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CHANGES IN HORNBLLENDE AT ABOUT 800°C.

VIRGIL E. BARNES, *University of Wisconsin.*

INTRODUCTION

In recent years much activity has been displayed in the study of the amphiboles and repeatedly the problem connected with the change on heating of common hornblende to a material having the appearance and optical properties of basaltic hornblende has been attacked and partially solved. The purpose of this paper is to solve the problem definitely. The writer wishes to acknowledge the helpful guidance by Dr. A. N. Winchell and the suggestions on optical methods offered by Dr. R. C. Emmons, and is also deeply indebted to the Canadian Geological Survey for the sample of analyzed edenite from Argenteuil County, Quebec, and to the Milwaukee Museum for a sample of actinolite from Val Malenco, Italy.

HISTORICAL REVIEW

It has been known for nearly 50 years that common hornblende when heated to a sufficiently high temperature takes on the properties of basaltic hornblende; namely, a change in color and pleochroism from greens to browns, an increase in absorption, an increase in double refraction and a decrease in the extinction angle ($Z \wedge c$) from about 20° to 0°.

Rosenbusch¹ in 1885 noted that a dark green hornblende with little pleochroism when heated became red and had strong absorption.

Schneider² in 1891 studied a series of basaltic hornblendes and found that upon heating them in superheated steam he obtained a change in extinction angle to near 0°, and an increase in pleochroism and absorption. The ferrous iron content and the extinction angle of the unheated hornblendes taken presumably on the prism (110) face, are given in Table I. He did not give the ferrous iron content after heating, but said that practically none is pre-

¹ Rosenbusch, H.: *Mikroskopische Physiographie*, II Aufl., Bd. 1, 463, 1885.

² Schneider, C.: Sur Kenntniss basaltischer Hornblendes. *Zeit. Kryst.*, 18, 580, 1891.

sent and that the extinction angle has been reduced to 0° , and that the pleochroism and absorption have increased except in the last

TABLE I

Locality	FeO	Extinction
Laacher See	7.03%	$8\frac{1}{2}^\circ$
Altenbusch	6.27	6-8
Hartlingen	4.53	2-4
Wolkenburg	3.19	1-3
Bohmen	2.89	1
Ortenberg	0.57	0

two samples which already had strong pleochroism and absorption. He believed that volcanic steam converted the ferrous to ferric iron thus giving basaltic hornblendes.

During the same year Belowski³ in a short article stated that he believed the change was due to oxidation. During the following year Belowski's⁴ Inaugural-Dissertation was published; in this he elaborated his stand. He heated hornblende, actinolite and tremolite in a current of air and obtained in all, except the tremolite, an increase in double refraction and absorption, a decrease in the extinction angle ($Z \wedge c$) and a change in pleochroism from greens to browns. Table II shows the iron content before heating and the extinction angle before and after heating. He stated that: "Through

TABLE II

Mineral	Locality	FeO	Fe ₂ O ₃	Extinction	
				Before	After
Hornblende	Arendal	6.97%	14.48%	$18\frac{1}{2}^\circ$	0°
Actinolite	Zillerthal	6.25		14°	2°
Tremolite	Campo Longo	0.50		No change	

the action of heat, oxidation is permitted to go on, changing green hornblende in rocks to brown hornblende." He cited as proof of this, hornblende crystals in some of the Ecuadorian rocks that have centers of green hornblende and borders (Resorptionränder) of brown hornblende.

Weinschenk⁵ in 1912 suggested that basaltic hornblende is due to the presence of ferric oxide and titanium oxide. He also noted the change in optical properties on heating.

³ Belowski, M.: *Neues Jahrbuch für Mineralogie*, Bd. I, 219, 1891.

⁴ Belowski, M.: Die Gesteine der Ecuadorianischen West-Cordillere von Tulcan bis zu den Escaleras-Bergen. *Inaugural-Dissertation*. Berlin, 1892.

⁵ Weinschenk: *Petrographic Methods*, 291-292, 1912.

Winchell⁶ in 1924 suggested that possibly the peculiar optical properties of "basaltic hornblende" are due to the presence of Ti_2O_3 .

