again refers to it in his article on the Kheis series. He includes two photographs of the hill, one of which is reproduced by Dr. L. C. King in his book 'South African Scenery'. No further data are given by Rogers in this later article, but he suggests that the rock was formed by incorporation of Kheis sediments in a granite magma.

Methods.

Owing to the close similarity between the specific gravity and refractive indices of the cordierite and quartz it was found expedient to cut slices of the rock and pick out the large cordierite crystals by hand so as to eliminate contamination by quartz. Further separation was done by centrifuge and electromagnet. Refractive indices were determined in sodium-light using a cell with temperature control. Optic axial angles were determined on grains showing acute bisectrix figures and direct measurements were made using a 5-circle universal stage.

Petrography.

The cordierite crystals are generally xenoblastic though idioblastic outline can be seen in some instances (fig. 1). Pinakoidal cleavage is prominent. Cyclic twinning occurs fairly commonly. Pleochroic haloes have not been found. The cordierite crystals are remarkably free from inclusions, and although apatite, iron ore, biotite, sericite, and andalusite do occur as inclusions, the last three are rare and the ore is mainly in the form of minute black specks. Alteration, which is not pronounced, is to a brownish-yellow isotropic substance and to a pale-green mica. The only other minerals of nearly comparable size to the cordierites are sporadically distributed crystals of potash-felspar and biotite. The remaining minerals occur interstitially. The felspars are invariably anhedral, the plagioclase is clear and unaltered, and has the composition of oligoclase.

The potash-felspar, which often forms comparatively large irregular crystals, is of a peculiar type with characteristic hazy cross-hatching. The refractive indices are slightly higher than normal; the optic axial angle is large and there is parallel extinction on (001). Apart from the much higher 2V it resembles the soda-microcline described by Professor H. H. Read (1923) as occurring in the Arnage-type rocks. It is apparently unstable in this mineral assemblage and is being replaced mainly by sericite and to a lesser extent by quartz and sillimanite. Biotite and andalusite are also apparently metastable, the former showing alteration to sericite and the latter to sillimanite. Andalusite crystals, except when in contact with quartz, invariably show peripheral armouring by a zone of sillimanite. Apatite and zircon are present as accessory constituents. The latter shows vivid pleochroic haloes in biotite. Blue tourmaline is rare and sporadic in distribution.

TABLE I. Minerals of the cordierite-rock, Upington.

| Mode.				Grain-sizes in mm.		Refractive indices			
				Average.	Maximum.	α	β	γ.	$2V_\alpha$.
Quartz ...	...	...	12·4	0·17 × 0·14	2·8 × 0·6	1·544	—	1·553	—
Potash-felspar ...		...	3·2	1·34 × 0·89	6·2 × 4·6	1·518	1·525	1·528	80°
Oligoclase	...	...	5·8	0·75 × 0·46	5·0 × 4·0	{ ′ on cleavage flakes 1·534–1·537 }			83–86°
Cordierite	...	...	63·1	5·5 × 3·7	25·0 × 12·0	·543	1·553	1·555	69–74°
Alteration products of cordierite		...	4·9	—	—	—	—	—	—
Sericite ...	...	...	4·2	0·24 × 0·06	2·1 × 0·5	—	1·592	—	41°
Biotite ...	...	...	1·6	1·55 × 0·78	15·0 × 4·0	1·595	—	1·649	0–5°
Sillimanite	...	...	3·4	—	1·5 × 0·3	—	1·671	—	—
Andalusite	...	...	1·1	0·46 × 0·25	1·6 × 0·5	1·628	1·638	1·639	84°
Iron ore	...	...	0·2	0·04 × 0·03	0·4 × 0·12	—	—	—	—
Apatite ...	...	...	0·1	0·09 × 0·06	0·76 × 0·66	1·634	—	1·638	—

