

MUSKOXITE, A NEW HYDROUS MAGNESIUM-FERRIC  
IRON OXIDE FROM THE MUSKOX INTRUSION, NORTH-  
WEST TERRITORIES, CANADA

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ABSTRACT

Muskoxite is a new hydrous Mg-Fe<sup>2+</sup> oxide of uncertain formula which occurs with serpentine in small fractures in drill cores from the Muskox Intrusion, Northwest Territories. Chemical analysis gave Fe<sub>2</sub>O<sub>3</sub> 41.1, FeO 0.0, MgO 35.4, H<sub>2</sub>O 23.8 sum 100.3% wt. Thermogravimetric analysis showed no significant weight loss at <105°C; 2.45% was lost up to 200°, 16.2% between 200 and 400°, and a gradual additional loss of 2.9% up to 800° (cumulative total 21.55%). The product is a mixture of spinel, hematite, and periclase.

Muskoxite is dark reddish brown; streak light orange-brown; hardness about 3; luster vitreous;  $\rho = 3.10$  to  $3.20 \pm 0.05$  (by suspension); perfect basal cleavage; biaxial negative with  $2V$  variable from 15 to 40°,  $n = 1.80$ –1.81. The mineral occurs typically as aggregates of intergrown minute crystals, less commonly as individual plates with hexagonal outline, paper-thin {001}. The X-ray powder pattern has strongest lines at 4.6 (*s*), 4.4 (*m* to *w*) 2.31 (*vs*), 1.74 (*m*), 1.46 Å (*w*). Single crystal films yield diffuse spots indicating that muskoxite is trigonal, with  $a = 3.1$  Å,  $c$  uncertain.

INTRODUCTION

The Muskox Intrusion is a layered ultramafic body which crops out in the Coppermine River area, Northwest Territories, from latitude 66°11'N, longitude 114°42'W to latitude 67°14'N, longitude 115°04'W. In 1963 three vertical holes were bored into the intrusion for scientific purposes and a total of 10,089 feet of diamond drilling was completed. The drilling project and core logs have been described by Findlay and Smith (1965).

In a previous paper (Jambor, 1969) the writer described coalingite which occurs in the cores. In the present paper the occurrence in the cores of the new mineral muskoxite is described. The new name, which is derived from the igneous complex in which the mineral occurs, has been approved by the Commission on New Minerals and Mineral Names, I.M.A. Muskoxite, like coalingite, has so far been recognized in the Muskox Intrusion only in specimens of drill core. Coalingite in the cores is known to have formed *in situ* within the approximately five-year interval since the cores were logged and stored. Muskoxite, on the other hand, was recognized and examined by X-ray diffraction methods during the logging of the cores. Specimens kept in the laboratory since then have not changed.

Nearly all the muskoxite occurs in the South drill hole (Findlay and Smith, 1965), but it has also been noted to occur very sparingly in cores from the North and East holes. In the South hole, it is present most

abundantly in serpentinite at a core depth from 1395 to 1506 feet. A detailed record of the distribution of the mineral can be found in the logs of the South hole drill core (Findlay and Smith, 1965) where the mineral is referred to as 'soft reddish-brown ferruginous material' or descriptive variants thereof.

About 75 veinlets of 1-mm thickness and 1 5/8-inch diameter (BX core) is an estimate of the magnitude of abundance of muskoxite in the 10,089 feet of core. Although the total amount of the mineral is thus relatively large (for mineralogical purposes), the acquisition of enough pure material for chemical and related analyses proved to be extremely taxing. The difficulty results primarily from the filling of remnant open spaces in the muskoxite veinlets by a younger serpentinite phase which is a pervasive, tenacious, effective contaminant.

#### PHYSICAL AND OPTICAL PROPERTIES

Muskoxite is dark reddish brown in color and has a light orange-brown streak. The hardness is about 3, but most material gives the impression of being much softer because of its fine-grained nature and the presence of a perfect basal cleavage. The density, measured by suspension of individual grains, ranges from 3.10 to  $3.20 \pm 0.05$ . Muskoxite is translucent and has a vitreous luster. The mineral typically occurs as aggregates of small crystals averaging less than a quarter of a millimeter in largest dimension. Also common are randomly-oriented anhedral grains in small veinlets, and fine-grained powdery material which is not visibly crystallized. In a few cases the mineral was also noted to occur as "cross-fiber" fillings of small fractures.

