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KYANITE, ANDALUSITE, AND SILLIMANITE IN THE SCHIST IN BOEHLS BUTTE QUADRANGLE, IDAHO*

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ABSTRACT

Kyanite, andalusite, and sillimanite are found together in the cordierite-bearing mica schist of the Prichard formation of the Precambrian Belt series exposed in the Boehls Butte quadrangle in the southern part of the Idaho panhandle. Microscopic studies of this schist suggest that the following inversions took place: (1) sillimanite→kyanite, (2) sillimanite→andalusite, (3) kyanite→andalusite, (4) kyanite→sillimanite, (5) andalusite→sillimanite. These inversions can be in part related to the fluctuation of temperature and stresses during the complex regional and thermal metamorphism to which the schist was subjected. In some thin sections all three modifications occur side by side, suggesting that they were crystallized close to the physical-chemical conditions in which all three may exist together. The association of epidote and plagioclase (An_{36}) in the calcium-rich beds of the same area suggests that the temperature during the crystallization was close to 400° C.

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Introduction

The three aluminum silicates—kyanite, andalusite, and sillimanite—occur together in the schist in Boehls Butte quadrangle and in an area

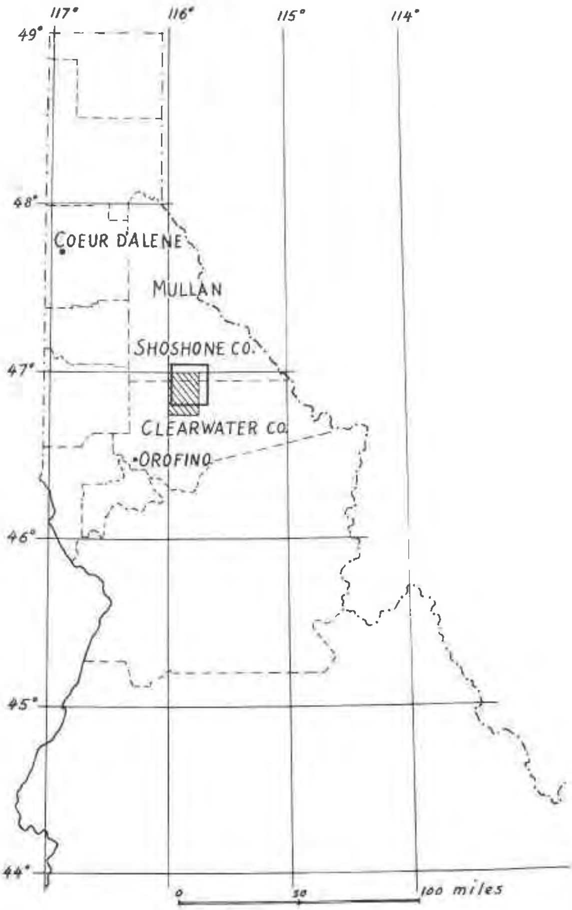

Fig. 1. Location of the area in Idaho. The area under discussion is surrounded with a heavy line. Boehls Butte quadrangle is shaded.

north of it. Boehls Butte quadrangle is situated in the southern part of the Idaho panhandle about 40 miles south of the Coeur d' Alene silver mining district (Fig. 1), in Clearwater and Shoshone Counties. The main rock type in this quadrangle is a folded coarse-grained mica schist belonging to the Prichard formation of the Precambrian Belt series. Quartzites and schists probably of the Burke, Revett, St. Regis, and Wallace formation of the Belt series are exposed in the southern part of the quadrangle, but these rocks do not contain more than possibly one of the aluminum silicates and therefore are not discussed in this paper. The mapping of this quadrangle was started during the summer of 1951 and is not yet completed. At the present stage of study, it is impossible to say how prevalent similar kyanite-andalusite-sillimanite-bearing schists are in the nearby areas, or whether they are confined entirely to the Prichard formation. The localities of the collected specimens, which contain all three modifications of Al_2SiO_5, are widely distributed in the Boehls Butte quadrangle and in an area just north of it (Fig. 2), suggesting that the occurrence of these minerals is a regional rather than a local feature.

General Geology

The Prichard formation in the Boehls Butte quadrangle consists of a highly metamorphosed bedded and folded mica schist with a fairly pure white to gray quartzite, more than 1000 feet thick, close to the middle of the formation. In the lower and upper schistose members the thin quartzitic layers are interbedded with more micaceous layers. The thickness of various beds ranges from a few millimeters to several meters, the thinly bedded schist and quartzite being dominant. In the micaceous layers, huge muscovite and light-brown biotite flakes give a glittering yellowish-brown luster to the cleavage surfaces. With a few exceptions, the cleavage parallels the bedding. Numerous small garnet amphibolite bodies and a few larger anorthosite bodies, both with mainly concordant contacts, occur in this schist. The schist and quartzite are moderately folded and faulted. The general strike of the beds is N 45°–70° W. Dips of 15° to 45° are common. The major fold axis trends about N 70° W and plunges 5° to 25° either to the east or to the west. Some outcrops show a strong lineation (wrinkling of s_1) and minor folding around an axis that trends about N 25° E.

Occurrence of the Three Aluminum Silicates Together

Kyanite, andalusite, and sillimanite occur in several localities in the mica-rich beds of the Prichard formation. Most of the schist carrying these three minerals is close to metasomatic anorthosite bodies (Fig. 2).

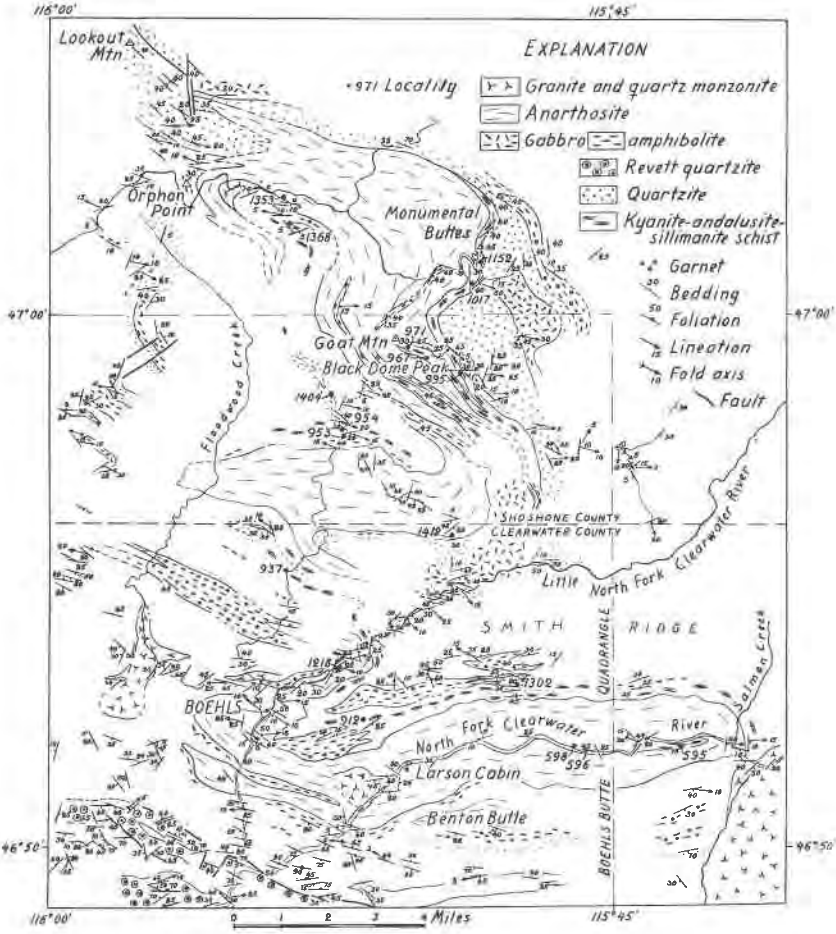

FIG. 2. Sketch map of Boehls Butte quadrangle and vicinity, showing the location of the kyanite-andalusite-sillimanite schist and the distribution of anorthosite and garnet amphibolite.