100·0
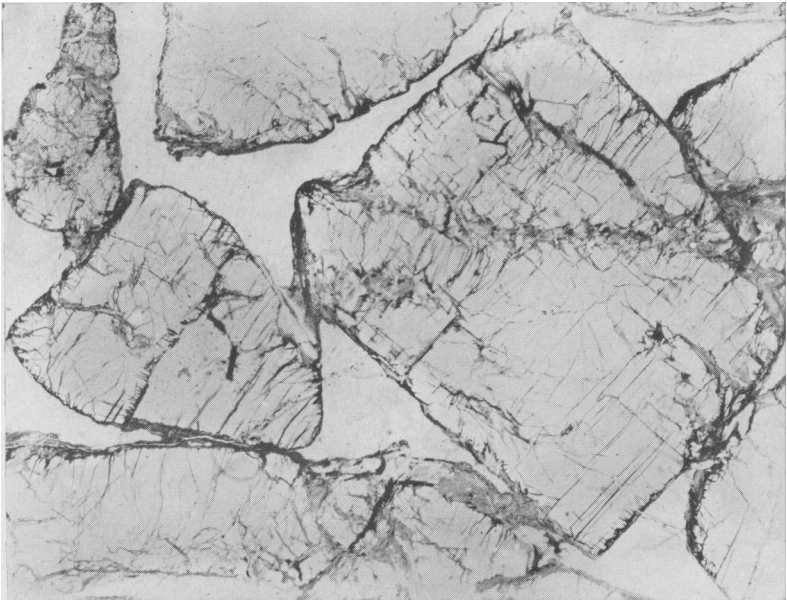
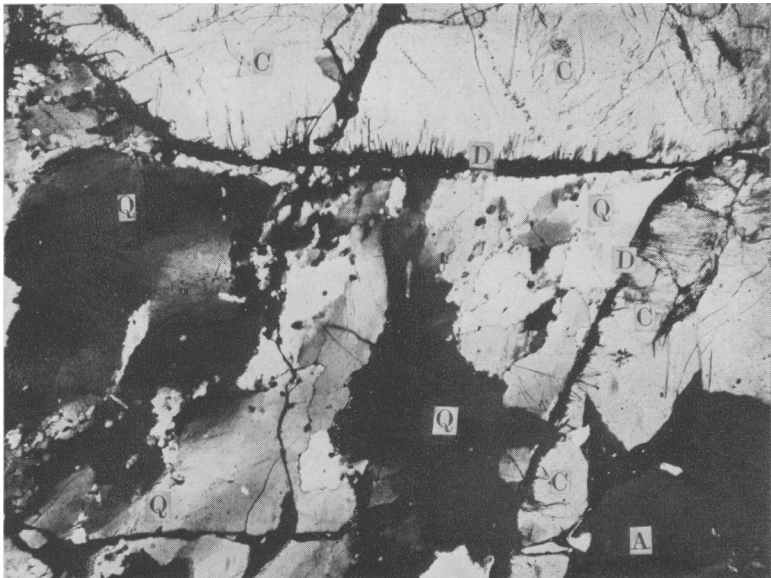FIG. 1. Cordierite-rock, Upington, showing idioblastic cordierite set in quartz. Ordinary light. × 5.

FIG. 2. Cordierite-rock, Upington, showing cordierite (C) bordered and penetrated by isotropic decomposition product (D), optically strained quartz (Q), and andalusite (A). Crossed nicols. × 53.

A peculiarity of structure is that the quartz, micas, felspars, and silli-manite generally show the effects of strain (fig. 2) whereas the cordierite is rarely affected. Table I lists the mode, grain-sizes, and chief optical properties of the minerals.

TABLE IIa. Chemical analysis of cordierite from cordierite-rock, Upington.

Analyst, P. L. le Roux, Division of Chemical Services, Pretoria.

Analysis.			Atomic ratios.			Atomic ratios to 18O.	
SiO_2	...	48·40	Si···· ...	...	0·8066	5·042	5·04
TiO_2	...	0·05	Al··· ...	...	0·6304	3·941	3·94
Al_2O_3	...	32·15	Fe·· ...	...	0·1361	0·851 ⎫	
Fe_2O_3	...	nil	Mn·· ...	...	0·0032	0·020 ⎬	2·00
FeO*	...	9·80	Mg·· ...	...	0·1812	1·133 ⎭	
MnO	...	0·23	OH· ...	...	0·1756	1·097	1·10
MgO	...	7·25	O·· ...	...	2·8793	18·000	18·00
CaO	...	trace					
Na_2O	...	0·39	Formula: $(Mg,Fe··,Mn)_{2·00}Al_{3·94}Si_{5·04}O_{18}.(H_2O)_{1·10}$				
K_2O	...	0·07					
H_2O+	...	1·58	$Mg_2Al_4Si_5O_{18} = 56·53\%$				
H_2O-	...	0·16	$(Fe,Mn)_2Al_4Si_5O_{18} = 43·47\%$				
P_2O_5	...	0·03	Sp. gr. 2·66				
		100·11	α 1·543, β 1·553, γ 1·555, $2V_\alpha$ 71° 40′ (average)				

