A NEW STUDY OF THE ANTHOPHYLLITE SERIES*†

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CONTENTS

ABSTRACT

The composition and some physical properties of 96 varieties in the anthophyllite series are studied. Included is data on seven new anthophyllites from the pre-Beltian Cherry Creek rocks of Southwestern Montana. Chemical analyses, spectrographic analyses, optical properties, densities, and unit-cell structure are presented for the Montana varieties. Similar information is presented in part for 89 varieties described in the literature. X-ray

structural studies are given for several doubtful varieties and some of these, such as amosite and high-manganese varieties from Bohemia, are shown to be monoclinic amphiboles. Main conclusions of the study are: 1. The anthophyllite and cummingtonite series are not isodimorphous. 2. The anthophyllite series is a 3-component one of limited isomorphism involving chiefly magnesium, iron, and aluminum. Iron (or Fe'' and Mn'') replaces magnesium from about 5% to about 50% of complete replacement calculated on the atomic basis. Aluminum replaces silicon nearly up to 2 atoms and the same is true of its replacement of Mg, Fe''; the formula $H_2Mg_5Al_2Si_6Al_2O_{24}$ is nearly fulfilled. 3. Magnanese is not important in the series. It is notable that many cummingtonites are high in manganese. Aluminum, high in many anthophyllites, is not a major constituent of the cummingtonite series. 4. Calcium is present in most anthophyllites, the average being about one-half of one per cent. About the same amount of sodium is present in many anthophyllites; potassium is present in negligible amounts in some anthophyllites and is absent in the rest. 5. The identification of anthophyllite is not certain unless based on x-ray methods. This is particularly true of asbestiform varieties.

The name anthophyllite should be used for all members of the series. Chemical suffixes as proposed by Schaller (1930) can be used to indicate any variation in composition if known. All synonyms, such as gedrite, amosite, picroamosite, and ferroanthophyllite, should be dropped.

The series can be characterized by the general formula $X_7Y_8O_{22}(OH, F)_2$ where X is chiefly Mg, Fe'', Al and in minor part Mn, Ti, Fe''', Ca, Na, K; Y is chiefly Si and in part Al. In X the maximum of Al is $(Mg, Fe'')_5Al_2$ and the maximum amount of Fe'' is about $(Mg_{3.5} Fe_{3.5})$. In Y the maximum amount of Al is (Si_6Al_2).

THE PROBLEM

The anthophyllite series, comprising the orthorhombic amphiboles and characterized in general by the formula $(Mg, Fe, Al)_7(Si, Al)_8O_{22}(OH, F)_2$, has long presented some fundamental problems to the mineralogist and petrologist. Although the simplest of the amphiboles, anthophyllite is complex enough in its chemical and physical properties so that no satisfactory study of the series has yet been achieved. A survey of the literature covering the period from the date of its first description (Schumacher 1801) to the present shows that it has been the subject of study by most of the better known mineralogists and petrologists of the times. However, much of the existing information is unsatisfactory. Many chemical analyses have been published without corresponding measurements of physical properties; many figures representing physical properties have been published without corresponding chemical analyses. In many studies, otherwise satisfactory descriptions of the chemical and physical properties are vitiated by an absence of paragenetic considerations.

One of the chief problems concerning the series is that of its relation to the chemically similar cummingtonite-grunerite series of the amphibole group. The varieties in this latter series are crystallographically monoclinic and the question is whether the two series are isodimorphous. In

other words, is there complete isomorphism in the two series between the magnesium and the iron end members? If this were so, there should be a cummingtonite with a composition close to $Mg_7Si_8O_{22}(OH)_2$ and an anthophyllite with a composition close to $Fe_7Si_8O_{22}(OH)_2$ (disregarding aluminum, manganese, and fluorine). If the two series are not isodimorphous, what are the limits of replacement of Mg by Fe″ in the anthophyllites and of Fe″ by Mg in the cummingtonites?

Kunitz in his study of the amphibole group (1930) combined the anthophyllites and cummingtonites in one series. Winchell (1931) disagreed with this and separated the two series. In discussing the anthophyllites he wrote, "Unfortunately no member of this series very high in iron has been studied as yet . . . ."

Sundius (1933) decided that the anthophyllites and cummingtonites were not isodimorphous as no undoubted anthophyllites with more than 40% of the iron "molecule" and no cummingtonites with more than 60% of the magnesium "molecule" were known. Later Winchell (1938) published a further study of the two series. Primarily on the basis of two descriptions of high-iron anthophyllites by Orlov (1932) and Peacock (1928) he decided that the anthophyllite series was filled out to about 90% of the iron end member. He concluded that, "Perhaps the most important conclusion to be derived from these studies is that the anthophyllite and cummingtonite series actually illustrate a case of isodimorphism, since the cummingtonite series extends beyond 60 numerical per cent of $H_2Mg_7Si_8O_{24}$ and the anthophyllite series extends at least to about 90 numerical per cent of $H_2Fe_7Si_8O_{24}$."

Collins (1942) in a short discussion of the correlation of optical properties and chemical composition in the two series concluded that Kunitz and Winchell (and Alling) were " . . . wrong in their belief that cummingtonite, anthophyllite, and gedrite form one homogeneous series."

The soundness of Winchell's conclusion of 1938 depends mainly on the validity of the so-called high-iron anthophyllites. The varieties described by Orlov and Peacock are asbestiform and the identification of such material by optical means is not satisfactory. As no x-ray diffraction studies of these specimens had been made their identification as anthophyllite could be questioned.

The importance of aluminum in the anthophyllite series has not been adequately considered by previous workers. Magnesium and iron have been thought to be the main variables but a cursory survey of anthophyllite analyses shows that alumina occurs in amounts greater than 10% in many varieties. This raises the question as to whether the series might not be best represented with three main variables, magnesium, iron, and aluminum.

A further question concerns the identification of anthophyllite in general. If the identification is based on optical methods alone many amphiboles might be determined as anthophyllite when they are really cummingtonite, tremolite, actinolite, or other monoclinic members. Also, the orthorhombic pyroxenes can be wrongly identified as anthophyllite and vice versa. A combination of optical and chemical determinations does not uniquely determine all varieties of anthophyllite; some would be confused with cummingtonite. It remains, then, to determine the proper method or methods for the identification of anthophyllite.

These questions and others which will be apparent in succeeding pages show that it is desirable to make a new study of the series. This paper is an attempt at such a study.

As a framework the properties of seven new varieties from the pre-Beltian Cherry Creek series of southwestern Montana are described.

This data* is combined with that from the literature to form the basis for answers to the problems outlined. Finally, a revision of the series is proposed and suggestions are made for further work.

NOMENCLATURE AND CLASSIFICATION

Anthophyllite was first described and named by Schumacher (1801). Schumacher's material came from near Kongsberg, Norway, and because of its clove-brown color he named it after the Greek word for clove, anthophyllum. The name was continued by other authors up to 1819. In succeeding years new synonyms were introduced such as *anthogrammit* (Breithaupt 1820), *prismatic schiller-spar* (Jameson 1821), *anthophyllite rayonne* (Haüy 1822), *antholite* (Breithaupt 1830), and *gedrite* (Dufrénoy 1836). None of these survived except gedrite which had been introduced by Dufrénoy for what he regarded as a new species from Gèdres in the Pyrenees. In later years as more analyses of gedrite were made and its physical properties determined it was seen that it was an aluminian variety of anthophyllite and the name is widely used today in that sense.

In Dana's first edition of his *System* (1837) the term *augitus phyllinus* was used but in the third edition (1850) the name was dropped and gedrite and anthophyllite were listed as varieties of hornblende.

The name *kupfferite* was introduced by Hermann (1862) to designate an amphibole similar to anthophyllite in composition but monoclinic in

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* The word "data," unavoidably appearing so often in this report as in much of scientific writing, is used in this paper as a collective noun in the singular. The singular equivalent of data, datum, is rarely if ever used in the sciences in the sense of a single fact and it would seem to me appropriate for scientists to switch to "data is" in place of "data are." There is ample American precedent by analogy for such usage.

form. The original material came from a graphite mine in the Tunkinsk Mountains of Russia and was apparently a chromian amphibole. Similar material from near Miask in the Ilmen Mountains was used for the analysis establishing the composition of the mineral. The name has since been used as a synonym for anthophyllite because it was later assumed that the original material was orthorhombic. After this the original material was again shown to be monoclinic and the name was then given to the magnesium end member of the cummingtonite series. However, no such end member has been found and to end all this confusion it would be best for the name to be dropped.

After 1862 new synonyms proposed were *snarumit* (Breithaupt 1865), *thalackerite* (Breithaupt; see Des Cloiszeaux 1868), *valléite* (Cesàro 1895, 1896), *ferroanthophyllite* (Shannon 1921), *amosite* (Hall 1918; Peacock 1928), and *picroamosite* (Serdiuchenko 1936).

Of these names, ferroanthophyllite assumed immediate importance. Shannon included a note on the nomenclature of the anthophyllite series as follows:

> Palmgren in 1917 found a similar amphibole in the eulysite of Södermannland, Sweden. . . . Palmgren also emphasizes the fact that this amphibole is distinct from anthophyllite, but, following Warren, whom he cites, he used the name eisenanthophyllite, which becomes iron anthophyllite in English. The present writer prefers the form ferroanthophyllite as the name for the iron end member of the anthophyllite group despite the fact that the magensium end member will then require the rather unwieldy name magnesioanthophyllite. This nomenclature is in accord with that recently used by American mineralogists to designate end members of isomorphous groups. The group name anthophyllite will then indicate intermediate mixtures of the two end members of the series, while the name gedrite will continue to indicate important admixture of the aluminous molecule. The possibility of occurrence of lime and manganese members of this series is remotely indicated.

In citing C. H. Warren, Palmgren had reference to Warren's description (1902) of a nearly pure iron anthophyllite from Rockport, Massachusetts. Material similar to that of Palmgren was described by Eckermann (1922) as occurring in the Mansjö Mountain, Sweden. It is interesting that all of this so-called high-iron anthophyllite, including that of Shannon, is either hypersthene (Palmgren's and Eckermann's), grunerite (Warren's), or actinolite (Shannon's).

Peacock (1928), in a study of amosite, decided that that material was high-iron orthorhombic amphibole. The name had been proposed by Hall (1918) for the ash-gray asbestos occurring in the Transvaal of Africa. Wherry (1921) found that it had what he considered to be the optical properties of ferroanthophyllite and he decided that amosite comprised both grunerite and ferroanthophyllite.

From his optical and chemical study Peacock concluded that:

Amosite evidently belongs to the orthorhombic amphiboles; but on account of the intermediate amount of sesquioxides carried by this mineral, and the fact that these constituents apparently link themselves partly in the subvalent gedrite manner and partly with full valency, amosite cannot be properly identified either with anthophyllite, ferroanthophyllite or gedrite. And therefore, if we are justified in retaining crocidolite, which differs from riebeckite only in its fibrous structure, then there are even better grounds for retaining amosite as a mineral species.

Strunz in his study of the silicates (1938) regarded amosite as monoclinic.

Picroamosite (containing 8.28% Fe_2O_3) was proposed as a new name by Serdiuchenko because "it is evidently a magnesial analogue of the amosite, because MgO is almost exclusively represented in the same, and not FeO as in the amosite, therefore the author has named it picroamosite." Serdiuchenko postulated two branches of the isomorphous range in the anthophyllite series, (a) ferroanthophyllite—amosite—gedrite, and (b) magnesioanthophyllite—picroamosite—ferrigedrite.

In the meantime, *Dana's* sixth edition (1892) listed anthophyllite as an orthorhombic amphibole (Dana no. 337) and gedrite was listed as an "aluminous" variety.

Berman (1937) in his important work on the constitution and classification of the natural silicates listed anthophyllite and gedrite as names to be used in the anthophyllite series of the amphibole group.

Winchell (1938) proposed, for the orthorhombic amphiboles, that, "the whole system may be called anthophyllite, the pure magnesian end-member being called magnesioanthophyllite (or maganthophyllite), the pure iron end-member ferroanthophyllite (or feranthophyllite), the high-alumina types gedrite and the high soda antholite." This last name, he said, had been applied to anthophyllite asbestos but he thought that the few available analyses suggested that this variety was always high in soda. Kupfferite, as the name applying to the nearly pure magnesian end member in the cummingtonite series, he said was so far unknown in nature.

Changing views as to the formula to be applied to anthophyllite can be shown by the following formulas in the six editions of *Dana's System:*

First (1837)   —3 parts of bisilicate of magnesia
                    1 part of bisilicate of iron
Second (1844)—None
Third (1850)   —$\ddot{F}e\ \ddot{S}i - Mg^3\ \ddot{S}i^2$
Fourth (1854)—$\ddot{F}e\ \ddot{S}i - Mg^3\ \ddot{S}i^2$
Fifth (1868)   —$\ddot{F}e\ \ddot{S}i - 3\ \dot{M}g\ \ddot{S}i$
Sixth (1892)   —$(Mg, Fe)\ SiO_3$

The formula $(Mg, Fe)\ SiO_3$ was generally accepted as correct until Warren's x-ray study (1930) showed that water was a necessary part of

the structure. That this was true for tremolite had been proposed by Schaller in 1916. Penfield (1890) and Coblentz (1911) had come earlier to similar conclusions for anthophyllite and tremolite.

On the basis of his x-ray study Warren proposed the formula $H_2Mg_7(SiO_3)_8$. A more general one, showing the isomorphism in the series, was adopted by Berman:

$$X_7(Z_4O_{11})_2(OH)_2$$
$$\text{where } X = \text{Mg, Fe, Mn, Al in part}$$
$$Z = \text{Si principally and Al in part}$$
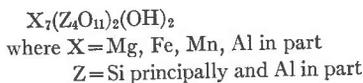
Specifically, this becomes $(Mg, Fe)_7Si_8O_{22}(OH)_2$ for anthophyllite and $(Mg,Fe,Al)_7(Al,Si)_8O_{22}(OH)_2$ for gedrite. It should be emphasized that by this scheme Al can replace Si up to a limit of 2 atoms and it can replace Mg and Fe also up to a limit of 2 atoms. The formula for such a maximum replacement would be $(Mg,Fe)_5Al_2(Si_6Al_2)O_{22}(OH)_2$. Also, OH can be replaced by F.

According to Berman, the cummingtonite series has the same general formula as that of anthophyllite. Specifically, also, the formulas are the same except that grunerite is $(Mg,Fe,Mn)_7Si_8O_{22}(OH)_2$.

These can be contrasted with the formulas given for tremolite $Ca_2Mg_5Si_8O_{22}(OH)_2$ and actinolite $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$.

Such is the status of the nomenclature and classification of the anthophyllite series as it appears in the literature.

CHEMICAL ANALYSES

Ninety-six chemical analyses are given, seven of them new. The 89 from the literature are all that I have been able to find, from John's in 1904 to the present. They show all degrees of accuracy and the material on which they were made no doubt covered a wide range of impurity. In general, analyses of a later date were more accurate, and the material purer, than those made earlier. This dictum is subject to exceptions; the analysis of Penfield (1890) is better than some made in the last fifteen years. It cannot be emphasized too strongly that a good analysis is wasted on impure material. Such a statement is axiomatic but even in late years there have been too many instances of such a waste of a chemist's time. It is hard to determine now the purity of the material used in the earlier analyses but the inference is that much of it was not pure enough for good analytical results. Standard practice today demands that material submitted for analysis be examined microscopically and re-cleaned if the purity is less than 99%. A good description of such practice is in Eskola (1936) and in Collins (1942).

All of the analyses are shown in tables 2 to 6 arranged in each table in order of increasing silica content. They are numbered consecutively and

wherever an analysis, or the anthophyllite it represents, is discussed in this study it will be referred to by that number. The seven new analyses on specimens from Montana are numbered 1, 8, 9, 14, 17, 29, and 30. They are shown separately in table 1 and are repeated in table 2.

TABLE 1. CHEMICAL ANALYSES OF MONTANA ANTHOPHYLLITES
Forest Gonyer, *analyst*

	1. (CC206F)	8. (CC298)	9. (Mont.40-12)	14. (CC121)	17. (CC352C)	29. (CC200A)	30. (Mont.40-8)
SiO_2	42.80	45.41	45.98	48.49	50.36	57.02	57.14
TiO_2	.49	.44	.53	.41	.43	None	Trace
Al_2O_3	17.78	15.84	14.92	13.26	8.06	1.40	1.94
Fe_2O_3	1.03	2.94	.62	1.28	2.18	None	None
FeO	18.32	15.32	17.42	14.60	18.36	8.71	11.12
MnO	.14	.07	.04	None	None	.09	.11
MgO	15.54	17.60	18.27	20.56	17.57	28.81	26.82
CaO	None	.14	.07	.04	.74	1.48	.64
Na_2O	1.52	.28	.47	.11	.70	.66	.27
K_2O	.03	None	None	None	None	None	.06
F	.31	None	None	None	None	None	None
H_2O+	1.94	1.84	1.51	1.48	1.69	1.59	2.06
	99.90						
$0 = F_2$	.13						
	99.77	99.88	99.83	100.23	99.99	99.76	100.16

These varieties occur in the rocks of the pre-Beltian Cherry Creek Series of southwestern Montana as follows:

1. Cherry Creek Area, Madison Co., Montana. In amphibolite with garnet, quartz, plagioclase, and rutile.
8. Cherry Creek area, Madison Co., Montana. In amphibolite with garnet, quartz, plagioclase, and staurolite.
9. Dillon Complex, Beaverhead Co., Montana. In schist bordering a metamorphosed ultramafic body (Dillon Complex) with quartz, feldspar, and spinel.
14. Ruby Dam Area, Madison Co., Montana. In amphibolite with garnet, quartz, plagioclase, chlorite, and rutile.
17. Cherry Creek Area, Madison Co., Montana. Same association as No. 1.
29. Cherry Creek Area, Madison Co., Montana. In isolated boulders with chlorite.
30. Dillon Complex, Beaverhead and Madison Counties, Montana. In the ultramafic body with actinolite, serpentine, enstatite, clinohumite, spinel, annabergite, and magnetite.

