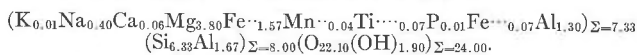


KYANITE-GARNET GEDRITITE NEAR OROFINO, IDAHO*

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ABSTRACT

In Clearwater County, Idaho, kyanite is found with amphibole in two rock types, (1) in kyanite-garnet gedritite near Orofino and (2) in hornblende-bearing layers of anorthosite in the Boehls Butte quadrangle. The associated rocks near Orofino are garnetiferous biotite gneisses, hornblende-biotite gneiss, garnet amphibolites, quartzites, and lime-silicate rocks of sedimentary origin. The major constituents in the kyanite-garnet gedritite are gedrite (38 per cent), quartz (26 per cent), oligoclase (16 per cent), and garnet (14 per cent). One to two per cent of kyanite in light bluish crystals is scattered throughout the rock. The formula of the gedrite calculated from the chemical analysis is



The garnet consists of about 49 per cent almandite and 43 per cent pyrope with some spessartite, grossularite, and andradite. The texture suggests that gedrite and garnet crystallized later than the other minerals. The chemical analysis of the gedritite shows more than 15 per cent Al_2O_3 , about 8.5 per cent each of FeO and MgO, but only 0.2 per cent K_2O and 1.7 per cent CaO.

The hornblende- and kyanite-bearing layers of the anorthosite are described briefly for comparison. The kyanite in these layers is a relict mineral, inherited from the schist that formerly occupied the area now covered by anorthosite. The occurrence of the kyanite in the anorthosite is most likely due to the slowness of reaction between the minerals of the parent rock, the schist, and the metasomatizing solutions that transformed the schist to anorthosite. For the occurrence of kyanite in the gedritite near Orofino a similar explanation is possible, but not conclusive because there are no signs of a possible disequilibrium between the fresh kyanite crystals and the enclosing gedrite. The Mg:Fe ratio of the gedrite falls within the Mg:Fe ratio possible in the cordierites, and the bulk composition of the kyanite-garnet gedritite is very close to that of cordierite gneisses and cordierite-anthophyllite rocks. Temperature and pressure during the recrystallization were close to the triple point of kyanite, andalusite, and sillimanite suggesting a somewhat lower temperature for the kyanite-gedrite assemblage than for the cordierite rocks which contain only sillimanite. The crystallization of kyanite and gedrite instead of cordierite in this rock is probably due to a stress during the recrystallization.

INTRODUCTION

Kyanite rarely occurs with amphibole in normal regionally metamorphosed rocks, as this pair of minerals is usually incompatible. As a rule, minerals like cordierite, garnet, and staurolite crystallize in the aluminous rocks rich in iron and magnesium. On some rare occasions, however, kyanite is found with amphiboles in metamorphosed sedimentary rocks as well as in metamorphosed igneous rocks. Among the sedimentary formations those occurring in the Alpine region (Garbenschiefer of the Tremola series and Quartenschiefer of the Lukmanier region) are best known (Hexner, 1908; Niggli, 1929). Kyanite with hornblende from an igneous environment was reported by Clough (1910, p.

* Publication authorized by the Director, U. S. Geological Survey.

35) from Lewisian gneiss in Scotland. Later, Tilley (1937) made a detailed study of these same kyanite amphibolites which are associated with eclogites and are undoubtedly of igneous origin. In some of these rocks the association of kyanite with amphiboles is probably due to the slowness of reactions during the conversion of kyanite-bearing eclogites to amphibolites. Tilley found that the content of Al_2O_3 in kyanite-garnet amphibolite in Glenelg is higher than that in its parent eclogite and concluded that migration and segregation of material takes place during the conversion.

The hornblende in the kyanite amphibolites mentioned above is a common green calcium-bearing aluminous variety. The occurrence of kyanite with an orthorhombic amphibole, aluminous anthophyllite (gedrite), has been described by Tilley (1939) from Shueretsky district in Karelia. According to Ignatiev (1934) the associated rocks there are Precambrian schist, gneisses, amphibolites, gabbro-norites, granites, and pegmatites. The garnet-gedrite-biotite rocks (gedritites) are found as narrow bands in the amphibolites in the central parts of synclines and are considered to be products of transformation after amphibolite.

A common green hornblende occurs with kyanite in some layers in anorthosite in the Boehls Butte quadrangle, Idaho. This occurrence is described in another paper¹ and only the result of the study is briefly discussed here. The kyanite is an abundant constituent in the schist around the anorthosite bodies and remnants of this schist are common in the anorthosite. The layers that are rich in hornblende and kyanite are thought to represent metasomatized remnants of this schist. The kyanite is an earlier mineral inherited from the schist, and the constituents of the amphibole were introduced during the formation of the anorthosite as were also the constituents of the plagioclase.

The kyanite-bearing garnet gedrite described in this paper was found in 1952 in the western part of Clearwater County, Idaho, in the canyon of Orofino Creek, four miles east of the town of Orofino (Fig. 1). The associated rocks there belong to a metamorphosed sedimentary series probably of Precambrian age. Quartz dioritic and tonalitic rocks of igneous and metasomatic origin occur as small masses in the metasedimentary rocks. A detailed study was made of the gedrite-bearing rocks and their minerals in the hope of throwing new light on the rare paragenesis of kyanite and amphibole.

FIELD RELATIONS

The kyanite-garnet gedrite is exposed in a southward-facing railroad cut, four miles east of the town of Orofino. The country rocks are gneisses,

¹ Manuscript titled "Anorthosite and associated rocks in Boehls Butte quadrangle and vicinity, Idaho."

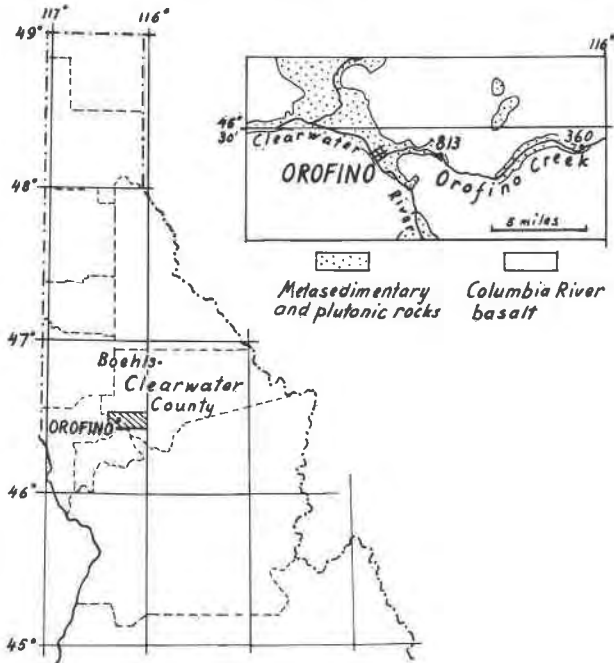


FIG. 1. Location of the kyanite-garnet gedritite. The sketch on right shows the shaded square on the map of northern Idaho (on the left). In this sketch the locations of kyanite-garnet gedritite and garnet amphibolite are indicated by numbers 813 and 360 respectively.

schists, and amphibolites, all belonging to the metasedimentary rock series that was called the Orofino series by Anderson (1930). Stratigraphy, structure, and petrology of this series has been described by the present author in another paper² and therefore only the layers immediately associated with gedrite-bearing rocks are described in this report. The detailed field relations are shown schematically in Fig. 2. Gedrite is found in several layers, the thickness of which ranges from 10 cm. to 15 m., in garnetiferous biotite and biotite-hornblende gneiss. In the thickest layer (813 in Fig. 2) small- to medium-size crystals of light-bluish to colorless kyanite were detected. Biotite-hornblende gneiss exposed under this thickest gedrite layer includes a few thin layers rich in gedrite (*a*, *b*, *c* just west of 812 in Fig. 2), but no kyanite was found in them. Another thick layer rich in gedrite and containing numerous large garnets, but only occasional tiny grains of kyanite, occurs lower in the series (810 in Fig. 2) under a layer of garnetiferous biotite and hornblende-biotite

² Manuscript titled "Metasomatic metamorphism along the northwest border zone of the Idaho batholith."