Crystals of muskoxite have two distinct habits, both of which occur abundantly. The more distinct habit is that of paper-thin {001} plates which are commonly hexagonal in outline. The plates are generally coalesced either into divergent groups or reticular aggregates. The edges of the plates are commonly modified by (dipyramidal?) forms whose presence is in most cases apparent only under the petrographic microscope.

Less distinct is a habit in which the grains are more equant as a result of intergrowth. When exposed in vugs these commonly appear to be single crystals; they are trigonal in outline, with three gently sloping "pyramidal" faces and "pedial" termination. The "pyramidal" faces are always surrounded by serpentinite matrix so that prismatic faces, if present, are not exposed. Without exception, this matrix boundary also marks the position below which intergrowth is present. Hence, what appears on the surface to be a single crystal is in three dimensions always an aggregate. The morphology of muskoxite is thus imperfectly known,

but the observed forms suggest that the mineral may belong to the crystal classes 32 or  $\bar{3}m$ .

In immersion oil under the petrographic microscope, muskoxite is nonpleochroic and amber to deep red in color. The perfect basal cleavage yields brittle micaceous flakes. These have a mean refractive index of 1.80 to  $1.81 \pm 0.01$ , and give biaxial negative figures in which optic angle ranges from about  $10^\circ$  to as much as  $40^\circ$ . The deviation from uniaxial optics is thus rather pronounced. Similar effects in layer silicates and layer hydroxides are not uncommon and are generally attributed to mechanical effects or stacking faults.

#### CHEMICAL ANALYSIS

A chemical analysis was made on a 200-mg sample of muskoxite initially concentrated by magnetic and heavy liquid techniques and subsequently purified by hand-picking the  $-150$  mesh fractions. The analytical results (Table 1) correspond to  $Mg_{3.41}Fe_2O_{6.41} \cdot 5.1H_2O$ . Carbon

TABLE 1. CHEMICAL ANALYSIS OF MUSKOXITE

	Wt. %	Mole proportions	$2Fe_2O_3 \cdot 7MgO \cdot 10H_2O$ Wt. %
$Fe_2O_3$	41.1	2.0	40.86
FeO	0.0		
MgO	35.4	6.82	36.10
$H_2O$	23.8	10.26	23.04
	100.3		100.00

Analyst: J. A. Maxwell.

dioxide was also determined in the analysis, but the amount present is less than one percent and an accurate value could not be obtained from the material available. Because the unit-cell dimensions and the structural combination of the elements in muskoxite are not known, a rigidly established formula is not as yet possible. The oxide and hydroxide forms of the analysis respectively correspond to  $3.41 MgO \cdot Fe_2O_3 \cdot 5.1H_2O$  and  $3.41Mg(OH)_2 \cdot 2FeO(OH) \cdot 0.7H_2O$ . Heating experiments, which will be described in a later section, have shown that part of the water can be driven out of the mineral without any indication of an attendant structural collapse. Presumably, therefore, it is appropriate to show  $H_2O$  as a discrete entity.

## INFRARED SPECTRUM

The infrared spectra of muskoxite and coalingite are shown in Figure 1. The strongest absorbance for each mineral appears in the  $3700$  to  $3300\text{ cm}^{-1}$  ( $2.7$ – $3.0\mu\text{m}$ ) range as a broad band. For coalingite, the band consists of three strong peaks at approximately  $3690$ ,  $3600$  and  $3460\text{ cm}^{-1}$  ( $2.7$ ,  $2.8$ , and  $2.9\mu\text{m}$ ); in muskoxite the broad band has a small shoulder of medium intensity at  $3600\text{ cm}^{-1}$  ( $2.8\mu\text{m}$ ). The peaks in the  $3600$ – $3700\text{ cm}^{-1}$  range are assigned to O-H stretching vibrations whereas

