CHLORITOID FROM MEGANTIC COUNTY, QUEBEC[1]

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ABSTRACT

Chloritoid occurs as greenish black plates (up to 1×20 mm.) in quartz-carbonate veins, at the Harvey Hill mine, 5 miles E. of Leeds, Megantic County, Quebec. Cleavage (001) good, (*hhl*) poor. $H=6\frac{1}{2}$. $G=3.528$. The monoclinic unit cell with space-group $C2/c$, has $a=9.45$, $b=5.48$, $c=18.16$ A, $\beta=101°\ 30'$, and contains $4[(Fe, Mg)_2Al_2(Al_2Si_2)O_{10}(OH)_4]$. Twinning lamellar, probably with twin axis [130], composition plane (001). Optically positive; $X=b$, $Z:(001)=+15°$, $Z:[001]=+26\frac{1}{2}°$. α (greenish grey to olive green)$=1.716$, β (bluish grey to idigo)$=1.719$, γ (colourless to greenish yellow)$=1.725$ (all ± 0.001 for Na); $2V=66\pm 2°$, $r>v$.

Early crystal measurements indicate the forms $c(001)$, $m(110)$, $e(401)$, $i(\bar{4}01)$, $k(114)$, $h(\bar{1}11)$; an angle-table for these forms is given on $a:b:c=1.7245:1:3.3141$, $\beta=101°30'$ (*x*-ray). The powder pattern of chloritoid is indexed and a review of 20 analyses establishes the composition $(Fe'',Mg)_2(Al, Fe''')_2(Al_2Si_2)O_{10}(OH)_4$.

Chloritoid was named by G. Rose (1837, in Dana, 1892, p. 640) from its superficial resemblance to chlorite, and the mineral is generally placed in the Clintonite Group or Brittle Micas which are chemically intermediate between the true micas and the chlorites. The brittle micas resemble the true micas in crystal form, cleavage, and optical properties, but they differ in the brittleness of their cleavage plates. Chloritoid is particularly distinguished by its difficult basal cleavage and high hardness ($6\frac{1}{2}$). Analyses of chloritoid and also the optical and physical properties vary somewhat; this led to the introduction of such names as barytophyllite, masonite, sismondine, struverite, and salmite, which are included under chloritoid by Dana. The empirical formula given by Dana (1892) is $H_2(Fe,Mg)Al_2SiO_7$; and later work, by Simpson (1931) and by Balk and Barth (1934) has confirmed these proportions, when allowance was made for inclusions of quartz and rutile.

Although chloritoid has been studied many times in the past, its properties are still not completely described. A specimen from the Harvey Hill Mine in Megantic County, Quebec (Royal Ontario Museum M6366) provided sharply crystallized material for a full examination. Similar material was described and analysed by Hunt (1861) whose analysis has been used in the calculation of the cell content.

GEOLOGY AND PETROGRAPHY

The Harvey Hill Mine, 5 miles E. of Leeds, Megantic County, was a copper prospect and producer from approximately 1850 to 1900. According to Bancroft (1915) the mine is located in slaty schists of Precambrian

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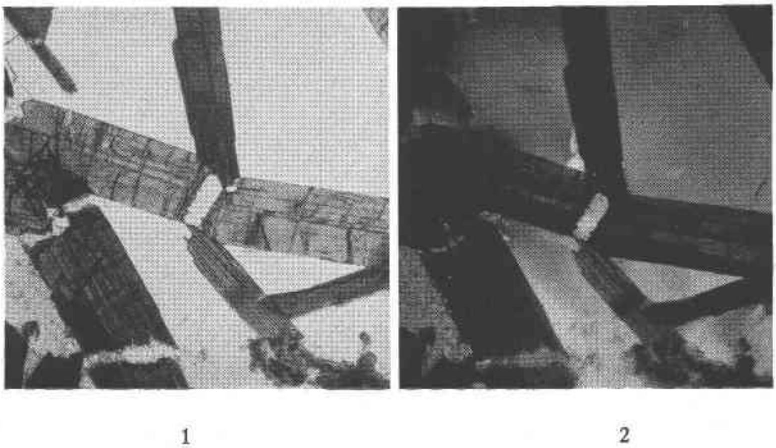
age; some bands in these schists are rich in chloritoid. Veins composed of quartz, calcite, and dolomite traverse the schists and it seems likely that the museum specimen came from one of these veins, for it is composed largely of quartz and carbonate with a small amount of light grey-green wall-rock.