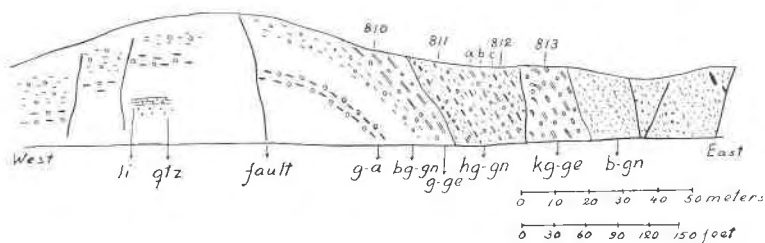


FIG. 2. Generalized geologic section in the railroad cut 4 miles east of Orofino where kyanite-garnet gedritite occurs. *kg-ge*=kyanite-garnet gedritite, *g-ge*=garnet gedritite, *b-gn*=thin-bedded biotite gneiss with lime-silicate bearing layers, *hg-gn*=hornblende-biotite-garnet gneiss, *g-a*=garnet amphibolite, *li*=limestone, *qtz*=quartzite, *bg-gn*=biotite-garnet-gneiss. Numbers 810 to 813 refer to layers from which specimens were taken.

gneiss. This layer is underlain by biotite-garnet gneiss, which in turn lies above garnet amphibolite. About 50 m. to the west the lowest part of this sequence is repeated because of folding and faulting. The strata form a gentle anticline broken by several faults. Several faults occur also on the eastern limb of the anticline east of the kyanite-garnet gedritite, where thin-bedded layers of biotite gneiss with lime-silicate-bearing layers alternate with quartzite, biotite-plagioclase gneiss, and biotite-garnet schist. Accumulations³ of ferromagnesian minerals, mainly hornblende, occur in the quartzitic layers.

PETROGRAPHIC DESCRIPTION OF THE KYANITE-GARNET GEDRITITE AND ASSOCIATED ROCKS

Kyanite-garnet gedritite

The kyanite-garnet gedritite (813 in Fig. 2) is dark green, speckled red by garnets, medium grained, and crudely foliated. The foliation is due to a parallel arrangement of long gedrite prisms and is partly obscured by the occurrence of numerous garnets of medium size and by small, irregularly shaped clusters of quartz and feldspar. Pale-blue kyanite crystals ranging from $\frac{1}{4}$ to 1 cm. in length can be seen with the naked eye. A study under the microscope revealed numerous small kyanite crystals, most of them included in large green gedrite prisms (Fig. 3 and Pl. 1). Also, a few tiny crystals of staurolite, numerous small grains of brown rutile, and a few flakes of green, strongly pleochroic biotite are included in the gedrite. Sillimanite was found in one specimen studied. Garnet crystals ranging from 2 to 10 mm. in diameter include many fairly large quartz grains, some rutile, ilmenite, and magnetite. The major light constituent is

³ See footnote 2.



FIG. 3. Camera lucida drawing of kyanite-garnet gedritite near Orofino showing kyanite included in gedrite. *ky*=kyanite, *ge*=gedrite, *q*=quartz, *ru*=rutile.

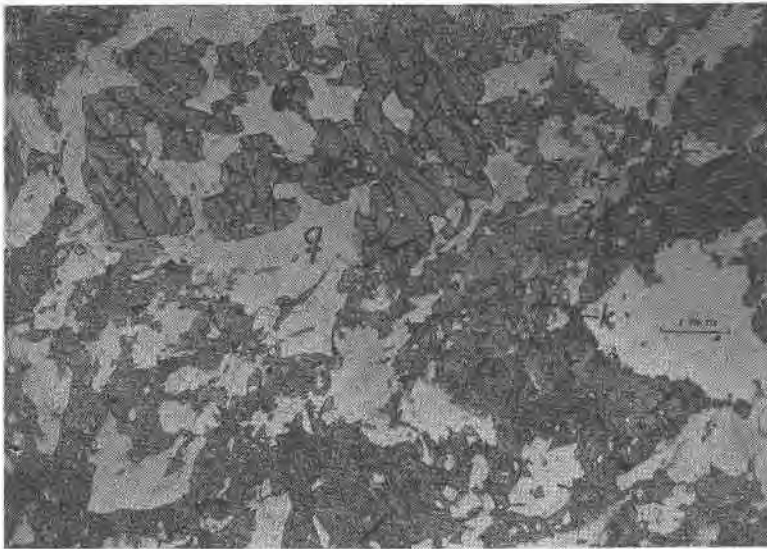


PLATE 1. Photomicrograph of kyanite-garnet-gedritite. *k*=kyanite; *g*=garnet; *a*=gedrite; *q*=quartz; small black grains are ilmenite and magnetite. Plane polarized light.

quartz, the anhedral grains of which range from 0.1 to 0.3 mm. in diameter. Plagioclase (An_{20}) occurs in anhedral grains with quartz. A few grains of magnetite, ilmenite, and apatite occur as accessories.

Garnet-gedritite

The layer of garnet gedritite (810 in Fig. 2), averaging 13 m. in thickness, is more strongly foliated than the kyanite-bearing gedritite. Weathering has changed its color to rusty brown. The garnets in this layer are much larger, ranging from 1 to 4 cm. in diameter, and show dodecahedral (110) and trapezohedral (211) faces. There is more plagioclase (An_{20}) and quartz than in the kyanite-garnet gedritite, both of these constituents showing a tendency to cluster into irregularly shaped discontinuous veinlets parallel to the foliation. The gedrite prisms are about 1 cm. long and clustered but still have their longest dimensions parallel to the lineation on the plane of foliation. Numerous small flakes of ilmenite occur between the other minerals. A few tiny grains of rutile and biotite are the additional constituents.

Hornblende-biotite-garnet gneiss

A dark-gray fairly homogeneous fine- to medium-grained rock (811 in Fig. 2) above the garnet gedritite consists of plagioclase (40 per cent), quartz (36 per cent), hornblende (19 per cent), and garnet (5 per cent) with some biotite and magnetite. Garnets in this layer are much smaller than in the gedrite-bearing layers, averaging only about 0.1 mm. in diameter. The biotite, which is found only in some layers, is a common brown variety with $\gamma = 1.617 \pm 0.002$. Hornblende is green and strongly pleochroic, as is the hornblende in garnet amphibolite. Most of the quartz and plagioclase are evenly distributed throughout the rock; only a few small clusters can be seen. Magnetite and apatite occur as accessories.

The upper part of this gneiss contains three gedrite-bearing layers (*a*, *b*, and *c* just west of 812 in Fig. 2), each ranging from 10 to 20 cm. in thickness. These three layers contain only a little biotite and garnet, but the amount of gedrite averages 30 per cent. Tourmaline, brown grains of rutile, apatite, and magnetite are the accessories.

Biotite-garnet gneiss

The gedrite-bearing layers grade over to a medium-grained gneiss in which biotite instead of gedrite occurs as a major dark constituent. This biotite-garnet gneiss (812 in Fig. 2) consists of quartz (39 per cent), plagioclase (An_{20} , 36 per cent), biotite (20 per cent), and garnet (4 per cent) with sillimanite and kyanite (together 1 per cent). Rutile and ilmenite-magnetite occur as accessories.

The texture is much like that of the nearby gedrite-bearing layers, a part of plagioclase and quartz occurring in clusters of large grains. Biotite is found in flakes of medium size with small grains of quartz and plagioclase. The diameter of large grains of quartz and plagioclase ranges from 1 to 2 mm. and that of small ones from 0.1 to 0.3 mm. Garnet crystals are 1 to 2 mm. in diameter.

Biotite in this rock is strongly pleochroic in dark and light brown with $\gamma = 1.617 \pm 0.001$. The flakes are subparallel to the foliation as is common in the gneissic rocks. A similar biotite-garnet gneiss occurs as layers in the hornblende-garnet gneiss and as a thicker layer under the garnet gedritite.

Thin-bedded biotite gneiss with lime-silicate-bearing layers

The rock east of the kyanite-garnet gedritite is medium gray, thin bedded, and fine grained. The thickness of layers ranges from $\frac{1}{2}$ to 3 cm., the thinner layers consisting of plagioclase (An_{37}), quartz, hornblende, diopside, zoisite, and garnet with some scapolite, sphene, and magnetite. Diopside is partly altered to hornblende, and scapolite to sericite. The thicker layers consist mainly of quartz, plagioclase, and biotite. Some quartzitic layers and medium-grained biotite-plagioclase gneiss layers, 5 to 20 cm. thick, are interbedded with this thin-bedded rock.

