

THE CHEMISTRY, OPTICS, AND GENESIS OF THE  
HASTINGSITE GROUP OF AMPHIBOLES

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INTRODUCTION. The chief amphiboles found in the alkaline rocks are riebeckite, various members of the hastingsite group as defined in the present paper, and barkevikite. Riebeckite is found in rocks supersaturated with silica, such as alkaline granites, comendites, and paisanites. Members of the ferrous end of the hastingsite group are found in hastingsite granites, nordmarkites, and nephelite syenites. Barkevikite and the magnesian members of the hastingsite group are found in diorites, essexites, and related calcic rocks. The present paper is concerned only with the hastingsite group, for which two new analyses are given.

Although a number of chemical analyses of the hastingsite group are available, the optical data are very incomplete. Data on the indices of refraction are particularly lacking. In order to correct these deficiencies the writer has obtained either the original specimen from which the chemical analysis was made or material as nearly identical as possible. It is indeed unfortunate that so many chemical analyses are published without adequate optical data. Mineralogists and petrographers should realize that a chemical analysis without such optical data does little to advance the science of petrography.

The writer is very much indebted to Dr. E. S. Larsen of Harvard University for permission to use the unpublished chemical and optical data for an amphibole (magnesian hastingsite) from Iron Hill, Colorado. Dr. E. V. Shannon has kindly sent me a specimen of the Custer County ferrohastingsite which he analyzed. (5)\*

FERROHASTINGSITE.† Ferrohastingsite was originally described as hastingsite from the nephelite syenites of Hastings County, Ontario, by Adams and Harrington. (1) Since then a number of analyses of ferrohastingsite have been published from various localities and we may now safely say that this and closely related amphiboles are the common amphiboles in the nephelite syenites, nordmarkites, and hastingsite granites. The available chemical and optical data are given in TABLE I.

\* See the bibliography at the end of this paper.

† The basis of the nomenclature of the hastingsite group is discussed on a later page.

TABLE I. CHEMICAL DATA ON FERROHASTINGSITE

	a.	b.	c.	d.	e.	Average
SiO <sub>2</sub>	34.184	37.49	37.40	38.50	36.86	36.96
Al <sub>2</sub> O <sub>3</sub>	11.527	10.81	12.34	10.88	12.10	11.55
Fe <sub>2</sub> O <sub>3</sub>	12.621	7.52	4.16	6.70	7.41	7.70
FeO	21.979	25.14	25.84	27.28	23.35	24.77
MgO	1.353	1.35	2.20	1.40	1.90	1.64
CaO	9.867	9.77	9.72	11.30	10.59	10.27
Na <sub>2</sub> O	3.290	2.06	1.80	1.22	3.20	2.31
K <sub>2</sub> O	2.286	1.91	1.36	1.66	1.20	1.68
H <sub>2</sub> O+	0.348	2.01	0.00	1.27	0.60	0.62
H <sub>2</sub> O-	0.629	0.95	0.60	0.00	0.70	0.43
MnO	n. d.	0.86	1.24	tr.	0.77	0.72
TiO <sub>2</sub>	98.084	99.87	3.20	tr.	n. d.	1.35
Total			99.86	100.21	98.68	100.00
Sp. Gr.	3.433		3.375 at 4°C.		3.5	3.4

(a) Ferrohastingsite from nephelite syenite, Dunganon, Hastings County, Ontario (1). The optical data were obtained by the present writer on hastingsite from a nephelite syenite found near Gooderham, Ontario. The incomplete optical data given by Graham (2) checks sufficiently with that obtained by the author to indicate that the material is essentially the same as that analyzed.

(b) Ferrohastingsite from nephelite syenite, Almunge, Sweden. (3) The optical data have been obtained in part by the present writer from a canadite (nephelite syenite) pegmatite. 2V has been calculated from 2E as given by Quensel (3), the extinction angle obtained by me is much less than that given by Quensel. The ferrohastingsite found in the nordmarkites of Almunge has an orientation  $Y=b$  and an optic angle about  $2V=45^\circ$ .