The chloritoid is most abundant in the quartz-carbonate vein with a smaller amount in the wall-rock. It occurs in greenish black plates up to 1 mm. thick and 20 mm. wide, rarely showing roughly hexagonal outlines and more often traversed by quartz-filled fractures intersecting at about 60°. A thin section from the vein portion of the specimen (Figs. 1, 2) shows plates of chloritoid embedded in coarse quartz, with smaller quantities of calcite, apatite, and white mica. The plates are sometimes fractured and recemented by finer grained quartz. These chloritoid plates are otherwise quite free from inclusions. A similar occurrence of chloritoid, from Crestlianderstobel in the Swiss Alps, has been described by Friedlaender (1930). Here the chloritoid occurs in a schistose rock and contains inclusions of quartz, but small quartz veins traversing the rock contain aggregates of the mineral free of inclusions.



FIGS. 1, 2. Chloritoid, Megantic County, Quebec; thin section showing basal plates on edge in quartz-carbonate vein; ×13. Fig. 1 (left). One nicol. Fig. 2 (right). Crossed nicols, showing lamellar twinning.

PHYSICAL PROPERTIES

The large greenish black plates of chloritoid are almost opaque, but small fragments are transparent and bottle-green in colour. There is a perfect but difficult cleavage parallel to (001), and the lamellae break easily roughly perpendicular to this plane. Fragments broken in this way are often quite irregular in outline, but occasionally there are two distinct breaks intersecting at 60°. The faces produced are very imperfect and give a diffuse train of signals on the optical goniometer. *X*-ray work proved that these poor cleavages are of the type (*hhl*) (Fig. 3).

The lustre is vitreous to brilliant on the (001) face, but subvitreous on irregular surfaces. The powder is grey-green in colour. Careful hardness measurements placed the mineral between feldspar and quartz; this value of 6½ is the upper limit which has been reported for chloritoid by previous investigators. The remarkable hardness distinguishes chloritoid from other members of the Brittle-Mica Group and suggests that it may not properly belong in this group.

Specific gravity measurements were made using Clerici's solution and the Westphal balance, from which an average value of 3.528 was obtained. This is in close agreement with the value 3.513 reported by Hunt for chloritoid from Megantic County.

CRYSTAL FORM

Plates of chloritoid from Megantic County generally have ragged edges, but occasionally a rough hexagonal outline can be detected. Faces other than (001) are lacking and the latter is often curved and not parallel to its opposite face. In several cases crystals were elongated in the [110] direction, as proved by a series of rotation and Weissenberg *x*-ray photographs.

Tschermak and Sipöcz (1879) were able to measure the interfacial angles between *c*(001) and five other faces on chloritoid from Pregratten, Tyrol. Since this is the only record of such measurements, an attempt has been made to correlate Tschermak's measured angles with angles calculated from the cell elements. A tentative and not wholly satisfactory correlation of forms and angles is given below.

Tschermak	Measured	Milne	Calculated
cm = (001):(332)	83° 25′	*cm* = (001):(110)	84° 10¼′
ce = (001):(011)	71	*ce* = (001):(401)	71 25
cj = (001):(061)	86 30	*cj* = (001):(40$\bar{1}$)	85 57½
cn = (001):($\bar{1}$11)	86 06	*cn* = (001):($\bar{1}$11)	80 40
ck = (001): —	40 ca.	*ck* = (001):(114)	40 34½

Table 1 gives a formal angle-table for the forms indicated by Tschermak's measurements, with reference to the geometrical elements of the crystal lattice determined later by *x*-rays.