Garnet amphibolite

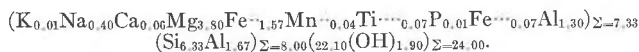
Garnet amphibolite is similar to the garnet amphibolite studied earlier from another locality along Orofino Creek. It consists essentially of the same minerals as the hornblende-garnet gneiss but in different quantities, the amount of hornblende being larger and that of quartz smaller. Sphene and apatite are common additional constituents. No kyanite was found in any thin-sections of garnet amphibolite in the area near Orofino.

MINERALOGY OF THE KYANITE-GARNET GEDRITITE

Gedrite

The major constituent of the gedritite is a dark green amphibole that under the microscope shows only a faint pleochroism in light greenish-gray and a parallel extinction under crossed nicols. The indices of refraction, measured in immersion liquids, are $\alpha(\text{pale}) = 1.649 \pm 0.001$; $\beta(\text{pale green}) = 1.656 \pm 0.001$, $\gamma(\text{pale green}) = 1.669 \pm 0.001$. The index of refraction of the liquid was measured by Abbé refractometer right after finding the correct value in order to avoid the influence of change of temperature. The specific gravity of 3.15 ± 0.02 was obtained from cleavage splinter by Berman balance. This mineral was separated from specimen no. 813 by R. P. Marquiss and analyzed chemically by Lucile N. Tarrant, both

of the U. S. Geological Survey. Microscopic study of a sample of the analyzed material showed some tiny inclusions of rutile and quartz, a few grains of garnet, and a small flake of biotite. The result of chemical analysis (Table 1) shows that this amphibole is an aluminous magnesium-iron silicate with very little calcium belonging to the anthophyllite-gedrite group. The calculation gives the following formula with total oxygen calculated to a base of 24:



Aluminum substitutes for a part of the Si and also for a part of the Mg in the structure. The atomic Mg:Fe ratio is about 2:1. This chemical composition and the optical properties are close to those of the gedrite described by Tilley (1939) from a similar kyanite-gedritite in eastern Karelia. A comparison with a great number of representatives of the anthophyllite series listed by Rabbitt (1948) shows that the gedrite near Orofino is indeed chemically and optically close to the gedrite of Karelia. According to Tilley the kyanite-garnet gedritite in Karelia occurs with garnet amphibolite and garnet-gedritite in a metamorphic series that includes coarse-grained garnet and kyanite gneisses. Thus the occurrence in Karelia and that near Orofino seem petrographically and mineralogically much alike except that no sillimanite has been reported from Karelia.

TABLE 1. CHEMICAL COMPOSITION OF AMPHIBOLE (No. 813a) IN
KYANITE-GARNET GEDRITITE (No. 813)

Lucile N. Tarrant, analyst, U. S. Geological Survey

Constituents	Weight per cent	Molecular equivalent	Number of atoms
SiO ₂	44.89	7474	Si 6.33
Al ₂ O ₃	17.91	1757	Al 1.67
Fe ₂ O ₃	0.67	42	Al 1.30
FeO	13.31	1853	Fe ⁺⁺⁺ 0.07
MnO	0.37	52	Fe ⁺⁺ 1.57
MgO	18.09	4487	Mn 0.04
CaO	0.40	71	Mg 3.80
Na ₂ O	1.45	234	Ti 0.07
K ₂ O	0.05	5	P 0.01
TiO ₂	0.67	84	Ca 0.06
P ₂ O ₅	0.04	3	Na 0.40
H ₂ O+	2.02	1121	K 0.01
H ₂ O-	0.00		H 1.90
			O 24.00
Total	99.87		

Garnet

Garnet in the kyanite-garnet gedritite near Orofino is pink in a fresh surface but turns brownish red during weathering. The grains are sub-hedral and contain large quartz inclusions which may exceed 50 per cent of the total volume of a garnet. The index of refraction is $n = 1.775 \pm 0.002$ and the specific gravity is 3.83 ± 0.02 . The chemical analysis (Table 2) shows that this garnet consists of about 49 per cent almandite and 43 per cent pyrope, the rest (8 per cent) is spessartite, grossularite, and andradite. The unit cell dimension as determined by F. A. Hildebrand, U. S. Geological Survey, is $a_0 = 11.526 \pm 0.006 \text{ \AA}$.

Kyanite

Kyanite occurs in small prisms the length of which ranges from 0.1 to 10 mm. Most crystals occur with quartz and feldspar but many are included in gedrite and a few in garnet. The kyanite crystals are light bluish or colorless, showing good cleavages parallel to the length of the prisms. The indices of refraction are $\alpha = 1.712 \pm 0.001$, $\beta = 1.723 \pm 0.001$, $\gamma = 1.728 \pm 0.001$; $-2V$ is large.

Staurolite

Some tiny grains of staurolite with pleochroism yellow to pale yellow are included in gedrite and in garnet.

TABLE 2. CHEMICAL COMPOSITION OF GARNET (No. 813g) IN KYANITE-GARNET GEDRITITE

Analyst, Lucile N. Tarrant, U. S. Geological Survey
Mineral separation by R. P. Marquiss, U. S. Geological Survey

Constituent	Weight per cent	Molecular equivalent	Composition
SiO ₂	39.60	6593	Pyrope 42.69
Al ₂ O ₃	22.45	2202	Almandite 49.13
Fe ₂ O ₃	.62	39	Spessartite 3.46
FeO	22.77	3156	Grossularite 2.90
MnO	1.58	223	Andradite 1.82
MgO	11.05	2741	
CaO	1.70	303	$a_0 = 11.526 \pm 0.006 \text{ \AA}$
Na ₂ O	0.00		
K ₂ O	0.00		$n = 1.775 \pm 0.002$
TiO ₂	0.28	35	
P ₂ O ₅	0.04	3	
H ₂ O+			
H ₂ O-			
Total	100.09		

Sillimanite

A few clusters of fairly large prisms of a colorless mineral (Fig. 4) were found in one thin section studied. The prisms show a parallel extinction and a diagonal cleavage in their nearly square cross sections. The optic plane is parallel to this cleavage and $+2V$ is small. These properties prove the prisms to be sillimanite.

Quartz

Quartz is the main light-colored constituent, its amount averaging 25 per cent. It occurs in elongated or rounded grains the size of which ranges from 0.1 to 15 mm. or as elongated clusters of grains between the gedrite prisms and as tiny round inclusions in garnet and in gedrite.

Plagioclase

The amount of plagioclase, $An_{20}(\gamma = 1.546 \pm 0.001)$, is less than that of quartz. This mineral occurs as anhedral grains with quartz. Most grains are twinned according to the albite law.

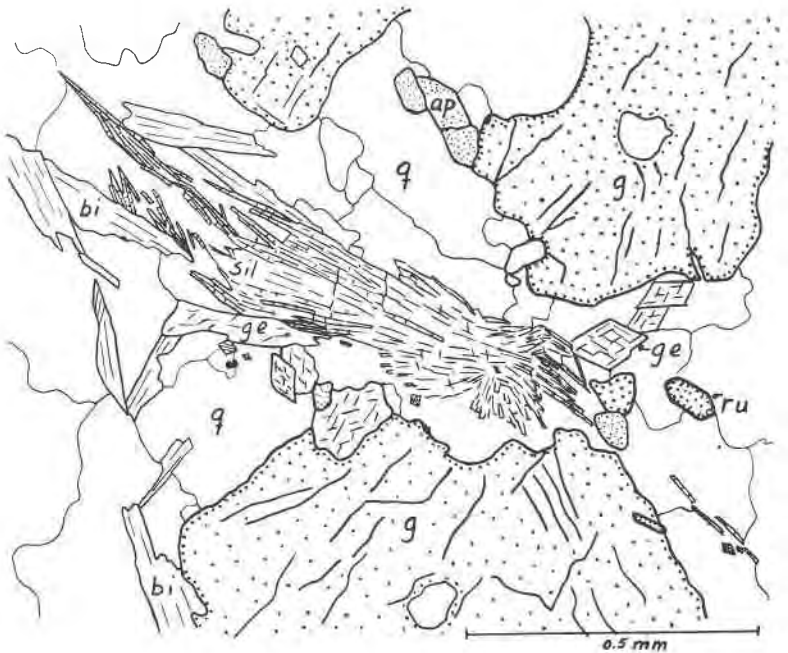


FIG. 4. Camera lucida drawing of sillimanite in kyanite-garnet gedritite near Orofino. *sil*=sillimanite, *ge*=gedrite, *g*=garnet, *q*=quartz, *bi*=biotite, *ru*=rutile, *ap*=apatite. Kyanite is found outside the field shown in the figure.