TABLE 1A. OPTICAL DATA ON FERROHASTINGSITE

	a	b	c	d	e	Average
Indices $\left\{ \begin{array}{l} \alpha \\ \beta \\ \gamma \end{array} \right.$	1.705 1.731 1.732	1.697 1.713 1.714	1.698 1.719 1.722	1.693 1.710 1.713		1.698 1.720 1.723
Optic angle (2V)	about 25°	about 16°	47°	small		small
Dispersion	strong $\rho < \nu$	strong $\rho < \nu$	medium $\rho > \nu$			strong to medium
Orientation	Z = b	Z = b	Y = b	Y = b	Y = b	varies Z = b in nephelite syenites Y = b in quartz-bearing rocks.
Extinction angle	Y $\wedge$ c = 13°	Y $\wedge$ c = 15°	Z $\wedge$ c = 20°	Z $\wedge$ c = 17°	Z $\wedge$ c = 9°	Z $\wedge$ c $\left. \vphantom{\begin{array}{l} Z \\ Y \end{array}} \right\} = 9^\circ \text{ to } 20^\circ$
Pleochroism $\left\{ \begin{array}{l} X \\ Y \\ Z \end{array} \right.$	yellow deep greenish blue (almost opaque) deep olive green	yellow bluish green olive green	yellow olive green deep green	greenish brown brownish green smoky blue green	light olive green yellowish green bluish green	yellow olive green (deep bluish green) deep bluish green (olive green) Z = Y > X
formula	Z > Y > X	Y > Z > X	Y > Z > X	Z > Y > X	Z $\bar{\bar{S}}$ Y > X	

The optical character is always negative.

- (c) Ferrohastingsite from porphyritic nordmarkite, Jackson, New Hampshire (4). W.H. Herdman of Glasgow, Scotland, analyzed the material for me. The optical data have been obtained from the same material as that analyzed. 2V was measured on the Fedorow stage and the error is not over three degrees. The mineral was separated from the rock by means of an electro-magnet and heavy solutions; it was at least 99 per cent. pure.
- (d) Ferrohastingsite from a contact (?) metamorphic limestone, Custer County, Idaho (5). The United States National Museum kindly loaned me for optical study a sample of the original material analysed by Shannon.
- (e) Ferrohastingsite (hudsonite) from a pegmatite, Cornwall, Orange County, New York (6). No specimens of this material were available to the writer, hence the original data given by Weidman, though incomplete, are quoted. Z  $\wedge$  c is in the obtuse angle  $\beta$ .

TABLE II. CHEMICAL DATA ON FEMAGHASTINGSITE AND MAGNESIOHASTINGSITE

	f	g	h <sub>1</sub>	h <sub>2</sub>	i
SiO <sub>2</sub>	38.04	38.633	39.23	39.23	43.30
Al <sub>2</sub> O <sub>3</sub>	13.50	11.974	11.94	14.38	10.69
Fe <sub>2</sub> O <sub>3</sub>	6.21	3.903	5.92	2.92	3.94
FeO	15.85	11.523	12.04	8.56	7.00
MgO	7.26	10.200	11.01	13.01	16.02
CaO	12.42	12.807	11.21	11.70	9.73
Na <sub>2</sub> O	3.21	3.139	2.33	3.05	4.58
K <sub>2</sub> O	1.68	1.489	0.99	0.98	0.66
H <sub>2</sub> O+	n. d.	n. d.	{ 0.36	0.36	1.80
H <sub>2</sub> O -	n. d.	n. d.	0.10	0.65	0.35
MnO	1.21	0.729	7.99	4.53	1.55
TiO <sub>2</sub>	1.06	5.035			
Total	100.44	99.432	99.54	99.37	99.62
Sp. Gr.	3.518 at 20°C	?	?	3.159 at 12.5°C	3.160 at 4°C
FeO/MgO	1.22	0.63	0.61	0.37	0.24

All of these minerals are biaxial negative. The FeO/MgO ratio is determined from the molecular proportions.