* The values originally given were FeO 3·74; Fe_2O_3 5·68. Because of the exceptionally high Fe_2O_3 check determinations were made by my colleague Mr. H. C. G. Vincent and the average of five of his results is quoted here.

TABLE IIb. Chemical analysis of biotite from cordierite-rock, Upington.
Analyst, H. C. G. Vincent.

Analysis.			Atomic ratios.			Atomic ratio to 12O.	
SiO_2	...	34·77	Si···· ...	...	0·5789	2·6790 ⎫	4·00
Al_2O_3	...	19·05	Al··· ...	...	0·3740	1·7312 ⎰ 1·3210 ⎱ 0·4102	
TiO_2	...	2·84	Ti···· ...	...	0·0355	0·1645 ⎫	
Fe_2O_3	...	0·88	Fe··· ...	...	0·0110	0·0510	
Cr_2O_3	...	nil	Fe·· ...	...	0·2883	1·3350 ⎬ 2·93	
FeO	...	20·71	Mn·· ...	...	0·0014	0·0065	
MnO	...	0·10	Mg·· ...	...	0·2076	0·9607 ⎭	
MgO	...	8·37	Ca·· ...	...	0·0046	0·0215 ⎫	
CaO	...	0·26	Na· ...	...	0·0078	0·0358 ⎬ 0·89	
BaO	...	trace	K· ...	...	0·1802	0·8344 ⎭	
Li_2O	...	nil	OH· ...	...	0·3818	1·7670	1·77
Na_2O	...	0·24	O·· ...	...	2·5921	12·0000	12·00
K_2O	...	8·49					
H_2O+	...	3·44	Formula: $(K,Na,Ca)_{0·89}(Mg,Fe··,Mn,Al,Ti)_{2·93}$				
H_2O-	...	0·33	$(Si,Al)_{4·00}O_{12}.(H_2O)_{1·77}$				
Cl	...	nil					
F ...	...	nil	Sp. gr. 3·06				
		99·48	α 1·595 (pale straw), γ 1·649 (reddish brown), $2V_\alpha$ 0–5°				

The analysis of the cordierite shows good correspondence with the standard formula. According to A. N. Winchell's diagrams (1937) a cordierite containing 43·5 % $Fe_2Al_4Si_5O_{18}$ should have α 1·551, β 1·558, γ 1·564, Sp. gr. 2·67, $2V_\alpha$ 48°. R. E. Folinsbee (1941), on the other hand, gives different graphs for correlation of chemical and optical properties in cordierites, and the Upington cordierite shows much closer agreement with these. A comparison between the properties of the Upington cordierite and the values obtained from Folinsbee's graphs for a cordierite of similar composition is given below.

	Upington cordierite.	Folinsbee's data.
γ plotted against composition	1·555	1·560
$\gamma - \alpha$,, ,, ,, ...	0·0118	0·0117
2V ,, ,, weight of effective alkalis ...	71° 40′	68°

In view of the variability in optical properties of cordierite, attention to which has been drawn by A. N. Winchell (1937) and A. Brammall (1933) amongst others, closer agreement is not to be expected.
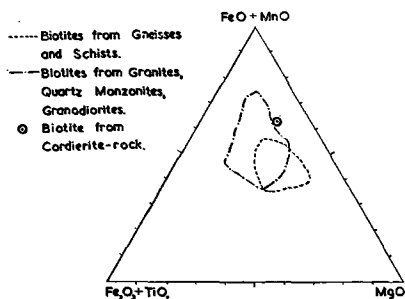