The original specimens have been deposited in the collection of the Department of Mineralogy at Harvard University and duplicates will be given to the U. S. National Museum. Thus the numbering system for these specimens is as follows:

Analysis No.	Field No.	Harvard No.	U.S.N.M. No.
1	CC206F	97574	105352
8	CC298	97575	105353
9	Mont.40-12	97576	105354
14	CC121	97577	105355
17	CC352C	97578	105356
29	CC200A	97579	105357
30	Mont.40-8	97580	105358

TABLE 2. SELECTED MODERN ANALYSES OF ANTHOPHYLLITE, 1890–1946

A.—Chemical weight per cent; A is weight per cent MgO+CaO+Na$_2$O+K$_2$O, B is weight per cent FeO+Fe$_2$O$_3$+MnO+TiO$_2$, and C is weight per cent of Al$_2$O$_3$ where A+B+C equal 100 per cent

No.	SiO$_2$	TiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	FeO	MnO	MgO	CaO	Na$_2$O	K$_2$O	F	H$_2$O−	H$_2$O+	Total	FeO+Fe$_2$O$_3$+MnO+TiO$_2$	A	B	C
1	42.80	.49	17.78	1.03	18.32	.14	15.54	None	1.52	.03	.31	—	1.94	99.90	19.98	31.2	36.4	32.4
2	43.70	.55	10.88	3.52	26.53	.24	11.48	.54	1.24	.15	—	—	1.21	100.04	30.84	24.4	55.9	19.7
3	44.09	.31	17.22	1.87	15.02	.14	17.12	.51	1.24	tr	—	.29	2.03	99.55	17.34	35.3	32.2	32.5
4	44.22	—	23.79	.20	9.21	.11	20.69	—	——1.86——		—		1.42	100.31	9.37	38.3	17.7	44.0
5	44.32	—	16.04	2.80	16.88	.09	15.95	.77	—	—	—	—	1.31	100.02	19.77	34.1	36.3	29.5
6	44.70	.57	14.72	1.62	18.96	.21	14.89	.69	1.34	None	—	.29	2.27	100.26	21.36	32.0	40.3	27.7
7	45.38	—	14.70	.94	18.14	.31	15.26	.62	1.20	.19	—	.23	2.77	99.74	19.39	33.6	37.7	28.7
8	45.41	.44	15.84	2.44	15.32	.07	17.60	.14	.28	None	None	—	1.84	99.88	18.77	34.2	35.7	30.1
9	45.98	.53	14.92	.62	17.42	.04	18.27	.07	.47	None	None	—	1.51	99.83	18.66	36.0	35.5	28.5
10	46.50	.89	15.48	.89	16.01	None	17.62	.81	.77	.12	—	—	1.19	100.28	17.79	36.7	33.9	29.4
11	47.24	—	9.63	—	21.29	2.70	15.62	1.16	.35	—	—	—	2.31	100.30	23.99	33.8	46.3	19.9
12	47.86	.63	14.09	.33	14.41	.14	19.89	.57	.93	.06	—	None	2.46	100.42	13.88	43.4	28.1	28.5
13	48.00	1.00	7.63	1.11	26.11	.18	12.66	.64	1.21	.24	—	—	1.09	99.87	28.40	29.1	55.9	15.0
14	48.49	.41	13.26	1.28	14.60	.04	20.56	.04	.11	None	None	—	1.48	100.23	16.29	41.2	32.4	26.4
15	49.66	—	6.74	1.23	18.09	.05	18.62	3.38	—	—	—	—	1.56	99.33	19.37	45.7	40.3	14.0
16	50.10	.73	7.35	None	22.18	.25	16.64	.60	.54	None	—	—	1.15	99.63	23.16	36.8	48.0	15.2
17	50.36	.43	8.06	2.18	18.36	.14	17.57	.74	.70	None	None	—	1.69	99.99	20.87	39.7	43.5	16.8
18	51.06	—	1.90	1.22	24.81	2.03	16.41	.52	—	—	—	—	2.14	100.09	28.06	36.1	59.9	4.0
19	51.62	—	10.32	1.94	3.72	.87	26.82	1.29	.32	.68	—	—	2.23	99.81	6.53	63.3	14.2	22.5
20	52.26	1.11	10.35	4.31	17.13	—	12.52	—	—	—	—	—	2.00	99.68	22.55	27.6	49.6	22.8
21	52.48	.05	4.35	7.03	9.02	—	25.06	.14	—	.26	—		2.00	100.39	16.10	55.6	35.1	9.3
22	53.93	.02	1.79	1.84	20.50	.25	18.92	.12	.15	—	.07	.52	2.08	100.19	22.61	44.1	51.8	4.1
23	55.20	.06	2.83	3.43	8.11	—	28.46	.76	—	—	—	.14	1.27	100.26	11.60	67.0	26.5	6.5
24	55.34	—	2.56	—	15.29	.51	22.80	.63	.19	.12	—	—	2.34	99.78	15.80	56.4	37.5	6.1
25	55.90	None	1.13	8.28	.68	.49	29.26	.94	None	None	—	—	3.20	99.88	9.45	74.1	23.2	2.7
26	55.97	—	.59	1.46	15.38	.48	23.04	.37	.11	.03	.45	—	2.33	100.21	17.32	56.8	41.8	1.4
27	56.27	—	2.07	.40	13.81	.59	23.99	1.15	—	—	—	—	1.83	100.11	14.80	59.9	35.2	4.9
28	56.40	—	1.15	—	11.40	—	28.68	.50	—	—	—	—	1.63	99.76	11.40	69.9	27.3	2.8
29	57.02	None	1.40	None	8.71	.09	28.81	1.48	.66	None	None	—	1.59	99.76	8.80	75.2	21.4	3.4
30	57.14	tr	1.94	None	11.12	.11	26.82	.64	.27	.06	None	—	2.06	100.16	11.23	68.8	26.6	4.6
31	57.19	—	.92	—	7.98	.28	28.03	.76	—	—	—	.48	3.83	99.59	8.26	75.8	21.8	2.4
32	57.46	tr	.79	.81	13.21	.50	24.44	.32	—	.14	—	.06	2.58	100.62	14.52	62.0	36.0	2.0
33	57.60	—	1.94	1.58	6.62	—	30.32	tr	—	—	—	.20	2.66	100.92	8.20	75.0	20.3	4.7
34	57.86	—	2.46	.63	5.96	.33	29.38	.86	.41	—	—	—	2.45	100.34	6.92	76.6	17.3	6.1
35	57.98	—	.63	—	10.39	.31	28.69	.20	—	—	—	.12	1.67	99.99	10.70	71.8	26.6	1.6
36	58.03	—	—	4.87	5.95	—	28.57	—	1.12	.19	—	.17	1.20	100.10	10.82	73.4	26.6	—
37	58.38	—	.10	—	8.37	—	28.82	.61	—	—	—	.68	2.75	99.71	8.27	77.6	22.1	.3
38	58.43	tr	.10	.72	6.84	.12	29.66	tr	tr	tr	—	.16	3.76	99.79	7.68	79.2	20.5	.3
39	58.74	.02	.12	.66	5.61	.06	29.95	tr	tr	tr	—	.24	4.59	99.99	6.35	82.2	17.4	.4
40	58.75	—	1.27	—	5.60	—	31.53	—	.51	—	—	.25	1.70	99.61	5.60	82.3	14.4	3.3
41	58.82	—	.66	.52	—	2.53	30.81	3.45	—	—	.28	—	2.64	99.93	3.05	90.2	8.1	1.7
42	59.12	—	.91	1.01	6.89	.23	29.67	.06	.30	—	—	—	1.97	100.16	8.13	76.9	20.8	2.3
43	59.29	.03	.59	.29	.06	2.77	30.98	1.26	.37	.19	.20	—	3.80	99.83	3.15	89.8	8.6	1.6
44	59.56	—	.66	.76	7.49	.17	28.97	—	—	—	—	.31	2.38	100.30	8.32	76.1	22.1	1.8
45	59.60	—	5.72	.84	3.24	.01	27.94	.22	.12	.04	—	—	2.27	100.00	4.09	74.3	10.7	15.0
46	60.16	tr	.39	.50	5.88	.05	29.04	None	——.33——		—	.21	2.72	100.14	6.43	81.1	17.8	1.1

B.—Number of atoms of each element based on the general anthophyllite formula (Mg, Fe″, Fe‴, Mn, Ti, Al)$_7$ (Si, Al)$_8$ O$_{22}$ (OH, F)$_2$ with minor amounts of (Ca, Na, K) which is one-fourth the content of the unit cell. Col. A is the ratio of aluminum replacing silicon to the aluminum plus ferric iron replacing magnesium, etc. Col. B is the atomic per cent of Fe″+Fe‴+Mn+Ti where Mg+Fe″+Fe‴+Mn+Ti+Al(1) equal 100 per cent

No.	Ca	Na	K	Mg	Fe″	Fe‴	Mn	Ti	Al(1)	Total	Si	Al	Total	OH	F	O	A	B
1	—	.41	—	3.37	2.21	.10	.02	.05	1.24	7.40	6.20	1.80	8.00	1.86	.14	22.00	1.34	35.6
2	.09	.37	.02	2.63	3.37	.40	.03	.06	.63	7.60	6.68	1.32	8.00	1.22	—	22.78	1.28	51.0
3	.08	.32	—	3.67	1.78	.20	—	.03	1.20	7.28	6.30	1.70	8.00	1.92	—	22.08	1.21	27.6
4	.09	—	—	4.24	1.05	.01	.01	—	1.91	7.31	6.07	1.93	8.00	1.30	—	22.70	1.00	16.6
5	.12	.43	—	3.47	2.04	.31	.01	—	1.18	7.58	6.44	1.56	8.00	1.25	—	22.75	1.04	31.2
6	.11	.36	—	3.23	2.28	.17	.03	.06	.97	7.21	6.47	1.53	8.00	2.19	—	21.81	1.34	35.1
7	.09	.32	.03	3.28	2.16	.10	.03	—	.99	7.00	6.51	1.49	8.00	2.63	—	21.37	1.36	32.6
8	.01	.07	—	3.78	1.83	.31	—	.04	1.16	7.20	6.50	1.50	8.00	1.75	—	22.25	1.02	30.2
9	—	.12	—	3.93	2.08	.07	—	.05	1.11	7.24	6.60	1.40	8.00	1.43	—	22.57	1.18	30.5
10	.12	.10	—	3.77	1.88	.10	—	.09	1.24	7.30	6.64	1.36	8.00	1.13	—	22.87	1.01	27.6
11	.17	.09	—	3.42	2.59	—	.33	—	.56	7.16	6.91	1.09	8.00	2.25	—	21.75	1.94	40.7
12	.08	.25	—	4.17	1.56	.02	.02	—	.99	7.09	6.68	1.32	8.00	2.28	—	21.72	1.30	22.6
13	.10	.34	.04	2.87	3.28	.12	.02	.11	.62	6.88	7.26	.74	8.00	1.09	—	22.91	1.00	47.2
14	—	.02	—	4.34	1.71	.13	—	.04	1.01	7.25	6.82	1.18	8.00	1.39	—	22.61	1.03	25.9
15	.50	—	—	4.07	2.20	.14	—	—	.48	7.39	7.25	.75	8.00	1.51	—	22.49	1.20	31.8
16	.10	.14	—	3.68	2.72	—	.02	.08	.65	7.39	7.38	.62	8.00	1.11	—	22.89	.95	38.1
17	.11	.18	—	3.67	2.11	.24	—	.04	.31	6.67	7.01	.99	8.00	1.55	—	22.45	1.80	35.8
18	.08	—	—	3.65	3.06	.14	.25	—		7.18	7.58	.34	7.92	2.12	—	21.88	2.42	48.1
19	.19	.08	.12	5.45	.41	.20	.10	—	.63	7.18	6.99	1.01	8.00	2.00	—	22.00	1.21	9.9
20	—	—	—	2.67	2.02	.46	—	.23	1.14	6.52	7.42	.58	8.00	1.89	—	22.11	.36	41.6
21	.02	—	—	5.22	1.04	.73	—	—		7.01	7.29	.69	7.98	1.85	.15	22.00	.94	25.2
22	.01	.03	—	4.09	2.46	.19	.02	—	.08	6.88	7.77	.23	8.00	1.99	.24	21.77	.85	38.8
23	.10	—	—	5.90	.94	.34	—	—	.08	7.36	7.64	.36	8.00	1.16	—	22.84	.85	17.3
24	.09	.05	.02	4.79	1.79	—	.06	—	.17	6.97	7.75	.25	8.00	2.18	—	21.82	1.47	26.5
25	.13	—	—	5.86	.07	.83	.06	—		6.95	7.47	.18	7.65	2.83	—	21.17	.21	14.4
26	.05	.03	—	4.83	1.79	.15	.06	—	—	6.91	7.83	.10	7.93	2.16	.20	21.64	.66	28.9
27	.16	—	—	5.02	1.61	.05	.07	—	.19	7.10	7.86	.14	8.00	1.68	—	22.32	.58	24.3
28	.07	—	—	5.96	1.31	—	—	—	—	7.34	7.81	.18	7.99	1.49	—	22.51	—	17.9
29	.21	.16	—	5.55	.99	—	.01	—	.08	7.40	7.85	.15	8.00	1.42	—	22.58	1.87	13.5
30	.09	.06	.01	5.51	1.26	—	.01	—	.15	7.09	7.84	.16	8.00	1.88	—	22.12	1.06	17.9
31	.10	—	—	5.65	.89	—	.03	—	—	6.67	7.69	.15	7.84	3.42	—	20.58	—	13.7
32	.04	.03	—	5.06	1.50	.08	.04	—	.06	6.81	7.93	.07	8.00	2.35	—	21.65	.50	23.3
33	—	—	—	6.06	.73	.16	—	—	—	6.95	7.36	.30	7.66	2.35	—	21.65	1.87	12.5
34	.12	.10	—	5.89	.66	.06	.06	—	.14	7.00	7.74	.26	8.00	2.18	—	21.82	1.30	10.7
35	.03	—	—	5.91	1.18	—	.04	—	.06	7.22	7.96	.04	8.00	2.47	—	22.47	.66	16.9
36	—	.30	.03	5.89	.68	.49	—	—	—	7.39	7.98	—	7.98	1.09	—	22.91	—	15.8
37	.09	—	—	5.86	.95	—	—	—	—	6.90	7.92	.02	7.94	2.44	—	21.56	—	13.7
38	—	—	—	5.92	.75	.06	.01	—	—	6.74	7.77	.02	7.79	3.32	—	20.68	.33	12.2
39	—	.06	—	5.88	.62	.06	—	—	—	6.56	7.71	.02	7.73	4.01	—	19.99	.33	10.4
40	—	.06	—	6.38	.63	—	—	—	.13	7.20	7.92	.08	8.00	1.52	—	22.58	.63	8.7
41	.49	.05	—	6.13	—	.05	.28	—	—	7.00	7.80	.11	7.91	2.32	.12	21.56	2.20	4.7
42	.01	.06	—	5.99	.77	.10	.02	—	.11	7.06	7.96	.04	8.00	1.76	—	22.24	.19	12.7
43	.18	.10	.03	6.04	.01	.03	.31	—	.06	6.70	7.76	.09	7.85	3.32	.08	20.60	3.00	5.2
44	—	—	—	5.83	.83	.06	.02	—	.10	6.84	8.00	—	8.00	2.13	—	21.87	—	13.5
45	.03	.03	—	5.50	.35	.08	—	—	.71	6.70	7.83	.17	8.00	2.00	—	22.00	2.12	6.4
46	.06	—	—	5.83	.67	.05	—	—	.06	6.67	8.05	—	8.05	2.42	—	21.58	—	10.7

1. Deduct .13 for O=F$_2$
12. All TiO$_2$ is rutile; P$_2$O$_5$=.05
16. V$_2$O$_3$=.09
20. Average of two analyses
21. Deduct .12 for O=F$_2$
22. Deduct .22 for O=F$_2$
26. Deduct .19 for O=F$_2$
31. Cr$_2$O$_3$=.12
32. Vol.=.21; CO$_2$=.10; Cr$_2$O$_3$=tr.
37. Average of 3 analyses
38. P$_2$O$_5$=.00
39. P$_2$O$_5$=.00
41. Deduct .12 for O=F$_2$
43. Deduct .08 for O=F$_2$
45. Average of 2 analyses recalculated to 2(OH)

No.	Date	Author	Locality	Analyst
1	1948	Rabbitt	Cherry Creek Area, Madison Co., Montana	Forest Gonyer
2	1936	Eskola	Isopää, Kalvola, Finland	Tauno Kervinen
3	1939	Tilley	Karelia, U.S.S.R.	H. C. G. Vincent
4	1931	Henderson	Masons Creek, Franklin Co., North Carolina	E. P. Henderson
5	1908	Evans and Bancroft	Haliburton Co., Ontario, Canada	N. N. Evans
6	1942	Collins	Sutherland, England	Geochemical Laboratories
7	1931	Simpson	Bullsbrook, Western Australia	D. G. Murray
8	1948	Rabbitt	Cherry Creek Area, Madison Co., Montana	Forest Gonyer
9	1948	Rabbitt	Dillon Complex, Beaverhead Co., Montana	Forest Gonyer
10	1934	Ignatiev	Karelia, U.S.S.R.	Author (?)
11	1930	Kunitz	Haddam, Connecticut	W. Kunitz
12	1895	Emerson	Warwick, Massachusetts	E. A. Schneider
13	1914	Eskola	Träskböle, Finland	Pentti Eskola
14	1948	Rabbitt	Ruby River, Madison Co., Montana	Forest Gonyer
15	1920	Shannon	Chesterfield, Massachusetts	E. V. Shannon
16	1914	Eskola	Träskböle, Finland	Pentti Eskola
17	1948	Rabbitt	Cherry Creek Area, Madison Co., Montana	Forest Gonyer
18	1930	Kunitz	Bamble, Norway	W. Kunitz
19	1930	Kunitz	Ötztal, Tyrol	W. Kunitz
20	1937	Rama Rao	Bidaloti, Mysore, India	E. R. Tirumalacher
21	1922	La Croix	Mt. Tsilaizina, Madagascar	Raoult
22	1933	Sundius	Trondhjem, Norway	A. Bygdén
23	1922	La Croix	Mt. Tsilaizina, Madagascar	Raoult
24	1930	Kunitz	Kjernerud, Norway	W. Kunitz
25	1936	Serdiuchenko	Malaya Laba River, North Caucasus, U.S.S.R.	G. Maksimovich
26	1930	Johansson	Falun, Sweden	K. Johansson
27	1917	Ishyul	Kongsberg, Norway	Author (?)
28	1898	Pratt	Bakersville, Mitchell Co., North Carolina	Charles Baskerville
29	1948	Rabbitt	Cherry Creek Area, Madison Co., Montana	Forest Gonyer
30	1948	Rabbitt	Dillon Complex, Beaverhead Co., Montana	Forest Gonyer
31	1902	Rosický	Böhmisch-Schützendorf, Near Deutsch-Brod, Bohemia	Hynek Němeček
32	1939	Uralsky and Buchneva	Kochnevsky, Southern Urals, U.S.S.R.	Authors (?)
33	1926	Shannon	Kamiah, Idaho Co., Idaho	E. V. Shannon
34	1930	Kunitz	Miask, U.S.S.R.	W. Kunitz
35	1890	Penfield	Franklin, Macon Co., North Carolina	S. L. Penfield
36	1932	Stappenbeck	Morogoro, Tanganyika Territory, Africa	Author (?)
37	1902	Friedel	St. Germain-l'Hermite, France	G. Friedel
38	1936	Rimann	Paakila, Finland	G. Grosser
39	1936	Rimann	Paakila, Finland	G. Grosser
40	1913	D'Achiardi	St. Piero in Campo, Island of Elba	Author (?)
41	1930	Kunitz	Edwards, St. Lawrence Co., New York	W. Kunitz
42	1936	Haapala	Paakkilanniemi, Finland	R. Kalajoki
43	1908	Allen and Clement	Edwards, St. Lawrence Co., New York	E. T. Allen and J. K. Clement
44	1936	Haapala	Tiillikainen, Finland	E. Savolainen
45	1943	Bugge	Vormlitjern, Sondeled, Norway	M. Kluever
46	1939	Uralsky and Buchneva	Mramorsky, Middle Urals, U.S.S.R.	Authors (?)