Polysynthetic twinning is universal, with (001) as the composition face (Fig. 2). Consideration of the new cell dimensions indicates the probability of twinning according to the law: twin axis [130], composition plane (001). The basal planes on the two individuals would be brought

TABLE 1. CHLORITOID: $(Fe, Mg)_2Al_2(Al_2Si_2)O_{10}(OH)_4$

Monoclinic, $C2/c$

$a:b:c=1.7245:1:3.3141$; $\beta=101° 30'$

$p_0:q_0:r_0=0.5918:1:0.3079$; $\mu=78° 30'$

$p_0'=1.9611$, $q_0'=3.3141$, $x_0'=0.2134$

Form	ϕ	ρ	ϕ_2	ρ_2=B	C	A
c (001)	90° 00′	11° 30′	78° 30′	90° 00′	0° 00′	78° 30′
m (110)	30 37	90 00	0 00	30 37	84 10	59 23
e (401)	90 00	82 55	7 05	90 00	71 25	7 05
j ($\bar{4}01$)	−90 00	82 32	172 32½	90 00	94 02½	172 32½
k (114)	39 56½	47 13	55 15	55 45½	40 34½	64 09
h ($\bar{1}11$)	−27 56½	75 04½	15 22	31 23½	80 40	96 56

into exact parallelism and the zone axes [100], [110], [010], on one individual would fall very nearly over the zone axes [130], [010], [110], respectively, on the other individual. This is comparable with the twinning in muscovite described by Peacock and Ferguson (1943), except that in muscovite the *a* and *b* axes are interchanged as compared to chloritoid, and hence the twin axis is [310].

OPTICAL PROPERTIES

The acute positive bisectrix Z is inclined at 15° to the normal to (001), as measured with the universal stage on the same crystal which was later used for *x*-ray work. It will be seen in Table 2 that the positive sign of chloritoid is well established, with Z inclined to the normal to (001) at angles varying from 5° to 30°. Correlation of optical observations and *x*-ray measurements on a single crystal from Megantic County showed that X corresponds to the symmetry axis *b*; this does not agree with the observations of Balk and Barth, who reported that Y was always contained in the cleavage plane (001) and presumably is therefore coincident with *b*. The inclination of Z to the *c*-axis is $Z:c=+26\frac{1}{2}°$ and hence $Y:c=-63\frac{1}{2}°$.

Fragments of the mineral approximately 0.25 mms. in thickness exhibit a remarkable pleochroism, X greenish grey to olive green, Y bluish grey to indigo, and Z colourless to greenish yellow, giving the absorption formula, $Y>X>Z$. All past observers have noted this relationship, the average colours being X green, Y blue, Z pale yellow.

The indices α and β were obtained by immersion, with sodium light, from flat-lying cleavage flakes. Because of the small inclination of Y to the cleavage plane (001) the error in β is negligible. The value of γ was obtained from fragments lying perpendicular to *c*(001) and giving the maximum extinction angle (15°). The refractive indices (Na) are:

$$\alpha=1.716,\ \beta=1.719,\ \gamma=1.725,\ \text{all}\ \pm 0.001$$

Observations by other authors give values for β ranging from 1.719 to 1.728, with an average birefringence of 0.009.

The optic axial angle, $2V$, was obtained from the apparent optic axial angle in glass, $2G$, measured with sodium light on the universal stage, using glass hemispheres of refractive index n. The angle V is related to the angle G by the relationship, $\text{Sin } V = \text{Sin } G \cdot n/\beta$. $2V$ may be calculated from the refractive indices using the approximate formula $\text{Cos}^2 V = (\beta-\alpha)/(\gamma-\alpha)$. The values obtained by the two methods are:

$$2V = 66 \pm 2° \text{ (measured)}, 66° \text{ (calculated)}$$

Previously reported measurements of $2V$ are mostly in the range 50° – 68°. The dispersion is perceptible, $r > v$. This agrees with other observations recorded in Table 2, except that Balk and Barth (1934) reported the dispersion of Dutchess County chloritoid to be anomalous, with green on the convex side of the hyperbolas and yellow on the concave side.