Probably the same temperature and pressure that were required to form the three associated aluminum silicates were suitable for the unusual kind of metasomatism in this area. A part of the aluminum in the schist may have been introduced during the metasomatism. Cordierite is rare elsewhere in the Belt series, and so its abundant occurrence in the kyanite-andalusite-sillimanite schist and gneiss is noteworthy. Two locations near the anorthosite exposed at Boehls and along the North Fork of the Clearwater River (912 and 595, Fig. 2), two near the anorthosite on Goat Mountain (971 and 995, Fig. 2), some between these two areas (953 and 954, Fig. 2), and one northwest of Goat Mountain (1368) are described in detail.

Kyanite-andalusite-sillimanite-cordierite gneiss on Smith Ridge

The schist along Smith Ridge north of the anorthosite exposed at Boehls and along the river is mainly thin-bedded biotite schist with garnet-bearing layers. Small sills of gabbro and garnet amphibolite occur in the schist parallel to the bedding. Some of these bodies are only about 10 cm. thick and 2 to 3 meters long and were probably formed by replacement. Several large boulders of kyanite-andalusite-sillimanite-cordierite gneiss were found on the south slope of the ridge close to its top (912, Fig. 2). No outcrops were found in this locality, but the analogy with similar occurrences to the north and south suggests that the gneiss is a layer in the garnet-biotite schist.

Description of the gneiss

The kyanite-andalusite-sillimanite-cordierite gneiss is light bluish gray and coarse-grained. The alignment of minerals is less pronounced than in the surrounding schist. White grains of andalusite and kyanite are easily visible against the mixture of brown biotite and light grayish cordierite (Pl. 1*a*). Andalusite occurs as large rounded nodules or as individual large grains. Kyanite occurs as white prisms ranging from 1 to 15 mm. in length.

The microscopic study shows that this rock consists of abundant cordierite (about 37 per cent), biotite, and plagioclase, with less quartz, andalusite, sillimanite, corundum, kyanite and sericitic mica (Pl. 1*b*). The cordierite occurs in dull round grains that contain small sericite and some tiny sillimanite inclusions mainly parallel to the cracks and along the borders. Also there is some pinitization along the borders.

The biotite flakes, ranging from 1 to 2 mm. in length, are very light brown and show a crude alignment. The three aluminum silicates tend to occur in clusters. Study under the microscope indicates that many of the white andalusite nodules appear to contain kyanite and sillimanite.

Optical properties of the minerals in the gneiss

The indices of refraction of the three aluminum silicates in the gneiss on Smith Ridge are shown in Table 1. They seem to be practically the same as those commonly reported for these minerals.

The indices of refraction of the cordierite are $\alpha = 1.530 \pm 0.001$, $\beta = 1.535 \pm 0.001$, $\gamma = 1.538 \pm 0.001$; the cordierite is biaxial negative with $2V = 84.5°$. The pleochroism of biotite is Z pale brown and X yellowish; the indices of refraction are $\alpha = 1.558 \pm 0.001$, $\beta = 1.601 \pm 0.001$, $\gamma = 1.601$

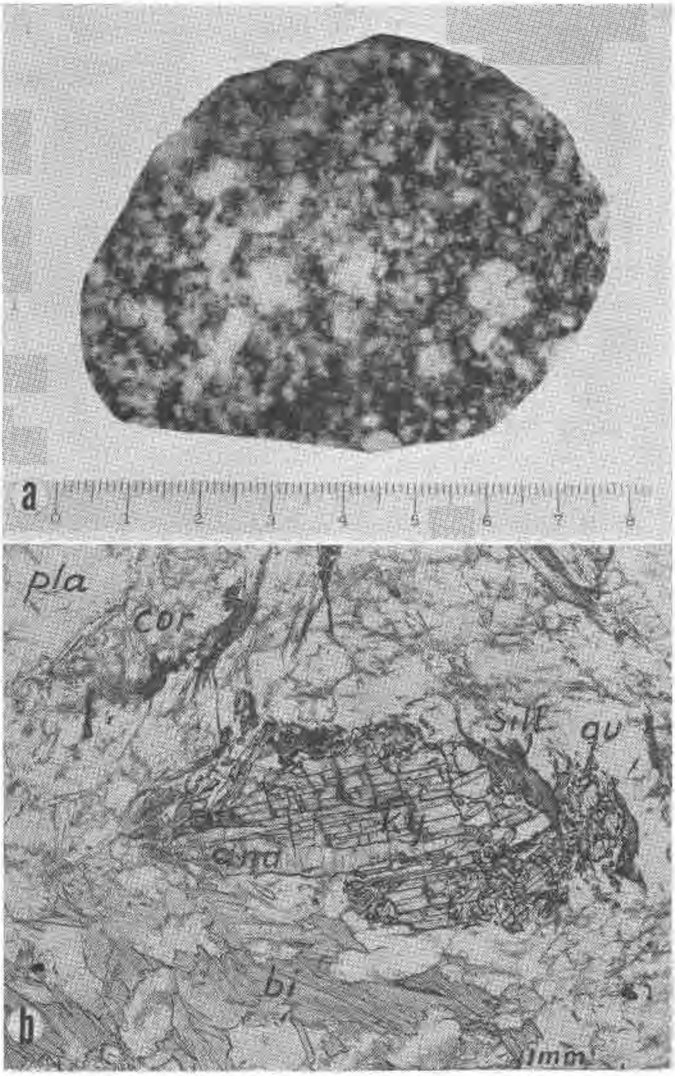

PLATE 1

a. Polished hand specimen of kyanite-andalusite-sillimanite-cordierite gneiss from Smith Ridge (912), Boehls Butte quadrangle. The white minerals are andalusite and kyanite.
b. Photomicrograph of the same rock as in *a* (912). ky = kyanite, and = andalusite, sill = sillimanite, cor = cordierite, bi = biotite, pla = plagioclase, qu = quartz, +Nicols.

TABLE 1. INDICES OF REFRACTION OF KYANITE, ANDALUSITE, AND SILLIMANITE IN SCHIST FROM SMITH RIDGE, BOEHLS BUTTE QUADRANGLE (912, FIG. 2)

Kyanite	Andalusite	Sillimanite
$\alpha=1.7125\pm0.001$	$\alpha=1.631\pm0.001$	$\alpha=1.654\pm0.001$
$\beta=1.722\ \pm0.001$	$\beta=1.637\pm0.001$	$\beta=1.656\pm0.001$
$\gamma=1.727\ \pm0.001$	$\gamma=1.642\pm0.001$	$\gamma=1.677\pm0.001$

±0.001 with $2V=0°$. *X*-ray powder photographs of this cordierite and biotite, made by F. A. Hildebrand of the Geological Survey, show typical cordierite and biotite patterns.

Chemical composition of the minerals and the gneiss

Kyanite, cordierite, and biotite were separated by means of heavy liquids and analyzed chemically. Their composition and specific gravities are shown in Table 2.

The composition of kyanite is practically the same as that of the

TABLE 2. CHEMICAL ANALYSES OF KYANITE, CORDIERITE, AND BIOTITE FROM THE KYANITE-ANDALUSITE-SILLIMANITE-CORDIERITE GNEISS, FROM SMITH RIDGE, BOEHLS BUTTE QUADRANGLE (912, FIG. 2)

	Kyanite[1] (sp. gr. >3.3)		Cordierite[1] (sp. gr. 2.583–2.603)				Biotite[2] (sp. gr. 2.872–2.891)				
	Weight per cent	Molecular equivalent	Weight per cent	Molecular equivalent		Ratio	Weight per cent	Molecular equivalent		Number of atoms	
SiO_2	35.84	5944	49.46	8202		5	39.29	6541	Si	5.49	8.00
TiO_2	0.01	1	0.01	1			0.58	72	Al	2.51	
Al_2O_3	63.48	6330	33.58	3292	3301	2	21.06	2064	Al	0.96	
Fe_2O_3	0.22	14	0.14	9			0.30	19	Ti	0.05	
FeO	0.08	11	2.12	295			5.81	809	Fe	0.03	5.7
MnO	0.00		0.08	11	3302	2	0.04	6	Fe	0.68	
MgO	0.41	102	12.06	2991			19.13	4744	Mn	0.01	
CaO	0.00		0.03	5			0.00		Mg	3.97	
Na_2O	0.00		0.14	23			0.33	53	Ca	0.00	
K_2O	0.08	8	0.30	32			8.60	913	Na	0.09	1.61
P_2O_5	0.00		0.00						K	1.52	
F							0.08	42	H	4.36	4.39
H_2O-	0.01	6	0.10	55			0.07	39	F	0.03	
H_2O+	0.15	83	1.71	949			4.69	2603	O	24.0	24.00
	100.27		99.73				99.98 −O 0.03 99.95				

[1] Lucile N. Tarrant, *analyst*.