The analyses will be discussed under headings to correspond to those of the tables:

> 1. Selected modern analyses, 1890–1946
> 2. Selected older analyses prior to 1890
> 3. Anthophyllite asbestos from Merrill (1895)
> 4. Poor and incomplete analyses
> 5. Analyses of doubtful and discredited varieties

Selected Modern Analyses, 1890–1946

There are 46 analyses in this category. Criteria for their inclusion are somewhat arbitrary:

1. The analysis must bear a date 1890 or later. Penfield's careful work on the anthophyllite of Franklin County, North Carolina, was published in 1890.

2. The summation of the analysis mut be $100.00\% \pm 0.5\%$. This standard was set by Hillebrand and Washington on good grounds. Such a summation, of course, does not in itself assure the accuracy of the analysis.

3. In the calculation of the formula, on the basis of 24 (O, OH, F) and 8 (Si, Al), the summation of (Ca, Na, K, Fe'', Fe''', Mn, Ti, Al) must be 7 ± 0.5. This figure will be called X. Considering all the errors involved, good anthophyllite analyses which can be checked independently will produce an X close to 7 and or the figure falls outside the indicated limits there must be serious error in the analysis or the material is impure, or both.

4. Although fulfilling the conditions above, the analysis must withstand general inspection, admittedly largely subjective. For instance, some constituent such as SiO_2 or MgO might fall far outside the limits shown by the analyses as a group and no convincing evidence be presented to establish the material as anthophyllite on optical or other grounds. An example of this is number 88. It was made in 1896, fulfilling condition 1. The analysis totals 99.32%, not quite meeting condition 2. X equals 7.5 which meets condition 3. MgO equals 7.32%, much too low for any ordinary anthophyllite, and Na_2O equals 3.21%, which is much too high. No good optical data is presented, so the analysis is listed in table 6 as a doubtful variety.

However, certain liberties have been taken with these specifications. I have included two analyses by Shannon (1920 and 1925), numbers 15 and 33, the first of which totals 99.32% and the second 100.92%. But X in the first is 7.39 and in the second 6.95. Furthermore, they are accompanied by optical and other data and the errors in the analysis can not be too serious.

Table 2 consists of part A, the chemical weights per cent; part B, the calculated formulas; and also columns for author, date, locality, and analyst. Part A also contains a column showing the total weights per cent of $FeO + Fe_2O_3 + TiO_2 + MnO$. Column A $(MgO + CaO + Na_2O + K_2O)$, column B $(FeO + Fe_2O_3 + TiO_2 + MnO)$, and column C (Al_2O_3) show the weights per cent of these combinations of oxides, their combined total being 100%. These figures are used to plot the chemical field of anthophyllite on a triangular diagram (fig. 2).

TABLE 3. SELECTED OLDER ANALYSES OF ANTHOPHYLLITE PRIOR TO 1890

A. Chemical weight per cent

No.	SiO₂	TiO₂	Al₂O₃	Fe₂O₃	FeO	MnO	MgO	CaO	Na₂O	K₂O	F	H₂O−	H₂O+	Total
47	42.86	—	16.52	—	18.82	—	15.51	1.90	—	—	—	—	4.50	100.11
48	43.58	—	17.07	—	15.96	—	18.30	.75	—	—	—	—	3.92	99.58
49	46.74	—	13.70	—	28.09	—	8.76	.77	—	—	—	—	1.90	99.96
50	51.80	—	12.40	—	3.67	—	27.60	—	|— 1.44 —|		—	—	3.00	99.91
51	56.88	—	2.45	—	9.65	—	28.50	—	.21	—	—	—	2.28	100.14
52	59.23	—	.19	—	8.27	—	31.02	—	—	—	—	—	1.31	100.02

51. NiO = .17

B. Number of atoms, based on the general amphibole formula (O+OH+F equals 24) where X equals
Ca+Na+K+Mg+Fe″+Fe‴+Mn+Ti+Al and Y equals Si+Al

No.	X	Y	O	(OH, F)
47	6.50	8.00	19.79	4.21
48	7.23	8.00	20.16	3.84
49	6.90	8.00	22.13	1.87
50	7.00	8.00	22.16	1.84
51	7.05	8.00	21.91	2.09
52	7.27	8.00	22.81	1.19

No.	Date	Author	Locality	Analyst
47	1861	Des Cloizeaux	Gèdres, Pyrenees Mountains, France	F. Pisani
48	1862	Des Cloizeaux	Gèdres, Pyrenees, Mountains, France	F. Pisani
49	1868	Des Cloizeaux	United States	G. Lechartier
50	1877	Pisani	Bamble, Norway	F. Pisani
51	1882	Genth	Castle Rock, Delaware County, Pennsylvania	F. A. Genth
52	1842	Rose	Tschussowaja Springs, Ural Mts., U.S.S.R.	G. Rose

TABLE 4. ANALYSES OF SOME ANTHOPHYLLITE ASBESTOS FROM MERRILL (1895)

No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	F	H_2O-	H_2O+	Total
53	54.56	—	1.47	—	12.39	—	25.28	1.86	—	—	—	—	2.95	98.51
54	54.79	—	{ 13.65 }		—	—	28.52	—	—	—	—	—	2.55	99.51
55	55.92	—	3.69	—	11.00	tr	26.32	.60	—	—	—	—	2.40	99.94
56	56.21	—	2.78	—	8.58	—	28.95	.82	—	—	—	—	2.23	99.57
57	56.52	—	3.57	—	10.08	tr	27.13	tr	—	—	—	—	2.96	100.26
58	56.72	—	1.54	—	10.76	—	27.46	.10	—	—	—	—	2.88	99.49
59	57.00	—	{ 10.32 }		—	—	29.98	tr	—	—	—	—	2.29	99.59
60	57.31	—	1.57	—	7.06	—	30.24	.08	.57	.14	—	—	2.73	98.91
61	57.73	—	.72	—	8.61	—	28.77	.45	.68	.43	—	—	2.52	99.14
62	59.00	—	.91	—	6.09	—	29.90				—	—	2.35	99.81

No.	U.S.N.M. No.	Locality	Analyst
53	62090	Carbon County, Wyoming	G. P. Merrill
54	44232	Franklin County, North Carolina	G. P. Merrill
55	—	Tallapoosa County(?), Alabama	G. P. Merrill
56	—	Lenoir, Caldwell County, North Carolina	G. P. Merrill
57	56351	Rabun County, Georgia	G. P. Merrill
58	62604	Alberton, Maryland	G. P. Merrill
59	62748	Warrenton, Warrenton County, North Carolina	G. P. Merrill
60	67001	San Diego, California	G. P. Merrill
61	60842	Nacoochee, Georgia	R. L. Packard
62	50876	Mitchell County, North Carolina	G. P. Merrill

JOHN C. RABBITT

TABLE 5. POOR AND INCOMPLETE ANALYSES OF ANTHOPHYLLITE

A. Chemical weight per cent

No.	SiO₂	TiO₂	Al₂O₃	Fe₂O₃	FeO	MnO	MgO	CaO	Na₂O	K₂O	F	H₂O−	H₂O+	Total
62a	38.81	—	9.31	—	45.83	—	4.13	.67	—	—	—	—	2.30	101.05
63	41.59	.97	12.81	5.90	14.81	tr	15.13	3.55	.43	.12	2.34	.86	1.68	100.35
64	43.92	—	11.34	—	16.81	1.47	19.14	3.02	—	—	—	—	1.68	97.38
65	50.37	—	10.82	—	15.89	—	19.75	.84	1.59	—	—	—	—	99.26
66	50.80	—	3.60	3.70	6.80	—	26.10	1.20	.20	—	—	—	5.80	98.20
67	51.74	—	8.55	—	20.35	.41	16.45	1.79	—	—	—	—	—	99.29
68	51.88	—	1.01	—	6.21	—	41.02	—	—	—	—	—	.81	100.93
69	52.05	—	9.46	—	20.72	.26	17.24	1.35	—	—	—	—	—	101.08
70	54.48	—	4.68	—	8.16	.32	29.80	.32	—	—	—	None	1.22	98.98
71	55.12	—	.55	—	8.20	.33	31.18	.75	1.55	1.01	—	—	2.21	100.90
72	56.00	—	3.00	—	13.00	4.00	23.00	2.00	—	—	—	—	—	101.00
73	56.00	—	13.30	—	6.00	3.00	14.00	3.33	—	—	—	—	1.43	97.06
74	56.16	—	2.65	—	14.13	.91	23.19	1.51	—	—	—	—	2.38	100.93
74a	56.34	—	2.33	—	9.76	2.05	23.99	.80	—	—	—	1.13	1.64	98.04
75	56.74	—	—	—	13.94	2.38	24.35	—	.60	—	—	—	1.67	99.08
76	56.86	—	4.50	—	8.13	.87	25.87	1.09	—	—	—	—	3.36	100.68
77	57.12	—	tr	—	13.52	—	25.92	1.32	—	—	—	—	1.36	99.24
78	57.39	—	2.04	.42	6.53	—	29.08	.69	—	—	—	—	2.56	98.71
79	57.90	—	13.55	—	1.90	—	19.40	.87	4.50	—	—	—	2.86	100.98
79a	58.02	—	—	1.28	—	2.88	27.99	5.04	—	.89	—	—	3.13	99.23
80	58.19	—	.18	—	7.93	—	30.79	—	—	—	—	—	1.86	98.95
81	58.48	—	—	—	9.22	.88	31.38	.04	—	—	—	—	—	100.00
82	59.25	—	2.45	—	6.49	1.05	28.16	1.57	—	—	—	—	—	98.97

63. Average of 2 analyses; deduct .93 for O=F₂; P₂O₅=.16

B. Number of atoms, based on the general amphibole formula (O+OH+F equals 24) where X equals $Ca+Na+K+Mg+Fe''+Fe'''+Mn+Ti+Al$ and Y equals $Si+Al$

No.	X	Y	O	(OH, F)	No.	Date	Author	Locality	Analyst
62a	7.36	8.00	21.51	2.49	62a	1836	Dufrénoy	Gèdres, Pyrenees Mountains, France	A. Dufrénoy
63	8.01	8.00	21.25	2.75	63	1915	Pawlica	The Tatra, Czechoslovakia	W. Pawlica
64	7.84	8.00	22.37	1.63	64	1882	Sjögren	Snarum, Norway	G. W. Peterson
65	7.98	8.00	24.00	—	65	1905	Böggild	Avisisarlik, Greenland	C. Christensen
66	6.69	7.46	19.02	4.98	66	1888	Teall	The Lizard, Cornwall	X. Player
67	7.60	8.00	24.00	—	67	1878	Wiik	Stansvik, Finland	O. Rosenius
68	9.15	7.27	23.26	.74	68	1894	Doelter	Schneeberg, Germany	J. Ippen
69	7.44	8.00	24.00	—	69	1878	Wiik	Stansvik, Finland	K. Stadius
70	7.41	8.00	22.89	1.11	70	1928	Ross and others	Webster, North Carolina	Forest Gonyet
71	7.79	7.38	22.08	1.92	71	1873	Leeds	Delaware County, Pennsylvania	A. R. Leeds
72	7.26	8.49	24.00	—	72	1862	Des Cloizeaux	Kongsberg, Norway	F. Pisani
73	6.44	8.00	22.52	1.48	73	1831	Vopelius	Kongsberg, Norway	L. Gmelin
74	7.47	8.00	21.67	2.33	74	1809	John	Kongsberg, Norway	J. Fr. John
74a	6.47	8.00	22.50	1.50	74a	1914	Schirmeisen	Podoli, Near Bobrau, Moravia	Matthia Krebs
75	7.10	8.05	22.43	1.57	75	1831	Vopelius	Kongsberg, Norway	L. Vopelius
76	6.58	8.00	21.03	2.97	76	1879	Heddle	Mainland, Shetland Islands	F. Heddle
77	7.25	8.05	22.73	1.27	77	1836	Thomson	United States	T. Thomson
78	6.88	8.00	21.69	2.31	78	1874	Brezina	Hermannschlag, Moravia	E. Ludwig
79	6.61	8.00	21.52	2.48	79	1877	Pisani	Snarum, Norway	F. Pisani
79a	6.90	7.81	21.21	2.79	79a	1896	Cesàro	Edwards, St. Lawrence Co., New York	Renard
80	7.21	7.97	22.31	1.69	80	1843	Rose	Tschussowaja Springs, Ural Mts., U.S.S.R.	G. Rose
81	7.72	8.14	24.00	—	81	1835	Lappe	Koruk, Greenland	M. Lappe
82	7.30	8.21	24.00	—	82	1873	Leeds	Lafayette, Pennsylvania	A. R. Leeds

TABLE 6. DOUBTFUL AND DISCREDITED VARIETIES OF ANTHOPHYLLITE

A. Chemical weight per cent

No.	SiO₂	TiO₂	Al₂O₃	Fe₂O₃	FeO	MnO	MgO	CaO	Na₂O	K₂O	F	H₂O−	H₂O+	Total
83	42.98	—	2.14	1.50	37.82	10.66	5.91	1.50	—	—	—	—	5.23	97.08
84	45.87	tr	2.34	6.32	29.34	10.66	1.37	2.31	2.30	—	—	.30	1.86	100.37
85	46.18	—	21.78	.44	2.77	—	25.05	—	—	—	—	—	1.37	99.89
86	47.04	tr	7.02	2.43	26.10	.15	4.96	10.84	tr	tr	—	.45	1.05	100.19
87	47.35	tr	4.20	3.34	36.60	.28	5.80	.77	tr	tr	—	.35	1.25	100.03
88	47.40	—	13.68	—	23.38	2.36	7.32	—	3.20	tr	—	—	1.97	99.32
89	52.44	—	2.62	—	5.71	—	35.83	.43	—	—	—	—	2.74	99.77
90	53.69	—	1.65	.32	5.94	16.10	20.50	1.25	—	—	—	.02	.70	100.17
91	57.12	—	—	—	6.36	tr	29.44	—	—	—	—	—	5.74	99.14
92	57.70	None	2.00	tr	5.32	tr	21.12	5.10	7.40	None	None	.30	1.80	100.74
93	62.66	—	13.33	—	12.00	3.25	4.00	3.33	—	—	—	—	1.43	100.00

86. P_2O_5=tr; S=.05; SO_4=.00; CO_2=.10.
87. P_2O_5=.04; S=.05; SO_4=.00; CO_2=tr.

B. Number of atoms, based on the general amphibole formula (O+OH+F equals 24) where X equals Ca+Na+K+Mg+Fe''+Fe'''+Mn+Ti+Al and Y equals Si+Al

No.	X	Y	O	(OH, F)	No.	Date	Author	Locality	Analyst
83	—	—	—	—	83	1931	Winchell	Mesabi Range, Minnesota	C. R. Wise
84	6.90	7.95	21.98	2.02	84	1932	Orlov	Jacobeni, Bukovina	Author(?)
85	7.76	8.00	22.78	1.22	85	1889	Ussing	Fiskernäs, Greenland	Author(?)
86	7.30	8.00	22.91	1.09	86	1928	Peacock	Kalkfontein, Cape Province, Africa	W. H. & F. Herdsman
87	7.19	8.00	22.68	1.32	87	1928	Peacock	Penge, Transvaal, Africa	W. H. & F. Herdsman
88	7.24	8.00	22.05	1.95	88	1896	Weibull	Dalekarlien, Norway	J. Petrén
89	7.90	7.50	21.54	2.46	89	1932	Wiesander	Tannwaldgraben, Austria	Author(?)
90	7.64	8.00	23.33	.67	90	1927	Slavik	Chaveltice, Bohemia	V. Veselý
91	6.47	7.59	19.24	4.76	91	1895	Merrill	Salls Mountain, Georgia	R. L. Packard
92	8.00	8.00	22.36	1.64	92	1930	Laudermilk and Woodford	Coffee Creek, Trinity County, California	J. D. Laudermilk
93	5.14	8.55	22.71	1.29	93	1806	John	Kongsberg, Norway	J. Fr. John

Part B shows the number of atoms in the formulas, calculated on the basis of 8 (Si, Al) and 24 (O, OH, F) which is one-fourth the content of the unit cell. It has been suggested by Berman (1937), among others, based on the examination of hundreds of amphibole formulas, that a maximum of 2 silicon atoms can be replaced by aluminum. Where such a replacement occurs an adjustment of valence must take place by the replacement of Mg or Fe″ by ferric iron or by other means. If such a replacement by Al occurred and if the anthophyllite series were a completely isomorphous one from the magnesium to the iron end, then the "end members" with their weights per cent of the constituent oxides would be:

1. $H_2Mg_7Si_8O_{24}$
   MgO $= 35.99\%$
   $SiO_2 = 61.70\%$
   $H_2O = 2.31\%$

2. $H_2Fe_7Si_8O_{24}$
   FeO $= 50.25\%$
   $SiO_2 = 47.96\%$
   $H_2O = 1.79\%$

3. $H_2Mg_5Al_2Si_6Al_2O_{24}$
   $Al_2O_3 = 26.08\%$
   MgO $= 25.58\%$
   $SiO_2 = 46.04\%$
   $H_2O = 2.30\%$

4. $H_2Fe_5Al_2Si_6Al_2O_{24}$
   $Al_2O_3 = 21.66\%$
   FeO $= 38.17\%$
   $SiO_2 = 38.25\%$
   $H_2O = 1.92\%$

and the possible range in the oxides would then be:

SiO_2	38.25–61.70%
H_2O	1.79– 2.31%
FeO	up to 50.25%
MgO	up to 35.99%
Al_2O_3	up to 25.58%

This is based on ideal considerations. In the natural material small amounts of Ca, Na, K, Ti, and Mn are nearly always present in the crystal structure. It would be expected that Na and K would be less common, and Ca, Ti, and Mn more common in replacing Mg and Fe; the analyses show this to be true.

Part B of table 2 also contains a column showing the ratio of Al replacing Si to Al plus Fe‴ replacing Mg, Fe″, etc. Ideally, this ratio should be 1 and where it departs widely from that figure some other adjustment of valence may have occurred or the analysis may be wrong (or the material impure). These questions could be considered fruitfully only if there were a thousand or more analyses with which to work.

Finally, part B also has a column showing the atomic per cent of Fe‴+Fe″+Ti+Mn where these atoms and Ca+Na+K+Mg+Al equal 100%. These figures are useful in considering the degree of isomorphism in the series.

In all of these calculations the figures are carried to the second decimal

place; this is probably not justified by the accuracy of the analyses. The ordinary routine mineral analysis is not so accurate as the figures presented would indicate. Rarely, in the case of the more important oxides, as SiO_2, does the second decimal place mean anything; the mineralogist and petrographer would be happy to know that the figures were correct to a few figures in the first decimal place.