TABLE 2. CHLORITOID: OPTICAL OBSERVATIONS

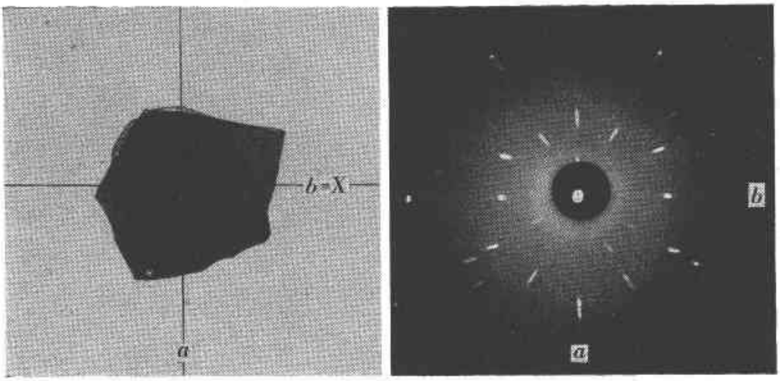
	1	2	3	4	5	6	7
α	1.716	1.715	1.720	1.722	1.724	1.724	—
β	1.719	1.719	1.722	1.725	1.726	1.726	1.728
γ	1.725	1.737	1.731	1.728	1.730	1.737	—
$\gamma-\alpha$	0.009	0.022	0.011	0.006	0.006	0.013	0.007
X	Greenish grey to olive green	Olive to olive green	Colourless to pale gn. yellow	Pale grey green	Greenish blue	Greenish brown to grass green	Yellowish green
Y	Blue grey to indigo	Blue	Plum to indigo blue	Slate blue	Blue	Deep blue to bluish green	Bluish green
Z	Colourless to greenish yellow	Pale	Yellow to colourless	Yellow to colourless	Pale yellow	Yellowish green	Pale yell. to colourless
$X=b$	—	—	—	$Y=b$	—	—	—
Z:(001)	15°	—	20°	5°–22°	30°	21°	15°
Sign	+	—	+	+	+	—	+
$2V$	66°	50°	36°–60°	60°	68°	63°	—
Disp.	$r>v$	—	$r>v$	Anomalous	$r>v$	—	—

1. Megantic Co., Que. (anal. 13, Table 4); Milne (this paper).
2. Saas Valley, Switzerland (anal. 3); Friedlaender (1930).
3. Locality unknown; Larsen and Berman (1934, p. 131).
4. Dutchess Co., N.Y. (anal. 19); Balk and Barth (1934).
5. Champion Mine, Michigan (anal. 11); Milne (this paper).
6. Crestlianderstobel, Switzerland (anal. 8); Friedlaender (1930).
7. Deep River Region, N.C. (anal. 20); Stukey (1926).

STRUCTURAL CRYSTALLOGRAPHY

A thin cleavage flake of chloritoid (Fig. 3), free from twinning and showing evidence of two cleavage directions intersecting at 60° in the basal plane, was selected for x-ray measurements. The plane containing Y and Z bisects the angle between the two cleavage traces. One edge of the plate, which appeared to be due to such a cleavage, gave a train of poor signals on the optical goniometer; individual signals could not be measured but the zone was well defined.

A basal Laue photograph (Fig. 4) was taken of this crystal using tungsten radiation. The diffraction pattern indicates a plane of symmetry, with the optical direction X coinciding with the perpendicular to this plane. Y and Z lie in the plane of symmetry.



3 4

FIGS. 3, 4. Chloritoid, Megantic County, Quebec. Untwinned single crystal plate used for x-ray photographs, with traces of poor (hhl) cleavage. The directions of the axes a and $b=X$ are indicated. Fig. 3 (left). One nicol; ×20. Fig. 4 (right). Laue photograph showing plane of symmetry perpendicular to $b=X$.

The crystal was then set up for rotation about the symmetry axis (X direction) and a rotation photograph and zero, first and second layer Weissenberg resolutions were taken. These photographs showed that the symmetry is monoclinic; the smallest and least oblique cell has the dimensions:[3]

$$a=9.45,\ b=5.48,\ c=18.16\ \text{A},\ \beta=101°/30'$$

The systematically missing spectra, namely (hkl) present only with $(h+k)$ even, $(h0l)$ present only with h even and l even lead to the space-groups, Cc or $C2/c$.