[2] Lee C. Peck, *analyst*.

kyanite in the schist at Goat Mountain (Table 4). The only differences are somewhat larger amounts of Al_2O_3 and MgO in the kyanite along Smith Ridge. The higher percentage of MgO in the kyanite at Smith Ridge may be due to the impurities; the two kyanites are optically identical.

The ratio $(MgO+FeO+CaO):Al_2O_3:SiO_2$ in the cordierite is 2:2:5 and the ratio FeO:MgO is 1:10. Thus, this cordierite is an almost pure magnesium member of the naturally occurring cordierites (Folinsbee, 1941). The chemical composition and the indices of refraction are close to those of a cordierite from Attu, Finland (Pehrman, 1932), but the optic sign is negative, whereas that of the cordierite from Attu is positive. Folinsbee (1941) has suggested that the optic angle would tend to increase with decrease in alkali content. The properties of the cordierite on Smith Ridge accord with this suggestion.

The analysis of biotite shows that this mineral is rich in magnesium and aluminum. The formula calculated (Table 2, number of atoms) is $(OH)_4H_{0.4}K_{1.6}(Mg,Fe)_{4.7}Al\cdot Al_{2.5}Si_{5.5}\cdot O_{20}$. This differs from the ideal formula $(OH)_4K_2(Mg,Fe)_6Al_2Si_6O_{20}$ mainly in a larger amount of Al. Part of the Si in the $AlSi_3O_{10}$ sheets is substituted by Al, which also substitutes for a part of the Mg and Fe atoms in the structure. The substitution of Al for Si and Mg is common in eastonite, the ideal formula of which is $(OH)_4K_2Mg_5Al\cdot Al_3Si_5O_{20}$. The substitution of Al for Si in the biotite from Smith Ridge puts that biotite well between these two end members. The Mg:Fe ratio is 6:1 and there is only a little fluorine.

Table 3 shows the chemical, measured, and calculated mineralogical composition of the kyanite-andalusite-sillimanite-cordierite gneiss from Smith Ridge. The thin sections do not show calcite. Most of the Al_2SiO_5 is kyanite. The norm shows 26.33 per cent excess of Al_2O_3 and 23.07 per cent $MgSiO_3$. Plagioclase (An_{17}) is richer in albite than this mineral in the adjacent garnet-biotite schist, where it is generally about An_{25}. Thus, this gneiss layer is exceptionally poor in calcium and rich in magnesium and aluminum.

Relation of the aluminum silicates in the gneiss

The relation between the three aluminum silicates is not always clear. There are two types of sillimanite, brownish fibrous nodules and colorless needles (Fig. 3). The brownish nodules have colorless needles in their borders, and fresh kyanite is found next to the nodules. The colorless needles occur also around andalusite and kyanite, suggesting that these needles were formed at the expense of kyanite and andalusite. Most of the andalusite occurs as fresh large grains showing only slight strain shadows. However, some kyanite is surrounded by small grains of strained andalusite (cf. Pl. 4*b*) suggesting a transformation kyanite

TABLE 3. CHEMICAL AND MINERALOGICAL COMPOSITION AND NORM OF THE KYANITE-ANDALUSITE-SILLIMANITE-CORDIERITE GNEISS FROM SMITH RIDGE, BOEHLS BUTTE QUADRANGLE

	Weight per cent[1]	Mol.	Norm		Mode	
SiO_2	48.20	7993	qu	12.80	quartz	3.20
TiO_2	0.14	17	or	13.73	plagioclase (An_{17})	15.65
Al_2O_3	32.54	3190	ab	14.09		
Fe_2O_3	0.23	14	an	2.70	biotite	25.14
FeO	2.24	312	cor	26.33	sericite	0.20
MnO	0.05	7	en	23.07	cordierite	37.10
MgO	9.30	2306	fs	3.80	kyanite, andalusite, sillimanite	17.86
CaO	0.84	150	ap	0.03		
Na_2O	1.66	268	il	0.25		
K_2O	2.32	246	mt	0.32	(calcite)	(0.50)
P_2O_5	0.01	1	cal	0.50	apatite	0.02
				97.62		99.67
CO_2	0.22	50				
H_2O-	0.12	67	H_2O	2.38	$+H_2O$	0.46
H_2O+	2.26	1249		100.00		100.13
	100.13					

[1] *Analyst:* Lucile N. Tarrant.

→andalusite. The relations shown in the thin section are not definitive, but by analogy with the occurrence at Goat Mountain the suggested relation is strengthened. Figure 3 shows these two types of sillimanite, two types of andalusite, and kyanite side by side in the thin section. Probably the brown sillimanite (sill I) is earlier and was in part altered to kyanite (ky), which in turn was altered to strained andalusite (and I). Many of the small fragments when immersed in heavy liquids showed parallel intergrowths of thin lamellae of kyanite and sillimanite, suggesting a simultaneous crystallization. Part of the colorless needles of sillimanite were probably derived directly at the expense of brown sillimanite. The place of the individual large andalusite crystals (and II) in the sequence of recrystallization is not clear except that they are earlier than the late sillimanite needles.

Other occurrences

Further field studies have revealed that layers of a similar kyanite-andalusite-sillimanite-cordierite gneiss are well exposed in the deep gorge of the Little North Fork of the Clearwater River north of Smith Ridge (1218, Fig. 2). These layers are on the top of the anorthosite, as is also a layer of a coarse kyanite-andalusite-sillimanite-cordierite schist on the south slope of Smith Ridge along the North Fork of the Clearwater River (1302, Fig. 2).

Boulders and small outcrops of coarse bluish-gray kyanite-andalusite-cordierite-biotite gneiss with some sillimanite were found along the road leading from Boehls to Goat Mountain, about a mile south of the county boundary (937, Fig. 2). An anorthosite body occurs just north of this locality and abundant loose amphibole-bearing quartzite blocks south of it. Some of these blocks contain cummingtonite, and others have diopside, hornblende, and magnesium-rich biotite as dark constituents. Epidote with plagioclase (An_{37}) was found in some.

Andalusite-kyanite schist on the North Fork of Clearwater River

The andalusite-kyanite-sillimanite-biotite schist on the south side of the North Fork of Clearwater River about 6 miles east of Larson Cabin (595, Fig. 2) is a dark-gray biotite schist with white andalusite nodules and white quartz blebs (Pl. 2*a*). The andalusite nodules range from 1 mm. to 4 cm. in diameter. The quartz blebs are usually larger and elongated parallel to the schistosity. Microscopic study shows that in addition to andalusite this schist contains abundant kyanite and some sillimanite (Pl. 2*b*). The other minerals are quartz, plagioclase (An_{46}), biotite, muscovite, tourmaline, and cordierite.

Minerals in the schist

Most of the andalusite nodules are surrounded by a narrow rim of quartz and many of them include sericite. The indices of refraction of andalusite are $\alpha = 1.631 \pm 0.001$, $\beta = 1.638 \pm 0.001$, $\gamma = 1.643 \pm 0.001$.