The biotite analysis shows slight deficiencies in the W, XY, and OH groups. These, however, are in no way abnormal and there is very fair agreement with the general formula $W(X,Y)_{2-3}Z_4O_{10}(O,OH,F)_2$ (Berman, 1937). The absence of fluorine and chlorine is noteworthy. Plotted on a

FIG. 3. Plot of the biotite from the cordierite-rock, Upington, on the basis of E. W. Heinrich's diagram (1946).

triangular diagram with apices $FeO+MnO$, $Fe_2O_3+TiO_2$, and MgO, according to the method employed by E. W. Heinrich (1946), this biotite falls outside all the fields, but is nearest to the fields for granites, quartz-monzonites, and granodiorites and for gneisses and schists (fig. 3). This result is to be expected considering the peculiar composition of the rock and the fact that biotites from pelitic rocks are not included. The relationship between the index of refraction (γ) and chemical composition (weight percentage $FeO+2(Fe_2O_3+TiO_2)$) shows very good agreement with E. W. Heinrich's curve, the value obtained from the graph being 1·650 and the measured value 1·649. The biotite

lies approximately on the boundary between the fields for biotites associated with muscovite, topaz, &c., and for biotites unaccompanied by other mafic minerals when plotted on the triangular diagram adopted by S. R. Nockolds (1947) with apices MgO, total Fe as FeO, and Al_2O_3. The reddish-brown colour is to be expected from a biotite with high FeO and TiO_2 and low MgO according to A. J. Hall (1941).

TABLE III. Chemical analysis of cordierite-rock, Upington.

Analyst, P. L. le Roux, Division of Chemical Services, Pretoria.

Analysis.			Norm.			Mode.		
SiO_2	...	52·39	Quartz	...	...	30·8	Quartz	...	...	12·4
TiO_2	...	0·25	Orthoclase ...	...	8·9	K-felspar	...	...	3·2
Al_2O_3	...	29·29	Albite	...	...	8·4	Oligoclase	...	...	5·8
Fe_2O_3	...	3·92	Anorthite	...	...	1·1	Cordierite	...	...	63·1
FeO	...	3·59	Corundum ...	...	25·6	Alteration products		
MnO	...	0·18	Hypersthene {En		13·4	of cordierite	...	4·9
MgO	...	5·37	Hypersthene {Fs ...		3·4	Sericite	...	...	4·2
CaO	...	0·38	Ilmenite	...	...	0·5	Biotite	...	...	1·6
Na_2O	...	1·03	Magnetite	...	...	5·6	Sillimanite ...	...	3·4
K_2O	...	1·47	Apatite	...	...	0·3	Andalusite ...	...	1·1
H_2O+	...	2·41	Water	...	...	2·6	Iron ore	...	...	0·2
H_2O-	...	0·21			———	Apatite	...	...	0·1
P_2O_5	...	0·19			100·6			———
	———							100·0
	100·68							

Composition calculated to ACF diagram of Eskola (Turner, 1948, p. 57), A 59·5, C 0·85, F 39·65.

The high corundum content of the norm is a reflection of the mica and aluminium silicates present in the mode. The rock is manifestly of sedimentary origin having all the characteristics of sedimentary parentage and it lies in the sedimentary field when plotted on a Or. Cor—Ab.—An. Femic triangular diagram (fig. 4). Compared with the average of 78 Palaeozoic shales (Clarke, 1924) it is high in alumina and magnesia and low in silica, lime, and potash. This difference in composition may be due to an initial peculiarity of the sediment, though this is considered unlikely. Alternatively, it may have been acquired later as the result of alumina and magnesia metasomatism.

The texture and mineral assemblage of this rock are both peculiar and difficulties are encountered in trying to classify it. In texture the rock is porphyroblastic but shows no gneissic banding, and the interstitial material is not hornfelsic but shows granulation of the quartz and other features consistent with the operation of stress at a late stage in the metamorphism (fig. 2).