In the discussion that follows, the variation of the different oxides is considered and this will give a rounded picture of the chemical side of the series.

SiO_2.—Silica ranges from 42.08% to 60.13%. This nearly covers the theoretical limits of 38.25–61.70%. As the table is arranged in order of increasing silica content it is easy to see that there are no significant gaps in this range. Naturally, with increasing iron and aluminum, silica decreases, the greatest decrease coinciding with increase in alumina.

In the calculated formulas, the number of atoms of silicon ranges from 6.07 (no. 4) to 8.00 for number 44 and 8.05 for number 46. Number 4 represents almost the theoretical maximum replacement of silicon by aluminum. The other two are examples of no replacement and are typical of those anthophyllites nearly or quite aluminum-free.

In most of the examples there is enough silicon and aluminum to satisfy the theoretical maximum of 8 atoms. Some, notably in the aluminum-poor, magnesium-rich range, show a deficiency of either one of these two elements or both, the worst being number 25, where the total is 7.65, followed by number 33, total 7.66, and number 39, total 7.73.

TiO_2.—Titania is present in small amount in many, if not all anthophyllites, notably in the high-aluminum, high-iron ones. It should always be looked for but of the 46 analyses it was determined in only 24. Apparently where alumina is about 10% or more TiO_2 ranges from 0.41% to 1.11%. As alumina decreases the titania falls off sharply to a range from traces to 0.06%. Titanium thus seems to go with either aluminum or iron or both.

CaO, Na_2O, and K_2O.—Calcium is nearly always determined and ranges up to 3.45% CaO. There is some possibility that this represents impurity. The usual amount is about 0.5% and this seems to be definitely in the crystal structure.

Soda is not always determined but where it is the range is up to 1.34%, with the average being about 0.5%. In four analyses, only total alkali is given, a practice to be condemned. There is no doubt that some soda enters the crystal structure.

Potassium is usually present in negligible amounts or is completely absent. It should always be determined for the sake of completeness but where more than about 0.5% is present impurity should be suspected.

Potassium, on account of its large ionic volume as compared to magnesium and iron, would not be expected to enter the anthophyllite structure to any large extent. The figures confirm this idea.

Al_2O_3.—Alumina is more important in the anthophyllite series than has been realized. The series is usually regarded as a magnesium-iron one but it is clear that it is a ternary system. Of the 46 analyses, 14 show more than 10% Al_2O_3 and 20 show more than 5%. The amount ranges up to 23.79% (no. 4). Despite this, there are such statements as Winchell's (1931) to the effect that "the anthophyllite series differs from all other amphiboles, not only in simplicity of composition, due to the absence of Ca, Al, and Na atoms . . . ." Sundius (1933) does not stress the importance of aluminum although he does plot the composition of the Ca-poor amphiboles on a three-component diagram, one component being $Al_2O_3 + Fe_2O_3$. Tilley (1939) uses a similar diagram in which Al_2O_3 is one of the components.

The substitution of Al atoms for Si atoms and the accompanying substitution of Al (and Fe''') for Mg and Fe'' is reflected in the formulas. The ratio of Al in the first case to Al + Fe''' in the second, which should be 1, rarely is so perfect. Analysis number 4, showing almost the maximum replacement, has a ratio of 1 but many others diverge widely from this (nos. 6, 7, 11, 12, 17, 18, and others).

In general, high-alumina means high-iron but there are many exceptions. The peak of alumina content seems to come about midway in the series; it is noteworthy that aluminum is a minor element in the cummingtonite series which is high in iron.

FeO and Fe_2O_3.—Ferrous iron ranges up to 26.53%. In reality the series is not filled out to the magnesium end as numbers 41 and 43, which contain practically no FeO, do have 2.53% and 2.77% MnO plus 0.52% and 0.29% Fe_2O_3 respectively. These, from Edwards, New York, are the purest anthophyllites known.

At the iron end it is apparent that the series is not completely isomorphous. A pure iron end member would contain 50.25% FeO. One with the maximum amount of alumina would contain 38.17% FeO (with 21.66% Al_2O_3). Number 2 shows the highest iron content (26.53%) and FeO + Fe_2O_3 + MnO equals 30.29% (with Al_2O_3 10.88%). It is seen that the series is one of limited miscibility. Evidence will be presented to show that the so-called anthophyllites with an FeO content higher than that of number 2 are monoclinic by x-ray examination. In the formulas the Mg/Fe'' + Fe''' + Mn ratio of number 2 is 2.63/3.80.

Ferric iron is present in limited amount in many anthophyllites. It is doubtful if all the Fe_2O_3 reported by the chemist is always a true reflection of the original amount. The ease with which FeO is oxidized in the prepa-

ration of the sample makes any figure representing Fe_2O_3 subject to suspicion. Only by exercising extreme care can the chemist make an accurate determination of this oxide. For this reason, such figures as 0.20% (no. 4) and 0.33% (no. 12) are not important. However, we must accept 7.03% (no. 21) and 8.28% (no. 25) as representing a real presence of Fe''' in the structure. In principle we might expect high Fe_2O_3 to go with high Al_2O_3 but this is not clearly apparent. Ferric iron seems to follow ferrous iron as much as aluminum, a condition which may reflect some oxidation.

MnO.—Manganese is not important in the anthophyllite series. Four analyses (nos. 11, 18, 41, 43) show more than 1.00% MnO, the highest being 2.77%. The rest average about 0.25%. Some high-Mn anthophyllites (up to 16.10% MnO) have been described but it will be shown in the section on *x*-ray study that these are cummingtonites. The cummingtonite series contains many varieties high in manganese. It may be that Mn, with an ionic volume of 3.14, more easily substitutes for Fe'', with an ionic volume of 2.39, than for Mg with an ionic volume of 1.97.

MgO.—Magnesia ranges from 11.48% (no. 2) to 31.53% (no. 40). In the formulas, number 40 shows the highest Mg content (6.38) but $X = 7.20$ and $Fe'' = 0.63$. Number 41, on the other hand, has a Mg content of 6.13 and $Mg + Ca + Na$ equal 6.67 where X is 7.00. There is no Fe'', and $Fe''' + Mn$ equal 0.33. This purest anthophyllite thus has a ratio of $Mg + Ca + Na/Fe''' + Mn$ of 6.67/0.33, fairly close to an end member.

Fluorine.—No amphibole analysis is complete without a fluorine determination, but there are only twelve such determinations, including the seven made on the Montana specimens, in the list. Six of the Montana analyses show no fluorine; the other (no. 1) shows 0.31%. This seems to be an average amount for those that have any fluorine but it is to be regretted that more determinations have not been made. It is true that a good fluorine determination on an amphibole is not easy for any chemist, but the analysis should always be required.

Water.—Up to 1930 it was generally believed that anthophyllite was anhydrous despite the fact that Schaller (1916) had shown that OH was part of the tremolite formula. Penfield (1890) also realized that the water always appearing in an amphibole analysis was water of constitution and he devised the Penfield method for the determination of such water in amphiboles and other silicates (Penfield 1894). This method, with some modifications of apparatus, is the one in general use today. In the period before 1890, water of constitution (H_2O+) was determined usually by ignition; the material was heated in a crucible to red heat and the loss in weight computed as "loss on ignition" equated to H_2O+. H_2O- was

computed as adsorbed water and was driven off by heating the sample to 105°–110° C.

Determination of water by ignition is subject to serious error. Any ferrous iron present will oxidize to ferric iron and a gain in weight might result. Hence the method should not be used today.

The Penfield method was used in the determination of H_2O in the seven Montana specimens. In six of the seven specimens what was regarded as normal amounts of water were secured at the temperature used in the method, about 1000° C. for five minutes. The seventh specimen (no. 30) showed only 0.28% H_2O by this procedure. This was so much lower than the water content of any other anthophyllite that the determination was repeated and the heating was continued for 15 minutes. This resulted in 1.43% H_2O which indicated that something might be wrong with the method. The material was subjected to differential thermal analysis (described further on in this section) and it was seen that water was not fully driven off at a temperature of 1050° C. maintained for 15 minutes.

Mr. Forest Gonyer then suggested that a method be used based on the use of the tubulated crucible described by Gooch. In this method, the material is fused with anhydrous sodium carbonate in a type of tubulated crucible and water can be collected in any one of a number of ways. If done carefully, this procedure assures that all the water is driven off; the collection of the water involves merely the technical skill of the chemist. In this method, 2.06% H_2O was secured from specimen number 30, which was calculated to 1.88 (OH) in the formula. It is thought that this represents the best possible determination of water.

This tends to confirm the belief held by some chemists and mineralogists that all determinations of water in amphiboles involving the Penfield or similar methods may be and probably are wrong. It has been known for a long time that water in the amphiboles cannot easily be driven off, even at 1000° C. or 1100° C. There have been, of course, many studies made of this problem together with the parallel one of whether or not the loss of water was accompanied by atmospheric oxidation. Barnes (1930) presented a summary of this work and in a study of his own, in heating hornblende to 800° C., concluded in part that

> In dehydration, hydrogen and not water (except water that is not a constituent part of the space lattice) is given off, and the oxygen remains in the mineral, either oxidizing ferrous to ferric iron or, when ferrous iron is not present, remaining because of its size.

There is no general agreement on the behavior of water in the amphiboles during heating nor at what temperatures the different fractions of water are given off. For instance, Belyankin and Donskaya (1939) in a specimen of actinolite containing 3.73% H_2O, found that on heating,

the loss of total water was 1.68% at 400° C., 2.42% at 800° C., and 3.64%, or nearly all, at 950° C. Here, of course, it is not certain that the original analysis secured all of the water.

In trying to solve some of these questions a differential thermal analysis was made on three of the Montana specimens (nos. 14, 29, 30) and a high-iron cummingtonite from the same area as number 17. The runs were made by Dr. Carl Beck who has made a differential thermal analysis study of carbonates for a Ph.D. thesis (May 1946) in the Department of Mineralogy at Harvard University. The resulting curves are reproduced in figure 1 together with a curve for gibbsite from Dr. Beck's thesis. These curves show exothermic and endothermic reactions occurring in the specimen during heating. The reactions are reproduced as deviations of the trace of the zero line, endothermic below and exothermic above. The area of the deviation is proportional to the energy involved. The curves start at 50° C. and proceed up to 1050° C. (the safe limit of the apparatus) at a steady rate of 50° C. for about every 4 minutes.

The curves are disappointing in that no clear interpretation is possible and no markedly sharp breaks are evident. The difficulty in interpretation is due to the simultaneous loss of water and oxidation of ferrous iron. The first is endothermic, the second exothermic, and the resultant trace may be above or below the zero line. The curves do show that there is a gradual loss of water from 150° C. to about 500° C. and that probably another loss begins at about 750°–850° C. Number 14 shows a rather sharp shallow break from 1000° to 1025° C. and the same break occurs in number 29. This is probably a sudden loss of water; all of the specimens show a vague continuing loss at 1050° C. at the conclusion of the runs and it can be said that in none has all the water been driven off. In contrast to these curves the gibbsite shows a clear deep break at 250° C., reaching a maximum at about 350° C. The trace returns to the zero line at 425° C. and continues unswervingly on this line to the end of the run at 1000° C. This break shows the loss of water and the curve is most satisfactory.

This study settled nothing but tended to confirm the idea that water is not thoroughly driven off in the Penfield method. Time did not permit the redetermination of the water in the other six Montana specimens and it must be admitted that in them the figures for H_2O are probably somewhat low.

Chemical Field.—The 46 analyses are plotted on a triangular diagram as shown in figure 2. The three components are weights per cent of ($MgO + CaO + Na_2O + K_2O$), ($FeO + Fe_2O_3 + TiO_2 + MnO$), and Al_2O_3, the combination of these oxides equalling 100%. The numbers of the Montana specimens are underlined. It is seen that there is a distinct concentra-
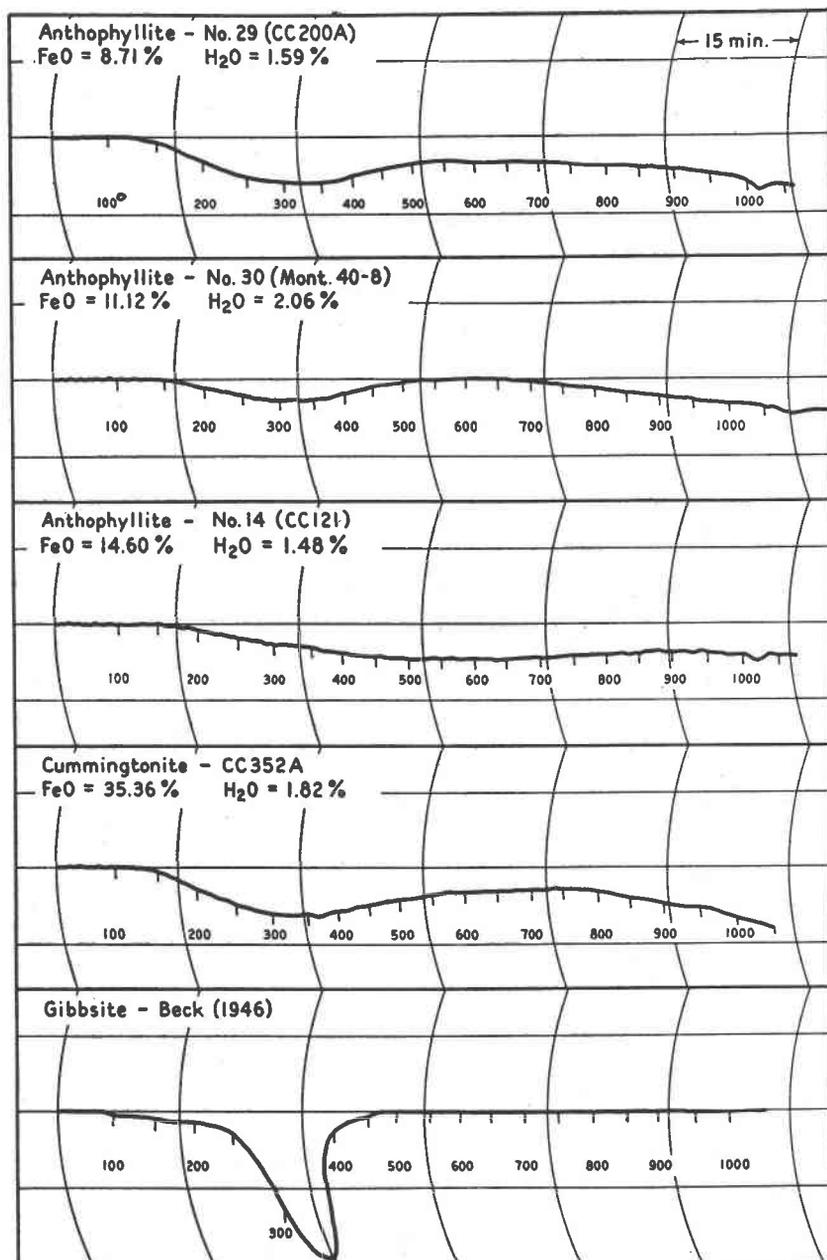
FIG. 1. Differential thermal analysis curves for three anthophyllites and one cummingtonite. These are compared to one for gibbsite which shows clearly a loss of water reaching a peak at about 350° C. Figures running horizontally along the bottom of each curve are degrees C.

tion at the high-magnesia, low-alumina corner of the plot and another approximately in the center. The iron corner, of course, is blank and
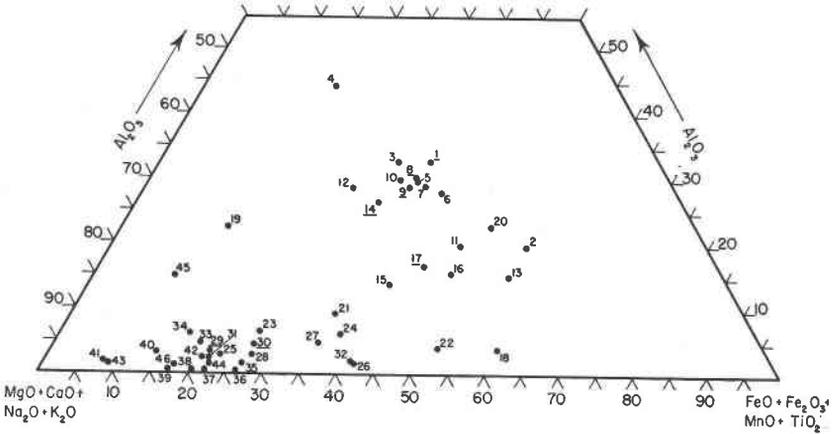
Fig. 2. Composition of 46 anthophyllites whose compositions are shown in table 2. The numbers of the Montana varieties are underlined. The plot is based on the chemical weights per cent of the oxides shown, the sum of these oxides being 100%.
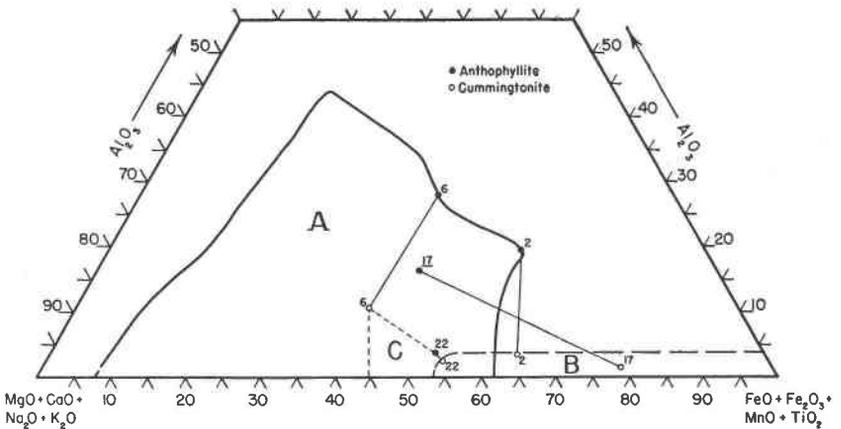
Fig. 3. The chemical fields of anthophyllite and cummingtonite outlined from figure 2. "A" is the anthophyllite field; "B" is the cummingtonite field after Sundius (1933); "C" is a possible extension of "B" to accommodate the cummingtonite of Collins (1942). The four pairs of anthophyllite and cummingtonite whose analyses are given in table 7 are plotted and connected with lines.

there is a blank area centering around 40(FeO), 15(Al_2O_3), and 45(MgO). There are not enough analyses to show if this gap is real or not.

The field outlined by these analyses is shown in figure 3. "A" represents the anthophyllite field, "B" is the cummingtonite field, after Sundius (1933), and "C" is a possible extension of this field which includes a cummingtonite recently described by Collins (1942). Three occurrences of anthophyllite with cummingtonite have been described (nos. 2, 6, 22) and a fourth from Montana (no. 17) is presented here. These are shown in figure 3, the numbered solid dots representing anthophyllites tied to their accompanying cummingtonites shown by similarly numbered circles. It is probable that pair number 22 was in equilibrium but it is apparent, both from the author's description and the plot, that the others were not. The cummingtonite of number 6 is unusual in being high in alumina, and in being rather deep in the anthophyllite field. This may indicate a large overlap in the two fields.

