

New biopyriboles from Chester, Vermont: I. Descriptive mineralogy

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Abstract

Four new magnesium–iron chain-silicate minerals have been identified from a metamorphosed ultramafic body near Chester, Vermont. They occur with anthophyllite, cummingtonite, and talc between the chlorite and actinolite zones at the boundary of the body. The cell parameters of the minerals are diagnostic: (1) jimthompsonite is orthorhombic, $Pbca$, $a = 18.6$, $b = 27.2$, $c = 5.30\text{\AA}$; (2) clinojimthompsonite is monoclinic, $C2/c$, $a = 9.87$, $b = 27.2$, $c = 5.32\text{\AA}$, $\beta = 109.5^\circ$; (3) chesterite is orthorhombic, $A2_1ma$, $a = 18.6$, $b = 45.3$, $c = 5.30\text{\AA}$; (4) an unnamed mineral is monoclinic, $A2/m$, Am , or $A2$, $a = 9.87$, $b = 45.3$, $c = 5.29\text{\AA}$, $\beta = 109.7^\circ$. The physical and optical properties are close to those of low-Ca amphiboles. The cleavage angles (37.8° and 44.7°) are lower than those of amphiboles, and intergrowths of the minerals with anthophyllite and cummingtonite are petrographically distinctive. The minerals are biopyriboles and are chemically intermediate between anthophyllite and talc. The ideal chemical composition for jimthompsonite and clinojimthompsonite is $(\text{Mg,Fe})_{10}\text{Si}_{12}\text{O}_{32}(\text{OH})_4$, and that of chesterite is $(\text{Mg,Fe})_{17}\text{Si}_{20}\text{O}_{54}(\text{OH})_6$. The new minerals might easily be confused with amphiboles if their electron microprobe analyses were considered alone.

Introduction

Physical similarities among pyroxenes, amphiboles, and micas led Johanness (1911) to call these mineral groups collectively the “biopyriboles.” Solution of the major biopyribole structure types later showed that the similarities were not fortuitous, but rather were a direct result of structural similarities. Thompson (1970) has pointed out that most amphiboles can be thought of as alternating slabs of mica and pyroxene structure cut parallel to (010) along the ideal $C2/m$ mica a -glide planes and pyroxene c -glides. These M (mica) and P (pyroxene) slabs, when assembled with the proper operations, form the MP double-chain amphibole structure. Thompson (1978) has also suggested that slab mixtures with different mica–pyroxene ratios might be found. Our work confirms this prediction and reveals the biopyriboles as a coherent mineral family, comprising several distinct but closely related structure types.

This paper describes four new minerals and their occurrence in a talc quarry at Chester, Vermont (Veblen and Burnham, 1975, 1976; Veblen, 1976;

Veblen *et al.*, 1977). Physical and optical data, unit-cell parameters, electron microprobe chemical analyses, and X-ray powder diffraction patterns calculated from the refined crystal structures are reported for three of the new minerals. Nomenclature for these three well-characterized minerals is also presented. Only preliminary unit-cell dimensions and possible space groups are reported for the fourth mineral, which remains unnamed.

All four minerals, which are structurally and chemically intermediate between anthophyllite and talc, were found during examination of single crystals by X-ray precession photography, and the crystal structures of three of them have been solved and refined using diffractometer-measured X-ray diffraction data. Two of the minerals consist of triple silicate chains connected by octahedral cation strips, while the other two are the first known mixed-chain silicate structures, containing both double and triple silicate chains. The structural crystallography is described in a subsequent paper (Veblen and Burnham, 1978).

Identification of the new minerals is not simple, because they occur together as fine intergrowths. Nevertheless, the information provided in this paper should enable mineralogists and petrologists to dis-

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tinguish the new minerals from other biopyriboles, and also from each other.

Nomenclature

Names for three of the new minerals have been approved by the International Mineralogical Association Commission on New Minerals and Mineral Names. The orthorhombic and monoclinic minerals with b axes of $\sim 27\text{\AA}$ that contain only triple silicate chains are named jimthompsonite and clinojimthompsonite, after Professor James B. Thompson of Harvard University. The orthorhombic mineral containing mixed double and triple silicate chains with $b \approx 45\text{\AA}$ is named chesterite, for the locality near Chester, Vermont. Although what is presumed to be the monoclinic analog of chesterite has been identified, its occurrence as very fine intergrowths in chesterite has so far precluded measurement of its physical properties and confirmation of either its chemical composition or crystal structure.

Following the usage of Johannsen (1911) and Thompson (1970), *biopyriboles* are minerals that can be represented as mixtures of (010) pyroxene and mica slabs; *pyriboles* are the subset of biopyriboles excluding the micas. In this structural classification, talc is considered as a member of the mica group.

Cell parameters and space groups

The new minerals were first distinguished from amphiboles by their b cell dimensions. Figure 1 compares 0-level a -axis precession photographs of enstatite, anthophyllite, jimthompsonite, and chesterite. The photographs show the effects of differing b -axis lengths and exhibit the following extinction criteria: $k = 2n + 1$ missing for enstatite and jimthompsonite, and $k + l = 2n + 1$ missing for anthophyllite and chesterite.