The mineral assemblage fits into neither the pyroxene-hornfels nor the amphibole-hornfels facies of F. J. Turner (1948, pp. 70–76), sericite and potash-felspar being anomalous in the former case and the association potash-felspar–cordierite in the latter. The components suggested
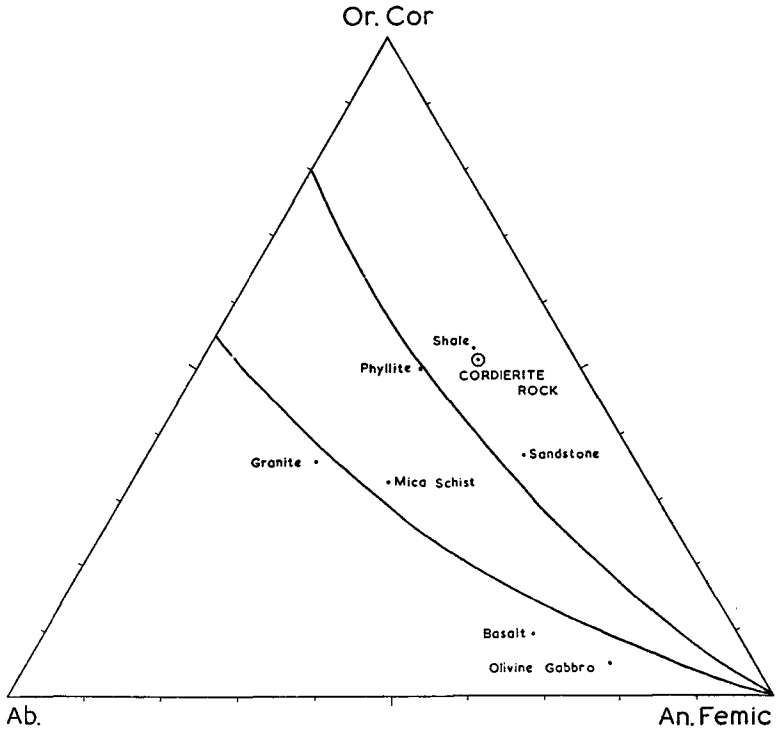

FIG. 4. The average normative composition (excluding quartz) of the commoner rock types. After A. Brammall (1933).

by the mineralogy and chemical composition of the constituents are: SiO_2; Al_2O_3; $(Mg,Fe,Mn)O$; $(Na_2,Ca)O.Al_2O_3$; $K_2O.Al_2O_3$; and H_2O. Applying the mineralogical phase rule one would expect an equilibrium assemblage of six phases, whereas in fact there are eight phases present. These anomalies all suggest disequilibrium. Judging by the microscope evidence, the unstable minerals in this association appear to be potash-felspar, andalusite, and possibly biotite, all of which are partially replaced by sericite, sillimanite, and quartz. If this is a correct interpretation, the rock formerly consisted essentially of a six-phase assemblage

corresponding to class 2 of Turner's pyroxene-hornfels facies, viz. andalusite-cordierite-plagioclase-quartz-orthoclase-biotite, with silli-manite metastable and partially replacing andalusite. As the tempera-ture dropped and stress became relatively more important, conditions were such as to favour the development of minerals belonging to the cordierite-anthophyllite subfacies of the amphibole facies. Andalusite (or sillimanite), potash-felspar, and water reacted to form sericite and quartz. This reaction, however, was not completed and the resulting assemblage contains minerals of both facies. It is possible that the sillimanite may not have been formed at an early high-temperature stage of the metamorphism and that it has resulted from late metaso-matic crystallization similar to that envisaged by J. Watson (1948) in the Kildonan migmatites of Sutherland. Metasomatism has certainly played a part in the reconstruction of the rock if only in producing the sporadic blue tourmalines, the apatite, and the water necessary for sericitization.

Comparison with similar rock types.

The cordierite-bearing Orijärvi rocks from Finland described by P. Eskola (1914, 1915) and the Arnage-type rocks from Aberdeenshire described by H. H. Read (1923) present the closest analogies to the Upington cordierite-rock.

Many types of cordierite-bearing rocks occur in the Orijärvi region. Those that appear most closely comparable to the Upington rock are the andalusite-bearing quartz-mica-rock and the cordierite-gneiss, but in both cases there are significant differences. These Orijärvi rocks are equilibrium assemblages considered to have been developed under con-ditions of moderate temperature and pressure, with the former dominant and in the presence of excess water. Neither contains potash-felspar which is incompatible with cordierite in this region. The textures of the rocks are also quite different, particularly in the case of the andalusite-bearing quartz-mica-rock which is strongly brecciated and very variable in composition. The calculated chemical composition of the cordierite-gneiss shows higher SiO_2, CaO, and K_2O and lower Al_2O_3, MgO, Na_2O, and H_2O, than the Upington rock. Both these Orijärvi rocks are con-sidered by Eskola to be of metasomatic origin.