Kyanite crystals in this rock (595, Fig. 2) are rather small, but in the nearby anorthositized[1] schist (596, 598, Fig. 2) they grow as large holoblasts including quartz or are surrounded by andalusite (pl. 3*a* and *b*). Sillimanite in the schist (595) occurs as small needles either next to the kyanite or andalusite or among the other minerals.

Biotite is light greenish brown with bright interference colors. It has $\alpha = 1.568 \pm 0.001$ and γ and $\beta = 1.610 \pm 0.001$. Sericite is scarce and is usually included in biotite. Quartz and plagioclase (An_{46}) are the light-colored constituents; they occur as small lenticles and as scattered grains among the other minerals. Tourmaline in small prisms and a little magnetite are the accessories.

Relation of the aluminum silicates in the schist

All three modifications of Al_2SiO_5 occur as individual grains in the schist, and there are no signs of alterations or disequilibrium except for

[1] Term according to Barth, 1952, pp. 229, 363.

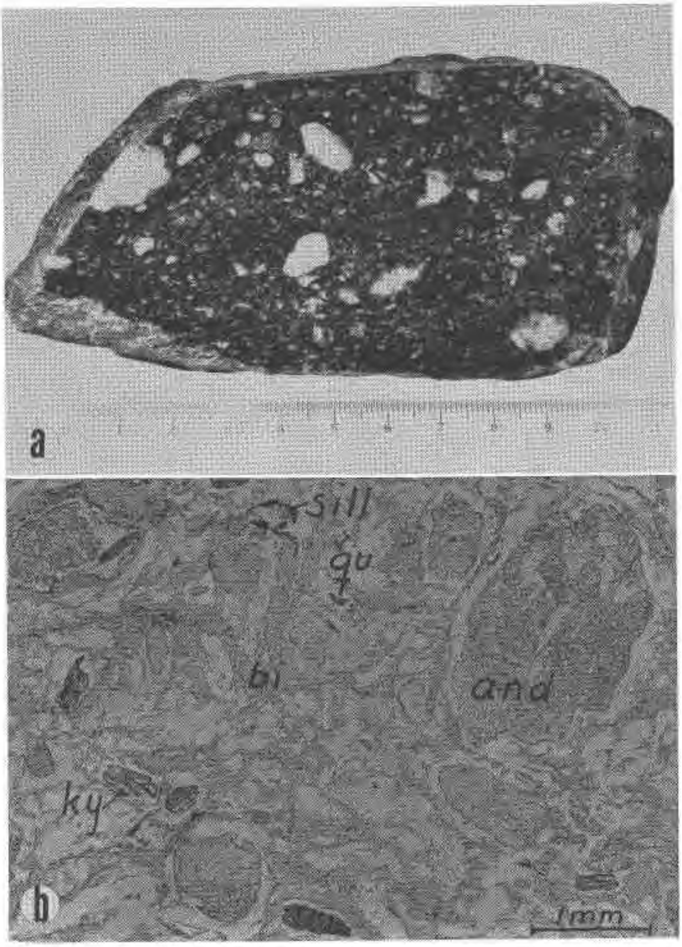

PLATE 2

a. Polished hand specimen of a kyanite-andalusite-sillimanite schist from North Fork of Clearwater River, 1 mile west of the mouth of Salmon Creek (595), Clearwater County, Idaho. The large rounded white areas are andalusite; small white minerals are kyanite. Abundant biotite makes the rock dark.

b. Photomicrograph of the same rock (595). ky=kyanite, and=andalusite, sill=sillimanite, bi=biotite, qu=quartz, +Nicols.

an unusual texture of the andalusite. The rounded nodules of andalusite are built of small elongated grains, part of which are arranged in a radiate manner. The small grains show strain shadows under the microscope. This texture is typical of the major part of the andalusite in this area, and it is clearly shown under crossed nicols in Plate 4*b*.

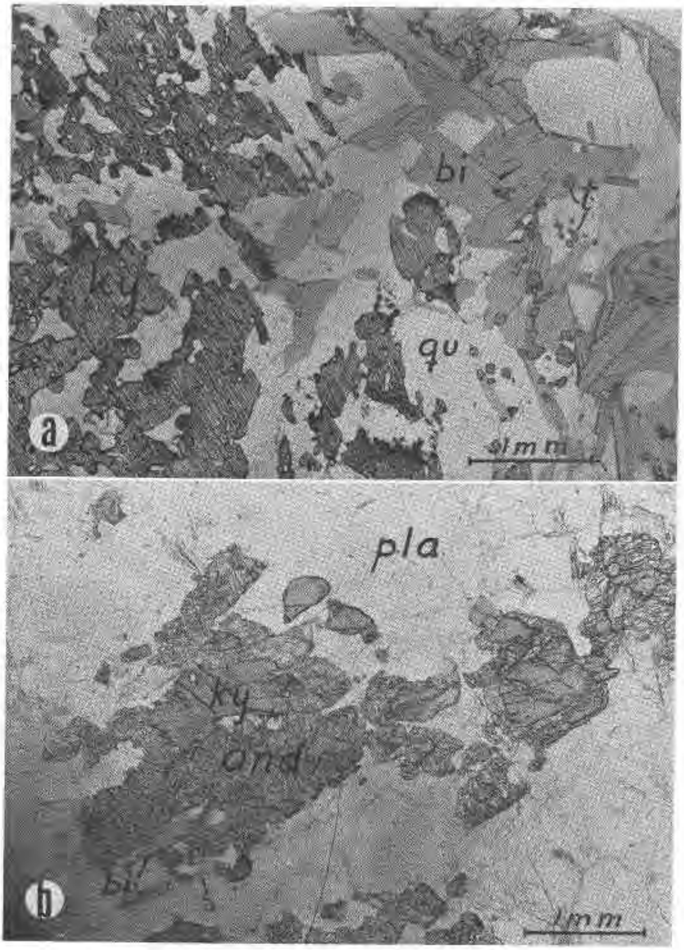

PLATE 3

a. Kyanite holoblasts in a schist layer in anorthosite from 596, North Fork of Clearwater River, 3 miles west of mouth of Salmon Creek, Boehls Butte quadrangle. ky=kyanite, bi=biotite, t=tourmaline, qu=quartz, —Nicols.

b. Kyanite surrounded by andalusite in the anorthosite at 598, on North Fork of Clearwater River, 3 miles west of the mouth of Salmon Creek, Boehls Butte quadrangle. —Nicols.

Continuation of the schist layer

The westward extension of this schist parallel to the strike is metasomatically transformed to kyanite- and andalusite-bearing anorthosite, and the place of the eastward extension is occupied by an intrusive quartz monzonite which in places contains dark spots of cordierite. With two

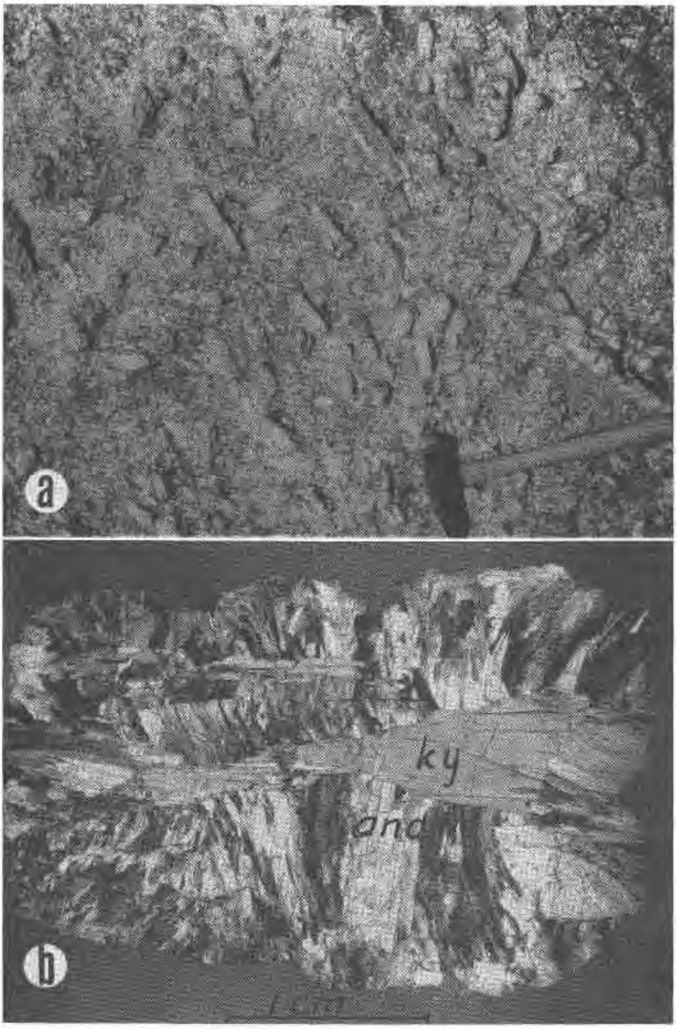

PLATE 4

a. Photograph of an outcrop of a coarse kyanite-andalusite-sillimanite schist, 971 from Goat Mountain, Boehls Butte quadrangle. Large kyanite crystals stand out on the rock surface.