Accessories

Many small round or slightly elongated grains and small euhedral prisms of brown rutile are scattered throughout the thin sections, many being included in gedrite and in garnet. Magnetite, ilmenite, and apatite occur as tiny anhedral grains among the other minerals.

SEQUENCE OF CRYSTALLIZATION

Gedrite and garnet occur in large crystals and include the other minerals, suggesting that these two minerals crystallized late. The neighboring gneiss layers consist of quartz, plagioclase, biotite, garnet, and kyanite with some staurolite. In the gedritite, similar grains of quartz, plagioclase, kyanite, and staurolite occur, but instead of numerous small flakes of biotite, large crystals of gedrite developed and included the earlier minerals. Garnet crystals grew larger also including the other minerals.

CHEMICAL COMPOSITION

A chemical analysis made of the other half of the same hand specimen of the kyanite-garnet gedritite, from which gedrite and garnet were separated, is shown in Table 3. Compared with the neighboring meta-sedimentary layers this rock is rich in Al, Fe, and Mg and very poor in K. Comparison with the garnet amphibolite suggests much less Ca in the gedrite rocks. A normal garnet amphibolite in this area contains up to 10 per cent CaO^4 whereas in the kyanite-garnet gedritite the amount of CaO is less than 2 per cent, being contained in garnet and plagioclase. The scarcity of potash is, however, more striking. The chemical analysis shows only 0.2 per cent K_2O , most of which is included in biotite. The measured mode of the nearby biotite-garnet gneiss suggests that this rock contains about 1.8 per cent K_2O which is less than present in the normal mica schist. It is clear that in the presence of potash, biotite instead of gedrite would have crystallized.

More than 10 per cent corundum appears in the molecular norm, a portion of this being contained in garnet and in gedrite and the excess appearing mainly as kyanite. The total of iron and magnesium metasilicates in the norm is about 37 per cent, thus very large for a sediment. The chemical composition of the kyanite-garnet gedritite is close to that of cordierite gneiss (Hietanen 1943, Table 3) and cordierite-anthophyllite rock (Eskola 1914, Table 28).

The analyses of kyanite-garnet gedritite (No. 813), gedrite (No. 813*a*), and garnet (No. 813*g*) were plotted in ACF diagram (Fig. 5). An analysis

⁴ See footnote 2.

of gedrite (No. 1a) from kyanite-garnet gedritite, Karelia (Tilley 1939, Table 1) and that of a garnet-gedritite (No. 2) from Karelia (Ignatiev 1934, Table 8, No. 1) were added for comparison. A number of analyses of other kyanite and amphibole-bearing rocks, of cordierite gneisses, and cordierite-anthophyllite rocks and their minerals are also given in Fig. 5.

TABLE 3. CHEMICAL COMPOSITION OF KYANITE-GARNET GEDRITITE (No. 813)

Lucile N. Tarrant, analyst, U. S. Geological Survey

Weight per cent	Cation per cent	Molecular norm	Mode (calculated to correspond to the chemical analysis)			
						Weight per cent
SiO ₂	60.29	SiO ₂ 56.77	Q	23.71	quartz	26.47
Al ₂ O ₃	15.34	AlO _{3/2} 17.02	Or	1.20	plagioclase (An ₂₀)	16.45
Fe ₂ O ₃	0.34	FeO _{3/2} 0.24	Ab	18.45	gedrite	38.30
FeO	8.75	FeO 6.89	An	6.65	garnet	14.65
MnO	0.41	MnO 0.33	C	10.43	kyanite	1.27
MgO	8.65	MgO 12.13	En	24.26	biotite	1.04
CaO	1.73	CaO 1.74	Fs	12.96	ilmenite	0.21
Na ₂ O	2.02	NaO _{1/2} 3.69	Ap	0.35	rutile	0.47
K ₂ O	0.20	KO _{1/2} 0.24	Il	1.24	apatite	0.35
TiO ₂	0.88	TiO ₂ 0.62	Mt	0.36	calcite	0.34
P ₂ O ₅	0.16	PO _{5/2} 0.13	Cc	0.38		
CO ₂	0.15	CO ₂ 0.19				99.55
F	0.03	F (0.09)			left over	
H ₂ O+	0.83	H ₂ O+ (2.61)			+H ₂ O-	0.04
H ₂ O-	0.04	H ₂ O- (0.12)			+CaO	0.22
Total	99.82	99.99	99.99			99.81
Less O	.01					
		O 161.82				
	99.81	OH 5.22				
Anions per 100 cations		167.04				

The composition of hornblende from the kyanite-garnet amphibolites from Glenelg (No. 3*h*) is very similar to that of hornblende in the kyanite-bearing anorthosite in Idaho (No. 608*h*) even though more aluminum is present in the anorthosite (compare Nos. 608 and 3 in Fig. 5). The kyanite-garnet gedritite (No. 813) contains far less calcium than the kyanite amphibolites described in literature (Tilley, 1937), coming in this respect close to the cordierite gneiss (No. 5) and cordierite-anthophyllite rocks (Nos. 6 and 7). The kyanite-hornblende layer (No. 608) in the anorthosite is richer in aluminum and calcium than the gedritite No. 813.

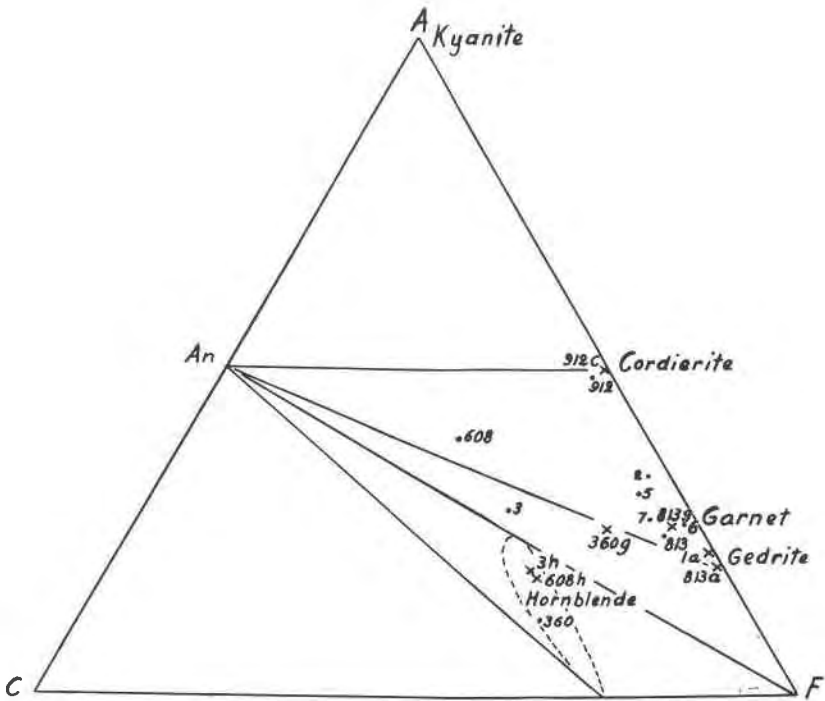


FIG. 5. ACF diagram showing the distribution of kyanite-garnet amphibolites, cordierite gneisses, and related rocks (.) and some of their minerals (x). Quartz and anorthite are stable with all assemblages given in parentheses for each rock listed below. The fields of stability for various assemblages are separated by lines connecting the plots for critical minerals.