(f) Femaghastingsite from akерite, Cuttingsville, Vermont (10). Theoretical data were determined by the present writer on the original analyzed material. This amphibole is zoned in some crystals, the core having an extinction angle as high as 66°, the periphery as low as 52°. 2V as given in the table has been measured on the Federow stage for the more common, unzoned variety and the error is not greater than one degree.

(g) Femaghastingsite from essexite, Mt. Johnson, P.Q. (7). The optical data have been determined on material that is from the same mountain. 2V has been measured on the Federow stage; the error is not greater than three degrees.

TABLE IIA. OPTICAL DATA ON FEMAGHASTINGSITE AND MAGNESIOHASTINGSITE

	f	g	$h_1$ and $h_2$	$i$
Indices $\begin{cases} \alpha \\ \beta \\ \gamma \end{cases}$	1.679 1.694 1.698	1.670 1.692 1.703	1.676 1.692 1.705	1.653 1.663 1.670
Optic angle (2V)	60° (52°-66°)	80°	76° (75°-81°)	64°
Dispersion	medium $\rho < \nu$	medium $\rho < \nu$	Perceptible $\rho > \nu$	low
Orientation	$Y = b$	$Y = b$	$Y = b$	$Y = b$
Extinction angle	$Z \wedge c = 11^\circ$ light brown brown	$Z \wedge c = 15^\circ$ light brown brown	$Z \wedge c = 16^\circ$ yellow deep brown	$Z \wedge c = 40^\circ$ pale yellow green
Pleochroism $\begin{cases} X \\ Y \\ Z \end{cases}$	greenish brown $Y > Z > X$	brown, hint of green $Y > Z > X$	deep brown deep brown $Y = Z > X$	green
Formula				

( $h_1$ ) Titaniferous femaghastingsite from diorite, Montreal (9). NiO 0.04 and SrO 0.01, making total 99.59.

( $h_2$ ) Magneshastingsite from essexite, Montreal (8).

( $h_1$ ) and ( $h_2$ ) According to Bancroft and Howard(9) these are the common amphiboles of the gabbros, diorites, wehrlites, and pyroxenites of Mount Royal. The optical data given above were determined by the author on an amphibole from an essexite. From a consideration of the optics of the whole hastingsite group I am inclined to believe that the optics were determined on the femaghastingsite type. 2V has been measured on the Federow stage; the error is not over two degrees. In those crystals that are zoned the core has a higher axial angle than the periphery.

(i) Magneshastingsite from metamorphosed limestone, Iron Hill, Colorado. The optics have been determined on the same material as that analyzed. This is a new analysis made by W. H. Hardsman of Glasgow, Scotland, on material collected by Dr. E. S. Larsen. The optics have been determined by Dr. Larsen, with the exception of 2V, which was measured by the writer on the Federow stage; the error is not over one degree. Although this is distinctly a metamorphic mineral, it is associated with nephelite rocks.