b. Photomicrograph of a cross section of a large kyanite crystal from the rock shown in *a*. Main part of the kyanite (ky) has inverted to andalusite (and), which grows perpendicular to the cleavage of the kyanite and shows strain shadows. Crossed Nicols.

exceptions only sillimanite and garnet were found in the mica schists south of this location.

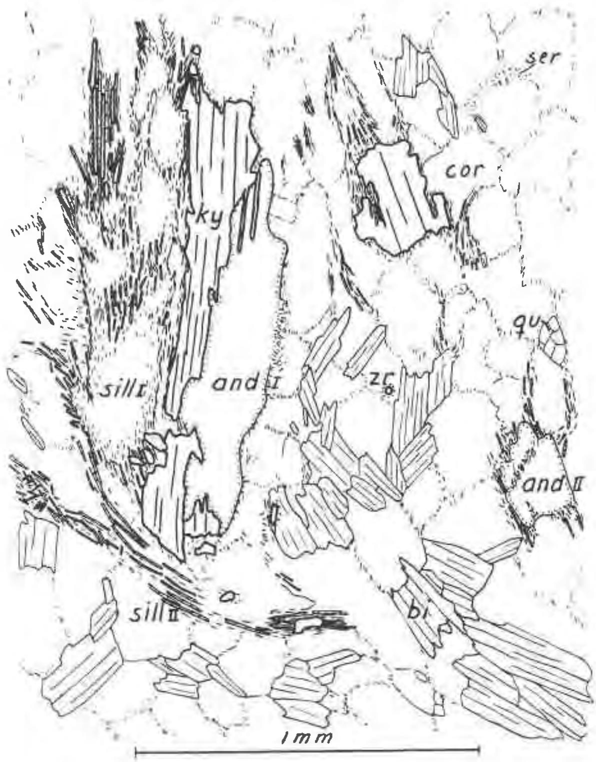

FIG. 3. A camera lucida drawing of the kyanite-andalusite-sillimanite-cordierite gneiss 912 from Smith Ridge, Clearwater County, Idaho. ky=kyanite, and I=early andalusite, and II=late andalusite, sill I=brown sillimanite, sill II=colorless sillimanite needles, cor =cordierite, bi=biotite, ser=sericite, qu=quartz, zr=zircon.

Kyanite-andalusite schist in the Goat Mountain area

The schist surrounding the anorthosite in the Goat Mountain area is exceptionally coarse grained, containing large kyanite and andalusite crystals. Sillimanite is usually present but only in small amounts. The occurrence of cordierite in some layers and staurolite in others indicates a variation in the amount of iron and magnesium.

The schist south of Goat Mountain Lookout contains many huge kyanite crystals embedded in coarse biotite-plagioclase schist. Plate 4*a* shows a photograph of an outcrop of this schist. Some of the kyanite crystals are 12 inches long. The other constituents of this coarse kyanite-andalusite schist are biotite, quartz, cordierite, plagioclase, sillimanite, white mica, and several small grains of corundum.

Minerals in the schist at Goat Mountain

The indices of refraction of the kyanite and andalusite are identical with those of the same minerals in the rock from locality 912 (Table 1). In addition the identity of these minerals was confirmed by *x*-ray powder patterns made by F. A. Hildebrand. Biotite is greenish and occurs in large flakes that show $\gamma=1.610\pm0.001$ and $\gamma-\alpha=0.045\pm0.001$. The greenish color and abundant iron oxide along the cleavage planes and borders suggest that alteration has started. The white mica occurs in groups of small soft flakes that have $\beta=1.594\pm0.001$ and $\gamma=1.600\pm0.001$. The *x*-ray determination made by F. A. Hildebrand shows that this mica is muscovite. In this rock cordierite occurs as elongated grains in biotite (Pl. 5*a*) and is altered to pinite along the borders and cracks. The composition of the plagioclase ranges from An_{10} to An_{17}, and a few crystals show weak zoning. Part of the plagioclase was probably introduced metasomatically during the anorthositization.

Chemical composition of kyanite and andalusite

Kyanite and andalusite were separated from a single large crystal (containing both of these minerals) and analyzed chemically. The results in Table 4 show that the chemical compositions of these minerals are prac-

TABLE 4. CHEMICAL ANALYSES[1] OF KYANITE AND ANDALUSITE FROM A LARGE CRYSTAL FROM GOAT MOUNTAIN, BOEHLS BUTTE QUADRANGLE

	Kyanite		Andalusite	
	Weight per cent	Mol.	Weight per cent	Mol.
SiO_2	36.76	6096	36.74	6093
TiO_2	0.01	1	0.01	1
Al_2O_3	62.74	6150	62.70	6149
Fe_2O_3	0.32	20	0.36	23
FeO	0.01	1	0.05	7
MnO	0.00		0.00	
MgO	0.04	10	0.03	7
CaO	0.00		0.02	4
Na_2O	0.00		0.00	
K_2O	0.12	13	0.07	7
P_2O_5	0.00		0.00	
H_2O-	0.01	6	0.01	6
H_2O+	0.14	78	0.15	83
	100.15		100.14	

[1] Lucile N. Tarrant, *analyst*.

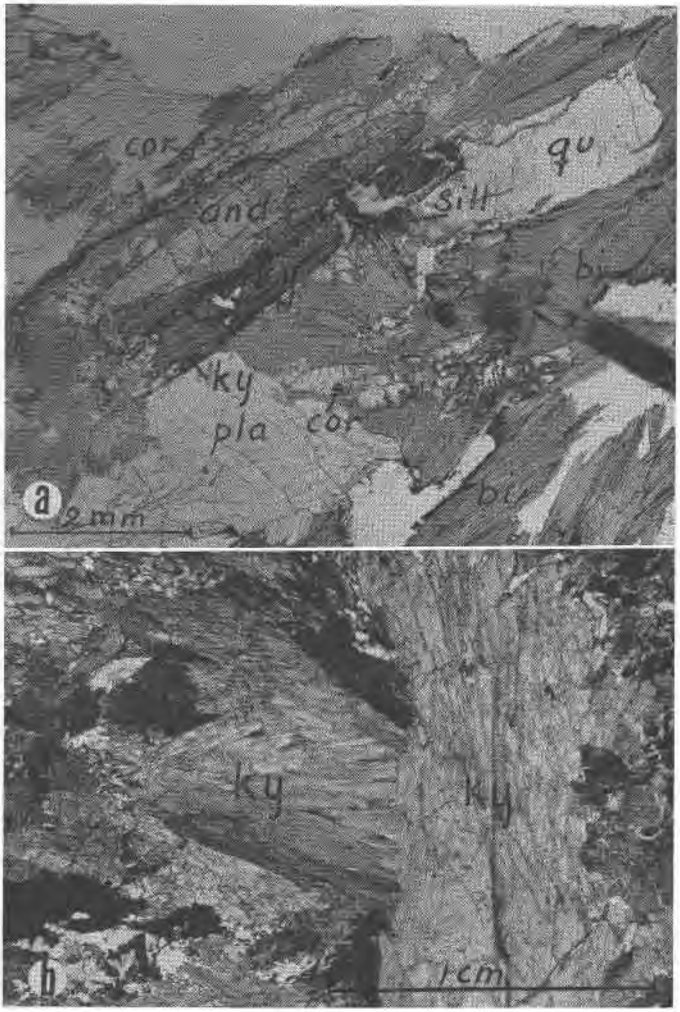

PLATE 5

a. Photomicrograph of a kyanite-andalusite-sillimanite schist from a locality half a mile east of 971 along the strike. This specimen, 967, is much finer grained than 971. ky =kyanite, and=andalusite, sill=sillimanite, cor=cordierite, bi=biotite, pla=plagioclase, qu=quartz. Note pinitization in cordierite (dark).