- 813 = kyanite-garnet gedritite near Orofino, Idaho (kyanite-sillimanite-garnet-gedrite)
- 813a = gedrite in rock No. 813
- 813g = garnet in rock No. 813
- 608 = kyanite- and hornblende-bearing layer in anorthosite, Boehls Butte quadrangle, Idaho (kyanite-hornblende-bytownite-andesine)
- 608h = hornblende in rock No. 608
- 1a = gedrite from kyanite-garnet gedritite, Shuretsky, Karelia
- 2 = garnet gedritite, Karelia (kyanite-garnet-gedrite)
- 3 = kyanite-garnet amphibolite, Glenelg, Scotland (kyanite-garnet-hornblende) (Tilley 1937, p. 560)
- 3h = hornblende in rock No. 3
- 360 = garnet-amphibolite, Orofino Creek, Idaho (garnet-hornblende)
- 360g = garnet from rock No. 360
- 912 = cordierite gneiss, Boehls Butte quadrangle, Idaho (kyanite-andalusite-sillimanite-cordierite-biotite) (Hietanen 1956, Table 3)
- 912c = cordierite from rock No. 912
- 5 = cordierite gneiss, Kalanti, Finland (cordierite-biotite-sillimanite) (Hietanen 1943, Table 3, No 4)
- 6 = cordierite-anthophyllite rock, Perniö, Finland (cordierite-anthophyllite) (Eskola 1914, Table 28, p. 171)
- 7 = cordierite-anthophyllite gneiss, Orijärvi, Finland (cordierite-anthophyllite-biotite) (Eskola 1915, Table 19, No. 50, p. 65)

Thus the gedrite seems to crystallize in the rocks poor in calcium whereas a common hornblende will appear if more calcium than needed for the formation of garnet is present. In the ACF diagram the analysis point for the gedritite No. 813 falls close to the gedrite corner of the anorthite-cordierite-gedrite triangle, into the same area as do the points for cordierite gneiss (No. 5) and the cordierite-anthophyllite rocks (Nos. 6 and 7), suggesting a disequilibrium for the kyanite. The thin-section study, however, speaks against the disequilibrium and a question arises as to whether an iron-magnesium ratio would have some bearing on the matter.

As pointed out earlier the kyanite gedritite contains very little potassium and calcium; therefore, an A'MF diagram (Fig. 6) with Al_2O_3 , FeO, and MgO in the corners is particularly suitable for comparison of this mineral assemblage with that of some cordierite-bearing rocks also poor in CaO and K_2O . All cordierite-bearing rocks contain fairly little calcium but the amount of potassium varies. In the cordierite-anthophyllite rocks the amount of potassium oxide is negligible but the cordierite gneisses may carry 2 to 4 per cent of this oxide. Cordierite gneisses of the low temperature field of the amphibolite facies contain only biotite but in a somewhat higher temperature microcline also appears. In kyanite-hornblende rocks the amount of calcium is considerable as shown by the ACF diagram. However, the Fe:Mg ratio for all these rocks can be successfully studied in a modified A'MF diagram (Fig. 6) which was prepared using Eskola's (1915) method for corrections for feldspars and accessories. In Fig. 6, also the amount of CaO is subtracted from the total of $\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ because much of the calcium is contained in plagioclase. For the corrections it is necessary to know the weight percentages of accessories (magnetite, ilmenite, apatite, calcite, etc.) which percentages were not available for all related assemblages given in the literature. In order to include analyses of several other kyanite-amphibole rocks and cordierite gneisses, a method of plotting, based on the molecular norm, was used in Fig. 7. As in the calculation of norm all CO_2 is calculated as calcite, all P_2O_5 as apatite, all Fe_2O_3 as magnetite, and K_2O , Na_2O , and CaO are combined with Al_2O_3 to form feldspars. The actual calculation is done in the following way: A is the number of Al ions after subtraction of the number of Al ions that is equal to the total number of combined Ca, Na, and K. F is the combined number of Fe and Mn ions after the amount to form magnetite with total of Fe_2O_3 was subtracted. M is the number of Mg ions. The total of A, M, and F is calculated to 100.

As a result of using the number of Al instead of that of Al_2O_3 , all points in Fig. 7 are moved toward A corner in comparison with their positions in Fig. 6, but this change does not effect the mutual relations between the

plots nor between the fields of stability which are separated by lines connecting the plots for critical minerals, such as kyanite-gedrite-garnet or cordierite-anthophyllite-garnet.

For comparison also the analyses of hornblende occurring with kyanite and that of biotite associated with cordierite are plotted even though hornblende contains a considerable amount of CaO and biotite K_2O . The A co-ordinate for these plots is modified in the similar manner as that for

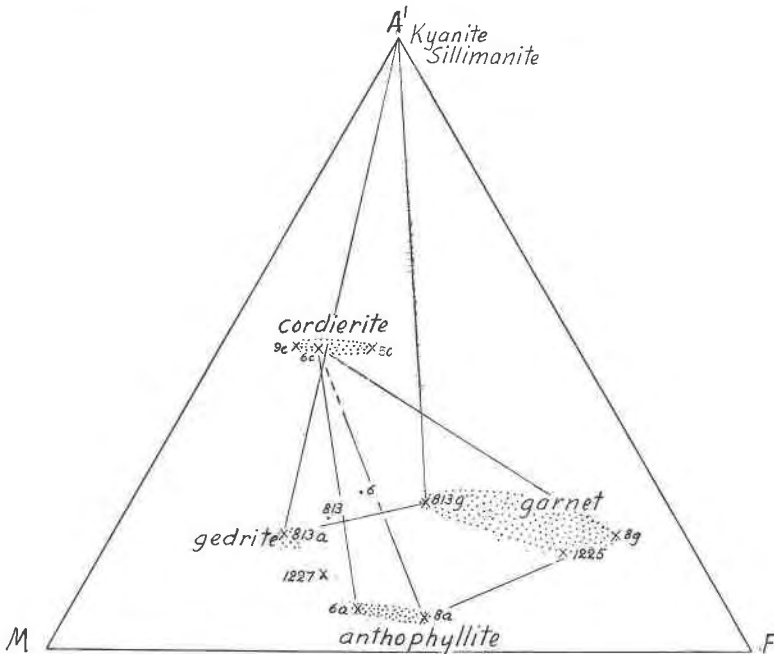


FIG. 6. $A'MF$ diagram showing the field of stability for assemblages kyanite-garnet-gedrite (triangle 813a-813g- A'), cordierite-anthophyllite (line 6a-6c), and cordierite-anthophyllite-garnet. $A' = A - CaO = Al_2O_3 + Fe_2O_3 - Na_2O - K_2O - CaO$, $F = FeO + MnO$, $M = MgO$. 5c, 6c, and 9c are cordierite. 813g, 8g, and 1225 are garnet and 813a, 1227, 6a, and 8a are minerals of the gedrite-anthophyllite series. 813 is kyanite-garnet gedritite and 6 cordierite-anthophyllite rocks. For complete reference see explanation under Fig. 7.

the other plots. As a result of this modification, the A co-ordinate is actually too small but the Fe:Mg ratio stays unchanged.

Analyses points for critical minerals—garnet, anthophyllite, gedrite, and cordierite—were plotted into the same diagram. Plots for analyses of two cordierite-biotite gneisses (Nos. 5 and 912), a cordierite-garnet-biotite gneiss (No. 10), two anthophyllite-cordierite rocks (Nos. 6 and 7), and a garnet amphibolite (No. 360) were added for comparison. The

