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Retrogression of cordierite to kyanite and andalusite at Fishtail Lake, Ontario, Canada

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SUMMARY. Cordierite commonly alters to chlorite–sericite, called pinite. Besides pinite alteration, cordierite from the Fishtail Lake shows textural evidence indicating retrogression to kyanite, andalusite, and coarse flakes of chlorite. This is consistent with the experimental data on the stability of cordierite and may be expected to be limited to potash-deficient rocks, such as the cordierite–garnet–gedrite bearing gneisses of the area. In common potash-bearing pelitic rocks, retrogression of cordierite results in the formation of sericite and chlorite. In gneisses containing sillimanite and cordierite, the breakdown of cordierite in this way results in the association of the three aluminosilicates (kyanite, andalusite, and sillimanite) in the same rock. The association of kyanite–andalusite in equilibrium probably suggests that the retrogression of cordierite took place close to the univariant line of kyanite–andalusite.

THE Fishtail Lake is located in the Grenville province of Ontario, Canada. The cordierite-bearing rocks with or without garnet and gedrite are associated with granitic gneisses, amphibolites, garnet-bearing gneisses devoid of cordierite, metamorphic pyroxenite, etc. The rocks of the area are probably metamorphosed in the sillimanite–orthoclase zone of the amphibolite facies of Turner (1968).

Cordierite is a common mineral in the rocks of the area and is easily distinguished from other minerals, e.g. quartz and plagioclase, by the presence of yellow pleochroic halos around zircon and alteration along the crystal boundaries. Mainly two types of alteration of cordierite have been reported: The most common type of alteration is to sericite–chlorite (pinite). Schreyer and Yoder (1961) have stated that these are 14 Å chlorite and 2 M_1 muscovite. Cordierite also alters to a greenish isotropic mineral, which according to Schreyer and Yoder (1961) is an extremely dense intergrowth of 1 M muscovite and 7 Å aluminous serpentine or septechlorite.

The author has studied in detail the various types of alteration products of cordierite from cordierite–gedrite- and cordierite–garnet–sillimanite-bearing rocks of the Fishtail Lake. Besides the common alteration products mentioned above, textural evidence showing alteration of cordierite to kyanite, andalusite, and coarse flakes of chlorite has been noted.

Kyanite, andalusite, and sillimanite occur in apparent equilibrium in the schists of Boehls Butte quadrangle, Idaho (Hietanen, 1956). The association of the three aluminosilicates in the Fishtail Lake reveals in its texture a different paragenesis from that described by Hietanen.

The purpose of the paper is to report this uncommon alteration of cordierite to aluminosilicates and the association of kyanite–sillimanite–andalusite in the same rock and to discuss their significance on the basis of experimental data. A detailed account of the mineralogy, petrography, and petrogenesis of cordierite-bearing rocks of the area is presented in a separate paper (Lal and Moorhouse, 1969).

Mineralogy. The cordierites are optically positive with 2V ranging from 77 to 90°. Twinning is very common. Several twinned grains were studied on the Universal stage following the method suggested by Venkatesh (1954). Only parallel repetition and interpenetration twins occur. Twinning on (110) is very common, while in a few sections twinning parallel to (130) is also developed.

TABLE I. *Chemical analyses of cordierite from Fishtail Lake* (*W. H. Herdsman, anal.*)

	1-1	112	80		1-1		112		80	
SiO_2	49·62	51·50	48·00	*Number of ions on the basis of 18 oxygen*						
Al_2O_3	30·04	30·02	32·82	Si	5·266	6·000	5·431	6·000	4·874	6·000
FeO	3·62	4·21	2·87	Al	0·734		0·569		1·126	
Fe_2O_3	2·49	1·16	2·64	Al	3·024		3·164		2·802	
TiO_2	0·30	0·18	0·20	Fe^{3+}	0·199	3·246	0·092	3·270	0·201	3·018
MnO	0·08	0·06	0·10	Ti	0·023		0·014		0·015	
CaO	0·20	—	—	Mg	1·749		1·631		1·774	
MgO	11·06	10·38	11·72	Fe^{2+}	0·343	2·122	0·371	2·007	0·237	2·019
K_2O	0·48	—	0·24	Mn	0·007		0·005		0·008	
Na_2O	0·42	1·68	0·84	Ca	0·023		—		—	
H_2O^+	1·55	0·93	0·83	FeO/FeO+MgO	16·4		18·5		12·1	
Total	99·86	100·12	100·26	(in mol %)						

1-1, from cordierite–garnet–sillimanite–biotite schist.
112, from cordierite–garnet-biotite–gedrite rock
80, from cordierite–biotite–gedrite rock.