b. Radiating needles of kyanite in kyanite-andalusite rock 995 from Goat Mountain Boehls Butte quadrangle. Crossed Nicols.

tically identical. Both are very pure aluminum silicates except for a small amount of Fe_2O_3, K_2O, and H_2O in each. The amount of the other oxides is negligible and within the limits of the analytical error. There is no no-table difference in the amounts of minor elements in the kyanite and andalusite (Table 5); small amounts of Ba, Cr, Cu, Ga, and V occur in each.

TABLE 5. SPECTROCHEMICAL ANALYSIS[1] FOR MINOR ELEMENTS IN KYANITE AND ANDALUSITE

	Kyanite Smith Ridge (Table 2)	*Kyanite* Goat Mountain (Table 4)	*Andalusite* Goat Mountain (Table 4)
Ba	0.003	0.007	0.002
Cr	0.0006	0.0001	0.0008
Cu	0.0008	0.0008	0.0004
Ga	0.001	0.0008	0.0008
V	0.001	0.001	0.001

Not found: Ag, As, B, Be, Bi, Cd, Co, Ge, In, La, Mo, Nb, Ni, Pb, Pt, Sb, Sc, Sn, Sr, Ta, Th, Tl, U, W, Y, Yb, Zn, Zr.

Relation of the aluminum silicates in the schist at Goat Mountain

The large kyanite crystals show the platy habit typical of this mineral. The major part of the andalusite occurs in similar platy crystals, suggesting that they are pseudomorphs after kyanite. Many crystals consist in part of white dull massive andalusite, whereas the other part is bluish clear kyanite with a good cleavage.

The same relations are clearly shown under the microscope. Plate 4*b* shows a cross section of a large kyanite crystal that is altered almost completely to andalusite. The andalusite crystals grow perpendicular to the cleavage and to the walls of the cracks in the kyanite, and they show undulatory extinction and a fan-shaped texture. In some individual units half consists of kyanite and the other half of andalusite, or remnants of kyanite occur as thin lamellae in the andalusite. Sillimanite needles grow around the kyanite crystals or are included in quartz and plagioclase.

"Sillimanite" gneiss

Another interesting rock in the Goat Mountain area is a coarse "sillimanite" gneiss that crops out on the south slope of the Black Dome Peak (995, Fig. 2). About 50 per cent of this rock consists of large radiating light-brownish fibrous nodules, which megascopically look like sillimanite but whose indices of refraction are $\alpha=1.713\pm0.001$, $\beta=1.722\pm0.001$, $\gamma=1.728\pm0.001$, that is, those of kyanite. Plate 5*b* shows a photomicrograph of such kyanite. This kyanite is probably a pseudomorph after

[1] Paul R. Barnett, *analyst*.

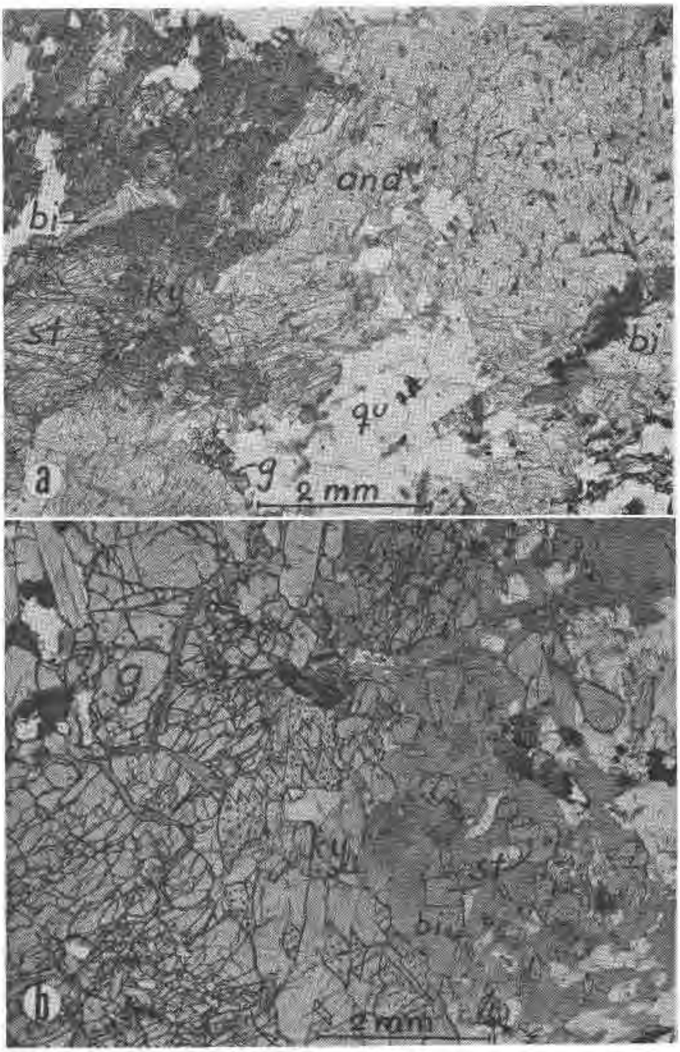

PLATE 6

a. Photomicrograph of a staurolite-kyanite-andalusite schist from a locality just north of 995 at Black Dome Peak, Boehls Butte quadrangle. st=staurolite, ky=kyanite, and =andalusite, g=garnet, bi=biotite.

b. Photomicrograph of a kyanite-garnet schist from a locality just north of 971 at Goat Mountain. ky=kyanite, g=garnet, st=staurolite, bi=biotite. Large kyanite crystals are twinned. Twinning lamellae are shown by dotted areas. Staurolite is included in biotite and occurs as small euhedral crystals.

sillimanite. Thin-section study shows that the other constituents in this rock are andalusite, quartz, and very light brown biotite, much like the biotite in the rock 912 (Table 2). Andalusite occurs in individual large grains and also as groups of small strained grains. The individual large grains contain small quartz inclusions and are not strained. The groups of small strained andalusite grains are similar to those which were interpreted as an alteration product after kyanite in the coarse kyanite-andalusite schist (971, Pl. 4). There are also long prisms with a weak undulating extinction and with some small quartz inclusions. It is possible that the individual unstrained andalusite grains were recrystallized at the expense of the strained crystals during the continued thermal metamorphism. Thus, the sequence of crystallization here might be as follows: sillimanite→kyanite→strained andalusite→clear andalusite. Some of the needlelike minerals are andalusite, and it is possible that part of the sillimanite was transformed directly to andalusite.

Staurolite-bearing schist

The rocks described above are rich in magnesium, containing cordierite and magnesian biotite. Above this magnesium-rich zone of the Goat Mountain area are iron-rich beds that contain abundant garnet, staurolite, reddish-brown or green biotite, and ilmenite. Brown grains of rutile and small round crystals of zircon occur as accessories. Also these layers are rich in kyanite and andalusite (Pl. 6*a* and 6*b*), but no sillimanite was found in thin sections made of specimens from Black Dome Peak and from an area just north of locality 971.