The only published work on the cell dimensions of chloritoid is by Machatschki and Mussgnug (1942). These authors reported the following values:

$$a=5.4,\ b=9.4,\ d(001)=17.85\ \text{A}$$

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[3] Using λ Cu$K\alpha_1=1.5418$ A.

The measurements of *a* and *b* are obviously rough and apparently interchanged, and no attempt was made to measure β. The value for $d(001)$ compares with that obtained during this investigation, namely 17.80 A.

Before the discovery of the exceptional crystal used in the above cell determination, a series of *x*-ray photographs of a log-shaped cleavage fragment had been taken. The fragment showed a good basal cleavage and, as was proved later, a very poor cleavage (*hhl*). Optical results were indefinite but the extinction was distinctly inclined suggesting triclinic symmetry. The resulting rotation and Weissenberg photographs gave a unit cell with the dimensions:

$$a'=9.49,\ b'=5.45,\ c'=17.98\ \text{A}$$
$$\alpha'\sim 90^\circ,\ \beta'=98^\circ\ 51',\ \gamma'\sim 90^\circ$$

A second-layer Weissenberg resolution indicated that α' and γ' are not exactly 90°, but it was impossible to measure the exact angles.

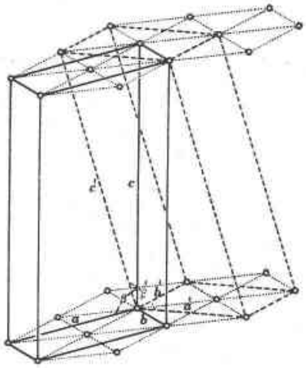

FIG. 5. Chloritoid. Crystal lattice showing the true monoclinic cell *a b c β*, and false triclinic cell *a′ b′ c′ β′*.

When the true monoclinic cell was finally determined, it was realized that there is present in the structure a false triclinic cell in which α' and γ' are close to 90° and a', b', c' are near to those of the true cell. The relationship between these cells is shown in Fig. 5. In order to check this relationship, the dimensions of the false triclinic cell (*T*) have been calculated from those of the true monoclinic cell (*M*).

True Cell (*M*)	False Cell (*T*)	
Measured	Measured	Calculated
$a=$ 9.45 A	$a'=$ 9.49 A	9.48 A
$b=$ 5.48	$b'=$ 5.45	5.46
$c=$18.16	$c'=$17.98	18.04
—	$\alpha'=$90°	88° 39′
$\beta=$101° 30′	$\beta'=$98 51	99 20
—	$\gamma=$90	89 45

Structural studies of the micas have shown that the cleavage plane in these minerals is parallel to hexagonal layers with $a=5.2$–5.3, $b=9.0$–9.2, and a vertical spacing of nearly 10.0 A between successive layers. The two-layer type (muscovite), is the most closely related in geometrical properties to chloritoid, but there are considerable differences, as shown below.

	Chloritoid	Muscovite
	$C2/c$	$C2/c$
$a=$	9.45 A	5.21 A
$b=$	5.48	9.02
$c=$	18.16	19.98
$\beta=$	101° 30′	96° 24′

A powder photograph of the material from Megantic County was taken with Fe radiation and a Mn filter. The measured spacings have been indexed and they are compared with calculated spacings in Table 3. So far as is known, these are the first x-ray powder data to be given for chloritoid.