The distortion index[1] of three cordierites from three different rocks was obtained on the X-ray diffractometer using Cu-$K\alpha_1$ radiation and a goniometer speed of $\frac{1}{4}$° per minute. The index varies from 0·23 to 0·25, which corresponds to the low cordierite of Schreyer and Schairer (1961).

Table I shows the chemical analyses of the cordierites from Fishtail Lake.

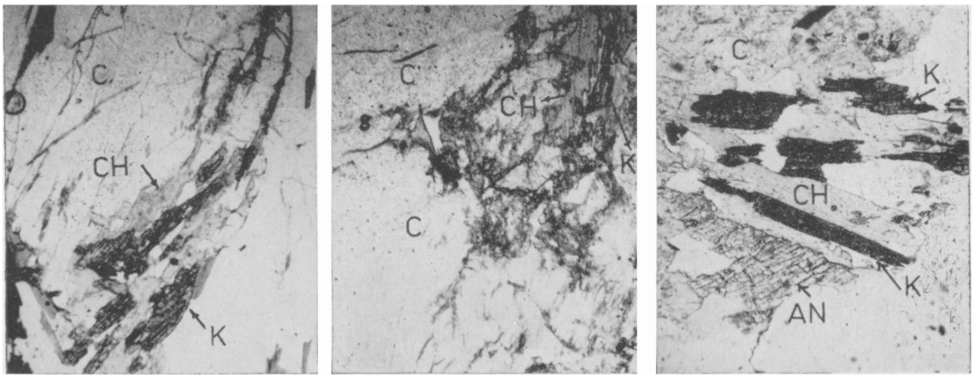
Textural relations. The various assemblages of the cordierite-bearing rocks of the area are: Garnet–cordierite–biotite–sillimanite–quartz; garnet–cordierite–biotite–quartz; cordierite–biotite–quartz; cordierite–sillimanite–biotite–quartz; garnet–cordierite–biotite–gedrite–quartz; and cordierite–biotite–gedrite–quartz.

The cordierite in the assemblages mentioned above is associated with quartz and is characteristically in oval masses with their longer direction elongated parallel to the foliation direction. From these oval masses of cordierite, long narrow protuberances extend along the grain borders of quartz. The small oval masses of cordierite usually consist of one individual grain, while the larger oval masses are coarse aggregates containing a little biotite and sillimanite or gedrite along the grain boundaries or as inclusions. Cordierite also forms a distinct, commonly discontinuous sheath or rim around garnet porphyroblasts. In the gedrite-bearing assemblages, cordierite is

[1] Miyashiro (1957) defines a distortion index (Δ) of cordierite as: $\Delta = (2\theta_{131} - 2\theta_{511} + 2\theta_{421})/2$, where θ is the Bragg angle in degrees for the Cu-$K\alpha_1$ radiation.

poikiloblastic in the dark bands and contains numerous inclusions of quartz, some of which show 'myrmekite'-like intergrowth. In the same band smaller cordierite grains are free of quartz inclusions.

The cordierite commonly shows pinitization to chlorite–sericite (2 M_1 muscovite and 14 Å chlorite) along the crystal boundaries. Greenish isotropic alteration of cordierite (1 M muscovite and 7 Å septechlorite) has also been observed. In those cordierite grains that are less altered, chlorite and sericite are the common alteration products.



FIGS. 1–3 (All in ordinary light, ×40). Fig. 1 (left). Coarse crystals of kyanite (K) and chlorite (CH) associated with altered cordierite (C) in garnet–cordierite–biotite schist. Andalusite is also present in altered cordierite in another portion of the thin section. Fig. 2 (middle). Crystals of kyanite (K) and chlorite (CH) associated with altered cordierite (C) in cordierite–biotite–gedrite schist. Note pinitization of cordierite along cracks and crystal outlines also. Fig. 3 (right). Kyanite (K), andalusite (AN) and chlorite (CH) associated with completely altered cordierite (C) in cordierite–quartz rock.