The analyses of the four anthophyllites and their corresponding cummingtonites are shown in table 7.

TABLE 7. ANALYSES OF ANTHOPHYLLITE AND CUMMINGTONITE,
EACH PAIR FROM THE SAME ROCK

(A=anthophyllite; C=cummingtonite)

	No. 2 (Eskola 1936)		No. 6 (Collins 1942)		No. 17		No. 22 (Sundius 1933)	
	A	C	A	C	A(CC352C)	C(CC352A)	A	C
SiO_2	43.70	50.70	44.70	49.60	50.36	50.32	53.93	54.28
TiO_2	.55	.31	.57	.26	.43	None	.02	.02
Al_2O_3	10.88	1.72	14.70	8.65	8.06	.86	1.79	1.26
Fe_2O_3	3.52	3.11	1.62	.48	2.18	1.75	1.84	.80
FeO	26.53	26.63	18.96	18.54	18.26	35.36	20.50	21.79
MnO	.24	.19	.21	1.08	None	.02	.25	.26
MgO	11.48	14.36	14.89	16.78	17.57	8.61	18.92	18.64
CaO	.54	.87	.69	.97	.74	.88	.12	.15
Na_2O	1.24	.60	1.34	.79	.70	.13	.15	.14
K_2O	.15	.15	None	None	None	None	.07	tr
H_2O+	1.21	1.46	2.27	2.52	1.69	1.82	2.08	2.16
F	—	—	—	—	None	None	.53	.57
Total	100.14	100.10	100.26	100.30	99.99	99.93	100.20	100.07

No. 6A—H_2O−=.29   No. 22A—Deduct .22 for $O=F_2$
No. 6C—H_2O−=.29; P_2O_5=.34   No. 22C—Deduct .24 for $O=F_2$
Analysts: No. 2, Tauno Kervinen; No. 6, Geochemical Laboratories; No. 17, Forest Gonyer; No. 22, A. Bygdén.

Selected Older Analyses Prior to 1890

The 6 analyses in this category are shown in table 3. Although they fulfill some of the conditions for "good" analysis they have not been used in the preceding discussion since they lack TiO_2, Fe_2O_3, and F determinations and are deficient in other ways. The formulas are not shown in detail but X, Y (Si+Al), O, and (OH, F) are included under heading B.

Anthophyllite Asbestos from Merrill (1895)

Table 4 contains 10 typical anthophyllite asbestos analyses presented in a study of asbestos and asbestiform minerals by Merrill (1895). They have been grouped in this way to show clearly the composition of such asbestos. As most of them are not complete analyses the formulas have not been calculated. They are complete enough, however, to show that they are not uncommonly high in soda although it is often said that amphibole asbestos is characterized by high soda content. Generally, these specimens are low in iron and aluminum, which may be a reflection of their environment. It cannot be said that all amphibole asbestos is low in iron as one of the amosites of Peacock (no. 87) has 39.94% $FeO+Fe_2O_3$.

These specimens are also characterized by a high water content, running from 2.29% to 2.95%. This is to be expected as water at the magnesium end of the series should be 2.31% and it decreases with increase of iron and aluminum. However, water determinations in Merrill's samples were made by the ignition method, so the results are not trustworthy.

Poor and Incomplete Analyses

There are 23 analyses under this heading, shown in table 5. In age they range from John's in 1809 to Ross's in 1928. They are included here because in one way or another they fail to meet the criteria established for "selected" analyses. In some of them (nos. 65, 67, 72, 81, and 82) no water determinations were made. In some, such as numbers 69 and 72, the summation is much too high, and in others, such as numbers 80 and 82, it is much too low. In the formulas X is much too high in some (nos. 63, 65, 69) and somewhat low in others (nos. 73, 74a). The one of Ross, number 70, is not a poor but an incomplete analysis. The analysis accompanying the original description of gedrite, number 62a, shows a very high FeO content (45.83%), which has not been duplicated in any of the many analyses made on gedrite from Gèdres since that time.

Despite their inadequacies these analyses do add somewhat to our knowledge of the chemical variation in the anthophyllite series.

Analyses of Doubtful and Discredited Varieties

Eleven analyses are listed under this heading in table 6. In the following discussion the reasons for regarding these specimens as doubtful or discredited anthophyllites are examined insofar as their composition is concerned.

Number 83.—This was presented by Winchell (1931) as "Anthophyllite, Mesabi Range, Minn. Incomplete analysis by C. R. Wise." Its high FeO content (37.82%), without any good evidence that it is orthorhombic, indicates that it is probably cummingtonite, or perhaps a mixture of that mineral and anthophyllite. The high H_2O content (5.32%) makes its purity questionable.

Number 84.—This specimen, a high-MnO (10.66%), high-FeO (29.34%) amphibole from Jacobemi, Bukovina, described by Orlov (1932), is probably the cummingtonite variety dannemorite. Evidence to that effect will be given in the section on x-ray properties.

Number 85.—The orthorhombic nature of this high-alumina (21.78%) amphibole described by Ussing (1889), from Fiskernäs, Greenland, has never been questioned. However, in a specimen in the Harvard collections (no. 86379) labeled "Anthophyllite and Sapphirine from Fiskernäs, Greenland" the amphibole is monoclinic. In all other respects (optical properties, color, and so forth) it matches the material described by Ussing. The situation is further confused as monoclinic colorless amphibole occurs in the same locality. Ussing was a careful worker and he presented detailed optics for his material, but his identification of this material might be mistaken. Until the Greenland specimen can be reexamined it should be regarded as a doubtful anthophyllite.

Numbers 86 and 87.—These analyses are of two amosites from South Africa described by Peacock (1928). It will be shown by x-ray evidence that both are monoclinic. As they are monoclinic, their composition shows that number 86 is probably actinolite (10.84% CaO, 29.34% FeO, 4.96% MgO) and number 87 is probably cummingtonite (36.60% FeO, 5.80% MgO, 0.77% CaO). Both of these specimens are asbestiform and their identification cannot be determined by optical methods.

Number 88.—Reasons have already been given in the section why this specimen from Norway should be considered as doubtful.

Number 89.—The chemical composition of this material from Austria, described by Weisander (1932) is not that of anthophyllite. It shows 35.83% MgO, only 0.16% short of the theoretical maximum but it also contains 5.71% FeO and 2.62% Al_2O_3 when these should be absent. SiO_2 is 52.44% when it should be more than 61% for such a MgO content. The analysis was poor, the material was impure, or the mineral was not anthophyllite.

Number 90.—Slavik's (1927) so-called manganese-rich anthophyllite from Chaveltice, Bohemia, will be shown by x-ray study to be monoclinic. This being so, its composition (MnO 16.10%, FeO 5.94%, MgO 20.50%) makes it the high-manganese variety of cummingtonite, dannemorite.

Number 91.—Samples of many of the anthophyllite asbestos specimens described by Merrill (1895) were sent to me by the U. S. National Museum for x-ray study. One of them from Salls Mountain, Georgia, number 61357, could not be found. Similar material, number 88286 was sent and was found to be chrysotile. This substitute material has not been analyzed and there is no assurance that it is the same as the original. Until anthophyllite is identified from this locality by x-ray study this occurrence must remain doubtful.

Number 92.—Laudermilk and Woodford's "Soda-rich anthophyllite asbestos" from California, described in 1930, will be shown by x-ray study to be monoclinic. As it has 5.10% CaO and 7.40% Na_2O, coupled with 21.12% MgO and 5.32% FeO, it can be called a soda tremolite.

Number 93.—This analysis by John (1806), the earliest from the literature, does not fit any probable anthophyllite. It would be futile to speculate as to what is wrong with it.

Spectrographic Analyses

No spectrographic analyses of anthophyllite were found in the literature. Some minor metals were determined spectrographically in the seven Montana anthophyllites (nos. 1, 8, 9, 14, 17, 29, 30), in one from Russia (no. 10), in two of Merrill's asbestos varieties (no. 53 from Wyoming and no. 59 from North Carolina), and in the cummingtonite (no. CC352A) occurring in the same rock as no. 17 (see table 7 and fig. 3).

TABLE 8. Spectrographic Analyses of 10 Anthophyllites and One Cummingtonite
Analyst, John C. Rabbitt

Anthophyllite	Weights per cent (dashes = <0.001%)												
	Ag	Ba	Co	Cr	Cu	Li	Mo	Ni	Pb	Sn	Sr	V	Zr
1. (CC206F)	.004	—	.003	—	.004	.03	—	.002	—	—	—	.001	—
8. (CC298)	.002	—	.007	.03	.005	.03	—	.01	—	—	—	.04	.001
9. (Mont.40-12)	.002	—	.006	.02	.005	.03	—	.008	—	—	—	.03	.002
10. (Ka10)	.003	—	.004	.01	.006	.04	—	.01	—	—	—	.01	.003
14. (CC121)	.002	—	.005	.003	.005	.03	—	.004	—	—	—	.03	.001
17. (CC352C)	.003	—	.008	.002	.02	.04	—	.006	—	—	—	.05	.001
29. (CC200A)	.002	—	.007	.2	.008	.005	—	.1	—	.002	—	.01	.002
30. (Mont.40-8)	.002	.006	.006	.03	.003	.02	—	.06	—	—	—	.001	.002
53. (USNM 62090)	.002	—	.007	.006	.03	.001	—	.07	—	—	—	—	.003
59. (USNM 62748)	.008	—	.008	.008	.02	.002	—	.06	—	—	.008	—	.001
Cummingtonite													
CC352A	.003	—	.003	.005	.01	.002	.001	.01	.001	.002	.001	.002	.005

Not found (<0.001%): As Au B Be Bi Cb Cd Ce Cs Ga Ge Hg In Ir Os Pd Pt Rh Ru Sb Sm Ta.

The results of the analyses are shown in table 8. Of the 35 metals determined, only 13 occurred in significant quantities ($>0.001\%$) in any of the samples. These are silver, barium, cobalt, chromium, copper, lithium, molybdenum, nickel, lead, tin, strontium, vanadium, and zirconium. None of these occurred in amounts greater than 0.2% (Cr in no. 29).

There does not seem to be any definite variation of these minor metals with any of the major constituents. The cummingtonite specimen has a greater diversity of the minor metals than the anthophyllites but the total weight per cent is much less than that of the anthophyllites except number 1.

There seems to be a greater concentration of nickel and copper in the high-magnesium anthophyllites (nos. 29, 53, 59) and a lower concentration of lithium than in the others. Until spectrographic data is secured on many more specimens the question of the variation of the minor metals in the members of the anthophyllite series must remain a matter for future study.

OPTICAL PROPERTIES

Montana Varieties

Indices of Refraction.—The indices of refraction were measured by the Emmons double-variation method. The apparatus used was one devised by Professor Cornelius Hurlbut (1947) of Harvard and it has some modifications of the standard Emmons apparatus. These changes lead to better temperature control and in practice seem to be satisfactory.

It is generally believed that measurements by the Emmons method are precise to about ±0.0002 and with extreme care to ±0.0001. It is my belief, however, that in routine operation the precision is never better than ±0.0005. When the difficulty of controlling the temperature to much better than $\pm0.5°$ is considered, together with the difficulty in maintaining the adjustment of the refractometer, it is probable that ±0.0005 is about the best that can be done. For most purposes in mineralogy indices to ±0.001 are more than adequate. For example, most cleavage flakes of anthophyllite vary slightly in index from end to end so that nZ can vary ±0.0005 or more on the same small flake. This is also true of the other indices. The chemical analysis is made on a countless number of these small flakes and represents an average composition. The indices are measured on one or two flakes but the range in all those used for chemical analysis might be ±0.001. If this be so, then comparing the chemical and optical properties of such material on the basis of index measurements to ±0.0005 or better is a waste of time. This

is true for complex minerals such as the amphiboles. There may be some justification for more precise work on minerals such as quartz in which any one grain in a large collection will have about the same composition and optical properties as the next. Even here the accuracy of the chemical analysis does not warrant such close work.

The indices as shown in table 9 are given to the fourth decimal place but from the preceding discussion it must be remembered that they are no better than ± 0.0005 and possibly ± 0.001. The indices nX, nY, and nZ are given for wave lengths of light corresponding to the F-line (4861.3 Å), the D-line (5892.9 Å), and the C-line (6562.8 Å). These figures lead to the dispersion of the indices, F–C. For nZ this ranges from 0.0133 in number 30 to 0.0220 in number 9. For nY it ranges from 0.0135 in number 29 to 0.0272 in number 9. For nX it ranges from 0.0178 in number 29 to 0.0297 in number 9. The extreme range, nZ to nX, for all of them is 0.0133 to 0.0297.

Dispersion of the indices is a property which has not been measured on many anthophyllites. I can find only two examples, 0.014 (presumably for nZ) in numbers 38 and 39 on asbestiform material from Paakila, Finland by Rimann (1936).

It was hoped that this dispersion might be a property which varied significantly with chemical composition, such as iron or aluminum content. Plots made on this assumption are disappointing; the dispersion varies erratically and shows no definite relation to composition. No plot is needed to show that the dispersion is in all varieties greater for nX than for nZ. More measurements of this property are needed and when a hundred or so are available some significant variation with composition should be revealed.

Birefringence, nZ minus nX, for the three wave lengths is also shown in table 9. For the F-line it ranges from 0.0094 in number 14 to 0.0165 in number 30. For the D-line it ranges from 0.0131 in number 17 to 0.0248 in number 30. For the C-line it ranges from 0.0150 in number 17 to 0.0280 in number 30. In general, birefringence increases with increasing magnesium.

Optic Sign and 2V.—It has never seemed to me worthwhile to attempt precise measurements of 2V. This property is inherent in the indices and can be calculated from them, or can be secured graphically. When questions of identity arise 2V can be easily estimated in microscopic examination to about $\pm 5°$, depending on its size. Whether on the Fedorov stage or by other methods, 2V can be measured only to about $\pm 1°$ (except with the axial angle apparatus when used on special materials). Nevertheless it is common to see figures for it given to minutes and in some cases to seconds.

TABLE 9. OPTICAL PROPERTIES OF SEVEN MONTANA ANTHOPHYLLITES

| | A.—Indices of refraction D=5892.9 Å | | | | C=6562.8 Å Birefringence Z−X | | |
| F=4861.3 Å | | | | Dispersion F−C | | | |
	F	D	C		F	D	C
1. (CC206F)							
Z	1.6910	1.6781	1.6726	.0184			
Y	1.6839	1.6670	1.6600	.0239	.0159	.0215	.0249
X	1.6751	1.6566	1.6477	.0274			
8. (CC298)							
Z	1.6821	1.6718	1.6673	.0148			
Y	1.6768	1.6630	1.6570	.0198	.0111	.0165	.0188
X	1.6710	1.6553	1.6485	.0225			
9. (Mont.40-12)							
Z	1.6850	1.6695	1.6630	.0220			
Y	1.6792	1.6603	1.6520	.0272	.0122	.0175	.0199
X	1.6728	1.6520	1.6431	.0297			
14. (CC121)							
Z	1.6725	1.6619	1.6574	.0151			
Y	1.6681	1.6545	1.6488	.0207	.0094	.0143	.0164
X	1.6631	1.6476	1.6410	.0221			
17. (CC352C)							
Z	1.6777	1.6671	1.6630	.0147			
Y	1.6736	1.6595	1.6540	.0196	.0097	.0131	.0150
X	1.6680	1.6540	1.6480	.0200			
29. (CC200A)							
Z	1.6451	1.6354	1.6315	.0136			
Y	1.6365	1.6370	1.6230	.0135	.0146	.0174	.0188
X	1.6305	1.6180	1.6127	.0178			
30. (Mont.40-8)							
Z	1.6505	1.6410	1.6372	.0133			
Y	1.6430	1.6280	1.6205	.0225	.0165	.0248	.0280
X	1.6340	1.6162	1.6092	.0248			

B.—Optic sign, 2V, orientation, and pleochroism

	F	D	C	X	Y	Z
1.	(−) 86°	(+) 87°	(±) 90°	pale tan	pale tan	tan
8.	(−) 88°	(+) 86°	(+) 85°	pale tan	pale tan	tan
9.	(−) 84°	(+) 87°	(+) 84°	pale tan	pale tan	smoke gray
14.	(−) 88°	(+) 87°	(+) 86°	pale tan	pale tan	tan
17.	(−) 84°	(+) 81°	(+) 78°	pale tan	pale tan	tan
29.	(+) 80°	(−) 88°	(−) 84°	colorless	colorless	colorless
30.	(−) 85°	(+) 88°	(+) 79°	colorless	colorless	colorless

Pleochroism in 1, 8, 14, and 17 is weak; in 9 it is moderate.
Absorption is X=Y<Z.
Orientation in all varieties: Z=c and Y=b.

For the Montana specimens 2V was approximated graphically from the indices and the figures are correct to about $\pm 2°$. Table 9 shows that for the D-line all the specimens are optically $(+)$ except number 29, and have 2V's greater than $80°$. All change sign for the F-line and all decrease in 2V for the C-line (except no. 1) but retain the same sign as that for the D-line.

Orientation and Pleochroism.—The orientation in these specimens, as in all anthophyllites, is $Z = c$ and $Y = b$. In immersion most fragments will lie on a cleavage face which is usually elongated. It is thus easy to measure nZ in this direction. Across the cleavage flake the index measured will be nX' and to measure true nX it is necessary to turn the grain, not a difficult operation. In any collection of grains some will be found showing an optic-axis interference figure and nY can be measured on such a grain. Here again it may be necessary to roll the grain somewhat to get the true figure.

In five of the specimens, pleochroism is perceptible and in two (nos. 29 and 30) it is not. In only one, number 9, is it anything more than weak. The colors to me seem to be shades of tan but they might also be referred to as clove, clove brown, straw yellow, buff, and so forth. In general pleochroism increases with increasing iron and this seems to be true for all anthophyllites. In all varieties the absorption is $X = Y < Z$.

Varieties from the Literature

Table 10 shows what optical properties are available for those anthophyllites which were discussed under the heading "Selected Modern Analyses, 1890–1946" in . the preceding section and whose chemical analyses are shown in table 2. Of these, exclusive of those from Montana, 26 have some optical data out of a total of 39. The completeness of the data ranges all the way from adequate for the thorough work of Penfield (1890) shown in number 35, to a mere notation of the optic sign by Emerson (1895) as in number 12. In only a few others is complete data presented (as in nos. 6 and 20) so that the best that can be done until more is secured is to draw broadly general conclusions from what is available.

Indices of Refraction.—Figure 4 shows nZ plotted against weight per cent of $FeO + Fe_2O_3 + TiO_2 + MnO$. This combination is valid, as ferrous iron and manganese affect the indices about equally and ferric iron and titanium are usually not present in quantities great enough to distort the results. There are many possible ways of plotting these figures. Winchell prefers to plot the properties against molecular percentages of end members. In the anthophyllite series he uses $H_2Mg_7Si_8O_{24}$—$H_2Fe_7-Si_8O_{24}$ (see Winchell 1938). Sundius (1933) used $MgSiO_3$—$Fe(Mn)SiO_3$.