TABLE 3. CHLORITOID: X-RAY POWDER PATTERN

Monoclinic $C2/c$

$a=9.45$ A, $b=5.48$, $c=18.16$ A, $\beta=101°\ 30'$

I	θ(Fe)	d(meas.)	(hkl)	d(calc.)	I	θ(Fe)	d(meas.)	(hkl)	d(calc.)
10	12.55°	4.46	(004)	4.45	$\frac{1}{2}$	29.22°	1.983	(315)	1.986
			(111)	4.45	1	30.92	1.884	($\bar{3}18$)	1.882
$\frac{1}{2}$	16.60	3.39	($\bar{1}14$)	3.41	$\frac{1}{2}$	32.68	1.794	(130)	1.793
3	19.08	2.96	(006)	2.97				($\bar{4}08$)	1.793
1	20.60	2.75	(020)	2.74	$\frac{1}{2}$	33.60	1.749	(510)	1.755
2	21.65	2.62	($\bar{1}16$)	2.63				($\bar{3}19$)	1.744
			($\bar{3}13$)	2.63	$\frac{1}{2}$	34.58	1.706	($\bar{5}15$)	1.706
			(022)	2.62				(317)	1.705
1	22.70	2.51	($\bar{3}14$)	2.50	$\frac{1}{2}$	35.92	1.650	($\bar{5}16$)	1.653
1	23.20	2.46	(312)	2.46	3	37.70	1.781	(135)	1.577
3	24.22	2.36	($\bar{4}02$)	2.36				($\bar{1}$.1.11)	1.580
			(220)	2.36	1	38.30	1.562	(424)	1.563
			($\bar{3}15$)	2.35				($\bar{1}36$)	1.561
3	24.88	2.30	(400)	2.31				(2.0.10)	1.560
			(313)	2.30				($\bar{3}33$)	1.560
			(206)	2.30	1	43.48	1.407	(3.1.12)	1.406
$\frac{1}{2}$	25.50	2.25	($\bar{4}04$)	2.24				($\bar{6}08$)	1.405
1	27.02	2.13	(402)	2.14	1	44.98	1.370	(040)	1.371
1	28.37	2.04	($\bar{4}06$)	2.03	1	45.40	1.360	($\bar{4}$.2.10)	1.362
			($\bar{3}17$)	2.03	$\frac{1}{2}$	47.15	1.321	($\bar{5}$.1.11)	1.320

Table 4. Chloritoid and Ottrelite: Selected Analyses with Atomic Proportions

	1	2	3	4	5	6	7
SiO_2	24.40	24.47	25.30	26.03	24.90	26.19	23.74
Al_2O_3	42.80	41.34	41.24	42.33	40.36	38.30	39.01
Fe_2O_3	—	0.38	2.39	4.09	—	6.00	3.04
FeO	19.17	18.52	18.02	14.32	26.17	21.11	23.98
MnO	—	0.91	0.09	—	—	—	0.49
MgO	6.17	6.80	3.60	7.30	2.54	3.30	1.61
CaO	—	0.30	—	0.35	—	—	1.02
K_2O	—	—	0.76	—	—	—	—
Na_2O	—	—	2.53	—	—	—	—
TiO_2	—	—	—	—	—	—	—
H_2O	6.90	6.98	6.15	6.56	6.23	5.50	7.72
	99.44	99.70	100.08	100.98	100.20	100.40	100.61
Si	1.93	1.94	1.96	1.96	1.98	2.00	2.01
Al	2.07	2.06	2.04	2.04	2.02	2.00	1.99
(Si, Al)	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Al	1.91	1.81	1.72	1.71	1.75	1.44	1.90
Fe'''	—	0.02	0.14	0.23	—	0.34	0.29
Fe''	1.26	1.23	1.17	0.90	1.74	1.35	1.70
Mn	—	0.06	0.01	—	—	—	0.04
Mg	0.73	0.81	0.41	0.82	0.30	0.38	0.20
Ca	—	0.03	—	0.03	—	—	0.09
K	—	—	0.08	—	—	—	—
Na	—	—	0.38	—	—	—	—
R	3.90	3.96	3.91	3.69	3.79	3.51	4.22
OH	3.62	3.70	3.17	3.40	3.40	2.80	4.36
O	10.00	10.00	10.00	10.00	10.00	10.00	10.00