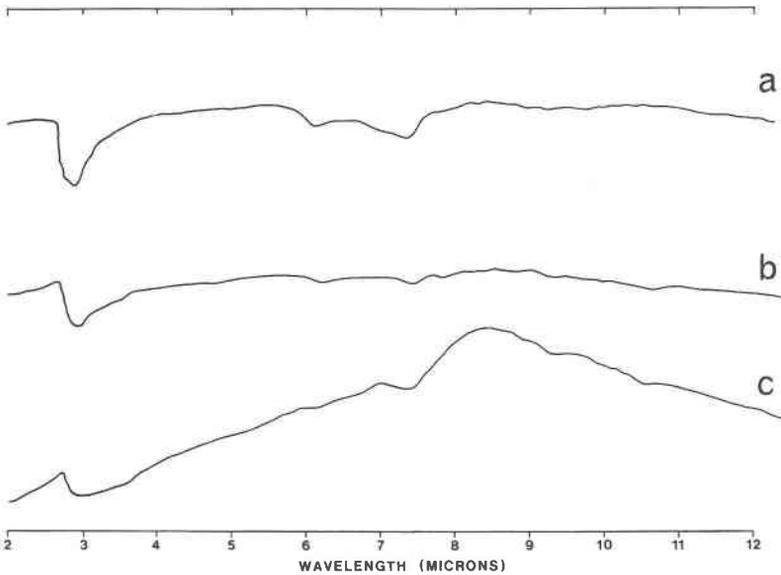


FIG. 1. Infrared spectra of coalingite (a) from the Muskox Intrusion; muskoxite (b); and mixture of manganiferous oxides (c) for which analyses are given in Table 4.

the strong, broad bands around  $3400\text{ cm}^{-1}$  ( $2.9$ – $3.0\mu\text{m}$ ) are attributed to “absorbed” or “zeolitic”  $\text{H}_2\text{O}$ , that is, water which can be driven out without affecting the structure. Weak bands appear at  $\sim 1620\text{ cm}^{-1}$  ( $6.2\mu\text{m}$ ) and  $\sim 1350\text{ cm}^{-1}$  ( $7.4\mu\text{m}$ ) in both minerals, but the absorbance is more pronounced in coalingite. The bands are respectively attributed to O-H bending vibrations from “absorbed”  $\text{H}_2\text{O}$  and to the stretching vibrations of  $\text{CO}_3$ .

The presence of carbonate in both coalingite and muskoxite is of interest in that it emphasizes the similarity of these two minerals. Although  $\text{CO}_3$  was specifically sought in the chemical analysis of muskoxite, the quantity found was much below one percent and could not be accurately

determined on the small amount of material available. The low CO<sub>3</sub> absorbance in the infrared curve lends support to the analytical results. In view of the low and variable carbonate content, one can infer that this component is not essential for the formation or stabilization of either muskoxite or coalingite.

#### X-RAY DATA

Precession photographs taken with Cu and Mo radiation show that muskoxite is trigonal (*P*) with diffraction symmetry  $\bar{3}m$  and  $a=3.07 \text{ \AA}$ . Photographs containing  $c^*$  show a mirror plane parallel to  $c$  and normal to  $[110]$ . As was the case for coalingite (Jambor, 1969), the  $hkl$  diffraction spots are streaked out parallel to  $c$ . Unlike coalingite, however, muskoxite shows a regular array of stronger  $hkl$  spots in a net having  $a=3.07$ ,  $c=4.6 \text{ \AA}$ . There are no systematic extinctions in this "pseudo-cell", which is only a portion of a much larger true cell, the dimensions of which are not known.

Part of a 0-level precession film of muskoxite is shown in Figure 2. In addition to the net comprising the "pseudo-cell", the film shows both the streaking and presence of weaker spots (intensity nodes) parallel to  $c^*$ . Two additional features are also present:

1. Numerous diffraction spots occur along the  $c^*$  axis; if they are assumed to be  $00l$  reflections, then  $c^*$  is  $\sim 92 \text{ \AA}$ . The first three measurable spots occur at  $d=7.6$  (weak),  $4.6$  (very strong), and  $4.4 \text{ \AA}$ . (strong). Lines having spacings equivalent to these appear in the X-ray powder diffraction pattern.