Table 1 compares the cell parameters and space groups with those of anthophyllite from Chester. The cell dimensions of anthophyllite, chesterite, and jimthompsonite were determined by least-squares refinement with 84, 95, and 98 measurements respectively from precision back-reflection Weissenberg films, using the program LCLSQ (Burnham, 1962) with systematic correction terms for absorption, film shrinkage, and camera eccentricity errors. All data for chesterite and jimthompsonite were obtained from the same crystals used for X-ray intensity measurements by remounting the crystals to obtain a second orientation. The clinojimthompsonite cell parameters were refined by a least-squares method using twelve diffractions manually centered on a four-circle dif-

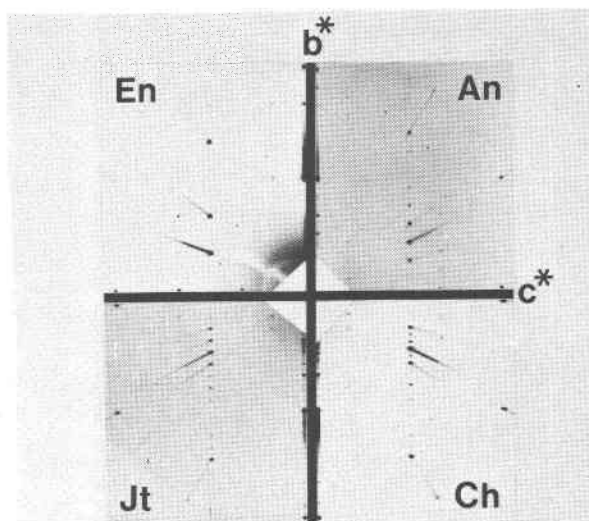


Fig. 1. 0-level a -axis precession photographs of enstatite (En), anthophyllite (An), jimthompsonite (Jt), and chesterite (Ch), showing differences in b^* length.

fractometer, while those of the unnamed mineral were measured from precession photographs.

Space groups of the minerals listed in Table 1 were determined by examination of extinction criteria on long-exposure precession films. The space group of jimthompsonite ($Pbca$) is uniquely determined, but the others are not; reasons for selecting one of several diffraction-equivalent space groups for each mineral are discussed in conjunction with the structural crystallography in a subsequent paper (Veblen and Burnham, 1978).

Occurrence and associations

The new minerals all occur in the blackwall zone² of a metamorphosed ultramafic body that is exposed in the Carleton talc quarry near Chester, Vermont. The geology of the quarry has been described by Gillson (1927), Phillips and Hess (1936), and Chidester *et al.* (1951). The generalized zoning sequence from country rock to ultramafic body is: (1) muscovite-quartz-garnet gneiss; (2) altered gneiss; (3) biotite and chlorite blackwall; (4) actinolite; (5) talc; (6) talc, magnesite, and serpentine.

The material used in this study is from a single block of blackwall found on the quarry dump, although similar material has been found in place on the northern wall of the flooded quarry (Richard

² The term "blackwall zone" is commonly used to describe the chlorite- or biotite-bearing metasomatic reaction zones that are frequently found at the boundaries of metamorphosed ultramafic bodies.

Table 1. Cell parameters and space groups of low-calcium chain silicates, Chester, Vermont

Orthorhombic	Monoclinic
Jimthompsonite	Clinojimthompsonite
$\underline{a} = 18.6263(3)A$	$\underline{a} = 9.874(4)A$
$\underline{b} = 27.2303(6)A$	$\underline{b} = 27.24(3)A$
$\underline{c} = 5.2970(3)A$	$\underline{c} = 5.316(3)A$
$V = 2686.6(2)A^3$	$\beta = 109.47(3)^\circ$
	$V = 1347.(3.)A^3$
Pbca	C2/c
$Z = 4[(Mg,Fe)_{10}Si_{12}O_{32}(OH)_4]$	$Z = 2[(Mg,Fe)_{10}Si_{12}O_{32}(OH)_4]$
Chesterite	Unnamed mineral
$\underline{a} = 18.6140(3)A$	$\underline{a} = 9.867A$
$\underline{b} = 45.306(1)A$	$\underline{b} = 45.31A$
$\underline{c} = 5.2966(3)A$	$\underline{c} = 5.292A$
$V = 4466.8(3)A^3$	$\beta = 109.7^\circ$
	$V = 2227.A^3$
A2₁ma	A2/m, Am, or A2
$Z = 4[(Mg,Fe)_{17}Si_{20}O_{54}(OH)_6]$	
Anthophyllite	
$\underline{a} = 18.5863(2)A$	
$\underline{b} = 18.0649(2)A$	
$\underline{c} = 5.2895(4)A$	
$V = 1776.0(1)A^3$	
Pnma	
$Z = 4[(Mg,Fe)_7Si_8O_{22}(OH)_2]$	

Sanford, personal communication). The block may be a section of a continuous blackwall zone, or it may be part of an isolated pod. The simplified zoning sequence observed in this block is: (1) chlorite; (2) fibrous talc; (3) fibrous talc, jimthompsonite, clinojimthompsonite, chesterite, the monoclinic analog of chesterite, anthophyllite, and cummingtonite; (4) anthophyllite, cummingtonite, chesterite, the monoclinic analog of chesterite, and actinolite; (5) actinolite and massive talc. Magnetite is found throughout as an accessory mineral, and cummingtonite has been observed as lamellae in actinolite and anthophyllite.