Graham⁷ in 1926 heated common hornblende in carbon dioxide and obtained the usual changes in optical properties that are found on heating in air. He stated that, "These experiments strongly suggest that the water is the controlling constituent." In a footnote, however, he made the following statement: "It is possible there may have been oxidation by water driven from the hornblende during heating, but this is a reaction of the original parts of the mineral and not an oxidation from atmospheric oxidation."

Kôzu, Yoshiki and Kani⁸ in 1927 heated hornblendes, common and basaltic, in nitrogen to prevent oxidation and found that the common hornblende changed to brown hornblende at about 750°C. They measured the expansion of the common hornblende in the direction of the *c*-axis during heating and found that at 750° contraction started in and continued to 790° at which point expansion again took place. The basaltic hornblendes gave a smooth curve of expansion over the same range of temperature. They stated that, "With regard to the fundamental cause producing the differences between these two varieties of hornblende, we can not say decidedly at present, but we are inclined to think they are due to the quantitative and structural changes in the main components, and are not only to be referred to the relative amounts of special constituents, such as the oxides of iron and titanium or the water in the crystal." They also showed that there is a break in the curve of loss of weight on heating for common hornblende between 700° and 800°C., at which point the loss of weight accelerates. Basaltic hornblende did not show this change. Table III gives the optical properties of unheated and heated hornblendes as obtained by them, and shows the increase of indices and birefringence, and the decrease of the extinction angle that takes place upon heating common hornblende and the lack of change obtained upon heating basaltic hornblende.

⁶ Winchell, A. N.: *Am. Jour. Sci.*, 5th Ser. Vol. 7, 287, 1924.

⁷ Graham, W. A. P.: *Am. Mineral.*, Vol. 11, No. 5, 118, 1926.

⁸ Kôzu, S., Yoshiki, B., and Kani, K.: *Science Reports of the Tôhoku Imperial University*, Ser. 3, Vol. III, No. 2, 143, 1927.

TABLE III⁹

Unheated	1	2	3	4	5	6	7
N_p'	1.651	1.659	1.664	1.668	1.672	1.689	1.701
N_o'	1.660	1.675	1.673	1.682	1.684	1.719	1.731
$c \wedge Z'$	24°	13°	15°	18°	13°	0°	0°
Heated							
N_p'	1.681	1.688	1.690	1.714	1.695	1.689	1.701
N_o'	1.698	1.714	1.723	1.740	1.727	1.719	1.731
$c \wedge Z'$	0°	0°	0°	0°	0°	0°	0°

1. Green hornblende—Iratsuyama, Prov. Iyo.
2. Soretite—Otsurumizu, Prov. Bungo.
3. Common hornblende—Ishigami-mura, Prov. Iwaki.
4. Common hornblende—Kitayamagata-mura, Prov. Rikuchû.
5. Common hornblende—Kamimatama-mura, Prov. Bungo.
6. Basaltic hornblende—Ikebukuro, Sakai-mura, Prov. Shinano.
7. Basaltic hornblende—Shichiseizan, Formosa.

Reade¹⁰ in 1928 heated common hornblende in hydrogen and found only a slight change in optical properties. He heated another sample in air and obtained the usual increase in birefringence and indices of refraction, decrease in the extinction angle ($Z \wedge c$) and change in color and pleochroism. This sample when reheated in hydrogen changed back to common hornblende.

In the fall of 1928 at the time the present work was started the most likely views published were three different solutions of the problem by Belowski, Graham and Kôzu and associates. Belowski attributed the change in optical properties to oxidation of ferrous to ferric iron, Graham thought dehydration to be the chief factor in the change and Kôzu and associates, although not making a direct statement, imply that the volume change and change of optical properties are due to inversion. With these views extant it was deemed advisable to introduce enough incontrovertible evidence to definitely prove which view or possibly combination of views is correct.

Since 1928 Kôzu and Yoshiki¹¹ have published another article

⁹ N_p' and N_o' are the minimum and maximum indices on a cleavage plate (110), and $c \wedge Z'$ is the extinction angle on the (110) face.