2. In addition to the main array of spots on the  $hk0$  net, there are a few very weak spots which, if they are assumed to belong to the main diffraction net, require that  $a^*$  be  $\sim 16 \text{ \AA}$ . However, the spots are so few and so weak that it is not possible to discern whether they occur with a regular periodicity; that they are "extraneous" is suggested by their absence on electron diffraction patterns and on upper levels precessed about  $c^*$ .

The complex single crystal features described above have been obtained from several grains of muskoxite, including paper-thin transparent crystal plates examined beforehand under the petrographic microscope. Although compositional zoning is commonly present at the margins of grains, microprobe scans indicate that only one mineral phase is present. The reproducibility of the single-crystal X-ray results from different fragments is also good evidence that muskoxite is not a mixture. The appearance of X-ray diffraction spots and X-ray powder diffraction lines having relatively large spacings in comparison to the  $3.07 \times 4.6 \text{ \AA}$  cell is adequate proof that a supercell is present. A  $c$ -axis of  $92 \text{ \AA}$  would seem

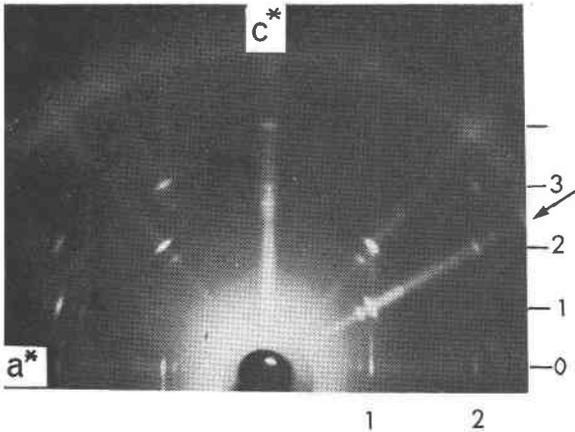


FIG. 2. Zero level  $a^*c^*$  precession photograph of muskoxite (unfiltered Mo radiation) with  $4.6 \times 3.1$  Å pseudocell outlined. Numerous extra spots appear on the  $c^*$  axis, and a few at  $hkl$  positions (for example, along the radiation streak marked with an arrow).

to be inordinately large, and it may be that there are explanations with which this writer is not familiar that may account for some of the observed diffraction effects. In order to index the X-ray powder pattern, however, a relatively large cell is unavoidable.

X-ray powder data for muskoxite are given in Table 2. For diffractometer smear mounts, the three strongest lines are at 4.6 Å (10), 4.4(1-2), and 2.31 (<1). Major intensity differences in powder data arise from preferred basal orientation; the above two strongest diffractometer lines also correspond to the two strongest spots along the  $c^*$  axis in single crystal photographs.

#### THERMAL DECOMPOSITION

Thermogravimetric analysis of a 40-mg sample of muskoxite was carried out using a heating rate of 3°C/min. No significant weight loss was detected at temperatures less than 105°C; 2.45 percent was lost up to 200°, 16.2 percent between 200 and 400°, and a gradual additional loss of 2.9 percent was obtained up to 800° (cumulative total 21.55 percent). The principal weight losses from muskoxite occur rather uniformly and the thermogravimetric curve lacks the plateau (indicative of little or only minor weight loss) which occurs between 200–300° C in coalingites from the Muskox Intrusion and the New Idria serpentinite, California. Some additional differences were examined by X-ray powder patterns of the products obtained in static heating experiments. The powder patterns are commonly difficult to interpret because of line broadening, diffuseness, and heterogeneity of the products.