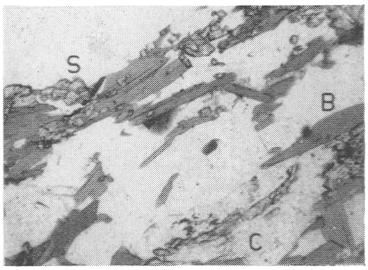
Besides this, in several thin sections kyanite and andalusite occur as inclusions and along the borders of much altered cordierite, where they are always associated with coarse flakes of chlorite (14 Å) and grains of quartz (figs. 1, 2, 3). The size of the chlorite flakes is roughly proportional to the size of the blades of kyanite and prisms of andalusite. Sillimanite, although a common mineral of the cordierite-bearing schists, is never seen associated with kyanite and andalusite in the altered cordierite. The kyanite and andalusite occur within altered cordierite either in the same or in different grains and they do not show any textural evidence indicating formation of one from the other. Even in the same grain they are not in close contact with each other, being usually separated by coarse flakes of chlorite and grains of quartz. The kyanite and andalusite crystals cut across the foliation direction indicating their later formation. In several thin sections dumortierite has been found in close association with kyanite and andalusite. Kyanite and andalusite *never* occur in the cordierite-free schists and gneisses of the area.[1]

In two thin sections of the cordierite-bearing rocks of the Fishtail Lake, all the three aluminosilicates occur in association. In these rocks, the kyanite and andalusite

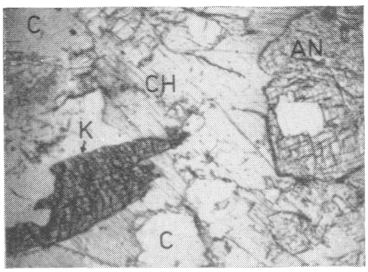
[1] Sillimanite, on the other hand, occurs in the cordierite-free schists and gneisses.

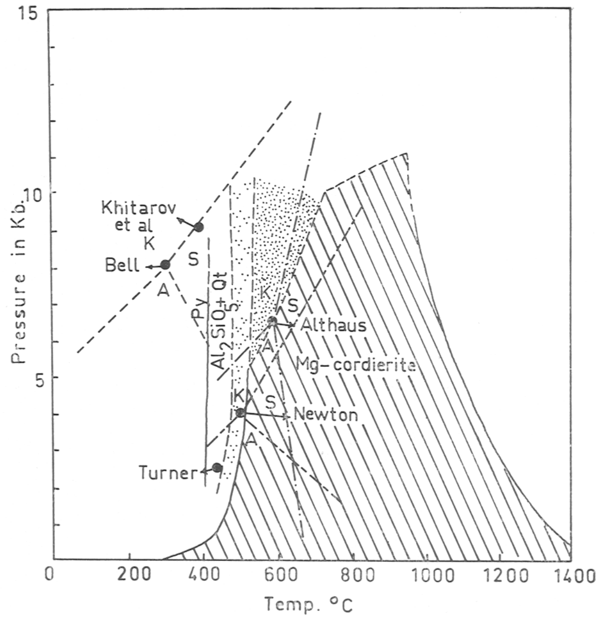
may occur in the same or in different grains of much altered cordierite and their textural relation is similar to the one described above (fig. 4*b*); whereas sillimanite, which coexists with cordierite, is closely associated with biotite and is elongated parallel to the foliation of the rock, they are seen wrapping around the porphyroblasts of garnet, cordierite, and lenticles of quartz. Sillimanite needles occur parallel to the

(*a*)



(*b*)





FIGS. 4 and 5. Fig. 4 (left). Association of kyanite, andalusite, and sillimanite in cordierite–biotite schist. (Ordinary light, ×40.) *a* (top): A part of the thin section showing sillimanite (S) associated with biotite (B); C, cordierite. *b* (bottom): Another part of the same thin section showing kyanite (K), andalusite (AN), and chlorite (CH) associated with altered cordierite (C). Fig. 5 (right). Stability field of Mg-cordierite (assuming P_{H_2O} = total pressure) and its breakdown products at lower temperatures (after Schreyer and Yoder, 1964, 1968). Triple points (solid circles) of kyanite–andalusite–sillimanite (after Bell, 1963; Khitarov *et al.*, 1963; Newton, 1966*b*; Althaus, 1967; and Turner, 1968) and the pyrophyllite ⇌ aluminosilicate+quartz reaction curve (after Kerrick, 1968) are also shown. (K, kyanite; A, andalusite; S, sillimanite; Py, pyrophyllite; Qt, quartz; ruled, stability field of Mg-cordierite; stippled, field of breakdown of Mg-cordierite to chlorite+aluminosilicates+quartz; three dots, field of breakdown of cordierite to pyrophyllite+chlorite). If the univariant curve of the reaction pyrophyllite ⇌ aluminosilicate+quartz represented in this figure is correct, the field of chlorite+aluminosilicates+quartz, which form by the breakdown of cordierite, would shift towards lower temperature up to the pyrophyllite breakdown curve.

cleavage of biotite with which they are intimately intergrown (fig. 4*a*). In some layers, a group of sillimanite needles occurs along the grain boundaries of quartz and cordierite without any association with biotite. As mentioned above, there is no textural evidence of replacement of one aluminosilicate by another.