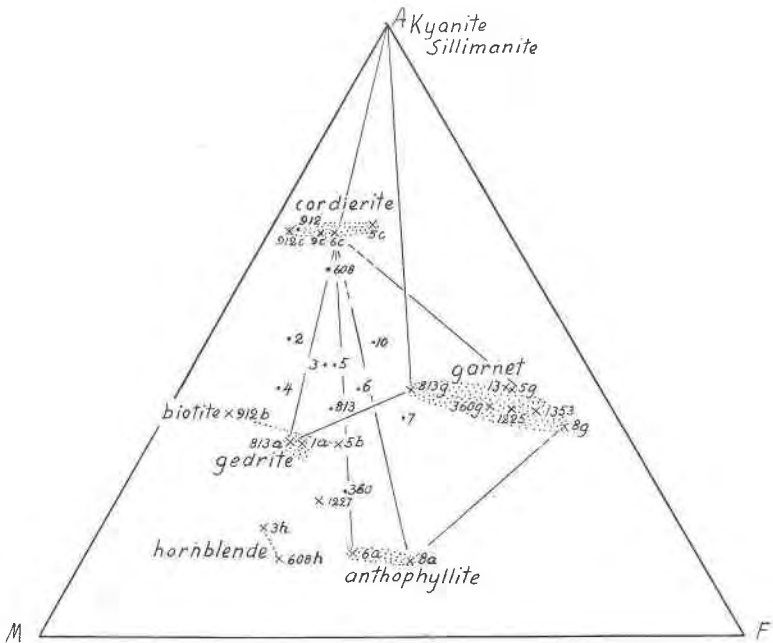


FIG. 7. AMF diagram showing the ratios of the modified numbers of Al, Fe, and Mg ions in kyanite-garnet amphibolites, garnet amphibolites, cordierite-bearing rocks (.), and in some of their minerals (x). A, M, and F refer to the number of ions calculated from chemical analyses as follows: $A = Al - (Ca + Na + K)$; $M = Mg$; $F = Fe + Mn - Fe_2$. Quartz and anorthite are stable with all assemblages given in parentheses for each rock listed below. The fields of stability for assemblages kyanite-garnet-gedrite, cordierite-anthophyllite, and cordierite-anthophyllite-garnet are shown. The fields of stability for any given assemblages can be easily constructed by connecting the plots for critical minerals.

813 = kyanite-garnet gedritite, Orofino, Idaho (kyanite-sillimanite-garnet-gedrite)

813a = gedrite from rock No. 813

813g = garnet from rock No. 813

608 = kyanite-hornblende rock from anorthosite, Boehls Butte quadrangle, Idaho (kyanite-hornblende-bytownite-andesine)

608h = hornblende from rock No. 608

1a = gedrite from kyanite-garnet gedritite, Karelia (Tilley 1939, Table 1)

2 = garnet-gedritite, Karelia (Ignatiev 1934, Table 8, No. 1) (kyanite-garnet-gedrite)

3 = kyanite-garnet amphibolite, Glenelg (Tilley 1937, Table 1, No. 3) (kyanite-garnet-hornblende)

3h = hornblende from rock No. 3

4 = kyanite-bearing hornblende-biotite schist (Niggli 1929, Table 1, No. 32, kyanite-hornblende-biotite)

360 = garnet amphibolite, Orofino, Idaho (garnet-hornblende)

360g = garnet from rock No. 360

(Continued on the next page)

distribution of the points for the rocks carrying either cordierite (912, 10, 5), or amphibole (608, 813), or both of these minerals (6, 7), shows that either amphibole or cordierite can crystallize from the compositions that have approximately the same Fe:Mg ratio. The position of the points for Nos. 2, 3, 4, 5, 6, 7, 10, 813, and 608 shows that the amount of aluminum varies considerably but stays within the same range for the cordierite-bearing rocks, the kyanite-amphibolites, and the gedritites.

It is apparent that the fields of stability for the assemblage kyanite-garnet-gedrite (triangle 813a-813g-A) overlaps that of cordierite-anthophyllite with or without garnet and sillimanite and that of garnet-cordierite with or without sillimanite and biotite. The bulk composition in the cordierite-kyanite-andalusite-biotite gneiss No. 912 is richer in magnesium (and in potassium), the triangle 912c-912b-A being completely outside the field of stability of the kyanite-garnet-gedrite. Thus these two rocks could coexist in equilibrium in the same PT-field provided that the other factors, such as content and chemical potential of water, were the same.

Hornblende contains a considerable amount of CaO and thus has ac-

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- 912 = cordierite gneiss, Boehls Butte quadrangle, Idaho (Hietanen 1956, Table 3) kyanite-andalusite-sillimanite-cordierite-biotite)
- 912c = cordierite from rock No. 912
- 912b = biotite from rock No. 912
- 5 = cordierite gneiss, Kalanti, Finland (Hietanen 1943, Table 3, No. 4) (cordierite-biotite-sillimanite)
- 5c = cordierite from cordierite gneiss, Rauma, Finland (Hietanen 1943, Table 1)
- 5g = garnet from cordierite gneiss, Kalanti, Finland (Hietanen 1943, Table 2)
- 5b = biotite from rock No. 5 (calculated)
- 6 = cordierite-anthophyllite rock, Perniö, Finland (Eskola 1914, Table 28, p. 171) (cordierite-anthophyllite)
- 6a = anthophyllite from rock No. 6 (Eskola 1914, Table 29, p. 172)
- 6c = cordierite from rock No. 6 (Eskola 1914, Table 29, p. 172)
- 7 = cordierite-anthophyllite gneiss, Orjärvi, Finland (Eskola 1915, Table 19, No. 50, p. 65) (cordierite-anthophyllite-biotite)
- 1227 = anthophyllite from garnet-anthophyllite biotite gneiss, Boehls Butte quadrangle, Idaho
- 1225 = garnet from garnet-anthophyllite biotite gneiss, Boehls Butte quadrangle, Idaho
- 1353 = garnet from anorthosite, Boehls Butte, quadrangle, Idaho
- 13 = almandine garnet from mica schist, Dent, Clearwater County, Idaho
- 8a = anthophyllite in garnetiferous anthophyllite-cordierite rock, Perniö, Finland (Eskola 1914, Table 30, p. 176)
- 8g = garnet in garnetiferous anthophyllite-cordierite rock, Perniö, Finland (Eskola 1914, p. 179)
- 9c = cordierite in cordierite-anthophyllite rock, Orjärvi, Finland (Eskola 1914, Table 31, p. 190)
- 10 = cordierite-garnet gneiss, Kalanti, Finland (Hietanen 1943, Table 3, No. 2, p. 16) (cordierite-garnet-biotite-microcline)

tually four major variables: Al, Fe, Mg, and Ca. If this mineral is plotted into a 4-component system (a tetrahedron with Al, Fe, Mg, and Ca in the corners, Fig. 8) it will lie at some distance beyond the AMF face and the stability field of the assemblage kyanite-hornblende-anorthite (such as No. 608) also would lie toward the Ca corner from the AMF face and would include the edge kyanite(A)-anorthite. However, the kyanite-garnet amphibolites (No. 3) contain garnet in addition to kyanite and hornblende and the stability field of such an assemblage would cover much of the same field as that of kyanite-garnet gedrites.

PARAGENESIS OF GEDRITE

Tilley (1939) has discussed the crystallization of gedrite and kyanite instead of cordierite and staurolite in metasedimentary formations. He remarks that, in the rocks rich in magnesium, staurolite cannot take the place of gedrite because of its ferrous character; and he raises the question as to whether the crystallization of kyanite and gedrite is linked to a magnesium-rich environment. Also in the garnet of the amphibolite facies the substitution of Mg for Fe is limited and therefore Mg-rich minerals such as cordierite and anthophyllite will crystallize. The A'MF and AMF diagrams (Fig. 6 and 7) in this paper shows that either cordierite or amphibole plus kyanite can crystallize in the rocks with the same Fe:Mg ratio. The study of the distribution of Fe, Mg, and Al in the critical minerals of all rocks concerned shows that the ratio Fe:Mg in the gedrites (Nos. 1*a* and 813*a*) falls within that in the cordierites but that the garnet takes more iron. The garnet (No. 813*g*) in the gedrite-bearing rock is richer in magnesium than the garnets common in cordierite gneisses (No. 5*g*, also compare Folinsbee, 1941). This makes the total percentage of magnesium in kyanite-garnet gedrite (No. 813) as high as is common in cordierite-garnet gneisses.

Why then does the gedrite instead of the cordierite crystallize in some rare occasions? Would a slight change in temperature or pressure or perhaps in the content of water cause the crystallization of amphibole and kyanite instead of cordierite? Or, could a shearing stress perhaps prevent the crystallization of cordierite and promote the crystallization of gedrite and kyanite? Shearing stress was suggested to be vital for the formation of kyanite in general by Tilley (1935) in his study of the rocks of the hornfels zone in Ross-shire, Scotland.