The relation between staurolite, kyanite, and andalusite at Black Dome Peak (Pl. 6*a*) suggests that staurolite was crystallized early and was partly altered to kyanite, which in turn was transformed to andalusite. With the kyanite and andalusite small flakes of biotite and ilmenite-magnetite occur; they contain the iron that was released from the staurolite. Biotite and garnet show incipient alteration to chlorite.

In the garnet-kyanite-andalusite schist just north of the coarse kyanite-andalusite schist (971, Fig. 2) small euhedral staurolite crystals are included in biotite, and kyanite occurs in large anhedral grains that show twinning (Pl. 6*b*). Andalusite appears in nodules of small strained grains. Garnet crystals abound, some of which measure 2 inches in diameter. In the Monumental Buttes area (1152, fig. 2) schist similar to the rock 971 is exposed between a coarse kyanite-andalusite schist and the quartzite in the middle of the Prichard formation. This schist is obviously a continuation of the iron-rich layer at Goat Mountain.

Sillimanite-kyanite-andalusite schist west of Goat Mountain

Layers rich in sillimanite are common in schist southwest of the anorthosite on Goat Mountain (953, 954, 1368, Fig. 2). Some of these layers contain abundant kyanite and others are rich in andalusite. Brown biotite, staurolite, and garnet are the common dark constituents. Most

FIG. 4. A camera lucida drawing of the sillimanite-andalusite schist 1368 from an area 2 miles southeast of Orphan Point on the southwest side of the anorthosite on Goat Mountain, showing replacement of biotite by sillimanite and sillimanite by andalusite. and = andalusite, sill I = brown sillimanite, sill II = colorless sillimanite needles, bi = biotite, qu = quartz, pla = plagioclase.

of this schist is strongly feldspathized, showing a complete transition from schist to anorthosite.

Microscopic study shows that biotite in this schist is partly altered to sillimanite. Most of the biotite is darker brown than in any of the schists described above. But those flakes that seem to be altering to sillimanite are pale in color. The alteration of biotite to sillimanite is clearly seen under the microscope in the schist 1368 and in specimens 954 and 1404 of feldspathized schist. First a nodule of brown fibrous sillimanite is formed. During the advancing crystallization larger colorless needles surround the brownish nodule, which then shows irregular parting. In the specimen 954 a part of the sillimanite in the nodule is crystallized as small prisms of sillimanite, the other part as larger crystal of kyanite which is then surrounded by sillimanite or andalusite. Andalusite also occurs as nodules built of strained small crystals and containing rounded quartz inclusions. In the specimen 1368 a part of the brown sillimanite nodules is inverted to andalusite, which shows a relic parting similar to that in the sillimanite (Fig. 4). There are also andalusite grains without such parting. Many of these andalusite grains include remnants of staurolite.

In the specimen 1404 sillimanite, kyanite, and andalusite occur in aggregates next to each other. Sillimanite aggregates consist of light brownish to colorless needles which show fan-shaped or parallel arrangement and grade over to andalusite. Some kyanite crystals include sillimanite and are surrounded by andalusite suggesting that reactions sillimanite→kyanite→andalusite took place. The reactions biotite→sillimanite and staurolite→andalusite indicate increase of aluminum and decrease of iron and potassium in this schist. The inversion sillimanite→andalusite probably took place during the same phase as the alteration of kyanite to andalusite in the Goat Mountain area.

Reactions similar to those in the schist were observed also in the anorthosite along its border zones. As a rule the border zones of the anorthosite contain abundant aluminum silicates, garnet, and biotite. Remnants of staurolite are common in the Goat Mountain area (e.g. loc. 1353) and cordierite occurs near Smith Ridge (loc. 1412).

Summary of the Alterations Involving the Aluminum Silicates

The following sequence of alterations were observed in thin sections:

(1) Biotite→sillimanite in six specimens (953, 954, 1353, 1368, 1404, 1412).
(2) Staurolite→kyanite in one specimen (997).
(3) Staurolite→andalusite in two specimens (1353, 1368).
(4) Sillimanite→kyanite in six specimens (912, 953, 954, 995, 1404, 1412).
(5) Sillimanite→andalusite in two specimens (1368, 1404).
(6) Kyanite→andalusite in ten specimens (596, 598, 953, 971, 995, 997, 1011, 1017, 1152, 1404).
(7) Kyanite→sillimanite in two specimens (912, 1218).
(8) Andalusite→sillimanite in two specimens (912, 1218).

The brownish fibrous sillimanite is derived, as an alteration product, from biotite, and this same sillimanite was found to be altering further to kyanite, andalusite, or colorless sillimanite. When sillimanite is formed at the expense of andalusite or kyanite (912), it is a needlelike colorless variety. Andalusite also exhibits two varieties: (1) normal-looking individual grains, and (2) clusters or nodules of small strained grains. The latter variety is an alteration product after kyanite.

In summary, it can be said that in the northern part of the Boehls Butte quadrangle the reactions: sillimanite→kyanite→andalusite are common, whereas in the southern part of the quadrangle the reactions kyanite→andalusite→sillimanite and kyanite→sillimanite can be seen. Thus, part of the reactions were reversed in the southern part during a later phase, probably during the emplacement of quartz monzonites. No transformation andalusite→kyanite was seen in the thin sections studied.

Relation of the Inversions of the Aluminum Silicates to the Sequence of Geologic Events

The sequence of alterations listed above show that, first, either sillimanite or sillimanite and kyanite were crystallized. According to the literature kyanite is usually found to crystallize at low temperatures, high pressures, and under stress; sillimanite at high temperature. Their contemporaneous crystallization suggests a fairly high pressure and temperatures at which both would be stable. Both these minerals were crystallized during the folding and regional metamorphism, as were staurolite, cordierite, and biotite, with which they are associated.

During a study of metasomatism in a wider region northwest of the Idaho batholith, it was found that there are several phases of igneous intrusion, metamorphism, and metasomatism. Folding and regional metamorphism were found to be earlier than the metasomatism that formed the anorthosite.

Three major phases of intrusion were distinguished on the basis of structural relations: (1) During the earliest phase small bodies of gabbro and quartz diorite were emplaced. These bodies reveal generally concordant contacts, and the mineral alignment is much like that in the folded country rock. (2) The quartz dioritic border zone of the Idaho batholith cuts the folded country rock in many places discordantly and is thus post-folding; minerals in the quartz diorite show less alignment than those in the small satellitic bodies. Late metasomatic development of andesine and hornblende in the schist and formation of anorthosite bodies are probably connected with this phase of intrusion. (3) Quartz monzonite and silicic tonalite were emplaced later than quartz diorite; they cut the rocks that were metasomatized during the emplacement of the quartz diorite. Thus, both temperature and stresses were fluctuating during the development of the mineral associations. Probably the fluctuation of stresses was favorably timed with that of the temperature to cause the inversions described above.

Crystallization may have proceeded as follows: raising of temperature during the regional metamorphism gave rise to the crystallization of kyanite at the expense of staurolite and crystallization of sillimanite at the expense of biotite. Probably the maximum temperature of regional metamorphism was attained and the temperature had started to fall while the stresses were still operating, causing a rare transformation of sillimanite to kyanite.

The inversion of kyanite to andalusite is later, belonging possibly to the period of the iron-magnesium metasomatism (Table 6), which is postfolding in this area.

In the anorthosite and near its contact, remnants of andalusite are included in metasomatic bytownite, showing that the andalusite crystallized before the anorthitic plagioclase was formed. In an area 20 to 30 miles southwest of Boehls, Fe and Mg were introduced before Ca and Na. In Boehls Butte quadrangle, layers and lenticles of garnet amphibolite, which are common in the schist around the anorthosite bodies and earlier than them, represent basic rocks formed during the iron-magnesium metasomatism. It is possible that the kyanite was altered in part to andalusite under the influence of the metasomatizing solutions during the formation of the garnet amphibolite. Later calcium, which was introduced shortly after iron and magnesium, reacted with this andalusite and formed bytownite.