1. Zermatt, Switzerland; anal. Damour in Des Cloizeaux (1884). 2. Shetland, Scotland; anal. Heddle (1879). 3. Saas Valley, Switzerland; anal. Jacob in Friedlaender (1930). 4. St. Marcel, Italy; anal. Suida, in Tschermak and Sipöcz (1879). 5. Grippe, Ile de Groix, France; anal. Renard, in Barrois (1884). 6. Pregratten, Tyrol; anal. Kobell (1854). 7. Kalgoorlie, W. Australia; anal. Simpson (1931). 8. Crestlianderstobel, Switzerland; anal. Jacob, in Friedlaender (1930). 9. St. Marcel, Italy; anal. Delesse (1846, in Hintze, 1897, p. 677). 10. Pregratten, Tyrol; anal. Sipöcz, in Tschermak and Sipöcz (1879). 11. Champion Mine, Michigan, U. S. A.; anal. Lane and Keller (1891). 12. St. Marcel, Italy; anal. Damour, in Des Cloizeaux (1884). 13. Leeds, Megantic County, Quebec, Canada; anal. Hunt (1861). 14. Krivoy Rog, Ukraine; anal. Tarasenko (1925). 15. Grossarl, Germany; anal. Cathrein (1887). 16. St. Marcel, Italy; anal. Kobell (1853). 17. Hetzschen, Germany; anal. Schröder

TABLE 4—(*continued*)

	8	9	10	11	12	13	14
SiO_2	26.62	24.10	24.90	24.29	25.50	26.30	27.30
Al_2O_3	37.65	40.71	40.99	34.00	38.13	37.10	37.80
Fe_2O_3	11.91	—	0.55	10.55	—	—	6.85
FeO	13.91	27.10	24.28	20.52	23.58	25.92	20.82
MnO	0.04	—	—	—	—	0.93	—
MgO	2.67	—	3.33	1.29	5.19	3.66	0.93
CaO	—	—	—	0.59	—	—	—
K_2O	0.46	—	—	0.97	—	—	—
Na_2O	1.21	—	—	0.35	—	—	—
TiO_2	0.21	—	—	0.28	—	—	—
H_2O	5.59	7.24	7.82	6.75	6.90	6.10	6.19
	100.27	99.15	101.87	99.59	99.30	100.01	99.89
Si	2.02	2.03	2.04	2.05	2.08	2.09	2.15
Al	1.98	1.97	1.96	1.95	1.92	1.91	1.85
(Si, Al)	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Al	1.39	2.07	2.00	1.42	1.74	1.57	1.65
Fe'''	0.68	—	0.03	0.67	—	—	0.40
Fe''	0.88	1.91	1.66	1.44	1.60	1.72	1.37
Mn	—	—	—	—	—	0.06	—
Mg	0.30	—	0.41	0.16	0.63	0.44	0.11
Ca	—	—	—	0.05	—	—	—
K	0.05	—	—	0.12	—	—	—
Na	0.18	—	—	0.06	—	—	—
R	3.48	3.98	4.10	3.92	3.97	3.79	3.53
OH	2.83	4.07	4.27	3.79	3.74	3.23	3.24
O	10.00	10.00	10.00	10.00	10.00	10.00	10.00

(1884, in Hintze, 1897, p. 677). 18. Kossoibrod, Ural Mts., Russia; anal. Bonsdorff, in Rose (1837, in Hintze, 1897, p. 677). 19. Dutchess County, N. Y., U. S. A.; anal. Balk and Barth (1934). 20. Deep River Region, N. Carolina, U. S. A.; anal. Stukey (1926).

COMPOSITION AND CELL CONTENT

The empirical molecular weight of chloritoid is $M = VG/1.6602 = 1959$, using the measured specific gravity $G = 3.528$. With this value the analysis of chloritoid from Megantic County, Quebec (Hunt, 1861) gives the accompanying empirical cell contents, and assumed grouping of the atoms in equivalent positions in the unit cell.