TABLE 10. OPTICAL PROPERTIES OF SOME ANTHOPHYLLITES FROM THE LITERATURE

	nX	nY	nZ	$nZ-nX$	Sign and 2V	Remarks
2.	1.674	—	1.697	.023	(+) —	
3.	1.651	—	1.672	.021	(+) —	
4.	1.642	1.655	1.661	.019	(−) large	Indices ±0.003
6.	1.652	1.656	1.666	.014	(+) 85°	Positive elongation
7.	1.643	1.653	1.659	.016	—	Positive elongation
10.	1.642	1.648	1.658	.016	(+) 78°	
12.	—	—	—	—	(−) —	
13.	—	1.662	1.676	—	70°–80°	
15.	1.644	—	1.660	.016	—	
16.	—	1.653	1.667	—	70°–80°	
20.	1.656	1.667	1.672	.015	(−) 57°	2V±2°; red<violet
21.	—	—	—	—	(−) —	
22.	1.6454	1.649	1.6605	.015	(+) 59.3°	Birefringence measured
24.	1.629	—	1.652	.021	(−) —	
25.	1.626	1.638	1.651	.025	(+) 87°	Red<violet
26.	1.6329	1.6384	1.6517	.0188	(+) 66°02′	2V measured with optic angle apparatus
33.	1.605	—	1.625	.020	—	
34.	1.608	—	1.631	.023	—	
35.	1.6195	1.6301	1.6404	.0209	(−) 88°46′	As corrected by Bowen; 2V measured with optic angle apparatus
38.	1.605	—	1.626	—	—	nX is nX'; F−C=0.014
39.	1.60	—	1.623	—	—	nX is nX'; F−C=0.014
40.	—	1.64	—	—	(−) 67°	nZ minus nY=0.0065
41.	1.598	—	1.623	.025	—	
43.	—	—	1.62	—	—	
44.	—	—	1.634	—	—	
45.	1.610	1.627	1.630	.020	(−) 69°	2V measured on the Fedorov stage

	Pleochroism and orientation		
	X	Y	Z
3.	greenish yellow	greenish yellow	grayish green
5.	pale yellow	brownish yellow	dove gray
6.	yellow	brownish	smoke gray
13.	pale clove brown	clove brown	dark brown
15.	colorless	colorless	colorless
16.	colorless	colorless	colorless
20.	pale yellow to colorless	same to pale brownish	lilac
25.	colorless	colorless	gray brown

In all of these Z=c, Y=b, the optic plane is parallel to (010), and absorption is X=Y<Z.

Orlov (1932) used the same system. Bowen used molecular per cent of FeSiO$_3$ in 1920 and the Winchell system in 1933 which was also used by Kunitz (1930). These are enough examples to show that this concept of molecular end members is well entrenched and yet it is founded on false premises. No such end members in the amphiboles are known in nature. No such mixing on a molecular basis occurs. However convenient it may be to plot the different properties in that way it must be admitted that it engenders and perpetuates a false notion of the variations in a mineral series. Collins (1942) phrases the objections well:

> Winchell . . . Sundius, and Alling plot the optical properties against percentages of "minals," which Alling claims gives a clearer picture than do the complex mineral compounds. In nature no pure "minals" exist. They are hypothetical compounds and the suitability of plotting optical properties against them is doubtful. The "minal" method shows a definite trend, increase of iron content causing increase in refractive indices, but beyond this its utility is doubtful.

Logically, the method to use would be to plot atomic percentages against the measured physical properties. If enough data were available, this would be the method of choice as the variation in an isomorphous series proceeds on an atomic (or ionic) basis. I have not used it here because of the lack of data although the calculated formulas in table 2 can be used as the basis for such a plot.

From the practical standpoint, the mineralogist is most concerned, in these complex series, with the variation of one or two elements such as iron. He would like to have a plot which involves the least amount of calculation and which shows the general trend. Such a plot is the one used here in figures 4 and 5. It is fully realized that this, in its way, is as artificial as the use of molecular end members. However, it does not postulate molecular end members nor molecular variation. Its virtue is that it proceeds directly from the chemical analyses, involves a minimum of calculation, and shows the general trends satisfactorily. In fact, from a numerical standpoint, plots made on any of the three systems mentioned will differ only as to scale although strictly speaking there will be a slight variation in the shape of the curves.

In the anthophyllite series, of course, a three-component diagram should be used, as alumina is significant, but lack of data precludes the usefulness of such a plot in showing the variation of the physical properties.

In figure 4 (showing the variation of nZ) the points do not fall very well on a straight line nor on a smooth curve. The line drawn shows (what is already known) that the increase in FeO, etc., raises the indices. For number 25, which falls far off the line, it shows that ferric iron has an undue influence on the indices. This specimen of Serdiuchenko (1936) from
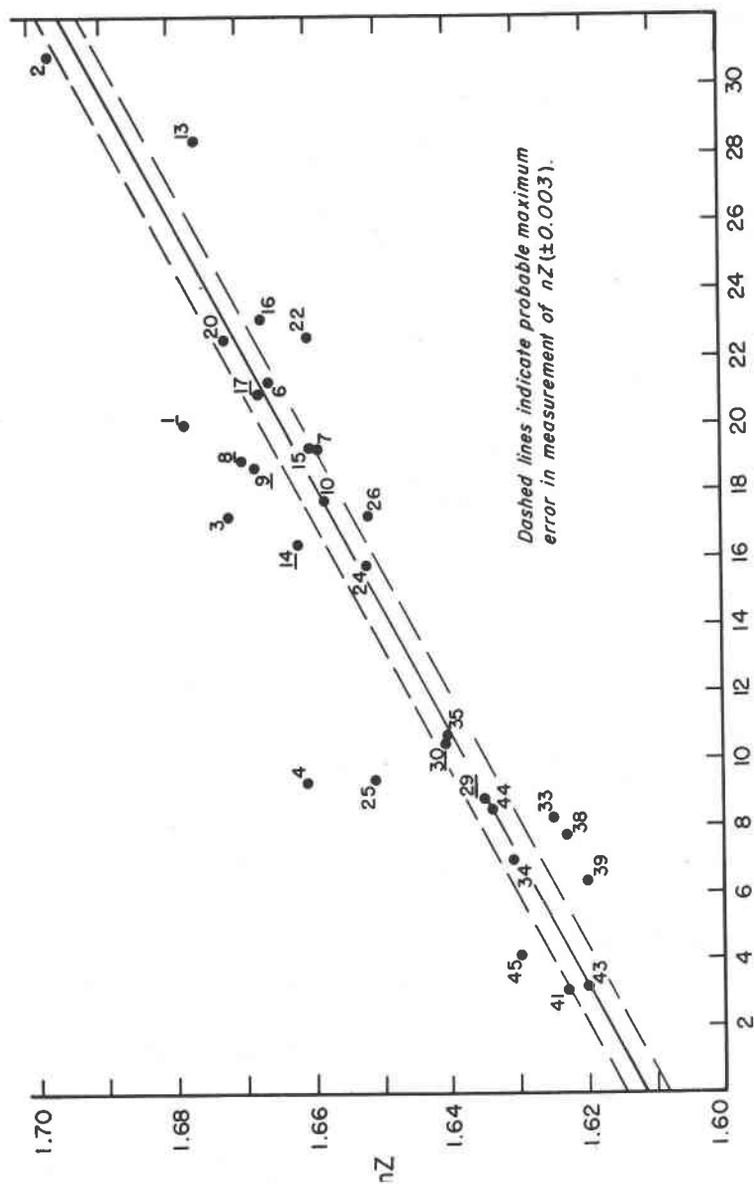
FIG. 4. The refractive index nZ plotted against chemical weights per cent of $FeO+Fe_2O_3+TiO_2+MnO$ for some anthophyllite varieties from the literature and the Montana varieties. The numbers of the Montana varieties are underlined.

Russia has 8.28% Fe_2O_3 and weighting the figures by a factor of two for ferric iron would bring it back close to the line. Number 4, the high-alumina (23.79%) specimen of Henderson from North Carolina, falls farthest from the line. Mr. Henderson sent me some of his material from the U. S. National Museum and my figures for the indices are the same as his. It must be concluded, then, that some element other than ferric or ferrous iron has increased the index. In this material Fe_2O_3 is only 0.20%, MnO is 0.16%, FeO is 9.21%, and TiO_2 was not determined. Indications are that aluminum is responsible for the high index. This belief is strengthened by the fact that the other specimens above the line are as high in alumina. These include number 1 (17.78%), number 2 (10.88%), number 3 (17.22%), number 8 (15.84%), number 9 (14.92%), and number 14 (13.26%). This is not conclusive as others (no. 6 with 14.72% Al_2O_3 and no. 10 with 15.48% Al_2O_3) fall on the line. However, number 45, near the high-magnesium end, has 5.72% Al_2O_3 (much more than other members at this end) and it falls well above the line. The concept is also strengthened by the fact that number 13 which should have about 15% Al_2O_3 in its magnesium-iron range, has only 7.63% and it falls well below the line.

Those Montana specimens (numbers underlined in the plot) high in alumina fall significantly above the line and those low in alumina, numbers 17, 29, 30, fall close to the line. When more data is available it is probable that a separate line can be drawn for the aluminian members. In general, even this two-component diagram shows an indication of the aluminum content as well as that of iron.

As nZ is the most significant index because, among other reasons, it is the one most easily and accurately measured in this mineral series, it is the only one plotted. Plots showing the variation of nY and nX are unsatisfactory. They show the same general trend as nZ but the points are much more scattered.

The birefringence is not plotted. The points are so widely scattered that no useful curve nor straight line can be drawn. The trend, however, shows that the birefringence increases with increase of magnesium. It also shows that out of 22 specimens, 12 fall in the range 0.010 to 0.020, two are 0.020, and 8 fall in the range 0.020 to 0.025 for the D-line. The limits for all are 0.013 and 0.025. No significant effect of aluminum on the birefringence is apparent.

Optic Sign and 2V.—Winchell (1933) says " . . . the optical sign is positive in maganthophyllite and antholite; it is negative in gedrite, and perhaps also in feranthophyllite." In *Dana's Textbook* (1932) anthophyllite is said to be optically positive and gedrite optically negative. If this

were true it would be a good way to identify the aluminian anthophyllites, but many if not most such members of the series are positive. Examples of these are numbers 2, 3, 6, and 10, and the Montana specimens numbers 1, 8, 9, and 14. Some of these aluminian members are negative, such as numbers 4, 12, and 20. The high-magnesium members are generally negative such as numbers 35, 40, 45 and the Montana specimen number 29, but number 30 is positive.

2V is usually large in the anthophyllites and an average figure would be above 80°. The lowest recorded are 59.3° in number 22 by Sundius (1933) from Norway and 57° in number 20 by Rama Rao (1937). In some specimens such as numbers 20 and 25 dispersion is perceptible. In both of these red > violet. The dispersion for the Montana specimens has been shown in table 9. In these red < violet in numbers 8, 14, 17, and 30; red > violet in numbers 1 and 29. In number 9 red = violet.

Orientation and Pleochroism.—In all members of the series $Z = c$ and $Y = b$. From the discussion on the optic sign it is evident that in most of the aluminian members nX is the acute bisectrix and in the high-magnesium ones nZ is usually the acute bisectrix.

Pleochroism is listed for 5 of the 26 specimens of table 10. It has been seen that 5 of the 7 Montana specimens show pleochroism. In general the aluminian and ferroan members show this property and it is probably a function of aluminum and iron. The colors exhibited are usually shades of tan and these are named subjectively by different observers as clove, clove brown, buff, cream, yellow, straw yellow, brown, brownish yellow, and so forth. This difference in color nomenclature is understandable but confusing and the best practice would be to adhere to some standard such as that of Ridgway (1912). The pleochroic colors for the Montana specimens are given in table 9 on a descriptive basis. An attempt was later made to classify two of them by the Ridgway scheme as follows:

Number 1. (CC206F)   Number 9. (Mont.40-12)
X = Y = Buffy citrine, 19′ k   X = Y = Light ochraceous buff, 15′ d
Z = Verona brown, 13″ k   Z = Warm sepia, 13″ m

This is not wholly satisfactory as the pleochroic colors are viewed in transmitted light and the colors of the Ridgway scale in reflected light. For specimens under the microscope some system based on photometric measurements would probably give good results.

Optical Limits in the Series

The optical limits in the series, on the basis of the inadequate data now available, are as follows:

	n_D	F–C
X =	1.598 to 1.674	0.017 to 0.029
Y =	1.605 to 1.685	0.013 to 0.027
Z =	1.615 to 1.697	0.013 to 0.022

$nZ - nX = 0.013$ to 0.025

2V ranges from $(-)$ 57° to $(+)$ 59°

DENSITY

The relative densities* of the Montana anthophyllites together with those of some from the literature are shown in table 11 and are plotted against weight per cent of $FeO + Fe_2O_3 + TiO_2 + MnO$ in figure 5. The densities for the Montana material were measured for me by Dr. R. E. Folinsbee of the Canadian Geological Survey, using the 10-ml quartz pycnometer after the method of Ellsworth (1928). These figures represent relative densities corrected to 4° C. from the indicated temperatures of measurement. They can be compared to the calculated densities secured by using the unit cell volumes from x-ray measurement and the atomic formulas calculated from the chemical analyses, according to the formula

$$d = \frac{nM}{VN}$$

where d = density

  n = number of molecules in unit cell

  M = molecular weight

  V = volume of unit cell (calculated from d-spacings based on the Siegbahn scale of x-ray wave lengths)

  N = Avogadro's number (the old value, 6.06×10^{23})

The measured and calculated densities agree fairly closely (except for no. 17) and the range of the differences is from 0.03% for number 29 to 1.3% for number 17. Theoretically they should be no better. Bannister and Hey (1938) say that the attainable accuracy for the Ellsworth method using 12 grams of material of density 4 is ±0.06%. Fairbairn and Sheppard (1945) for 10 grams of material of density 4 place the figure at ±0.025%. For the x-ray method Fairbairn and Sheppard regard the cell volume as the single variable and confine their calculation of

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* A statement by Fairbairn and Sheppard (1945) is relevant here: "Although widely used, 'specific gravity' is terminologically incorrect as a synonym for relative density, and is physically incorrect as a synonym for density determined by the x-radiation method. 'Gravity' implies the weight of a body, i.e., the earth's attraction for it, which is not an intrinsic property, whereas by definition density is the mass of a body per unit volume, the mass being an intrinsic and invariable property."

error to the powder method. Considering all errors inherent in that method of arriving at the cell constants, they show a curve T representing the maximum error for different values of θ, the angle of incidence of the x-ray beam. This curve varies from close to 0% at 90° to nearly 1.5%

TABLE 11. DENSITY OF ANTHOPHYLLITE

A.—Montana specimens

Number	Measured	Calculated	Suspension
1. (CC206F)	3.277	3.23	3.25
8. (CC298)	3.261	3.23	3.25
9. (Mont.40-12)	3.245	3.25	3.23
14. (CC121)	3.259	3.22	3.25
17. (CC352C)	3.279	3.16	3.23
29. (CC200A)	3.106	3.105	3.09
30. (Mon.40-8)	3.102	3.09	3.04

Measured figures from determinations by R. E. Folinsbee. All figures are densities corrected to 4° C.

Calculated figures based on the atomic formula and the volume of the unit cell.

Suspension refers to relative densities determined by suspension in heavy liquids and subsequent measurement of the liquids on a Westphal balance.

B.—Specimens from the literature

Number	Relative Density	Number	Relative Density	Number	Relative Density
2.	3.371	20.	3.22	35.	3.093
3.	3.259	21.	3.068	38.	2.97
4.	3.178	22.	3.241	39.	2.85
6.	3.24	24.	3.157	40.	2.95
7.	3.16	26.	3.157	41.	3.006
13.	3.23	34.	3.034		

at 50°. They do not consider the errors in chemical analysis which would be reflected in the molecular weight in the density formula. These errors, difficult to evaluate, might easily be appreciable. For instance, a decrease in the molecular weight of number 1 of 1% changes its calculated density from 3.23 to 3.206. A ±1% error in any of the figures of the chemical analysis would not be surprising; in many of the figures it might be more.

The errors quoted for the pycnometer method are probably well on
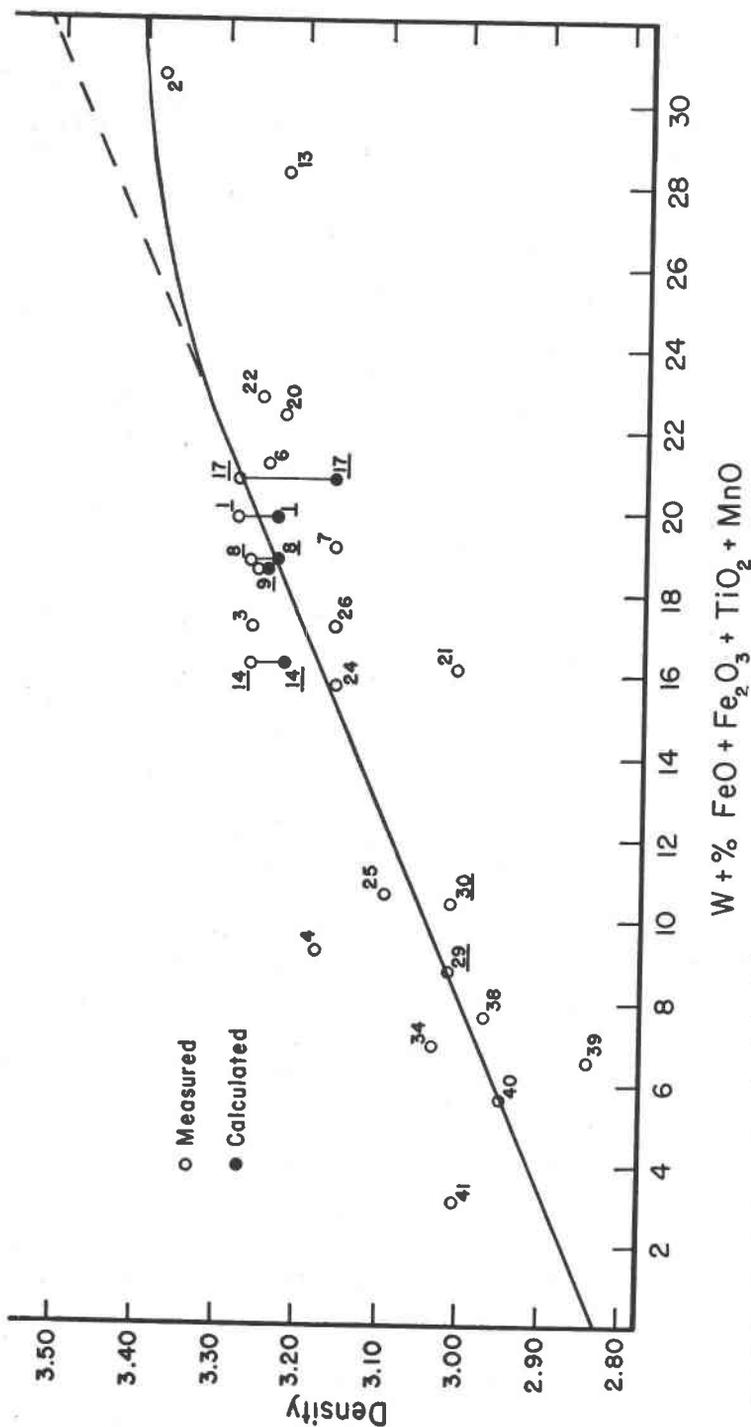
FIG. 5. Density plotted against chemical weights per cent of $FeO+Fe_2O_3+TiO_2+MnO$ for some anthophyllite varieties from the literature and the Montana varieties. The numbers of the Montana varieties are underlined. The measured and calculated figures for the Montana varieties are connected as shown; those for numbers 29 and 30 are nearly identical.

the optimistic side. The method is full of pitfalls in routine work and under the most favorable circumstances will probably produce figures no better than $\pm 1\%$ in actual operation. Considering the errors inherent in both the pycnometer and x-ray methods the correspondence shown for the Montana specimens is satisfactory.