Colorless sillimanite needles in the southern part of the Boehls Butte quadrangle are later than the andalusite. The transformation of kyanite and andalusite to sillimanite is probably due to a thermal effect caused by the emplacement of nearby igneous rocks belonging to the quartz monzonite series. It is noteworthy that only sillimanite occurs in the zone next to the batholith (south of the Boehls Butte quadrangle). It seems that sillimanite had already crystallized in this zone during the emplacement of the quartz dioritic border zone of the batholith and was in part altered to sericite during the emplacement of quartz monzonites. This transformation requires an addition of potash and occurs only locally.

The relation of these transformations to the sequence of the geologic events is summarized in Table 6.

Inversion of sillimanite to andalusite was seen in two thin sections from a schist west of Goat Mountain. This inversion was suspected in two specimens from the Goat Mountain area, but neither of these was convincing, as it was impossible to determine in thin section whether kyanite had appeared as a metastable form during the transformation. Tilley (1935) described the alteration of andalusite to kyanite in the Carn Chuinneag granite from Ross-shire, Scotland, where regional metamorphism was superimposed on normal thermal metamorphism; and Bosworth (1910) described such alteration around the Ross of Mull granite in Scotland; he also reported parallel growths of andalusite and sillimanite in cordierite-bearing rocks from the same area. Two of these minerals are commonly found together, and it is usually believed that these associations represent arrested transformations. Miyashiro (1949) has discussed stability relations of kyanite, andalusite, and sillimanite, suggesting that each of these minerals has its own stability field and that there is a triple point where all three are stable. However, his diagram

TABLE 6. RELATION OF THE TRANSFORMATION OF THE ALUMINUM SILICATES TO THE SEQUENCE OF GEOLOGIC EVENTS IN BOEHLS BUTTE QUADRANGLE

Geologic events	Transformations
1. Intrusion of gabbros and diorites; folding and regional metamorphism accompanied by metasomatism 1, that is, introduction of Fe, Mg, Al, Ca.	Biotite→sillimanite→kyanite Staurolite→kyanite
2. Emplacement of quartz dioritic border zone of the batholith accompanied by metasomatism 2. (*a*) Introduction of Fe and Mg (*b*) Introduction of Ca (anorthositization)	(*a*) Staurolite→andalusite Sillimanite→andalusite Kyanite→andalusite (*b*) Andalusite→bytownite (in part)
3. Emplacement of quartz monzonites accompanied by (*a*) Thermal metamorphism (*b*) Metasomatism 3 (introduction of alkalies)	(*a*) Kyanite→sillimanite Andalusite→sillimanite (*b*) Sillimanite→muscovite (locally)

fails to give definite figures for the temperature and pressure of the triple point. Turner and Verhoogen (1951, p. 412) have suggested that the sillimanite is a stable form and that andalusite would appear because the reaction producing andalusite is faster. Wilson (1929) suggested that in a dumortierite occurrence in Yuma County, Arizona, kyanite, andalusite, and sillimanite are metasomatic, the kyanite and andalusite being earlier than the sillimanite.

In the light of the present study the sillimanite could be inverted to kyanite by stresses operating at a moderate temperature. But this kyanite would be stable only under stress and would invert to andalusite under the influence of metasomatizing solutions when the stress is released, or revert to sillimanite if the temperature is raised (Fig. 5).

Many occurrences of kyanite in quartz veins show that kyanite can be formed at low temperatures without stress. Verhoogen (1951, p. 258) has shown that during the formation of minerals hydrostatic pressure can substitute for stress. Thus, kyanite would crystallize also under hydrostatic pressure at low temperature, whereas andalusite would be formed if the pressure were lower and/or the temperature somewhat higher.

It is interesting to note that cordierite, which is considered an anti-stress mineral, is a common constituent in the kyanite schists. In some specimens from the Goat Mountain area, it was included in biotite, thus appearing as an unstable relic; but in the Smith Ridge rock it is fresh

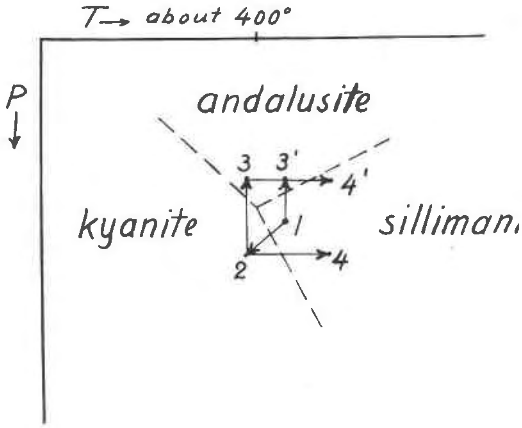

FIG. 5. Diagram showing the possible fields of stability and the inversions of the three aluminum silicates. Stresses or raising of pressure during a falling temperature would cause an inversion sillimanite→kyanite (1→2). During the metasomatism in static conditions kyanite and sillimanite were converted to andalusite (2→3, and 1→3′). Raising of temperature caused inversions andalusite→sillimanite (3 and 3′→4′) and kyanite→sillimanite (2→4).

and shows no signs of incompatability with the kyanite. This suggests that the stability fields of kyanite and cordierite overlap and that a somewhat higher pressure or a stronger stress than that needed to form kyanite is required to make the cordierite unstable.

Temperature and Pressure of the Inversions Sillimanite⇄Kyanite⇄Andalusite

The mineral assemblages are:

(1) Kyanite-andalusite-sillimanite-cordierite-biotite-muscovite-corundum.
(2) Kyanite-andalusite-sillimanite-staurolite-garnet-biotite-muscovite.
(3) Hornblende-diopside-epidote-andesine (An_{36}).

These assemblages suggest that the rocks in Boehls Butte quadrangle were metamorphosed in the border between the kyanite schist facies (Barth, 1952, p. 340) and the amphibolite facies, the temperature being thus around 400° C. In the contact zone between anorthosite on Goat Mountain and garnet amphibolite, abundant epidote occurs with plagioclase (An_{36}). According to Ramberg (1949) and Barth (1952), the temperature at which this plagioclase would crystallize with epidote is close to 400° C. It seems, therefore, that the temperature of the inversion sillimanite→kyanite→andalusite, a relation common in the Goat Mountain area, was close to 400°.

In the southern part of the area, where only sillimanite occurs, the temperature was probably between 400° and 500°, corresponding to the temperatures in the amphibolite facies.

The basification and anorthositization (Table 6) in the area south of Boehls Butte quadrangle probably took place at fairly shallow depths. It is only natural that the same conditions prevailed also in Boehls Butte quadrangle and that the inversion kyanite→andalusite, which is thought to be connected with this second period of metasomatism, therefore took place at moderate or low pressure.

Conclusion

The recorded transformations between kyanite, andalusite, and sillimanite are ascribed to the fluctuation of temperature and stresses (pressure) during a complex thermal metamorphism superimposed on a regional metamorphism in the border zone of the composite Idaho batholith. All the inversions except andalusite→kyanite were observed in the thin sections. This transformation in several areas where regional metamorphism has followed thermal metamorphism has been described in the literature. It seems, therefore, that at certain temperatures both andalusite and sillimanite can be inverted to kyanite under stress. On the other hand, andalusite and kyanite alter to sillimanite at higher temperatures, and kyanite readily to andalusite under the influence of metasomatizing solutions if stresess are released. Thus, each of the three modifications of Al_2SiO_5 may be transformed to the others under certain physico-chemical conditions. It is possible that each of these aluminum silicates has its own stability field and that these stability fields have a common point or overlap to some extent because two of the aluminum silicates, or in rare cases all three, may exist simultaneously. Kyanite is usually found in rocks metamorphosed at low temperatures under stress or high pressure, andalusite at moderate temperatures and low pressures under static conditions, and sillimanite at the highest temperatures in regionally metamorphosed areas. The occurrence of all three modifications together in the schist in Boehls Butte quadrangle suggests that the temperature and pressure during the complex regional and thermal metamorphism there fluctuated around the field where all modifications may exist in equilibrium. The association of epidote and plagioclase (An_{36}) suggests that the temperature field is around 400° C.

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