¹⁰ Reade, H. O.: *B. A. Thesis*, University of Wisconsin, 1928.

¹¹ Kôzu, S., and Yoshiki, B.: *Science Reports of the Tôhoku Imperial University*, 3rd Ser., Vol. III, No. 3, 177, 1929.

which tends to uphold the oxidation theory and Kunitz¹² has published an article containing material that definitely proves oxidation. The present work is much more complete than either of the above and substantiates the conclusion by Kunitz, and furthermore treats of the manner in which the change takes place.

Kôzu and Yoshiki show, in their latest publication, that the volcano Sambé is composed of two similar types of rocks, the only difference being in the hornblendes and biotites. In one type the hornblende is common green and the biotite is meroxene, in the other the hornblende is basaltic and the biotite anomite. They believed the latter to have been formed by reheating of the rock to over 750°C. Table IV gives the ferrous iron content, the loss on ignition and the optical properties of these minerals. It is apparent that some of the ferrous iron has been oxidized and that volatile constituents have been lost in the change to basaltic hornblende and anomite-biotite. They stated that the common hornblende and biotite must have been formed in a less oxidizing medium and under a higher pressure.

TABLE IV

	Hornblende		Biotite	
	Basaltic	Common	Anomite	Meroxene
FeO	7.69%	10.97%	5.96%	10.32%
Loss	0.08%	0.23%	1.53%	2.76%
N_p'	1.708	N_p 1.661		
N_o'	1.746	1.675	N_o 1.706	N_o 1.643

Table V gives the results obtained by Kunitz, in his last paper, of analyses and optical properties of hornblendes before and after

TABLE V

	Before Heating				After Heating				Total Fe as FeO
	Fe ₂ O ₃	$\frac{Fe_2O_3}{FeO}$	N_p	N_o	Fe ₂ O ₃	$\frac{Fe_2O_3}{FeO}$	N_p	N_o	
N. Hampshire	2.83	0.196	1.638	1.659	10.20	1.31	1.655	1.676	16.96
Arendal	4.58	0.351	1.658	1.677	4.26	3.24	1.676	1.697	17.20

¹² Kunitz, W.: Die Isomorphieverhältnisse in der Hornblendegruppe. *Neues Jahrbuch für Mineralogie*, LX Beilage Band, Abt. A, Zweites Heft, 1930.

heating. He stated that it is quite evident that oxidation accounts for the changes shown in Table V.

PROCEDURE

In order to settle definitely the process involved in the change from green hornblende to brown hornblende a series of fourteen hornblende samples including edenite and pargasite were studied optically before and after heating to ascertain the amount of change involved. Formerly only the green or iron-rich hornblendes were studied. The study was extended to the tremolite-actinolite series of which six samples were studied optically before and after heating.

Other workers obtained a change upon heating in steam, carbon dioxide and nitrogen so it is unnecessary to repeat heatings with any of these agents as mediums. It was deemed advisable to repeat the experiment using hydrogen, so a sample that had already been heated in air was reheated at a temperature of about 850°C., in a stream of unwashed hydrogen, generated by the addition of hydrochloric acid to zinc, and the optical properties again determined. With a temperature of 850°C., it was necessary to paraffin all joints to make them air tight to avoid an explosion, and the exhaust hydrogen was passed through water which served as a check valve against the entrance of air.

To complete the study two chemical analyses were obtained of materials differing considerably in optical properties, but yet capable of being classified as common or green hornblende. Partial analyses were obtained of these samples after heating; namely the tenor of ferrous and ferric iron, water and fluorine. Two other analyses available, one of edenite and the other of tremolite, are helpful in interpretation of results, but since practically no change was found on heating they were not analyzed afterwards.

For heating the samples a furnace made from a glazed porcelain tube an inch in diameter wrapped with nichromé wire and insulated with asbestos was used. Temperatures were obtained on a Hoskins type H. A. "Thermoelectric" pyrometer. All of the experiments were conducted at a temperature of about 850°C., over a period of three hours in order to be sure that the change proceeded to completion.