TABLE 2. X-RAY POWDER DIFFRACTION DATA FOR MUSKOXITE, COALINGITE, AND MIXTURE OF MANGANIFEROUS OXIDES

1		2		3		4	
<i>I</i> (est)	<i>d</i> (meas)Å	<i>I</i> (est)	<i>d</i> (meas)Å	<i>I</i> (est)	<i>d</i> (meas)Å	<i>I</i> (est)	<i>d</i> (meas)Å
$\frac{1}{2}$	10.1					1	10.5
1	7.3	$<\frac{1}{2}$	7.4			1	7.5
				4B	6.0		
8	4.61	10	4.63	2	4.74	10	4.57
2	4.44	5	4.44	8	4.24		
3	4.12	1	4.13			1	4.15
$<\frac{1}{2}$	3.90	$<\frac{1}{2}$	3.91				
1	3.72	$<\frac{1}{2}$	3.71				
		$<\frac{1}{2}$	2.77				
3	2.660	3	2.654	2	2.68	2	2.617
				$\frac{1}{2}$ B	2.48	6	2.550
10	2.308	10	2.315	10	2.34	6	2.283
				$<\frac{1}{2}$	2.14	7	2.220
				1B	1.885		
6	1.746	5	1.744	2	1.769	2	1.734
				1B	1.719	8	1.698
				$<\frac{1}{2}$	1.580		
4	1.543	3	1.537	4	1.559		
				$\frac{1}{2}$	1.509	$\frac{1}{2}$	1.514
2	1.459	plus additional		$\frac{1}{2}$	1.465	1	1.470
2	1.335	weak lines		1B	1.315		
2	1.282			1	1.298		

FeK $\alpha$  radiation, 57.3 mm camera, visually estimated intensities. Columns 1 and 2: representative patterns of muscovite. 3: coalingite from the Muskox Intrusion. 4: mixture of manganiferous oxides.

The gradual changes evident on heating muscovite were followed by using the pair of lines which in unheated material have spacings of about 2.31 and 2.66 Å (Table 2). The spacings of these lines progressively decrease with rising temperature to about 335°C. Coincident with this decrease in cell volume, the 2.66 Å line gradually increases in intensity whereas the 2.31 Å line gradually decreases in intensity and is no longer recognizable on X-ray films of material heated beyond 335°C. At 342°C, the sample becomes noticeably magnetic and a diffraction line equivalent to the (224) reflection of spinel (magnetite) makes a weak appearance. On further heating the (224) line increases in intensity and a spinel-type pattern with  $a=8.401\pm 0.006$  Å becomes more clearly recognizable.

The final decomposition product contains hematite, periclase, and the aforementioned spinel phase. Hematite is unmistakably present from 434° to 800°, but its formation in small amounts at lower temperatures

is suspected to have probably paralleled the gradual crystallization of spinel. Periclase in small amounts is difficult to detect in powder patterns because its principal diffraction lines are broad and diffuse at low temperature and overlap those of spinel. Nevertheless, in the presence of significant amounts of periclase the (400) and (440) spinel lines become anomalously intense, and on this basis periclase is identifiable at least in the 429–800° range. However, consideration of the composition of muskoxite shows that excess MgO becomes available when crystallization of magnetite and hematite begins, and it is therefore probable that the formation of periclase approximately coincides with the appearance of the spinel phase.

The results obtained from the static heating experiments are summarized in Table 3. Because there is an accompanying weight loss, the progressive decrease in the unit-cell volume of heated muskoxite is presumably, at least in part, due to the gradual expulsion of water. The strongly magnetic mixture of spinel, periclase, and hematite, which was obtained as the final thermal decomposition product of muskoxite, is a manifestation of the mineral's high iron content as compared to coalingite. This magnetic mixture markedly contrasts with the product ob-

TABLE 3. RESULTS OF STATIC HEATING OF MUSKOXITE

Time (hrs)	Temp. (°C)	Line A <sup>a</sup>	Line B	Relative Intensity	Comments <sup>b</sup>
—	room	2.33	2.66	A > B	Muskoxite
92	147	2.30	2.65	A > B	
23	187			A > B	
20	249	2.28	2.61	A > B	
42	267	2.27	2.59	A = B	First intensity change: line A fades, line B becomes more intense.
19	271			A < B	
17	276			A < B	
89	290			A < B	
22	335	2.23	2.53	A << B	
21	342	Faded	2.53	A << B	Second intensity change: spinel (224) line appears at 342°C and gradually increases in intensity. Spinel, periclase, and hematite product. All samples are magnetic.
46	362	↓			
44	390				
47	409				
62	429				
20	434				
18	465				
TGA	800				

<sup>a</sup> See Table 2 and text.

<sup>b</sup> Identifications based on 57.3 mm films, FeK<sub>α</sub> radiation.

tained from the New Idria and Muscox coalingites, both of which thermally decompose to a nonmagnetic periclase phase.