Actinolite and anthophyllite commonly occur as oriented intergrowths on planes near (100), attaining lengths of 5 cm. Three similar occurrences of tremolite and anthophyllite from the Gouverneur mining district in New York have been interpreted by Ross *et al.* (1968) as representing retrograde alteration of

tremolite to anthophyllite. At Chester the anthophyllite is replaced by chesterite, the unnamed mineral, jimthompsonite, clinojimthompsonite, and fibrous talc. The new minerals are thus part of a retrograde reaction sequence from anthophyllite to talc.

Habit, color, cleavages, and partings

The new minerals occur as intergrowths parallel to (010) in anthophyllite and cummingtonite, and form radiating sprays of prismatic crystals up to 5 cm long. The anthophyllite and the new minerals are transparent and have the same color, ranging from colorless to very light pinkish brown. All are colorless in thin section.

Cleavage angles were measured with a reflection goniometer on the single crystals used for X-ray intensity measurements. Chesterite possesses perfect {110} cleavage intersecting at 44.7° and 135.3°, while jimthompsonite has perfect {210} cleavage at 37.8° and 142.2°. In addition, both minerals break along {100} and {010}, but these directions may be partings, {100} resulting from breakage along fine monoclinic lamellae and {010} from separation along lamellae of another orthorhombic pyribole. The cleavages should be valuable diagnostic properties in well-crystallized specimens, but some material from Chester consists of several minerals so finely intergrown that the cleavage is not apparent; these specimens are often fibrous.

Structurally, the chesterite and jimthompsonite cleavages are analogous to the {210} cleavage of the orthopyroxenes and orthoamphiboles. Because the monoclinic polymorphs from Chester occur only as lamellae, their cleavages could not be observed, but on structural grounds one would predict a {120} cleavage for the unnamed mineral and a {110} cleavage for clinojimthompsonite.

Optical properties

Optical data for jimthompsonite, chesterite, and anthophyllite from Chester were obtained by using a spindle stage (Wilcox, 1959). The jimthompsonite and chesterite crystals were the same ones used for X-ray intensity measurement. The crystals were first mounted with their *b* axes coincident with the spindle axis, precise orientation being achieved by directly remounting the crystals from their X-ray goniometer-head mounts. Optic axial angles ($2V_x$) for sodium light were measured directly by spindle rotation, and dispersion was observed in blue-filtered light from an incandescent bulb. Principal indices of refraction were then measured for sodium light by mixing index

oils until a match was obtained (Becke line method); the index of the matched oil was measured with an Abbé refractometer calibrated with oils matched to n (fluorite) and ω (quartz). The crystals were then remounted with their c axes coincident with the spindle axis, and the indices were checked. Optic axial angles calculated from the indices of refraction agree with the observed values of $2V_x$ within the estimated precision of the measurements. The consistency of these measurements was further checked by measuring retardation ratios of the components of multiphase grains in thin section with a Berek compensator.

Optical properties (Table 2) can be used to differentiate between anthophyllite, chesterite, and jimthompsonite from the Chester wall zone, but comparison of these data with the numerous determinations for anthophyllite given by Rabbitt (1948) indicates that optical methods are probably not the best determinative means for distinguishing these minerals at other localities. Anthophyllite and gedrite show a wide range of optical properties, and the new minerals will probably show similar variations with compositional changes.

Clinojimthompsonite occurs only as thin lamellae and was not suitable for optical measurements. However, the extinction angle $N\Delta c \approx 10^\circ$ was measured.

The new minerals closely resemble amphiboles in thin section. In (001) sections the lower cleavage angles are revealed in some instances, but the cleavage is often indistinct or fibrous. The minerals usually occur together in (010) intergrowths, however, leading to a striking appearance under crossed polars for crystals with b near the plane of the section (Fig. 2a-c)³. Because pyribole exsolution features are usually restricted to planes near (100) and (001), there should be little difficulty in recognizing these intergrowths; anthophyllite-gedrite exsolution on (010) could, however, cause confusion. When the intergrowths have b inclined more steeply, but not normal, to the section plane, they can take on a softly striped appearance (like a multi-colored candy cane) in crossed polars (Fig. 2d).

Portions of some grains possess interference colors intermediate between those shown by anthophyllite, chesterite, and jimthompsonite, resulting in streaks parallel to (010) (Fig. 2a). These intermediate optical properties suggest that anthophyllite, chesterite, and

Table 2. Optical properties of anthophyllite, chesterite, and jimthompsonite from the Chester wall zone

Anthophyllite	Chesterite	Jimthompsonite
$\alpha = 1.620$	$\alpha = 1.617$	$\alpha = 1.605$
$\beta = 1.630$	$\beta = 1.632$	$\beta = 1.626$
$\gamma = 1.641$	$\gamma = 1.640$	$\gamma = 1.633$
$X = \frac{a}{b}$	$X = \frac{a}{b}$	$X = \frac{a}{b}$
$Y = \frac{b}{c}$	$Y = \frac{b}{c}$	$Y = \frac{b}{c}$
$Z = \frac{c}{x}$	$Z = \frac{c}{x}$	$Z = \frac{c}{x}$
$2V_x = 90^\circ$	$2V_x = 71^\circ$	$2V_x = 62^\circ$
	Negative	Negative
	$r > v$, weak	$r > v$, weak

Estimated errors: refr. ind.: ± 0.0005 , $2V$: $\pm 2^\circ$

jimthompsonite are intergrown on a scale too fine to be optically resolved, or that there are still more structural ordering schemes or areas of disordered chain sequence. Most grains, however, are optically uniform, and intergrowths usually exhibit optically-sharp boundaries between anthophyllite, chesterite, and jimthompsonite.