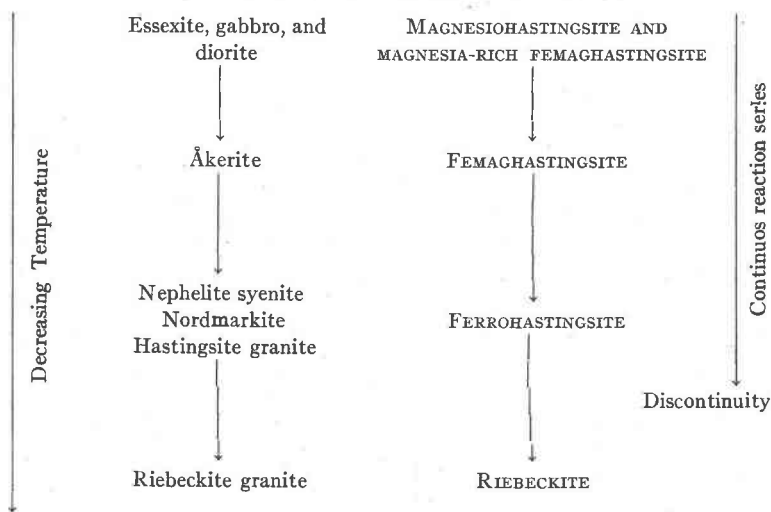
MAGNESIOHASTINGSITE AND FEMAGHASTINGSITE. Adams(7), Harrington(8), and Bancroft and Howard(9) have described amphiboles from the essexites of Mt. Johnson, P. Q., and Mount Royal, P. Q., which are chemically identical with ferrohastingsite except that part of the ferrous iron of ferrohastingsite is isomorphously replaced by magnesia (see *g* and *h* in TABLE II). An even more extreme member of the group has been found by Dr. E. S. Larsen in a metamorphic rock from Iron Hill, Colorado (*i* in TABLE II). Although closely allied, both chemically and petrologically, to ferrohastingsite, the distinctly higher content of magnesia necessitates a different designation. The classification of the hastingsite group is most logically based on the ratio of ferrous iron to magnesia (molecular proportions); if FeO/MgO exceeds two, the mineral is ferrohastingsite; if FeO/MgO is less than two, but greater than one-half, the mineral is femaghastingsite; if FeO/MgO is less than one-half, the mineral is magnesiohastingsite. The original hastingsite of Adams and Harrington (1) may thus be designated ferrohastingsite. The metamorphic amphibole from Iron Hill and the amphibole from the essexite of Mt. Royal may be considered magnesiohastingsite. The amphiboles from the essexite at Mt. Johnson and from the åkerite at Cuttingsville, Vermont (10), belong to the intermediate type, femaghastingsite (*f* and *g* in TABLE II).

RELATION OF CHEMICAL COMPOSITION AND OPTICAL PROPERTIES. From the above analyses and optical data the following facts are apparent. Most of the oxides in the hastingsite group are relatively constant with the exception of ferrous iron and magnesia which apparently isomorphously replace each other (see TABLES I and II).  $RO_2(SiO_2 + TiO_2)$  increases toward the magnesia end of the series due to the greater weight of iron relative to magnesium.  $TiO_2$  is somewhat variable, being particularly high in the calcic rocks of Quebec. The increase in magnesia affects the optics in the following manner:  $2V$  increases, the indices of refraction decrease, and the specific gravity is reduced.

PETROLOGICAL SIGNIFICANCE. From the analyses available there seems to be a very definite relation between the composition of the amphibole and the rock in which it occurs. Magnesiohastingsite evolves into ferrohastingsite along the lines shown in the diagram, TABLE III. The observations made on the femag-

hastingsite in the åkerite from Cuttingsville are particularly significant, for in this case we observed an intermediate type with a core (older phase) tending toward magnesiohastingsite and a periphery (younger phase) tending toward ferrohastingsite. Similar relations were found in one of the Mt. Royal amphiboles. Ferrohastingsite may originate not only as a reaction product from magnesiohastingsite and femaghastingsite, but it may also be directly precipitated from the magma or may originate as a reaction product from hedenbergite (4).

TABLE III. THE GENESIS OF THE HASTINGSITE GROUP.



Although the analyses considered in this paper have of necessity been chosen from a number of petrographic provinces, five of the most significant analyses come from the late-Devonian New England-Quebec alkaline province. They are the ferrohastingsite from Jackson, New Hampshire, the femaghastingsite from Cuttingsville, Mount Johnson, and Mount Royal, and the magnesiohastingsite from Mount Royal.