#### ASSOCIATED MANGANIFEROUS OXIDES

*Granular aggregates.* In addition to muscoxite and coalingite, numerous ill-defined mixtures of Mg-Fe-Mn oxides occur in variable, but generally minute, amounts in the drill cores. The most abundant of these mixtures is a manganese-rich aggregate which occurs in the North hole, predominantly in the serpentine at about the 1600-foot core depth. Like coalingite, this material is believed to have attained its present form by *in situ* alteration during storage. The precursor was recorded (Findlay and Smith, 1965) as being reddish brown serpentine and hematite filling numerous thin fractures. This material has subsequently blossomed into black submetallic aggregates of granules which have very little cohesive force. Thus, the cores containing the granules in fractures break readily, and in some cases the cores have fallen apart in their containers.

X-ray powder diffraction patterns of the granular aggregates are similar to those of muscoxite (Table 2), but there is some line shifting and also a conspicuous doubling of the lines having relatively low spacings. The source of these diffraction effects is not completely known, but from polished section examination of the granules, it seems most likely that the effects can be attributed to intimate intergrowth on a microscopic scale. The intergrowth can be subdivided in three portions (Fig. 3) each of which also shows compositional variability, but only to a limited extent. Representative electron microprobe analyses of the three portions and a chemical analysis of a bulk sample are given in Table 4. It has not been possible, because of small grain size, to correlate the chemical and X-ray diffraction data with any degree of confidence. However, quantitative estimates indicate that the powder pattern given in column 4 of Table 2 is probably a mixture of the materials represented by microprobe analyses 1 and 2 in Table 4. Analysis 1 material could conceivably be a manganian muscoxite.

*Veinlet material.* As is inferred above, some muscoxite of secondary origin may be present in the mixtures which have blossomed forth during the period of core storage. There are, in addition, several narrow ( $\sim 1$ mm width) compact veinlets of heterogeneous oxides whose origin is less obvious because there are no visible expansion or disintegration effects. Microprobe analysis of two areas from one of these veinlets is given in Table 4. In thin section the veinlet can be seen to consist of three irregularly distributed phases: (1) deep red, translucent areas which correspond to microprobe analysis *a* in Table 4; (2) darker red areas which

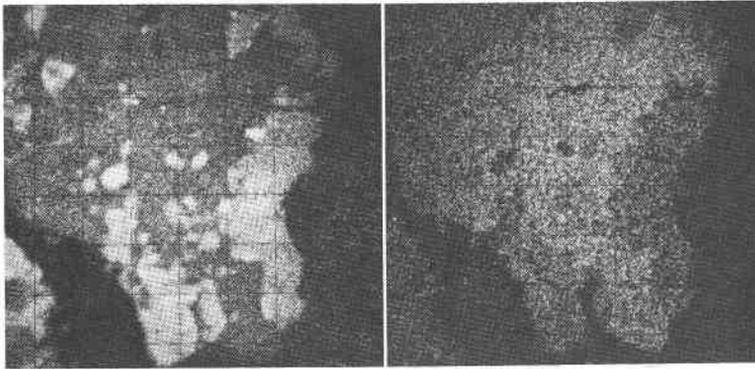


FIG. 3. X-ray scanning micrograph of manganiferous oxide mixture. Left: manganese X-ray image showing relatively low Mn content of most of the area (dark grey) corresponding to analysis 1 on Table 4; medium-grey areas correspond to analysis 2, and small whitish blebs to analysis 3 (richest in Mn). Right: magnesium X-ray image for the same area.

are barely translucent and correspond to analysis *b* in Table 4; (3) opaque areas and minute opaque grains disseminated in the red translucent areas.