Discussion. The textural evidence described above undoubtedly suggests a disequilibrium relation and demonstrates that the kyanite and andalusite were formed by retrogression of cordierite in the Fishtail Lake area. The experimental work of

Schreyer and Yoder (1964 and 1968) on Mg-cordierite shows that at water pressures between 5–10 kb and temperature of 500–700 °C (which probably lies within the field of metamorphism in the amphibolite facies of Turner, 1968), cordierite breaks down to chlorite, quartz, and aluminosilicates by the reaction (fig. 5) Cordierite+Vapour ⇌ Chlorite+Aluminosilicates+Quartz.

Schreyer and Yoder (1961) have suggested that in pelitic rocks of normal potash content, muscovite or sericite takes the place of aluminosilicates. The K_2O involved in the reaction may be derived from penetrating solutions, or it is possible that it originates from the concomitant breakdown of biotite. According to them Cordierite+Biotite+H_2O ⇌ Muscovite+Chlorite+Quartz.

During a detailed petrological and geochemical study of the cordierite-bearing rocks of the Fishtail Lake (Lal, 1966; Lal and Moorhouse, 1969) it was found that these rocks are deficient in potash (also in lime and soda). Thus it is suggested here that when they are subjected to retrogression at lower temperatures, below the normal stability limit of cordierite, pinitization takes place until all the potash available is consumed, and is then followed by the breakdown to aluminosilicates and chlorite.

The same alteration of cordierite in sillimanite–cordierite-bearing gneisses results in the appearance of all the three aluminosilicates kyanite, andalusite, and sillimanite in a single thin section. This again is a non-equilibrium assemblage in which the sillimanite is a relict from the original metamorphic crystallization of the rock, and the kyanite and andalusite are decomposition products of cordierite formed during a retrogressive episode at lower temperature and perhaps lower pressure.

The association of kyanite and andalusite suggests that *PT* conditions during the time of retrogression were probably near the univariant line of kyanite and andalusite (fig. 5). There has been considerable debate regarding the position of the triple point (Bell, 1963; Khitarov *et al.*, 1963; Weill, 1963; Weill and Fyfe, 1961; Newton, 1966*a* and 1966*b*; Fyfe and Turner, 1966; Althaus, 1967; Turner, 1968; etc.). The results of Bell and of Khitarov *et al.* conflict markedly with the recent experimental determinations by Fyfe and Turner, Newton, and Althaus (fig. 5) and have been much criticized by Fyfe and Turner, Winkler (1965, 1967), Turner (1967) and others. The retrogression of cordierite to kyanite, andalusite, and chlorite at the Fishtail Lake is also not in agreement with the triple points of Bell and Khitarov *et al.* The acceptance of their triple points requires the assumption of a long period of cooling between the crystallization of cordierite-bearing rocks and retrogressive changes, assuming P_{H_2O} = total pressure. Further it is difficult to explain the complete absence of sillimanite in retrogression products of cordierite. Assuming that P_{H_2O} = total pressure, the textural relation is better explained if the triple points of Newton, Fyfe and Turner, Althaus, or Turner are considered. The kyanite–andalusite univariant line of these authors lies close to the field of chlorite+aluminosilicates, which form by the breakdown of cordierite at lower temperatures[1] (fig. 5). On the other hand, the sillimanite field

[1] If the univariant curve of the reaction Pyrophyllite ⇌ Aluminosilicate+Quartz+H_2O (Kerrick, 1968) represented in fig. 5 is correct, the chlorite+aluminosilicates+quartz field would shift towards lower temperatures up to the univariant curve mentioned above.

overlaps the entire field of cordierite at higher temperatures, which is in agreement with the common association of coexisting sillimanite and cordierite and the absence of textural evidence showing retrogression of cordierite to sillimanite in the Fishtail Lake area.

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