The optical work was done on Emmons'¹³ double variation modi-

¹³ Emmons, R. C.: *Am. Mineral.*, Vol. 13, 504, 1928. *Am. Mineral.*, Vol. 14, 414, 1929; and *Am. Mineral.*, Vol. 14, 441, 1929.

fied universal stage in which is incorporated a Bausch & Lomb monochromator and Abbé refractometer, a Leitz universal stage modified by Emmons and a Leitz research model petrographic microscope. This apparatus embraces temperature and wavelength control. The temperature is regulated by a flow of water in series, first through the Abbé refractometer then through the cell on the universal stage, and is checked by two thermometers one on the refractometer and the other in the water line past the cell. With a strong flow of water the maximum difference between the thermometers is 2° at a temperature of 70°C . At lower temperatures the difference is inappreciable and usually double variation liquids are available to cover the range of index at these lower temperatures. At least five minutes are allowed after each temperature change before an index is read to allow the apparatus sufficient time to come to a constant temperature. The wavelength control is exercised through the monochromator and the width of the band of light used was for F, 150\AA , for D, 320\AA and for C, 460\AA . The wave length used from this band is essentially a mean value. For determining indices several checks falling within a range of 40\AA are obtained for the wave length at which the liquid is of the same index as the mineral.

A mineral mount for the universal stage consists of two or three grains between a pair of cover glasses with a double variation liquid of the proper index as an immersion medium, and as a contact liquid between the cell and the lower cover glass, and between the upper cover glass and the upper hemisphere. To avoid dilution of the index liquids the refractometer and cell are cleaned thoroughly with acetone before and after each determination. The best appearing grain is chosen and worked to the center of the field where it is fixed by tightening the screws which hold the upper hemisphere in position, care being taken not to exert enough pressure to fracture the grain. The usual procedure as outlined by Emmons¹⁴ is followed for orienting a grain on the universal stage. With hornblende at least 95 times out of a 100 the optic plane becomes vertical, enabling one to measure the optic angle and the indices N_g and N_m . N_p can usually be approached by rotating from either N_g or N_m , or, as in this work, from both, thus giving a check on the accuracy of the results. With rotation and optic angle readings it is necessary to correct the amount of rota-

¹⁴ Emmons, R. C.: *Am. Mineral.*, Vol. 14, 441, 1929.

tion when there is a difference in index of the mineral and the hemispheres. This correction was obtained by using Plates I and IV in Emmons' article. For obtaining N_p from the rotation reading it is necessary to use Plate II of the same article. This orientation gives parallel extinction and to obtain the extinction angle of the clinopinacoid section ($Z \wedge c$), it is necessary to rotate toward N_p recording the amount of rotation and the extinction angle observed; from these data $Z \wedge c$ can be calculated by using the equation $(1/\sin \alpha)\beta = Z \wedge c$, where α is the angle of rotation and β is the extinction angle at this rotation.

The data recorded include wave-length, index, ray being measured, and temperature of both thermometers as well as the amount and direction of rotation in case rotation is necessary. Corrections must be applied to indices obtained at wave-lengths other than sodium light from a graph supplied with the Abbé refractometer. The optic angle can be calculated by using the indices from either the equation, $\sin^2 V = N_m - N_p / N_g - N_p$, or the graphical solution of this equation.¹⁵ A sample of each mineral before and after heating was mounted in balsam and several determinations of the optic angle and extinction angle ($Z \wedge c$) were made on each sample.