X-ray powder patterns and microprobe analyses have shown that the opaque areas are magnetite, but for both translucent areas the X-ray patterns are those of muscoxite. The three strongest lines for analysis *a*

TABLE 4. MICROPROBE ANALYSES AND BULK COMPOSITION OF MANGANIFEROUS OXIDES FROM MUSKOX INTRUSION DRILL CORES<sup>a</sup>

	Granular aggregates			Veinlet in serpentine			
	Bulk chemical composition	Microprobe analyses			Microprobe analyses		
		1	2	3	a	b	
MgO	16.4	14.3	6.7	2.0	MgO	18.8	11.2
FeO <sub>3</sub>	48.2	46.7	42.3	29.2	Fe <sub>2</sub> O <sub>3</sub>	56.6	70.5
Mn <sub>2</sub> O <sub>3</sub>	16.5	7.4	35.8	52.9	Mn <sub>2</sub> O <sub>3</sub>	4.1	5.4
CO <sub>2</sub>	0.9	68.4	84.8	84.1		79.5	87.1
H <sub>2</sub> O	16.8						
	98.8 <sup>b</sup>						

<sup>a</sup> Microprobe analyses by A. G. Plant; chemical analysis by J. L. Bouvier. All values in wt. %, with total Fe as Fe<sub>2</sub>O<sub>3</sub> and Mn as Mn<sub>2</sub>O<sub>3</sub>.

<sup>b</sup> Optical spectrographic analysis by F. Hill gave Si 0.1–1.0%; Al, Ni, Sr 0.01–0.001%; Cr not found. Cr, S, Al not found by microprobe analysis.

material are 4.62, 2.260, and 1.727 Å; the equivalent lines for *b* are 4.63, 2.301, and 1.745 Å, and hence *b* has the larger unit cell.

At first glance it seems difficult to reconcile the X-ray and microprobe results. It must be remembered, however, that both iron and manganese are reported as trivalent oxides for convenience only; whether all or a part of the metals occur in different oxidation states is not known. Thus, analysis *b*, which appears to be the most formidable to explain, can be resolved by assuming that part of the iron is in the ferrous state (Table 5), and that the oxides plus water bring the total to 100 percent. On this basis, the formula derived is  $(\text{Fe}^{2+}, \text{Mg})_{3.42}(\text{Fe}^{3+}, \text{Mn})_2\text{O}_3 \cdot 4.13\text{H}_2\text{O}$ , or

TABLE 5. SUGGESTED PARTITION OF FERROUS-FERRIC IRON IN MICROPROBE ANALYSIS *b* OF TABLE 4

	Recalculated analysis	Atomic ratios	Proportions
MgO	11.2	0.278	3.42
FeO	35.76	0.498	
Fe <sub>2</sub> O <sub>3</sub>	30.74	0.193	1.00
Mn <sub>2</sub> O <sub>3</sub>	5.4	0.034	
H <sub>2</sub> O(?)	16.90	0.936	4.13
	100.00		

$3.42(\text{Fe}^{2+}, \text{Mg})(\text{OH})_2 \cdot 2(\text{Fe}, \text{Mn})\text{O}(\text{OH})$ . The latter formula requires 1.2 percent more water than is available (Table 5), but this is within the limit of error of the analysis. Thus, although the X-ray and microprobe data seemed to be incompatible, there appears to be a rational explanation, namely, that this compound is the iron analog of muskoxite.

Microprobe analysis *a* in Table 4 can be similarly recalculated and yields  $3.42(\text{Mg}, \text{Fe}^{2+})(\text{OH})_2 \cdot 2(\text{Fe}, \text{Mn})\text{O}(\text{OH}) \cdot 1.21\text{H}_2\text{O}$ . The significantly smaller cell dimensions of this compound are probably only partly attributable to its having a higher proportion of Mg in the divalent site as compared to that of associated material *b*. It seems likely that some  $\text{Fe}^{3+}$  enters the  $\text{Mg}^{2+}$  sites and the larger charge has the effect of further shrinking the cell. Part of the 1.21 molecules of  $\text{H}_2\text{O}$  indicated in the formula given above would therefore be OH for charge equalization rather than  $\text{H}_2\text{O}$ .

Finally, it should be noted that the "normal" muskoxite crystals and the iron analogue of muskoxite could have similar cell dimensions because in the latter compound there is an enlarging effect arising from  $\text{Fe}^{2+}$  substitution for  $\text{Mg}^{2+}$ , whereas in "normal" muskoxite the enlargement arises from excess interlayer water.