Chemical analysis

The results of electron microprobe analyses indicate that the major-element compositions of the new minerals are intermediate between those of anthophyllite and talc. Owing to the intergrown nature of the new minerals, pure samples could not be separated for water analysis.

Analyses (Table 3) were performed on an automated MAC Model 5 electron microprobe. All specimens and standards were carbon-coated. Operating voltage was 15 kV, with a reference current of 300 mA. A diopside-jadeite glass was used as the standard for Si, Al, Mg, Ca, and Na; natural aenigmatite, ilmenite, forsterite, chromite, rutile, and orthoclase were used for Fe, Mn, Ni, Cr, Ti, and K, respectively. Counting time was 20 seconds for both background and peaks; counting was stopped when the number of counts exceeded 30,000. Compositions were corrected by the alpha-matrix method of Bence and Albee (1968), using alpha factors calculated as described by Albee and Ray (1970).

The microprobe analyses show that the Chester pyriboles contain Mg, Fe, Mn, Ca, Al, Si, and Na; the elements Ni, Cr, Ti, and K are not present in measurable amounts. Energy scans performed with an EDAX 707A energy-dispersive analyzer on a Camca MS46 microprobe confirmed the absence of significant amounts of unexpected elements. The jimthompsonite analysis is the average of 11 analyzed points on the same crystal used for X-ray intensity measurement, plus three points from optically-identi-

³ A color photograph of such an intergrowth is on the cover of *Science*, October 28, 1977 (Veblen *et al.*, 1977). This photograph also shows the cleavage angles of anthophyllite, chesterite, and jimthompsonite.