TABLE 4—(*continued*)

	15	16	17	18	19	20
SiO_2	26.17	25.75	28.04	27.48	29.5	29.28
Al_2O_3	40.38	37.50	36.19	35.57	38.1	37.98
Fe_2O_3	—	—	—	—	2.3	2.32
FeO	26.41	21.00	29.79	27.05	21.5	21.97
MnO	—	—	—	0.30	0.2	0.29
MgO	0.08	6.20	1.25	4.29	1.6	1.28
CaO	—	—	0.20	—	—	—
K_2O	—	—	—	—	—	—
Na_2O	—	—	—	—	—	—
TiO_2	—	—	—	—	1.2	0.86
H_2O	6.96	7.80	5.88	6.95	5.6	6.04
	100.00	98.25	101.35	101.64	100.0	100.02
Si	2.16	2.17	2.20	2.22	2.26	2.27
Al	1.84	1.93	1.80	1.78	1.74	1.73
(Si, Al)	4.00	4.00	4.00	4.00	4.00	4.00
Al	2.00	1.80	1.55	1.60	1.69	1.75
Fe‴	—	—	—	—	0.13	0.13
Fe″	1.78	1.48	1.95	1.82	1.38	1.43
Mn	—	—	—	0.02	0.01	0.02
Mg	0.01	0.78	0.15	0.52	0.18	0.15
Ca	—	—	0.02	—	—	—
K	—	—	—	—	—	—
Na	—	—	—	—	—	—
R	3.79	4.06	3.67	3.96	3.39	3.48
OH	3.74	4.39	3.08	3.74	2.85	3.13
O	10.00	10.00	10.00	10.00	10.00	10.00

SiO_2	26.30	Si	8.58	16.00
Al_2O_3	37.10	Al	14.26	
FeO	25.92	Fe	7.07	
MnO	0.93	Mn	0.26	15.95
MgO	3.66	Mg	1.78	
H_2O	6.10	OH	13.26	
		O	41.03	
	100.01			

The similarity in geometrical properties between chloritoid and the micas indicates a sheet structure with the characteristic $(Si,Al)_4O_{10}$ ratio. On this basis part of the Al has as usual been grouped with Si to make 16 atoms (oxygen = 40) and the remainder placed with the other cations. The ratio of Al to Si is approximately 2:2 in chloritoid in contrast with 1:3 in the micas. The cell content may be written:

$$4[(\mathrm{Fe, Mg, Mn})_{2.28}\mathrm{Al}_{1.71}(\mathrm{Al}_{1.86}\mathrm{Si}_{2.14})\mathrm{O}_{10.26}(\mathrm{OH})_{3.32}]$$

This differs from the probable ideal cell content:

$$4[(\mathrm{Fe, Mg})_2\mathrm{Al}_2(\mathrm{Al}_2\mathrm{Si}_2)\mathrm{O}_{10}(\mathrm{OH})_4]$$

mainly in the term (OH) which may be low, due to analytical error.

The better available analyses of chloritoid are presented in Table 4, with atomic proportions calculated to oxygen, exclusive of hydroxyl, equals 10. Sufficient Al has been grouped with Si to make (Si, Al) = 4, and it is clear that the ratio Si:Al in this group is consistently near 2:2. The remaining Al has been grouped with Fe‴, Fe″, Mn, Mg, Ca, K, Na, to give total R adding to nearly 4. In this group Al or (Al,Fe‴) amounts to nearly 2 and the rest is essentially (Fe″,Mg). Mn, Ca, K, Na are apparently unessential and occasional $\mathrm{TiO_2}$ is neglected since rutile inclusions have been reported in chloritoid. (OH) ranges from about 3 to 4, with 4 evidently the full number. The composition of chloritoid is thus

$$(\mathrm{Fe, Mg})_2(\mathrm{Al, Fe'''})_2(\mathrm{Al}_2\mathrm{Si}_2)\mathrm{O}_{10}(\mathrm{OH})_4$$

in agreement with the formula derived from the studied material. This formula compares with the early empirical formula, $\mathrm{H_2(Fe,Mg)Al_2SiO_7}$; and in showing the $\mathrm{(Si,Al)_4O_{10}}$ groups of the platy silicates it has something in common with a structural formula suggested for chloritoid by Machatschki and Mussgung (1942):

$${}^{2}_{\infty}\mathrm{Fe}^{++}(\mathrm{OH})_2\{(\mathrm{OH})_2(\mathrm{Fe, Al, Mg})_3[(\mathrm{Si, Al})_4\mathrm{O}_{10}]\}$$

The present paper prepares the way for a determination of the structure of chloritoid but this has not been attempted.

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