ACCURACY

Emmons states the accuracy expected using this set up in the publication cited above. In this study the probable error is stated for each determination, based on the number of determinations, the closeness of the checks, the clearness of the Becke line, the checks obtained on the monochromator, and the color of the mineral, which, when strong, partially masks the Becke line. The accuracy of the indices for the D or sodium line is about twice that for the indices of the F and C lines. The statement of error for the calculated optic angle is based on the statement of error for the indices and for the observed optic angle, it is estimated that the error can be $\pm 2^\circ$ for sodium light and about $\pm 3^\circ$ for F and C. Fig. 1 shows the accuracy to be expected, with a statement of error for the indices of $\pm .0002$ and a birefringence of .0200. It will be noted that with the lowering of the optic angle the possible error increases rapidly. In comparing the optic angle obtained by observation and calculation it will be seen that the statement of error for the indices must in most cases be too large. The samples

¹⁵ Emmons, R. C.: *op. cit.*, Plate III.

from Frankfort, Pa., and Renfrew, Ont., have an index for N_g which is above the double variation liquids used, so N_g was calculated from N_m , N_p and the observed optic angle.

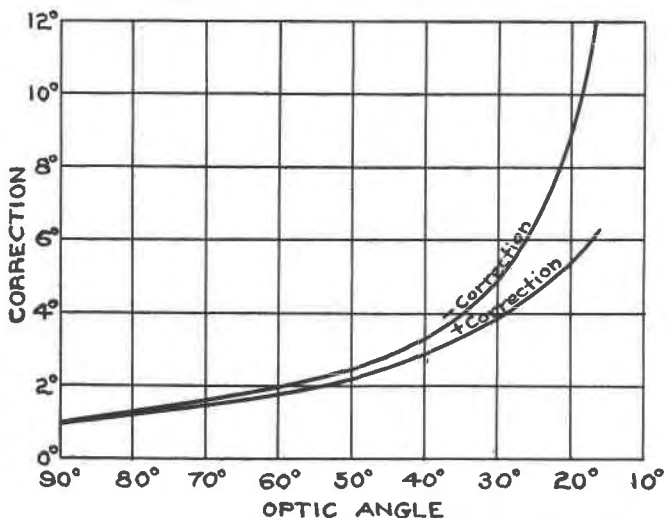


FIG. 1. Correction to be applied to the calculated optic angle, based on an assumed error of $\pm .0002$ for the indices and an assumed birefringence of .0200.

In Table VI a comparison of the accuracy of this method with other methods is given using the mineral from Argenteuil Co., Quebec. Ford¹⁶ used oriented plates and the total refractometer, and Kreutz¹⁷ used mineral prisms and a crystal goniometer. These checks are rather close considering that the samples from which the optical properties were obtained may not be from the same out-

TABLE VI

	Ford A	Kreutz B	Barnes C	Differences		
				A&B	A&C	B&C
N_g	1.6328	1.6332	1.6331	+ .0004	+ .0003	- .0001
N_m	1.6180	1.6180	1.6186	0	+ .0006	+ .0006
N_p	1.6128	1.6142	1.6143	+ .0014	+ .0015	+ .0001
$N_g - N_p$	0.0200	0.0190	0.0188	- .0010	- .0012	- .0002
$2V$	56°8'	51°55'	57°	-4°	+1°	+5°
$Z \wedge c$	29°44'	27°34'	27°	-2°	-2½°	-½°

¹⁶ Ford, W. E.: *Am. Jour. Sci.*, 37, 179, 1914.

¹⁷ Kreutz, S.: *Sitz. Akad. Wiss. Wien.*, 117, I, 875, 1908.

crop and that some hornblendes vary considerably in the same specimen. The check between the work of Kreutz and the present is the closer and speaks well for the accuracy of both methods. Kreutz also states the indices for several wave lengths, which are compared in Table VII with those obtained in the present work. Again excellent checks are obtained.

TABLE VII

Å	Kreutz A			Barnes B			Differences A&B		
	N_p	N_m	N_g	N_p	N_m	N_g	N_p	N_m	N_g
6710	1.6113	1.6149	1.6302	1.6113	1.6155	1.6295	0	.0006	.0007
5890	1.6142	1.6180	1.6332	1.6143	1.6186	1.6331	.0001	.0006	.0001
5350	1.6175	1.6211	1.6165	1.6175	1.6217	1.6363	0	.0006	.0002
4640		1.6270			1.6270				0

RESULTS

The results obtained in the present work show that the change of properties of the unheated hornblendes are in large part in direct proportion to the change in content of iron and that upon heating the properties are not changed at the iron-poor end of the series and are changed markedly at the iron-rich end of the series. The water content apparently has little effect on the optical properties as shown by lack of change in the low-iron hornblende when water is driven off. Inversion is found untenable as an explanation of the changes because no change takes place upon heating in hydrogen and because a chemical change takes place when heated in any other medium. Oxidation is proven to be the outstanding process causing the change in optical properties, as shown by optical studies before and after heating in both air and hydrogen, by the relation of weight-percent loss to the percentage of water from analysis, and by analyses of hornblende before and after heating.