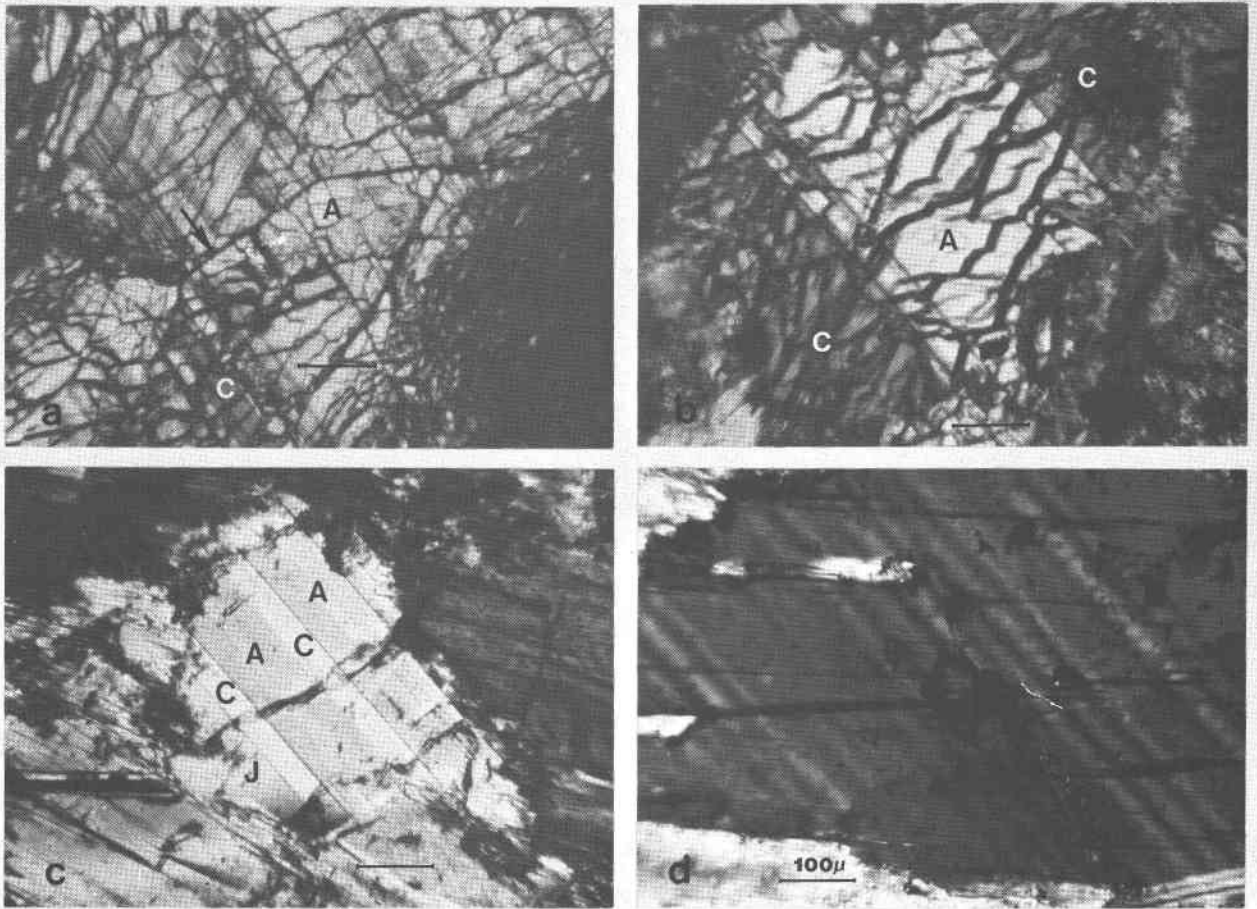


Fig. 2. Chester biopyrriboles in thin section. Scale bars represent 0.1 mm. (a) Section parallel to (001) of grain consisting mostly of anthophyllite. The anthophyllite is beginning to transform to chesterite, producing streaks parallel to (010). The straight crack parallel to (100) (arrowed) is probably a remanent "herringbone" twin plane, indicating that this grain was originally a monoclinic amphibole crystal. Crossed polars. (b) A (010) intergrowth of anthophyllite and chesterite, with the *b* axis near the plane of the section. Crossed polars. (c) A sharp (010) intergrowth of anthophyllite, chesterite, and jimthompsonite. The *b* axis is in the plane of the section, but no cleavage is visible. Crossed polars. (d) A (010) intergrowth of the pyriboles with the *b* axis near the section normal. Crossed polars.

fied grains in polished thin section. The clinojimthompsonite analysis is the average of four points on one of the lamellae in the crystal used for intensity-data collection; because the lamella width (2μ) is narrower than the volume activated by the electron beam, this analysis is undoubtedly "diluted" by jimthompsonite, which is the host mineral. The chesterite analysis is the average of 14 points in thin section. In addition, anthophyllite, foliated talc, and actinolite grains from the blackwall zone were analyzed, and the results given in Table 3 are averages of 17 points from anthophyllite, five from talc, and three from actinolite.

The average analyses of chesterite, jimthompsonite, and clinojimthompsonite are consistent with the refined structures (Veblén and Burnham, 1978). The

ideal chemical formula for chesterite is $M_{17}Si_{20}O_{54}(OH)_6$, and that for jimthompsonite and clinojimthompsonite is $M_{10}Si_{12}O_{32}(OH)_4$, where M refers to Mg and Fe^{2+} . The chesterite formula is thus the sum of the anthophyllite formula, $M_7Si_8O_{22}(OH)_2$, and the jimthompsonite formula. Figure 3, a ternary plot of octahedral cations *vs.* tetrahedral cations *vs.* $HO_{0.5}$, shows that the new pyriboles ideally are chemically intermediate between anthophyllite and talc and are collinear with enstatite, anthophyllite, and talc.

The analyses show that small amounts of Mn and Ca substitute for Mg and Fe; the Mn may be responsible for the light pinkish color, observable in hand specimen, of the low-Ca pyriboles. Only clinojimthompsonite appears to contain octahedral Al, but the quality of the analyses may not be good enough

to rule out the presence of some octahedral Al in the other minerals; small amounts of Al replace Si in the tetrahedral sites of all these pyriboles. If it is assumed that the Na shown in the analyses is restricted to the A sites of the minerals (which are analogous to the amphibole A site), then these sites in the analyzed anthophyllite, chesterite, jimthompsonite, and clinojimthompsonite are approximately 1, 2/3, 2 1/2, and 2 percent filled respectively.

The recalculation program of Brady (1974), used with chemical assumptions analogous to those utilized by Stout (1972) for the amphiboles, shows that Fe^{3+} is not a major component of the pyriboles from Chester. When the averaged microprobe analyses of Table 3 are normalized to the appropriate number of oxygens, and when it is assumed that all Na is restricted to A sites, the resulting $Fe^{3+}/(Fe^{3+} + Fe^{2+})$ ratios are 0.04 in anthophyllite, 0.00 in chesterite, 0.04 in jimthompsonite, and -0.05 in clinojimthompsonite.

From the averaged analyses, there is no obvious chemical difference between jimthompsonite and clinojimthompsonite. The largest apparent differences are in SiO_2 and Al_2O_3 , but there is overlap in the values of individual analysis points from the two

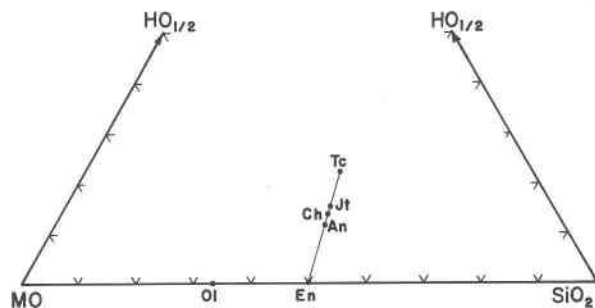


Fig. 3. Chemistry of the Chester biopyriboles. The ideal compositions, derived from crystal structures and averaged electron microprobe analyses, are represented here on a molar $MO-SiO_2-HO_{0.5}$ ternary diagram, in which M represents divalent octahedral cations (primarily Mg and Fe) and water is given as $HO_{0.5}$. In this representation, enstatite, anthophyllite, chesterite, jimthompsonite, clinojimthompsonite, and talc are compositionally collinear.

minerals, and the clinojimthompsonite average was calculated from only four analysis points; the SiO_2 difference and other differences are probably not statistically meaningful. Because anthophyllite and cummingtonite can apparently overlap in composition (Rice *et al.*, 1974), it is not surprising that jimthompsonite and clinojimthompsonite can be compositionally undifferentiable.