Pressure and temperature during the recrystallization

Let us first consider the pressure and temperature during the crystallization. The mineralogy of the gedrite-bearing rocks and that of the nearby layers suggests conditions of the amphibolite facies with a mod-

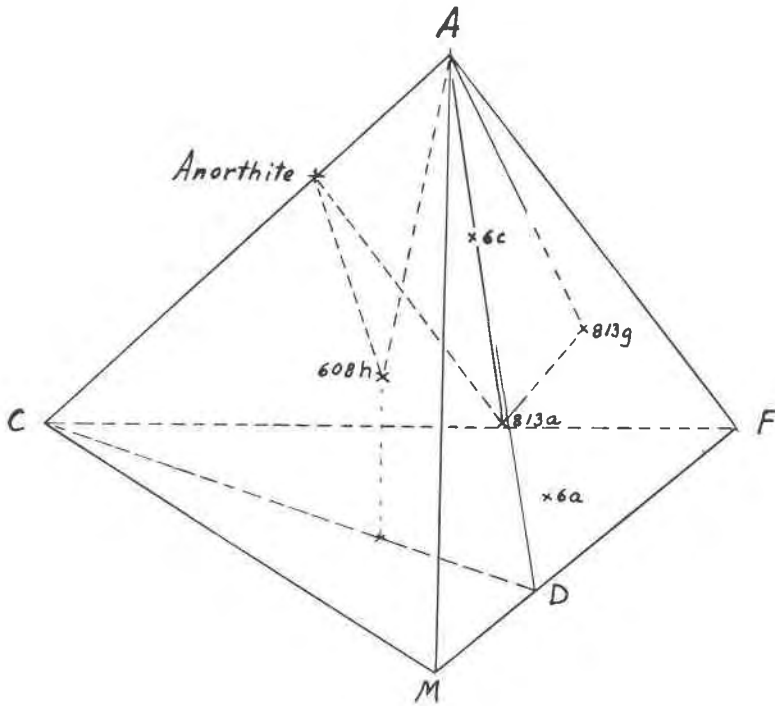


FIG. 8. 4-component system showing the relation between the stability fields of the assemblages of kyanite-garnet-gedrite-anorthite (subtetrahedron A-813g-813a-anorthite) and kyanite-hornblende-anorthite (triangle A608h-anorthite). The stability field of kyanite-garnet-hornblende-anorthite would be sub-tetrahedron A-813g-608h-anorthite. The point 608h lines on ACD plane inside the tetrahedron. The numbers refer to the same minerals as in Fig. 7.

erate temperature and high pressure. Sillimanite appears with kyanite but no andalusite was found in any of the specimens studied. Comparison with the study of the occurrence of kyanite, andalusite, and sillimanite together in the Boehls Butte quadrangle (Hietanen, 1956) suggests approximately the same temperature of crystallization for the rocks near Orofino and for those in the Boehls Butte quadrangle but the pressure was higher near Orofino. According to the suggested phase-diagram of Al_2SiO_5 (Fig. 9) andalusite would be stable only in low pressures; in higher pressures kyanite could occur with sillimanite without andalusite (Miyashiro, 1949). The occurrence of a few grains of staurolite and lack of potassium feldspar further restricts the temperature-pressure field between the PT-conditions of the crystallization of staurolite and potassium feldspar. Normally cordierite with biotite would be stable in this

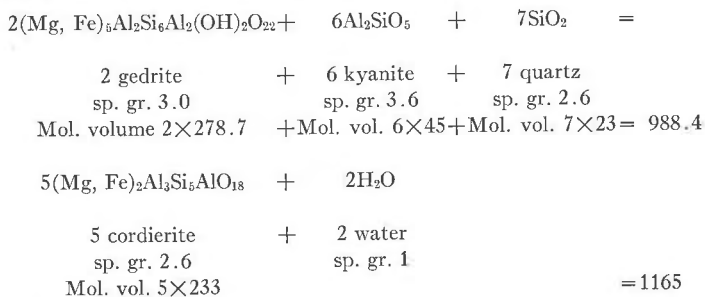
temperature-pressure field (cordierite-anthophyllite subfacies by Turner, 1948). In a higher temperature and pressure biotite would break down and yield cordierite and potassium feldspar, but not gedrite. In a lower temperature chlorite instead of cordierite is found in normal regionally metamorphosed rocks. It seems that the conditions under which the kyanite-garnet-gedrite assemblage crystallized were in some respect different from that of the conditions normally existing.

Comparison of the mineral assemblages of the rocks of the Orofino area with those of the cordierite gneisses of Finland (Hietanen 1943) suggests a somewhat lower temperature field for the Orofino area. Potassium feldspar is rare near Orofino and was not found with cordierite in the Boehls Butte quadrangle (Hietanen 1956). Near Orofino, sillimanite was found only in one thin section studied. The occurrence of some small crystals of staurolite, most of them included in the other minerals, suggests conditions of lower subfacies of the amphibolite facies during an earlier phase of crystallization. It is possible that near Orofino this lower temperature accompanied by a slight increase in pressure (or a stress) favored the crystallization of gedrite and kyanite instead of cordierite.

In some nearby layers epidote is found with plagioclase (An_{37-40}) suggesting, according to Barth (1952, p. 285), temperatures between 400° C. and 450° C. According to Schuiling's (1957) compilation of estimated temperatures and pressures, the triple point of the Al-silicates occurs at 540° C. in pressure of 3400 atmospheres. Both of these temperatures are in the range of that of the amphibolite facies.

Role of water

In addition to the higher pressure the content and chemical potential of water must be considered. The relation between the compositions and the specific gravities of the kyanite-gedrite assemblage and the cordierite can be shown with the following equation:



Cordierite is an anhydrous mineral and could be expected to crystallize in a dry environment. As a rule, however, cordierite is found with biotite

and other hydrous minerals suggesting that this point is not vital for its stability. Indeed, the experimental work by Yoder (1952, p. 583 and p. 609-612) shows that Mg cordierite can be formed hydrothermally at 490° C., but that at moderate pressures anthophyllite and pyrope are stable below 660° C. only in "water deficient" environment. The specific gravities show that the molar volume of the assemblage gedrite-kyanite-quartz is 15.2 per cent smaller than that of the cordierite on the right. The assemblage of the more tightly packed minerals could thus be expected to be stable in the higher pressure field. On the other hand, the high temperature usually causes dehydration and the crystallization of cordierite would be expected. This is in accordance with the consideration in figure 9 and together they would suggest that the crystallization of gedrite would require a higher pressure or a lower temperature than normally found for the rocks of the amphibolite facies.

Type of pressure

Verhoogen (1951) has shown that the chemical potential of a stressed solid is nearly equal to the chemical potential of the same solid, unstressed, but under a hydrostatic pressure equal to the mean hydrostatic pressure if the temperature is the same. The mean hydrostatic pressure is the mean of the three principal stresses acting upon a stressed solid. Also MacDonald (1957, p. 278) came to the conclusion that "the variation of chemical potential in the stressed solid is to a good approximation equal to the variation of chemical potential in a body under hydrostatic stress," and that "Transitions . . . involving large volume and entropy changes should not be affected by shearing stress." Accordingly, transitions such as andalusite to kyanite and crystallization of gedrite and kyanite instead of cordierite should not depend on stress and there would be no "stress" or "anti-stress" minerals in the sense Harker (1939) has suggested. However, considering the molar volumes of the minerals under discussion, we concluded that the high pressure (either hydrostatic or nonhydrostatic) during the crystallization would favor the formation of the kyanite-gedrite assemblage. At this point the geologic evidence must decide whether the pressure was hydrostatic or nonhydrostatic.

One of the main differences in the PT-conditions in nature and in the laboratory is different kinds of pressure. During the laboratory experiments the pressure is hydrostatic but in nature it is more often nonhydrostatic. In the areas where recrystallization has taken place contemporaneously with the deformation the rocks were subjected to a directed rather than to a hydrostatic pressure. It is well known that penetrative shearing has a catalytic influence on the recrystallization. Many minerals that are oriented at random in the sediments attain a preferred

orientation through recrystallization or through some other mechanism during the deformation. The chemical composition of these minerals is not changed; they are in chemical equilibrium with their environment but still the penetrative shearing will cause recrystallization and reorientation of the mineral grains in order to provide a preferred position in which the mineral can better endure the shearing stress or yield by translation.