Relative densities are also given as determined by the suspension method in which the grains are suspended in a heavy liquid (methylene iodide plus bromoform) and the density of the liquid then measured on a Westphal balance. For a modified form of this method using Clerici solution Fairbairn and Sheppard give an error of $\pm 0.025\%$ for material of density 4. However, in practice this method may be none too good with a complex mineral such as an amphibole. As the grains in a large collection are not of homogeneous composition a clean and sharp suspension is difficult to achieve and errors in the final result of $\pm 1\%$ are probably the minimum that can be expected. It is notable (table 11) that the densities measured by suspension on most of the specimens fall between the pycnometer and x-ray densities.

In number 17 the divergence in the measured and calculated densities is far beyond the limit of error. A careful check did not show the cause and time did not permit a more thorough investigation. The divergence could be ascribed to a faulty chemical analysis (particularly for FeO content), or the presence of a rare heavy metal in minor amount.

The value of a very accurate density measurement, considering the time and trouble which such a procedure entails, is questionable for minerals such as the amphiboles. The chemical analysis is applied to a large collection of grains and so is the pycnometric method. The calculated measurements come from x-ray data secured from one or two grains plus the chemical data. The resulting figures given to the third decimal place are misleading for the collection as a whole. For a study such as this, densities to the second decimal place are good enough. For number 1 in table 11, for instance, the density might have been given as 3.27 ± 0.03. This predicates an error of about $\pm 1\%$.

The densities shown for specimens from the literature in table 11 range from 2.85 for number 39 to 3.371 for number 2. This same range includes the Montana specimens. Theoretically, according to the curve drawn in figure 5, the possible range is 2.84 to 3.41. This should not be taken literally as the curve is not too satisfactory. The straight line as continued (dashed) in the figure might be better representative of the variation. Sufficient data is not available to decide this point. Many of the points such as numbers 4, 13, and 21 fall far off the curve which is not surprising, considering the difficulty of making good density measurements.

STRUCTURAL PROPERTIES

Morphological Crystallography

No terminated crystals of anthophyllite are known. Morphological data is given in *Dana* (1892) as follows:

> Orthorhombic. Axial ratio $a:b=0.51375:1$, Penfield. Prismatic angle, $mm''=$ 54°23'. Crystals rare, habit prismatic but prisms not terminated. Commonly lamellar, or fibrous massive; fibers often very slender. Also in aggregates of prisms, like actinolite.

To this is added, in *Dana's Textbook* (1932), the information that the cleavage is "prismatic, perfect; $b(010)$ less so; $a(100)$ sometimes distinct." Winchell (1933) says, "Crystals rare, usually fibrous; asbestiform types (always?) contain Na. Perfect (110) cleavages at 125°37'."

On anthophyllite from Edwards, St. Lawrence County, New York, Cesàro (1896) obtained $a:b:c=0.515:1:0.285$ from the forms (100), (110), (920) and the cleavages (100), (010), (110), (021), and perhaps (011) and (031).

The most useful diagnostic crystallographic measurement in the anthophyllite series is that of the cleavage angle. For the orthorhombic amphiboles it is always near 54°30' and for the monoclinic ones, except those in the cummingtonite series, it is near 55°30'. Cummingtonite has a cleavage angle close to that of anthophyllite, always less than 55°. Thus a simple goniometric measurement on a cleavage fragment of an amphibole will establish whether the mineral is anthophyllite or cummingtonite on the one hand (cleavage angle between 54° and 55°) or a monoclinic amphibole other than cummingtonite on the other hand (cleavage angle between 55° and 56°). Anthophyllite and cummingtonite cannot be differentiated in this way; x-ray or optical study is necessary.

The cleavage angles of the Montana specimens measured to $\pm 05'$ with the two-circle goniometer on cleavage fragments about 1 mm$\times$0.5 mm $\times$0.5 mm in size are

Number 1.—(CC206F)		54°10'
Number 8.—(CC298)		54°35'
Number 9.—(Mont.40–12)		54°25'
Number 14.—(CC121)		54°21'
Number 17.—(CC352C)		54°40'
Number 29.—(CC200A)		54°06'
Number 30.—(Mont.40–8)		54°37'

In addition to these, material similar to number 20 measured 54°25' and to number 10 measured 54°17'. The cummingtonite (CC352A) whose analysis is given in table 6 has a cleavage angle of 54°20'$\pm$05'. It is evident from these figures that there is no apparent variation of

cleavage angle and chemical composition, nor can it be shown from the available data that the angle varies with any other property.

In the literature, cleavage-angle measurements on anthophyllite are scarce. Of the 46 specimens which have been most widely discussed in this study only five have had the cleavage angles measured: numbers 5 (54°41′), 12 (56°), 15 (52°41′), 16 (55°10′), and 26 (54°21′). Many figures for this angle are to be found but they have usually been secured from unanalyzed fragments.

X-Ray Crystallography

The Unit Cell.—Johansson (1930) determined the constants of the unit cells of anthophyllite, cummingtonite, and actinolite by a combination of the powder and oscillation methods on material from Falun, Norway (no. 26). Crystallographic measurement gave him $a:b = 1.0267:1$ and a cleavage angle $210:2\bar{1}0 = 54°21′$. For the cell constants he obtained $a_0 = 18.52$ Å, $b_0 = 18.037$ Å, and $c_0 = 5.270$ Å which resulted in $a_0:b_0:c_0 = 1.02676:1:0.2922$. Using the formula $MgSiO_3$ he decided that there were 32 molecules in the unit cell and put it in the space group *Pnma*. In the powder photograph made with iron radiation he measured and indexed 47 lines.

Jansen (1933), using the rotation method on fibers from Hrubschitz, Moravia, found $c_0 = 5.28$ Å and from the structural data of Warren (see below) found $a_0 = 18.5$ Å, $b_0 = 17.9$ Å, and $c_0 = 5.27$ Å.

Warren and Modell (1930) in a classic study on material from Edwards, New York found by Weissenberg and oscillation methods that $a_0 = 18.5$ Å, $b_0 = 17.9$ Å, and $c_0 = 5.27$ Å and the corresponding axial ratios were found to be $a:b:c = 1.035:1:0.294$. The $a:b$ ratio is double that previously assumed and the general form $(h\ k\ l)$ becomes $(2h\ k\ l)$. The cleavage prism in terms of this cell has the symbol (210) instead of (110). The number of molecules of $H_2Mg_7(SiO_3)_8$ in the unit cell is four and the space group is *Pnma*. There are 156 atoms in the unit cell and 61 parameters are necessary to define their positions.

The amphibole structure is characterized by double silicon oxygen chains; the pyroxene structure is characterized by single silicon-oxygen chains. According to Warren and Modell, "In both groups of substances, the chains lie parallel to the 'c' axis of the crystal, and are most certainly responsible for the tendency which this class of substances shows for elongation parallel to the 'c' axis. In the amphiboles the tendency toward elongation along 'c' is often carried to the extreme, and the substance exists only as a fiber. Presumably there is a reinforcing action in the double chains giving them a mechanical strength along the chain direction, which is greater than that displayed by the single chains."

There is a close correspondence in the amphibole and pyroxene unit cells:

Anthophyllite $H_2Mg_7(SiO_3)_8$
Orthorhombic amphibole
$a_0 = 18.5$ Å
$b_0 = 17.9$ Å
$c_0 = 5.27$ Å

Enstatite $MgSiO_3$
Orthorhombic pyroxene
$a_0 = 18.20$ Å
$b_0 = 8.87$ Å
$c_0 = 5.20$ Å

Tremolite $H_2Ca_2Mg_5(SiO_3)_8$
Monoclinic amphibole
$a_0 = 9.78$ Å
$b_0 = 17.8$ Å
$c_0 = 5.26$ Å
$\beta = 73°58'$

Diopside $CaMg(SiO_3)_2$
Monoclinic pyroxene
$a_0 = 9.71$ Å
$b_0 = 8.89$ Å
$c_0 = 5.24$ Å
$\beta = 74°10'$

From this it is seen that the *b*-axis of anthophyllite is double that of enstatite and the *a*- and *c*-axes are identical. The same relationship holds between tremolite and diopside, the corresponding monoclinic forms. The *a*-axis of anthophyllite is double that of tremolite and the *a*-axis of enstatite is double that of diopside. This can be shown graphically (after Warren) as follows:

Monoclinic amphibole ————————————→ Orthorhombic amphibole
↑   ↑
double along *b*   double along *a*   double along *b*
Monoclinic pyroxene ————————————→ Orthorhombic pyroxene
double along *a*
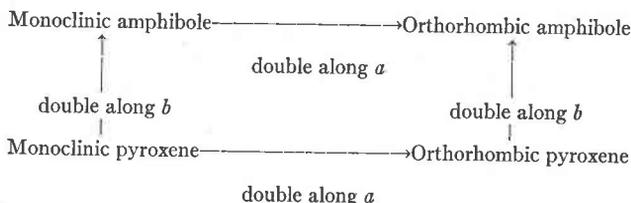
The structure of the unit cell of anthophyllite projected on (001) is shown in the paper by Warren and Modell (1930). A graphic representation of the amphibole and pyroxene chains is shown in the paper by Warren (1930) and the relationship between these chains and the amphibole and pyroxene cleavages is shown in the paper by Warren (1929). There is no need to reproduce them here.

X-ray measurements were made by the Weissenberg method using Cu/Ni radiation on the seven Montana specimens, an additional unanalyzed one from the Cherry Creek Area (CC384), one from Russia (similar to no. 10), and one from India, number 20. Rotation, 0-layer, and 1st-layer line pictures normal to the *c*-axes were taken of all specimens on cleavage fragments about 1 mm×0.5 mm×0.5 mm in size. The cell constants derived from these films as measured for me by Professor C. Wroe Wolfe of Boston University are, in *k*X units:

Number	a_0	b_0	c_0
1. (CC206F)	18.55	17.92	5.30
8. (CC298)	18.54	17.82	5.28
9. (Mont.40-12)	18.53	17.80	5.28
14. (CC121)	18.50	17.66	5.31
17. (CC352C)	18.55	17.95	5.31
29. (CC200A)	18.54	17.90	5.28
30. (Mont.40-8)	18.58	17.98	5.28
(CC384)	18.58	17.98	5.28
10. (Ka10)	18.55	17.80	5.28
20. ("Bidalotite")	18.55	18.10	5.28

This shows that c_0 and a_0 are remarkably constant. In c_0 the range is from 5.28 to 5.31 or 0.03. In a_0 it is from 18.50 to 18.58 or 0.08. In b_0, however, the range is much greater, from 17.66 to 18.10, or 0.44. It is apparent that any significant variation must lie in the figures for b_0. Plotting these against chemical weight per cent of SiO_2, or Al_2O_3, or $FeO + Fe_2O_3 + TiO_2 + MnO$ or any combination of ratios of these does not produce any systematic variation. It can be assumed that the cell dimensions must bear some systematic relation to composition but these figures do not reveal any. Here again more measurements are needed to show this fundamental relationship. There is no need of better measurements as the accuracy (or rather precision) attained is adequate when the x-ray, chemical, and optical data are compared.

Packing Index.—Fairbairn (1934) has developed, in a tentative way, a useful concept involving the packing index. He says, ". . . it is derived from the expression V ions/V unit cell $\times$ 100, which represents the percentage of the absolute volume of one formula unit occupied by ions. The packing unit is this quantity arbitrarily divided by 10 and thus P. I. = V ions/V cell $\times$ 10. The packing index of a substance therefore lies between 0 and 10, a convenient numerical range analogous to that expressing specific gravity or hardness." In discussing sources of error in the determination of the packing index he says that "all error is restricted for practical purposes to calculation of the volume of the ions in the crystal cell." There is a certain error in the figures given for ionic radii and the chemical analyses, from which are derived the atomic formulas, are fruitful sources of error. The radii for the cations are those for 6-fold co-ordination. Fairbairn believes that the average variation in radius is less than $\pm 5\%$ of his values which he regards as small compared to other uncertainties. Considering all the uncertainties and sources of error, he emphasizes that the packing indices are only semi-quantitative but that "correlations limited to minerals of the same type (e.g. silicates) can be made, however, with considerable confidence."

He shows that for 8 carbonates the packing index ranges from 0.7 to 4.7; for 10 sulfates from 1.2 to 5.1; for 8 phosphates from 2.3 to 5.7; for 132 silicates from 3.1 to 7.0; and for 19 oxides from 4.4 to 7.2. In general, density, hardness, and refractic index vary directly with packing index and it should be expected that a systematic variation would exist in members of a series. For this reason the packing indices of some anthophyllites whose cell dimensions were measured have been calculated, with the results shown in table 12.

TABLE 12. PACKING INDEX OF SOME ANTHOPHYLLITES

Number	Cell volume Å³	Ionic volume Å³	P. I.
1. (CC206F)	1761.81	1005.28	5.77
8. (CC298)	1744.52	1005.56	5.65
9. (Mont.40-12)	1741.52	1002.36	5.75
10. (Ka10)	1743.40	1001.20	5.74
14. (CC121)	1734.83	1001.00	5.77
17. (CC352C)	1768.08	1003.48	5.67
20. ("Bidalotite")	1772.78	996.84	5.61
29. (CC200A)	1752.25	1007.56	5.75
30. (Mont.40-8)	1761.03	1006.76	5.71

The cell volumes follow from the product $a_0b_0c_0$. The ionic volumes are calculated from the ionic radii ($V = 4.19\ r^3$) of the elements appearing in the formula. Fairbairn uses the following figures for elements in the amphiboles:

Element	Ionic Radius	Ionic Volume	Element	Ionic Radius	Ionic Volume
Aluminum	.57	.80	Manganese	.91	3.14
Calcium	1.06	4.99	Oxygen	1.32	9.64
Fluorine	1.33	9.85	Potassium	1.33	9.85
Ferrous Iron	.83	2.39	Silicon	.39	.25
Ferric Iron	.67	1.26	Sodium	.98	3.94
Magnesium	.78	1.97	Titanium	.64	1.09
			OH	1.40	11.48

The packing index does not vary as much as expected in these anthophyllites. The range is from 5.61 to 5.77 and considering the uncertainties in the calculation the range is probably within the limit of error. Nevertheless, the calculations reveal some things of interest. In considering ionic volume instead of ionic radii differences in the size of the ions are much more apparent. It is generally believed that manganese and mag-

nesium can readily substitute for each other in the anthophyllite structure as their radii are not too far apart (0.91 and 0.78) but the volumes show a large difference (3.14 and 1.97). It has been suggested in a preceding section of this paper that this may be the reason why manganese is more abundant in the cummingtonite series than in the anthophyllite series as the former is higher in iron. The volume of ferrous iron is 2.39 and manganese could more easily replace it than magnesium.

Another striking feature is that the oxygen ions account for about 85% of the ionic volume and O plus OH about 93%. Silicon accounts for only about 0.7%.

X-Ray Study of Doubtful Varieties

The identification of asbestiform anthophyllite is usually impossible by means other than x-ray study. Many authors have decided that their amphibole asbestos was orthorhombic because the smallest fibers under the microscope showed an apparent parallel extinction. To test the validity of this criterion an x-ray study of some anthophyllite asbestos was made.

Samples of the anthophyllite asbestos listed in Merrill's paper (1895) were obtained from Mr. E. P. Henderson of the U. S. National Museum and rotation pictures with Cu/Ni radiation were made normal to the fibers. These proved to be identical to the rotation pictures of numbers 14 (CC121) and 30 (Mont.40-8), for all the asbestos varieties listed in table 4 (nos. 53 to 62 inclusive). Number 91, from Salls Mountain, Georgia, had the same pattern as chrysotile and so was placed in table 6 as a doubtful species.

Zero-layer and 1st-layer line pictures were taken of the same fibers and these showed lines instead of spots; in effect they were powder pictures. Pictures were again taken of the same fibers but the fibers were kept stationary. Good rotation pictures were the result. This indicated that the c-axes were oriented parallel to the fibers, but that the a- and b-axes were distributed at random around the long direction. The smallest fiber (0.02 mm diameter) practical to work with gave the same results as the larger fibers (0.05 to 1 mm in diameter). This showed that the smallest individual fiber under the microscope, about the same diameter as the cross-hair of the eye piece, is a bundle of fibers.

The experiments were repeated on three amphibole asbestos specimens described by Merrill and secured from Mr. Henderson. These were USNM number 5694 from Roanoke, Virginia; number 8536 from Parkton, Maryland; and number 73462 from Chester, North Carolina. Under the microscope they all showed extinction angles $Z \wedge c$ greater than 15°. The results were the same as for the anthophyllite fibers except that the

pictures from the stationary fibers were not such good rotation patterns as those of the orthorhombic specimens. The rotation pictures were identical to those made on tremolite from Edwards, New York, showing that these asbestos specimens are monoclinic amphiboles.

These tests show that although Merrill's identifications by the microscope were sound, it is possible in theory, from the random distribution of the *a*- and *b*-axes around the long direction of the fibers, to have parallel extinction in this direction in a monoclinic amphibole asbestos. That this is also true in practice will be shown in the following discussion where the *x*-ray study of doubtful varieties is described in detail.

Number 92.—This high-soda asbestos, from Coffee Creek, Trinity County, California, was described by Laudermilk and Woodford in 1930 as a "Soda-rich anthophyllite asbestos." Individual fibers under the microscope showed parallel extinction along the length and so were assumed to be orthorhombic. A rotation picture normal to the fiber length with Cu/Ni radiation was identical to that of tremolite. A similar picture of a stationary fiber gave a good rotation picture identical to the first one. As an additional check, a powder picture was taken with Cu/Ni radiation and compared with powder pictures of the anthophyllite number 30 (Mont.40-8) and the tremolite from Edwards, New York. The picture matched that of tremolite exactly. The three most prominent lines and their intensities, together with those from Johansson's data (1930) are:

Anthophyllite 30 (Mont.40-8)		Tremolite Edwards, N. Y.		Variety from Coffee Cr., Cal.		Actinolite (Johansson 1930)	
d	*I*	*d*	*I*	*d*	*I*	*d*	*I*
3.030	10	3.124	10	3.125	10	3.126	10
3.235	9	2.705	9	2.704	9	2.706	9
2.531	8	2.522	8	2.525	8	2.524	8

It is apparent that this material is monoclinic and its chemical composition shows it to be a soda-rich tremolite and not a soda-rich anthophyllite.