The individual analyses that yielded the averages of Table 3 exhibit some scatter. The ratio $(Si+Al)/(Si+Al+Mg+Fe+Mn+Ca)$ is the ratio of tetrahedral cations to tetrahedral plus octahedral cations, assuming that all Al is tetrahedral, that there is no tetrahedral Fe^{3+} , and that the Na is restricted to the A site. A plot of this ratio for all the individual analyses (Fig. 4) exhibits considerable overlap for anthophyllite, chesterite, jimthompsonite, and clinojimthompsonite. It is not known how much of the scatter, if any, is due to real compositional variations, and how much is the result of analytical error. In spite of the scatter, however, it is clear that the new minerals are more silica-rich than anthophyllite and less so than talc. Because the new pyriboles are intermediate reaction products between anthophyllite and talc, it is conceivable that some of the chemical scatter is real. Variations in the tetrahedral/(tetrahedral + octahedral) ratio could result from stuffing cations which are normally octahedral into the A sites, or from creation of octahedral vacancies during the reactions. Submicroscopic lamellae of other biopyriboles could also contribute significantly to the analytical scatter.

It is well established (*e.g.* Papike and Cameron, 1976) that Fe, Mn, and Ca are usually concentrated over Mg in the outer distorted M sites of pyriboles,

Table 3. Average electron microprobe analyses of biopyriboles from the Chester blackwall zone

	Anth	Ch	Jt	Cjt	Talc	Actin
SiO_2	56.55	57.95	57.78	58.55	61.30	56.96
Al_2O_3	0.24	0.25	0.29	0.37	0.15	1.07
* FeO	16.03	14.14	12.22	12.13	6.28	6.49
MnO	1.15	0.99	0.72	0.73	0.06	0.37
MgO	23.44	24.24	25.14	24.93	28.00	21.36
CaO	0.50	0.42	0.38	0.50	0.02	11.99
Na_2O	0.04	0.03	0.12	0.10	0.04	0.22
** H_2O	2.12	2.60	2.92	2.93	4.61	2.16
Total	100.07	100.62	99.57	100.24	100.46	100.61
Numbers of Cations on the Basis of NOX Oxygens						
NOX	23	57	34	34	22	23
Tetrahedral:						
Si	7.96	19.94	11.91	11.97	7.93	7.87
Al	0.04	0.05	0.07	0.03	0.02	0.13
Total	8.00	19.99	11.98	12.00	7.95	8.00
Octahedral:						
Fe	1.89	4.07	2.11	2.07	0.68	0.75
Mn	0.14	0.29	0.13	0.13	0.01	0.04
Mg	4.92	12.43	7.73	7.59	5.40	4.40
Ca	0.08	0.16	0.08	0.11	0.00	1.77
Al	0.00	0.00	0.00	0.05	0.00	0.04
Total	7.03	16.95	10.05	9.95	6.09	7.00
Large cations:						
Na	0.01	0.02	0.05	0.04	0.00	0.06

*All iron was calculated as Fe^{2+} .

**The amount of water was calculated by assuming all OH sites to be filled with OH^{1-} (Veblen and Burnham, 1978).

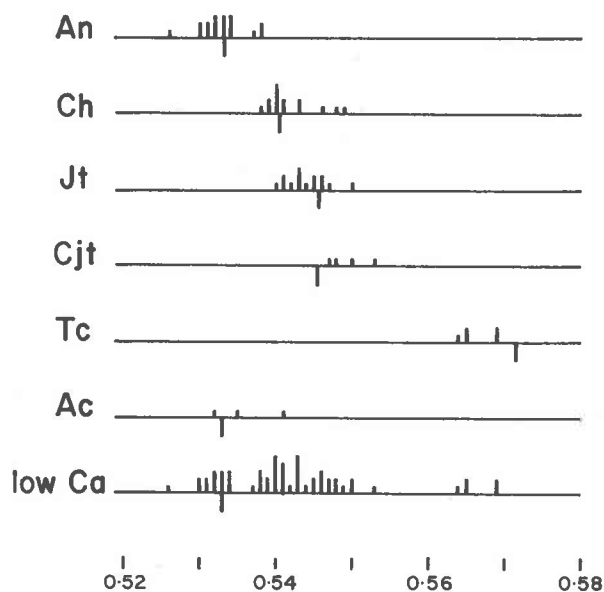


Fig. 4. $(\text{Si}+\text{Al})/(\text{Si}+\text{Al}+\text{Mg}+\text{Fe}+\text{Mn}+\text{Ca})$ ratios of individual electron microprobe analyses of anthophyllite, chesterite, jimthompsonite, clinojimthompsonite, talc, and actinolite from Chester. The number of analyses with a given ratio (rounded to 0.001) is indicated by the height of the vertical line segments; the shortest lines represent one analysis. Ideal ratios, based on structural formulas, are indicated by the vertical line segments below the horizontal lines. The line marked "low Ca" shows all the analyses, excluding those of actinolite. The observed ratios are not evenly distributed about the ideal amphibole ratio.

while Mg is concentrated in the inner more regular M sites. It might be expected, then, that the ratio $\text{Mg}/(\text{Mg}+\text{Fe}+\text{Mn}+\text{Ca})$ would increase from anthophyllite to chesterite to jimthompsonite when these minerals coexist, because the ratio of regular to distorted M sites increases. Figure 5 shows the $\text{Mg}/(\text{Mg}+\text{Fe}+\text{Mn}+\text{Ca})$ variations exhibited by the individual probe analyses, and, even though there is significant scatter, the expected increase in Mg over other octahedral cations is clear.