The results of the present optical study are stated in Table VIII and are plotted on Plates I to IV. In plate I the properties of the hornblende series are plotted using the average index of the unheated samples as a straight line variation. This plate shows more clearly than the tables the lack of change in the iron-poor end of

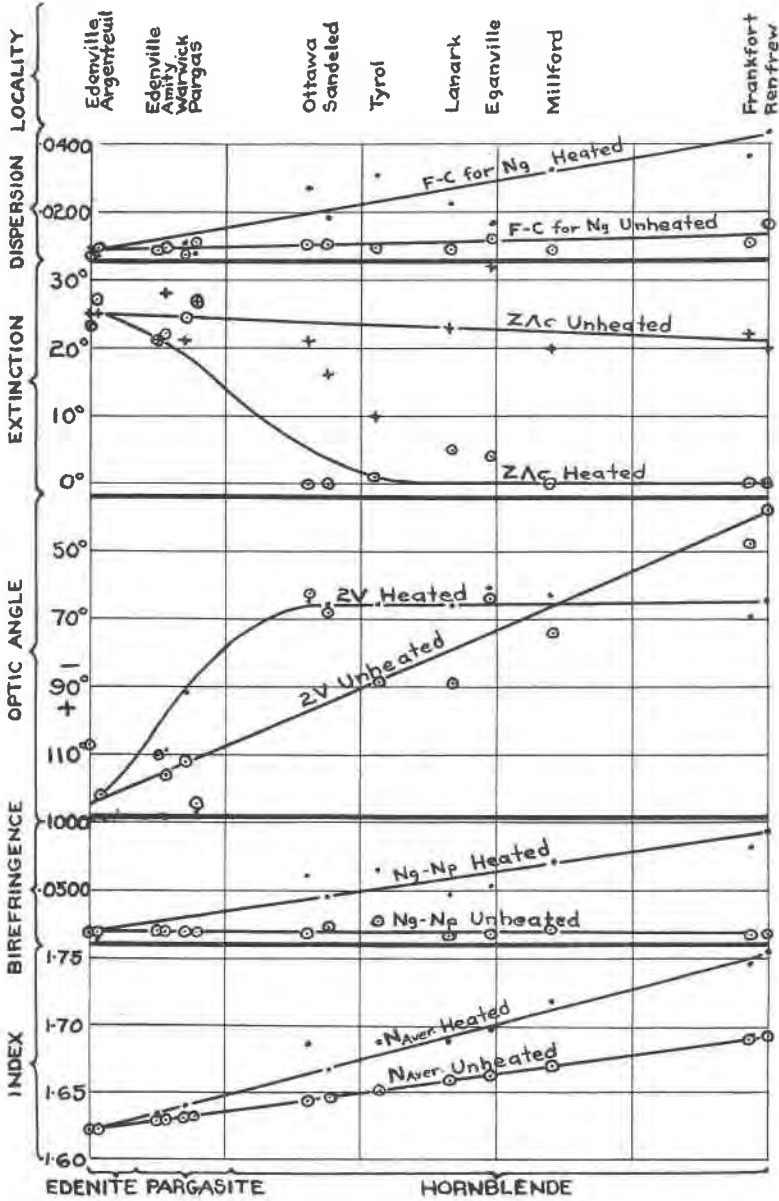


PLATE 1. Optical properties of the hornblende series plotted on the basis of the average index of the unheated hornblende as a straight line variation.

the hornblende series and the large change in the iron-rich portion of the series. This diagram shows, as is already known, that the hornblende series is of too complex a nature to be represented on a two dimension diagram. Generalizations that may be drawn