The capacity of a mineral to endure shearing varies in different directions. These directions are certain crystallographic directions, for example micas grow with their sheets of SiO_4 tetrahedra parallel to the shear plane and amphiboles their chains parallel to the direction of the shear. It is also well known that some minerals are more sensitive to the penetrative shearing than the others. These studies in the structural petrology show that the shearing stress plays an important role during the recrystallization, and it would be only natural that various minerals could endure the shearing in different proportions depending on their crystal structure. The sheet structure of the micas and the chain structure of the amphiboles endure a great amount of shearing whereas some other minerals may not have any "durable" crystallographic directions.

Kyanite is frequently found in non-stressed environments such as in pegmatites and in quartz veins. On the other hand, the anthophyllite-cordierite assemblage shows that these two minerals can crystallize under the same PT-conditions. However, cordierite is not normally found in strongly sheared schists. This suggests that Harker's (1939) concept of stress and anti-stress minerals in regard to the minerals under discussion should be modified to read as follows: The "stress" minerals may crystallize equally under hydrostatic or nonhydrostatic pressure but the anti-stress minerals cannot be formed under strong shearing stress. This modification does not contradict the theoretical considerations recently discussed by MacDonald (1957, p. 272).

Comparison of the texture of the kyanite- and gedrite-bearing rocks near Orofino with that of their neighboring layers suggests crystallization under stressed conditions for some layers, but in the other layers minerals show only a subordinate amount of orientation. The garnet gedrite layer shows signs of strongest deformation. The gedrite prisms are parallel to the axis of the folding and mark a strong *b* lineation. The deformation was apparently accompanied by a stretching parallel to the *b* axis. In the kyanite-garnet gedrite a similar lineation parallel to the *b* axis occurs even if this rock as a whole is less sheared. In the garnet gedrite the clusters of light constituents are elongated parallel to the axis whereas in the kyanite-bearing rock they are irregular in shape. The stretching parallel to the axis was probably intensified by a second fold-

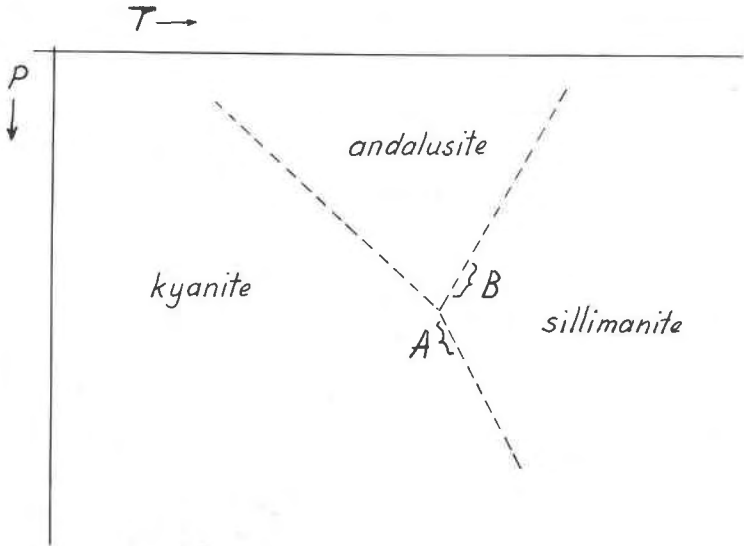


Fig. 9. Position of kyanite-garnet gedritite (region A) and cordierite-anthophyllite rocks (region B) in the suggested phase diagram of kyanite, andalusite, and sillimanite.

ing that bent the strata near Orofino to form an open drag around the axis that makes an angle of about 60° with the axis of smaller folds.

The layer of biotite-garnet gneiss that occurs between the two gedrite-bearing layers contains some staurolite and shows less sign of shearing than the gedrites. Biotite instead of gedrite crystallized in this layer, apparently owing to the presence of potash. Also, in the nearby schist the ferromagnesian minerals are garnet and biotite and the excess of aluminum, if present, crystallized as kyanite and sillimanite.

The cordierite gneisses in Finland show a fairly well developed mica orientation (Hietanen 1943) suggesting crystallization under stress. The mean hydrostatic pressure in this case, however, was probably smaller than that acting upon the kyanite-gedrite assemblage (see Fig. 9).

Comparison with kyanite-hornblende-anorthite assemblage

The occurrence of kyanite with hornblende in some layers in the anorthosite in the Boehls Butte quadrangle (Hietanen in press) is probably due to a later introduction of elements. The country rock of the anorthosite is a garnet-biotite schist rich in aluminum silicates. Some of the anorthosite contains several minerals inherited from the schist. In this case the occurrence of kyanite, andalusite, and sillimanite together in the neighboring layers fixes the temperature and pressure to the triple

point of figure 9. The older rocks in this area consisted of sedimentary formation in which layers rich in aluminum and layers rich in calcium alternated.* During the metamorphism first bytownite crystallized in the limy layers and Al-silicates with micas in the aluminous layers. Later, an introduction of sodium took place and was accompanied by an extensive rearrangement of material. Bytownite reacted with sodium forming andesine, but this reaction was not completed; numerous bytownite grains were left between and in the newly formed large andesine grains giving rise to the anorthositic rock with two plagioclases. Many segregations of ferromagnesian minerals show that iron and magnesium also were mobile. During the introduction of sodium a part of Ca, Fe, and Mg were removed from the anorthositic layers. These elements migrated to the nearby schistose layers (which were rich in Al-silicates) giving rise to the crystallization of hornblende with kyanite. The layers, in which kyanite occurs with hornblende, also contain bytownite and andesine, thus two plagioclases that should have reacted to form labradorite. The relation between the kyanite and hornblende is comparable with that between the bytownite and andesine. The kyanite can be an earlier mineral inherited from the schist and the hornblende crystallized later during the formation of anorthosite. Unless new information will prove otherwise, it is not safe to assume that kyanite in this rock is in equilibrium with hornblende.

In the light of the occurrence of kyanite with hornblende in the anorthosite one might think that a similar metasomatic addition of elements may have caused the crystallization of gedrite near Orofino. This suggestion is strengthened by the occurrence of several accumulations of ferromagnesian minerals in the nearby schist and quartzite layers. During a regional study of the rocks near Orofino these accumulations were found to be metasomatic.† The sequence of crystallization in the gedrite-bearing rocks also favors the metasomatic origin of gedrite. The parent rock may have been a similar biotite-garnet gneiss as found between the two gedrite-bearing layers. An addition of Mg and possibly of some Fe and a removal of K may have changed the composition of the biotite gneiss to be suitable for the formation of gedrite. In this case kyanite could be a relict mineral as it is in the anorthosite in the Boehls Butte quadrangle. However, in contrast to the kyanite in anorthosite the kyanite in the gedrite has quite fresh borders. It is usually surrounded by gedrite and there are no signs of disequilibrium.

In the country rocks of the anorthosite in the Boehls Butte quadrangle

* See footnote 1.

† See footnote 2.

cordierite crystallized in some aluminous layers rich in magnesium and gedrite with garnet in some other layers that are richer in iron; neither of these types of layers shows signs of an exceptionally strong shearing stress. In this case the crystallization of either cordierite or gedrite is apparently due to the chemical composition of the layers. The gedrite in the Boehls Butte quadrangle (No. 1227 in Fig. 7) is only a little richer in iron than the gedrite near Orofino; the garnet (No. 1225 in Fig. 7), however, contains considerably more iron than this mineral near Orofino (No. 813g).

CONCLUSION

It seems that, in addition to a suitable chemical composition (an environment rich in aluminum and magnesium, containing a moderate amount of iron and only a small amount of water), a slight increase in nonhydrostatic pressure (stress) favors the formation of gedrite and kyanite instead of cordierite in that temperature field of the amphibolite facies in which staurolite is changing to kyanite and garnet and in which first crystals of sillimanite may appear. This is very close to the same temperature-pressure point in which the three aluminum silicates—kyanite, andalusite, and sillimanite—can occur together. The occurrence of kyanite with the hornblende in some layers of the anorthosite suggests that in some cases kyanite may be found with amphibole because of slowness of reactions between the minerals of the parent rock and the introduced solutions carrying magnesium and iron.

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