In spite of radical structural differences, anthophyllite, chesterite, and jimthompsonite have ideal chemical compositions that are very close to each other. Given the scatter demonstrated in Figures 4 and 5, whether it be from analytical errors or real compositional variations, it would be very difficult to differentiate these pyriboles unambiguously from chemical methods alone. The bottom lines of Figures 4 and 5 show the distribution of the tetrahedral/(tetrahedral + octahedral) and $\text{Mg}/(\text{Mg}+\text{Fe}+\text{Mn}+\text{Ca})$ ratios for all of the analyzed points, excluding those for actinolite. These total distributions are simi-

lar to the distribution that one would achieve by randomly analyzing a mixture of these minerals, and because there are no obvious maxima in the distributions an unwary analyst might easily explain them as compositional variations in a single phase. The total distribution in Figure 4 is, however, clearly more silica-rich than that to be expected from ideal anthophyllite; that observation alone might alert the petrologist to the presence of phases intermediate between the amphiboles and the micas.

On balance, chemical data should prove most valuable when the minerals present have already been identified by other means. The ambiguity of the microprobe data emphasizes that these new minerals must be defined primarily on structural rather than chemical grounds. Similar phases with significant amounts of Al would be even harder to distinguish chemically, because the tetrahedral/octahedral ratio for Al is determined from microprobe data by using a structural assumption.

Powder diffraction

Powder diffraction profiles for chesterite, jimthompsonite, and clinojimthompsonite were calculated with the computer program POWD5 (Clark *et al.*, 1973), the same program used to calculate patterns for *Geol. Soc. Am. Memoir 122* (Borg and Smith, 1969). Using refined atomic positions, isotropic temperature factors, and occupancies (Veblén and Burnham, 1978), the patterns were calculated for $\text{CuK}\alpha$ radiation, assuming peak half-widths of $0.11^\circ 2\theta$ at $40^\circ 2\theta$ and a scan speed of $2^\circ 2\theta$ per inch. Summaries of peaks with integrated intensities greater than 1 percent of the largest intensity for chesterite, jimthompsonite, and clinojimthompsonite

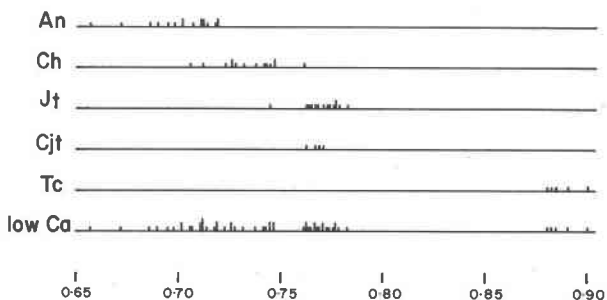


Fig. 5. The $\text{Mg}/(\text{Mg}+\text{Fe}+\text{Mn}+\text{Ca})$ ratios of individual electron microprobe analyses of biopyriboles from Chester. Presentation is the same as for Fig. 4. There is a significant degree of scatter in the analyses, but it can be seen that in going from anthophyllite to chesterite to jimthompsonite and clinojimthompsonite the minerals become increasingly magnesian.