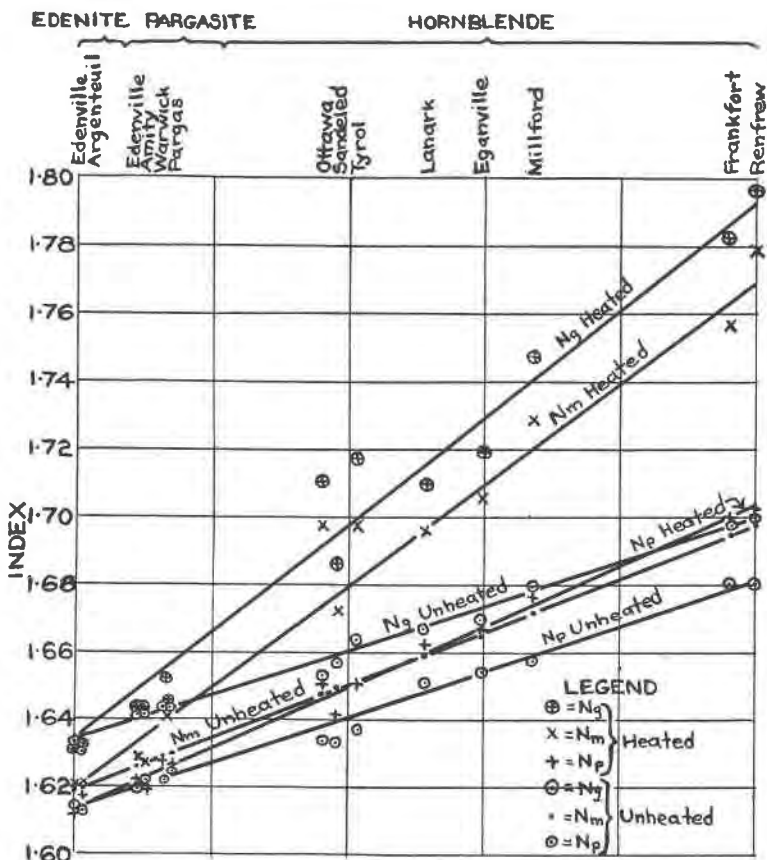


PLATE II. Indices of the hornblende series plotted on the basis of N_m of the unheated hornblendes as a straight line variation.

from Plate I are that the hornblendes with appreciable iron, on heating, increase markedly in average index, birefringence and dispersion, decrease in extinction angle ($Z \wedge c$) to near zero degrees and have a change of optic angle to near 65° . The optic angle in the hornblende series measured about X ranges from 38° at the

high-iron end of the series to 125° at the pargasite-edenite end of the series. The optical properties of edenite and pargasite are almost the same, the only marked difference being in color. It would be well to designate all the positive hornblendes under one name, preferably pargasite since it has priority in usage.