TABLE IV. CHEMICAL AND OPTICAL DATA ON ALKALI-HASTINGSITE

	j	k	
SiO <sub>2</sub>	35.42	37.80	
Al <sub>2</sub> O <sub>3</sub>	8.89	12.89	
Fe <sub>2</sub> O <sub>3</sub>	9.73	6.14	
FeO	24.48	12.55	
MgO	0.17	4.10	
CaO	6.93	13.64	
Na <sub>2</sub> O	5.13	5.26	
K <sub>2</sub> O	3.23	3.24	
H <sub>2</sub> O+ H <sub>2</sub> O-}	3.15	n.d.	
MnO	1.17	n.d.	
TiO <sub>2</sub>	1.34	4.54	
Total	99.64	100.16	
FeO/MgO	85.00	1.71	
Indices	$\alpha$	1.699	1.680
	$\beta$	1.719	1.695
	$\gamma$	1.721	1.705
Optic angle (2V)	about 36°	large	
Dispersion		strong $\rho < \nu$	
Orientation	Y = b	Y = b	
Extinction angle	Z $\wedge$ c = 20°	Z $\wedge$ c = 11°	
Pleochroism	X	greenish yellow	light yellowish brown
	Y	olive green	brown
	Z	bluish green	deep brown
	Formula	Y $\bar{\bar{=}}$ Z > X	Z > Y > X

Both minerals are biaxial negative.

The FeO/MgO ratio is determined from the molecular proportions.

(j) Alkali-ferrohastingsite from umptekite (quartz-bearing), Beverly, Mass. (11). The value for 2V has been calculated from 2E as given by Wright; the rest of the data have been determined from material in which Z  $\wedge$  c,  $\gamma - \alpha$  and  $\gamma - \beta$  checked with the data given by Wright.

(k) Alkali-femaghastingsite from camptonite at Campton Falls, New Hampshire (12). The optical data were determined on the amphibole from what is probably the same dike as that which yielded the material for the chemical analysis. The optics are very similar to those for the femaghastingsite from Cuttingsville and it will be noted that the chemical composition is not essentially different.



ALKALI-HASTINGSITE AND RELATED TYPES. In the alkaline rocks we also find a group of alkali-rich amphiboles which may have optical properties essentially identical to those of hastingsite despite the fact that some of the oxides differ by four per cent. In other words, even after the optical properties have been determined we can not state the chemical composition very definitely. If we compare the optical data of the alkali-ferrohastingsite from Beverly, Massachusetts, with the data on the ferrohastingsite from Jackson, New Hampshire, we see that they are almost identical; there is, nevertheless, considerable difference in chemical composition. The group is characterized by an alkali content of more than six per cent by weight.

SUMMARY. We may summarize the results as follows:

1. The hastingsite group comprises the common amphiboles of the alkaline rocks with the exception of the alkali granites, in which riebeckite may be present instead of hastingsite. Members of the hastingsite group are also found as contact alteration products in limestones.
2. Ferrohastingsite has a relatively definite chemical composition. The most striking chemical properties are the low silica (37%) and high ferrous iron (25%). Lime and alumina are abundant (each about 11%); ferric iron makes up about 8%; the alkalis are low, the total never exceeding six per cent by weight. Magnesia is very low. The specific gravity is high (about 3.45).
3. The most striking optical properties of ferrohastingsite are the high indices and the small optic angle. The optical orientation varies; the limited available data suggests that the mineral from the quartz-bearing rocks has  $Y=b$ , whereas that from the nephelite-bearing rocks commonly has  $Z=b$ .
4. Femaghastingsite and magnesiohastingsite are chemically similar to ferrohastingsite except that part of the ferrous iron is isomorphously replaced by magnesia.
5. The optical properties of magnesiohastingsite and femaghastingsite are determined largely by the magnesia-ferrous iron ratio. With increase in ferrous iron the indices and specific gravity increase but the optic angle decreases.
6. A definite evolution in the amphiboles of the alkaline rocks may be seen. Magnesiohastingsite and magnesia-rich femaghastingsite occur in the essexites and diorites, femaghastingsite in the åkerites, and ferrohastingsite in the nephelite syenites,

nordmarkites, and alkali granites. In the final stages of differentiation the concentration of silica and soda becomes so great that a completely new type of amphibole, riebeckite, is formed.

7. A number of alkali-rich amphiboles are also present in the alkaline rocks. These can not be readily separated by optical methods from the members of the hastingsite group.

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