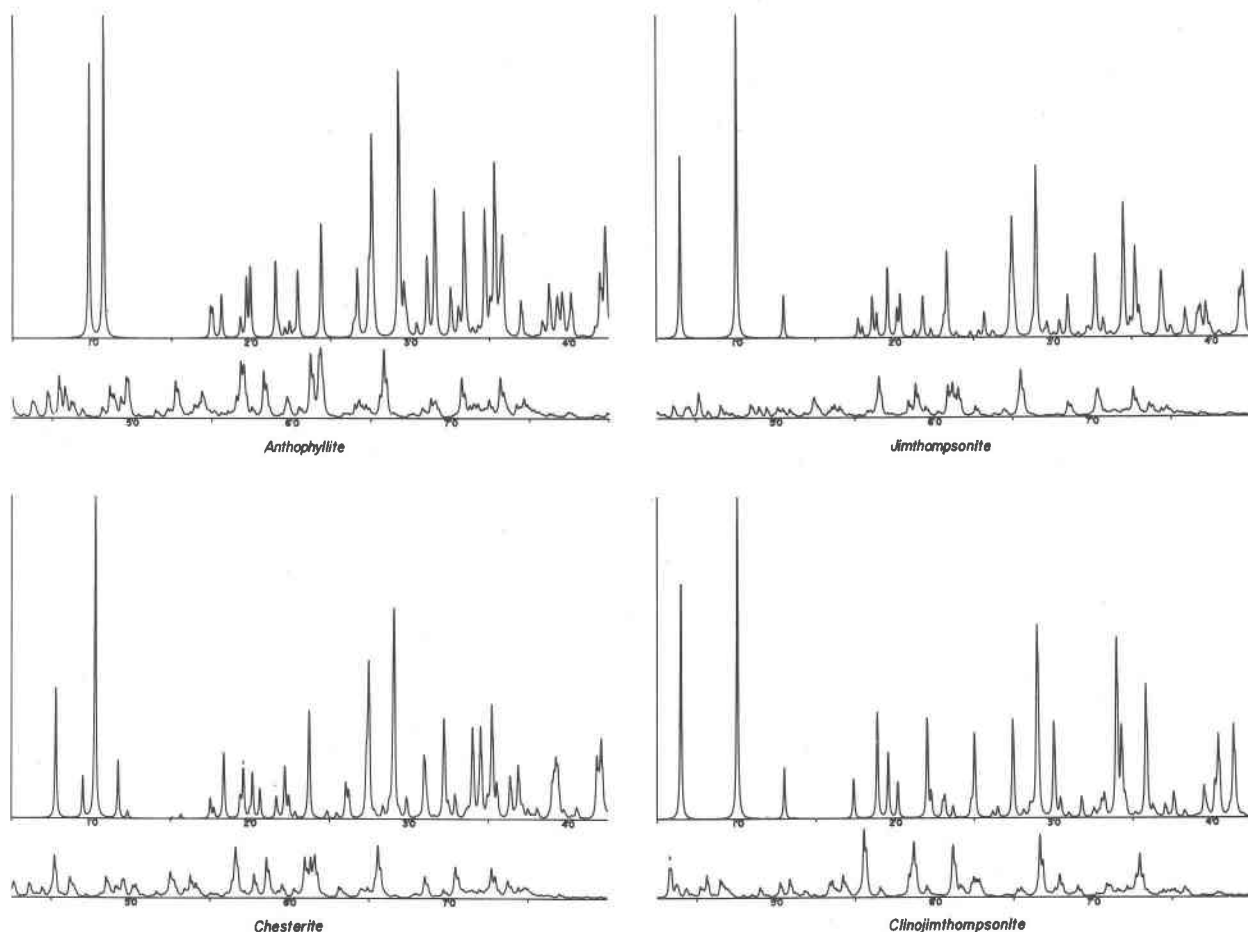


Fig. 6. Calculated X-ray powder-diffraction profiles of anthophyllite (Finger, 1970), chesterite, jimthompsonite, and clinojimthompsonite. Patterns were calculated using refined atomic coordinates, isotropic temperature factors, and occupancies (Veblen and Burnham, 1978). The patterns simulate random-orientation diffractometer traces with $\text{CuK}\alpha$ radiation, a peak half-width of $0.11^\circ 2\theta$ at $40^\circ 2\theta$, and a scan speed of 2° per inch. The numbers beneath each trace are $^\circ 2\theta$ for $\text{CuK}\alpha$.

are listed in Table 4⁴. The powder diffraction patterns are plotted in Figure 6, which also shows anthophyllite for comparison. The summary tables are in the same format as that used for *Geol. Soc. Am. Memoir 122*: 2THETA and D give the 2θ and interplanar spacing for reflection (HKL), and I(INT) and I(DS) give the uncorrected integrated intensity and integrated intensity corrected for Debye-Scherrer absorption, assuming that the peak can be resolved; PEAK and I(PK) refer to the peak positions and peak heights of the pattern produced by summing all the diffractions, after each has been given a Cauchy profile with the input half-width.

Table 4 and Figure 6 suggest that X-ray powder diffraction could be used to differentiate between the various biopyrriboles from Chester. The peaks below $15^\circ 2\theta$ ($\text{CuK}\alpha$) may be particularly useful, because they are very intense, but higher-angle peaks are required to separate jimthompsonite from clinojimthompsonite. The calculated powder-diffraction profiles might be useful for identifying fine-grained run products of petrologic experiments if the phases are present in large enough amounts. It must be remembered that these calculated patterns assume random orientation of the specimen, which will be difficult to achieve, given the prismatic or fibrous habit of all the minerals. Real intensities will differ from these calculated ones because of preferred orientation.

Powder-diffraction photographs of a mixture of the Chester pyrriboles estimated to contain 60 percent anthophyllite, 20 percent chesterite, and 20 percent

⁴ To obtain a copy of Table 4, order Document AM-78-078 from the Business Office, Mineralogical Society of America, 1909 K Street, N.W., Washington, D.C. 20006. Please remit \$1.00 in advance for the microfiche.

jimthompsonite are significantly less diagnostic than the powder calculations. A Debye-Scherrer film was unable to resolve the low-angle peaks. The only lines on a Guinier photograph that could be unambiguously assigned to minerals other than anthophyllite were the (200), (220), (620), and $(2 \cdot 13 \cdot 1)$ of chesterite at $d = 9.35, 8.59, 3.08,$ and 2.78\AA respectively and the (210) and (610) of jimthompsonite at 8.82 and 3.10 \AA . Small lamellae of the new minerals in anthophyllite would be very difficult to recognize by power-diffraction techniques.

Summary: identification of the Chester pyriboles

Although differences among the low-calcium biopyriboles from Chester have been demonstrated optically, chemically, and by powder diffraction, it is likely that positive identification of the new minerals at other localities will require single-crystal X-ray techniques. Optical study may prove difficult, owing to the intergrown nature of the minerals, and the effects of chemical substitutions on the optical properties are not known. The intergrowths are distinctive in thin section, however, and the cleavages of the new minerals when observed in non-fibrous occurrences may be seen to intersect at angles lower than those of amphiboles. Chemically, the new minerals are all very close to anthophyllite and cummingtonite, and electron microprobe analyses show too much scatter to be definitive. Powder diffraction is useful only when the minerals are individually present in large amounts.

The new minerals can easily be recognized by their distinctive X-ray precession photographs, which provide both cell-parameter and symmetry information, and by electron diffraction patterns. Even the components of fine multiphase intergrowths can be identified by these techniques. Single-crystal methods are, in fact, the only means by which the lamellar monoclinic phases can be recognized. Identification and study of these new minerals can best be accomplished by using a combination of X-ray, optical, and chemical methods, and not restricting oneself to a single technique.

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