## SUMMARY AND CONCLUSIONS

The name muscoxite is applied to the well-crystallized mineral for which the physical properties and complete chemical analysis (Table 1) have been obtained. With this definition, a general similarity in the chemical composition of muscoxite and coalingite is apparent (Table 6). In terms of the theoretical formula proposed by Mumpton *et al.* (1965), coalingite is so far known to range from  $Mg_{10}Fe_2(CO_3)(OH)_{24} \cdot 2H_2O$  (New Idria, California) to  $Mg_{8.31}Fe_2(CO_3)_{0.23}(OH)_{22.06} \cdot 1.5H_2O$  (Muscox Intrusion). Because of the low water content of muscoxite, its components are difficult to express in terms of the coalingite formula; for comparative purposes, a hypothetical and very rough approximation for

TABLE 6. COMPARATIVE ANALYSES OF COALINGITE AND MUSKOXITE

	Coalingite, New Idria <sup>a</sup> (Mumpton <i>et al.</i> , 1965)	Coalingite, Muscox intrusion (Jambor, 1969)	Muscoxite
Wt. %			
MgO	46.9	45.30	35.4
FeO	—	0.74	0.0
MnO	—	1.06	—
Fe <sub>2</sub> O <sub>3</sub>	18.6	22.07	41.1
CO <sub>2</sub>	5.1	1.69	<1
H <sub>2</sub> O	29.4	29.14	23.8
	100.0	100.00	100.3

<sup>a</sup> For simplification, the ideal formula  $Mg_{10}Fe_2CO_3(OH)_{24} \cdot 2H_2O$  derived by Mumpton *et al.* has been used. Likewise, for Muscox coalingite the chemical analysis has been recalculated to 100%.

muscoxite is  $Mg_{3.4}Fe_2(CO_3)_{<1}(OH)_{12}$ , which adequately shows the major chemical differences between typical muscoxite and coalingite. The qualifier "typical" is deliberate, for the chemically analyzed material is only considered to be representative of the mineral as it occurs in one portion of the Muscox drill cores. Like coalingite, the composition of muscoxite has been shown to be variable, although for neither mineral are the limits of variability known. Analyses to date suggest that coalingite is characterized by the presence of sufficient hydroxyl (plus carbonate) to balance the cation charges; in muscoxite, it has been necessary to assume that the ferric iron charge is balanced as  $FeO(OH)$ .

For practical purposes, the X-ray powder pattern, thermal decomposition product, and extremely high refractive index of muscoxite serve to distinguish it from coalingite. Of these criteria, the X-ray powder pattern

appears to be the most reliable because the effects of compositional changes are minimal. The thermal behavior is believed to be the least reliable because spinel will undoubtedly form from the decomposition of ferroan coalingite.

The origin of well-crystallized muskoxite is believed to have been primary in that it was deposited together with massive lizardite serpentine in small ( $< \frac{1}{4}$  inch) fractures which cut the serpentized rocks of the intrusion. As has been inferred in the section on associated manganiferous oxides, some muskoxite of secondary origin may be present in the mixtures which have formed during the period of core storage. Although muskoxite in pieces of drill core kept in an air-conditioned laboratory for the past five years has not changed, a few crystals of primary muskoxite in boxed core in the storage room have partly altered to coalingite. Mumpton and Thompson (1966) found that coalingite from the New Idria serpentinite originated by alteration of iron-bearing brucite. In the Muskox drill core, brucite has not been found and coalingite is believed to have formed by the alteration of various iron-bearing sulfide and oxide minerals, of which muskoxite is one.

#### ACKNOWLEDGMENTS

The work on muskoxite was carried out intermittently over a period of several years, during which time the writer was kindly assisted in various aspects of the study, such as mineral separations and X-ray work, by the following individuals: F. Aumento, M. Bonardi, R. N. Delabio, D. G. Fong, T. E. Lawrence, J. F. Rowand, J. F. Scoates, and R. Trischuk. Chemical and spectrographic analyses were provided by J.-L. Bouvier, F. Hill, and J. A. Maxwell, and the thermogravimetric curves by R. H. Lake. The writer is grateful for their assistance, and for critical reading of the manuscript by R. J. Traill. The microprobe work was carried out by A. G. Plant, to whom the writer is also indebted for much helpful criticism and discussion.

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*Manuscript received, October 22, 1968; accepted for publication, February 11, 1969.*