The rocks of the Arnage type described by Read differ from the Upington rock in containing abundant 'xenoliths', sporadic garnet, green spinel, small amounts of pyroxene, and in the absence of andalus-ite. Read gives two analyses both of which show higher FeO and CaO

and lower Al_2O_3, Fe_2O_3, and MgO. Read now considers the Arnage type to be the result of an earlier, pre-gabbroic, migmatization.

Summary.—The Upington cordierite-rock is thought to be the result of the metasomatism of an original pelitic sediment whereby it gained alumina and magnesia and was converted into a rock containing porphyroblastic cordierite together with potash-felspar, oligoclase, biotite, andalusite, and quartz. This stage corresponds to the pyroxene-hornfels facies of Turner. At the height of the metamorphism it is possible that some of the andalusite was converted into sillimanite. With falling temperature, increased stress, and in the presence of excess water the above assemblage was unstable and retrogressive metamorphism took place. Equilibrium under the changed conditions was not attained, though there was a partial replacement of potash-felspar and andalusite by sericite and quartz and pinitization of the cordierite. The groundmass minerals took the stress while the large cordierites remained relatively unstrained. The tourmaline and apatite probably belong to this late metasomatic phase.

References.

BERMAN (H.), 1937. Constitution and classification of the natural silicates. Amer. Min., vol. 22, pp. 342–408.

BRAMMALL (A.), 1933. Syntexis and differentiation. Geol. Mag., vol. 70, pp. 97–107.
—— and RAO (B. R.), 1936. The variable composition of cordierite in the Dartmoor granites. Min. Mag., vol. 24, pp. 257–259.

CLARKE (F. W.), 1924. The data of geochemistry. Bull. U.S. Geol. Surv., no. 770. [M.A. 3–64.]

ESKOLA (P.), 1914. On the petrology of the Orijärvi region in south-western Finland. Bull. Comm. Géol. Finlande, no. 40.
—— 1915. On the relations between chemical and mineralogical composition in the metamorphic rocks of the Orijärvi region. Ibid., no. 44.

FOLINSBEE (R. E.), 1941. Optic properties of cordierite in relation to alkalies in the cordierite-beryl structure. Amer. Min., vol. 26, pp. 485–500. [M.A. 8–227.]

HALL (A. J.), 1941. The relation between colour and chemical composition in the biotites. Amer. Min., vol. 26, pp. 29–33. [M.A. 8–161.]

HEINRICH (E. W.), 1946. Studies in the mica group; the biotite-phlogopite series. Amer. Journ. Sci., vol. 244, pp. 836–848. [M.A. 10–73.]

NOCKOLDS (S. R.), 1947. The relation between chemical composition and para-genesis in the biotite micas of igneous rocks. Amer. Journ. Sci., vol. 245, pp. 401–420. [M.A. 10–271.]

READ (H. H.), 1923. The petrology of the Arnage district in Aberdeenshire: a study of assimilation. Quart. Journ. Geol. Soc. London, vol. 79, pp. 446–486. [M.A. 2–537.]

ROGERS (A. W.), 1910. The Kheis series. Trans. Geol. Soc. South Africa, vol. 13, pp. 93–104.

—— and DU TOIT (A. L.), 1910. Report on the geology of parts of Kenhardt, Prieska, Victoria West and Carnarvon. Ann. Rep. Cape Geol. Comm. for 1909, pp. 9–108.

TURNER (F. J.), 1948. Mineralogical and structural evolution of the metamorphic rocks. Mem. Geol. Soc. Amer., no. 30. [M.A. 10–432.]

WATSON (J.), 1948. Late sillimanite in the migmatites of Kildonan, Sutherland. Geol. Mag., vol. 85, pp. 149–162.

WINCHELL (A. N.), 1937. Cordierite. Amer. Min., vol. 22, pp. 1175–1179. [M.A. 7–208.]