Numbers 86 and 87.—These two asbestos varieties, amosite, from South Africa were described by Peacock (1928) who considered them to be orthorhombic. His original specimens are in the Harvard collection under numbers 13067 (Kalkfontein, Cape Province) and 13092 (Penge, Transvaal).

Number 86 showed parallel extinction under the microscope on the smallest fiber. A rotation picture made normal to the fiber length with Cu/Ni radiation was identical to that of tremolite. A powder picture matched that of the Edwards tremolite with the three most prominent lines as follows:

Number 86		Edwards tremolite	
d	I	d	I
3.127	10	3.124	10
2.707	9	2.705	9
2.521	8	2.522	8

It is evident that this material is monoclinic. Its high CaO content (10.84%) and high FeO+Fe₂O₃ content (28.53%) make it an actinolite.

Number 87 also showed parallel extinction under the microscope. A rotation picture normal to the fiber length with Cu/Ni radiation proved to be similar but not identical to that of the anthophyllite number 30. There were slight differences in spacing in the 0-layer and a difference in the number of spots in the 1st layer. The picture was then compared with a rotation picture made with Cu/Ni radiation on the cummingtonite CC352A whose chemical analysis is given in table 7, and was identical to it. Again, as a check, powder pictures were taken of the amosite and cummingtonite and these were compared with anthophyllite and with the data of Johansson. The table below shows the results.

Anthophyllite 30 (Mont. 40-8)		Cummingtonite CC352A		Amosite 13092		Cummingtonite Johansson (1930)	
I	I	d	d	d	I	d	I
3.030	10	2.748	10	2.751	10	2.754	10
3.235	9	1.401	9	1.405	9	1.406	9
2.531	8	2.186	8	2.184	8	2.187	8

This comparison shows that amosite number 13092 and cummingtonite are the same and hence the material from Penge is monoclinic. Its chemical composition (39.94% FeO+Fe₂O₃, CaO 0.77%, MgO 5.80%) fits its designation as cummingtonite.

Numbers 90 and 84.—The asbestiform variety, number 90, from Chaveltice, Bohemia, was described by Slavik (1927) as a manganese-rich anthophyllite of which there are supposedly many examples in the manganese deposits of that region. Professor Slavik sent me some of his material so I was able to make an x-ray study of it. Under the microscope it showed parallel extinction along the length in the smallest fibers. A rotation picture normal to a fiber with Cu/Ni radiation did not fit anthophyllite but did fit cummingtonite. A powder picture with Cu/Ni radiation was identical to the cummingtonite powder picture:

Anthophyllite 30 (Mont.40-8)		Number 90 Chaveltice		Cummingtonite CC352A	
d	I	d	I	d	I
3.030	10	2.748	10	2.748	10
3.235	9	1.400	9	1.401	9
2.531	8	2.183	8	2.186	8

This material is cummingtonite and because of its high manganese content (MnO 16.10%) it belongs to the variety known as dannemorite. Such manganous varieties are common in the cummingtonite series but are not known in the anthophyllite series.

Orlov (1932) described the material listed under number 84, from Jacobemi, Bukovina, as a manganese-rich ferroanthophyllite. Professor Slavik, at my request, asked Professor Orlov for some of the original material but it had been lost in the destruction during the German occupation. By inference, however, this material, too, is cummingtonite. Savul, in his paper "Une dannemorite asbestiforme de Sarul Dornei" (1932), has described an asbestos variety with 14.39% FeO and 15.36% MnO which is monoclinic. He was able to measure the extinction angle on some of the fibers as about 14° and decided that the material belonged to the dannemorite variety of cummingtonite. Professor Slavik wrote to me that Jacobemi and a town called Dornavatra (Vatra Dornei) are "neighboring greater places next to the same manganese deposit." Sarul Dornei is about four miles southeast of Dornavatra and it is probable that it too is near the same manganese deposit. Hence we might assume that Orlov's and Sarul's asbestos came from contiguous deposits. Orlov's material has more FeO (29.34%) than Sarul's but in such a deposit the iron and manganese content of the asbestos must vary widely throughout the body. The probability is strong that Orlov's material belongs in the cummingtonite series.

Number 20.—This anthophyllite from the village of Bidaloti, Mysore Province, India, not asbestiform, was described by Rama Rao (1937) as "Bidalotite, a new orthorhombic pyroxene derived from cordierite." Mr. Rama Rao sent me some specimens of it. X-ray Weissenberg rotation, 0-layer, and 1st-layer line pictures with Cu/Ni radiation show it to be anthophyllite. In a number of thin sections its amphibole cleavage is well shown and its chemistry shows it to be an aluminian variety.

In the light of the foregoing identifications it is evident that no undoubted ferroanthophyllite has been found in nature. The following so-called ferroanthophyllites (including the ones discussed above) have been shown to be monoclinic amphiboles or orthorhombic pyroxenes:

Author	*Locality*	*Identity established as*
Shannon (1921)	Idaho	Actinolite (Kunitz 1930 and Winchell 1931)
Palmgren (1917)	Tunaberg, Sweden	Hypersthene (Sundius 1932)
Eckermann (1922)	Manjö Mtn., Sweden	Hypersthene (Sundius 1932)
Peacock (1928)	Cape Province, Africa	Actinolite (this paper)
Peacock (1928)	Transvaal, Africa	Cummingtonite (this paper)
Slavik (1927)	Chaveltice, Bohemia	Cummingtonite (this paper)
Warren (1903)	Rockport, Mass.	Cummingtonite (Bowen 1935)

In addition Winchell's (1931) material from the Mesabi Range, Minnesota, and that of Orlov (1932) from Jacobemi, Bukovina, are probably cummingtonites, although this has not been proved. On the basis of the x-ray study, supported by the chemical data, anthophyllite and cummingtonite do not form an isodimorphous series.

Miscellaneous Properties

Color

The color of the varieties of anthophyllite show a wide range but the designation "clove brown" by Schumacher (1801) is valid for most members of the series. The purer anthophyllites are light colored such as number 30 and the asbestiform varieties. Increase in iron and aluminum darkens the color to the typical clove brown (Ridgway classification no. $17''' \ m$) as shown by numbers 1 and 8. Some varieties exhibit a schiller; this is shown by number 9 which changes according to the light from dusky blue green (Ridgway no. $39'' \ m$) to dusky orient blue (Ridgway no. $45'' \ m$). Some specimens are gray such as number 29, and I have an unanalyzed specimen from the Dillon Complex in Montana which is yellowish green.

The color of the analyzed Montana varieties, according to the Ridgway scheme, is as follows:

1. (CC206F)	Clove brown, $17''' \ m$
8. (CC298)	Clove brown, $17''' \ m$
9. (Mont.40-12)	Dusky blue green, $39'' \ m$
14. (CC121)	Avellaneous, $17''' \ b$
17. (CC352C)	Avellaneous, $17''' \ b$
29. (CC200A)	Slate gray-carbon gray
30. (Mont.40-8)	Tilleul buff, $17''' \ f$

Texture

The texture of anthophyllite ranges from fibrous (asbestiform) to bladed (prismatic). The fibers in the asbestos varieties can be sub-divided into hair-like fibers smaller in diameter than the cross-hairs of a microscope eyepiece. In most anthophyllites, however, the individual crystals are prisms of the order of 5 mm long and 3 mm wide. In many specimens these prisms are arranged in characteristic rosettes and such a texture is referred to by many authors as fibrous radiated.

In some varieties the prisms resemble blades and these blades may be up to 10 cm long and 3 cm wide (no. 10). A more striking example is number 29 from Montana in which the blades (or prisms) are up to 16 cm long and 8 cm wide. These are the largest known anthophyllite crystals.

As anthophyllite varieties show a good amphibole cleavage, glistening

cleavage fragments are common in the hand specimen so specimens of anthophyllite usually show a high luster.

Fusion Point

The fusion point varies with the composition and there are no reliable figures for this property. Winchell (1912) quotes Brun's figures as 1230° C. for the fusion point with an inversion at 1150° C. No composition is given and the evidence for the inversion is doubtful. It is probable that the fusion point for pure anthophyllite is somewhere between 1600° and 1800° C. and from 1400° to 1600° C. for varieties high in iron (and aluminum?).

For other properties of anthophyllite such as hardness, streak, behavior before the blow pipe, and magnetic susceptibility, the reader is referred to the standard textbooks.

OCCURRENCE AND ROCK AND MINERAL ASSOCIATION

The distribution of anthophyllite and the rocks and minerals with which it is associated are shown in table 13. This table is confined to the 46 analyzed varieties listed in table 2 in the section on chemical data. The data on distribution and rock and mineral association is arranged alphabetically by countries and the countries are sub-divided by provinces or states. The varieties are identified by analysis numbers as in table 2. The geologic age of the enclosing rocks is given but it must be emphasized that this may not be the age of the formation of the anthophyllite.

It is apparent that anthophyllite is widespread, particularly in the pre-Cambrian rocks. It is strictly a metamorphic mineral as no varieties are known that have crystallized from a magma.

The paragenesis of anthophyllite has been studied by many workers (Eskola, Tilley, Bugge, and others) but due to insufficient data these studies have not been particularly satisfactory. No useful purpose would be served by quoting here from the voluminous literature on the subject.

TABLE 13. OCCURRENCE AND ROCK AND MINERAL ASSOCIATION OF ANTHOPHYLLITE

Country	Province or state	Analysis no. (see table 2)	Rock and mineral association	Geologic age
Australia	Southwest Division	7	At Bullsbrook in gabbro pegmatite; with plagioclase.	Pre-Cambrian
Austria	Tyrol	19	No information.	?
Canada	Ontario	5	In Haliburton Co. in amphibolite with garnet, cordierite, feldspar.	Pre-Cambrian
Czechoslovakia	Bohemia	31	At Schützendorf in serpentine with magnetite and olivine.	?
Finland	Oulun	38, 39	At Paakila as anthophyllite nephrite with talc and serpentine.	Pre-Cambrian
		42	At Paakkilanniemi as asbestos fibers in gneiss.	Pre-Cambrian
		44	At Tiilikainen as asbestos fibers in gneiss.	Pre-Cambrian
	Porin	13, 16	At Träskböle as radiating rosettes in gneiss with cordierite.	Pre-Cambrian
	Viipurin	2	At Kalvola in garnet amphibolite with garnet, cummingtonite, plagioclase, and biotite.	Pre-Cambrian
France	Ille et Vilaine	37	At St. Germain l'Hermite in nodulose serpentine with calcite, opal, and talc in granite gneiss.	Pre-Cambrian
Great Britain	Sutherland	6	At Strathy in the schists and granulites of the Moine series with cummingtonite, oligoclase, biotite, quartz, magnetite.	Pre-Cambrian
India	Mysore	20	At Bidaloti in biotite-cordierite-hypersthene granulite.	Pre-Cambrian
Italy	Island of Elba	40	At S. Piero in Campo in serpentine with talc, magnetite, spinel.	Pre-Cambrian
Madagascar		21	At Mt. Tzilaizina in crystalline schist with cordierite and quartz.	Pre-Cambrian
		23	In actinolite schist as asbestos.	Pre-Cambrian
Norway	Buskerud	27	At Kongsberg in mica schists, gneisses, and amphibolites and in the fahlbands with quartz, feldspar, hornblende, garnet, chalcopyrite, pyrite, pyrrhotite.	Pre-Cambrian
	Sor Trondelag	22	At Trondhjem in amphibolite with cummingtonite.	Pre-Cambrian
	Telemark	18	At Bamble as at Kongsberg.	Pre-Cambrian
		24	At Kjernerud as at Kongsberg.	Pre-Cambrian

TABLE 13—(*continued*)

Country	Province or state	Analysis no. (see table 2)	Rock and mineral association	Geologic age
		46	At Vormlitjern in gneiss and amphibolite with cordierite, plagioclase, hornblende, garnet.	Pre-Cambrian
Sweden	Jamtland	26	At Falun, "as slender needles imbedded in pyrite."	Pre-Cambrian
Tanganyika	Morogoro	36	In the M'Sembe, M'Kundi and N'Guru Ya N'Dege Hills as bands in gneiss and schist.	Pre-Cambrian
U.S.S.R.	Caucasus	25	On the banks of the Malaya Laba River in serpentine with talc.	Pre-Cambrian (?)
	Karelia	3, 10	At Shueretsky in coarse-grained gneiss with garnet, quartz kyanite, plagioclase, biotite.	Pre-Cambrian (?)
	Urals	32	At Kochnevsky as asbestos in talc.	Paleozoic (?)
		45	At Mramorsky as above.	?
		34	At Miask. No further information.	?
United States	Connecticut	11	At Haddam, Middlesex County, with cordierite in schist bordering a beryl-tourmaline pegmatite.	Paleozoic (?)
	Idaho	33	At Kamiah, Lewis County, as asbestos with olivine, talc, pyrite, and carbonates in lenticular bodies replacing dunite.	Pre-Cambrian
	Massachusetts	12	At Warwick, Franklin County, with talc and rutile in soapstone.	Paleozoic
		15	At Chesterfield, Hampshire County, with garnet, mica, and tourmaline.	Paleozoic
	Montana	30	In the Dillon Complex in Beaverhead and Madison Counties with actinolite, serpentine, enstatite, clinohumite, spinel, annabergite, magnetite.	Pre-Cambrian
		9	Along the borders of the Complex in schist with quartz, plagioclase, spinel.	Pre-Cambrian
		14	In the Ruby Dam Area, Madison County in amphibolite with garnet, quartz, plagioclase, chlorite, rutile.	Pre-Cambrian
		1, 17	In the Cherry Creek Area, Madison County, in amphibolite with garnet, quartz, feldspar, cummingtonite.	Pre-Cambrian
		8	Same as above, with staurolite.	Pre-Cambrian
		29	Madison County; in isolated boulders with chlorite.	Pre-Cambrian

TABLE 13.—(*continued*)

Country	Province or state	Analysis no. (see table 2)	Rock and mineral association	Geologic age
	New York	41, 43	At Edwards, St. Lawrence County, with nearly pure tremolite in schist.	Pre-Cambrian
	North Carolina	4	At Masons Creek, Franklin County, with rhodolite, hypersthene, and biotite in a dike (originally eclogite) in schist.	Pre-Cambrian
		35	At Corundum Hill, Macon County, with vermiculite, talc, actinolite, albite, corundum, chlorite, enstatite, in a zone bordering dunite.	Paleozoic
		28	At Bakersville, Mitchell County, in dunite boulders as above.	Paleozoic (?)

CONCLUSIONS AND SUGGESTIONS FOR A REVISION OF THE SERIES

From this study the following main conclusions can be drawn:

1. The anthophyllite and the cummingtonite series are not isodimorphous.

2. The anthophyllite series is a 3-component one of limited isomorphism involving chiefly magnesium, iron, and aluminum. Iron (or $Fe'' + Mn''$) replaces magnesium from about 5% to about 50% of complete replacement calculated on the atomic basis. Aluminum replaces silicon nearly up to 2 atoms and the same is true of its replacement of Mg, Fe''; thus the formula $H_2Mg_5Al_2Si_6Al_2O_{24}$ is nearly fulfilled.

3. Manganese is not important in the series. It is notable that many cummingtonites are high in manganese. Aluminum, high in many anthophyllites, is not a major constituent of the cummingtonite series.

4. Calcium is present in most anthophyllites, the average amount being about one half of one per cent; about the same amount of sodium is also present in many anthophyllites; potassium is present in negligible amounts in some anthophyllites and is absent in the rest.

5. The identification of anthophyllite is not certain unless based on *x*-ray methods. This is particularly true of the asbestiform varieties.

6. There is not enough data to determine adequately the relations of the physical properties and the composition of anthophyllite. Further study should be made of the series; this can be done profitably only when more data as to the physical properties and composition is secured. Such information, accompanied by field observations, can then be made the basis of a paragenetic study of the whole series. I hope to present soon a study of the paragenesis of the Montana varieties described in this paper.

The name anthophyllite should be used for all members of the series. Chemical suffixes as proposed by Schaller (1930) can be used to indicate any variation in the composition if known. Aluminum-rich members should be called aluminian anthophyllite and the term gedrite should be dropped. Members rich in ferrous iron should be called ferroan anthophyllite; ferrian anthophyllite would refer to members rich in ferric iron and thus the term would replace picroamosite which should be discarded. As amosite is not anthophyllite but refers to at least two different monoclinic amphiboles it should be restricted to commercial usage where it serves a useful purpose. Ferroanthophyllite and other synonyms denoting very high-iron anthophyllites should be dropped.

Under this scheme all varieties of orthorhombic amphibole would have one name, anthophyllite, which would be, as now, the name of the series also.

The series can be characterized by the general formula

$$X_7Y_8O_{22}(OH, F)_2$$
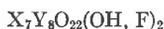
where X is chiefly Mg, Fe″, Al and in minor part Mn, Ti, Fe‴, Ca, Na, K. Y is chiefly Si and in part Al and where in X the maximum amount of Al is $(Mg, Fe″)_5Al_2$; the maximum amount of Fe″ is about $(Mg_{3.5}Fe_{3.5})$ and in Y the maximum amount of Al is (Si_6Al_2).

NOTE

A description by Yamada (1943) of anthophyllite from Wariyama, Iwate Prefecture, Japan, was called to my attention by Mr. Michael Fleischer after the manuscript of this report was finished. The variety is in Paleozoic hornfels ("Senmaya Contact Rocks") with quartz, plagioclase, cordierite, and biotite. Accessory minerals are apatite and tourmaline. Optics are: $nX = 1.664$, $nY = 1.671$, $nZ = 1.679$; $(+)$ $2V = 81°$, red < violet. Chemical analysis is SiO_2 48.80, TiO_2 0.47, Al_2O_3 8.10, Fe_2O_3 0.11, FeO 25.07, MnO 0.24, MgO 13.48, CaO 0.50, Na_2O 0.25, H_2O $(+)$ 2.74, H_2O $(-)$ 0.06; Total 99.82.

On the basis of 24 (O,OH) my calculation of the formula is $(Ca_{0.8}Na_{0.12})$ $(Mg_{2.95}Fe''_{3.07}Mn_{0.02}Ti_{0.04}Al_{0.52})$ $(Si_{7.15}Al_{0.85})$ $(O_{21.32}OH_{2.68})$, and in this $X = 6.80$, (Mg, Ca, Na)/Fe'', Mn, Ti $= 3.15/3.13$, so this is a ferroan anthophyllite near the iron limit of the series.

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