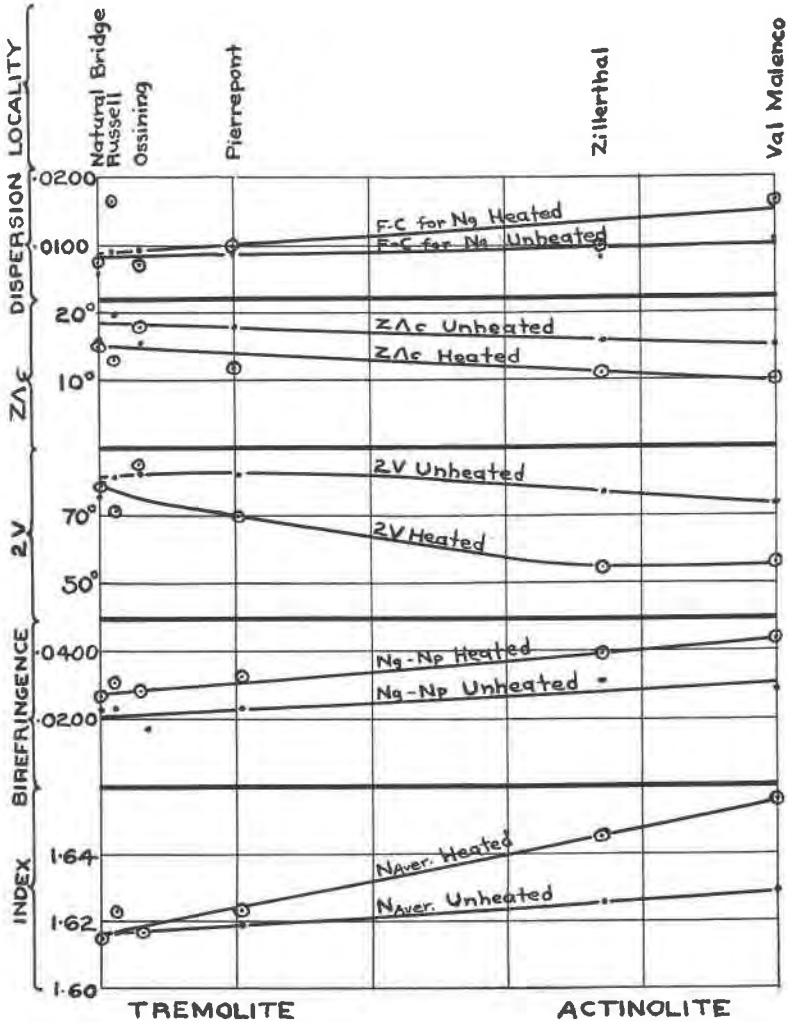


PLATE III. Optical properties of the tremolite-actinolite series plotted on the basis of the average index of the unheated samples as a straight line variation.

In Plate II the indices are plotted on the basis of N_m of the unheated samples as a straight line variation and the diagram shows the increase of indices with the increase in iron and the marked increase of indices upon heating at the high-iron end of the series. Plates III and IV are of the tremolite-actinolite series and are plotted on the same basis and show about the same facts as Plates I and II, respectively.

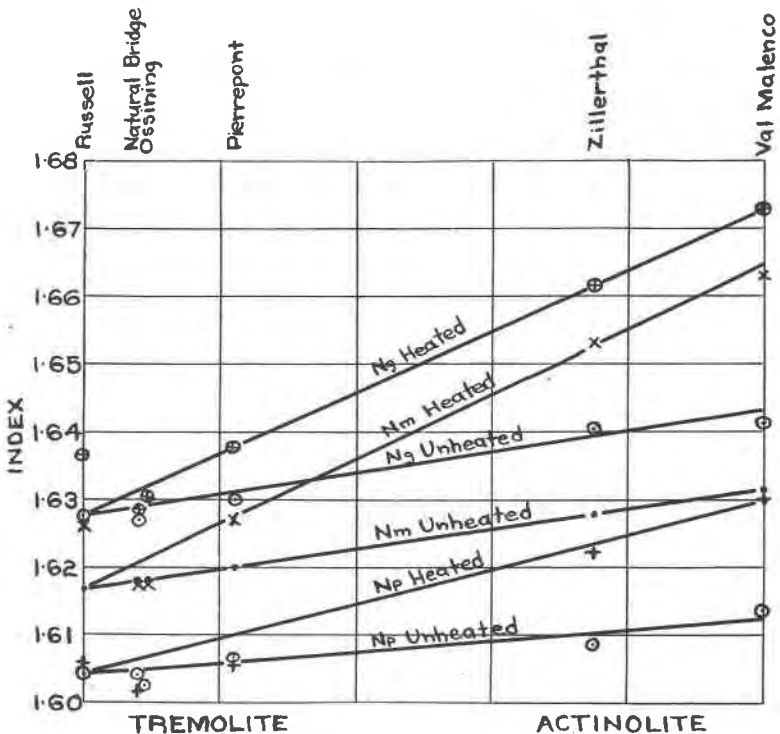


PLATE IV. Indices of the tremolite-actinolite series plotted on the basis of N_m of the unheated samples as a straight line variation.

The optical properties of the sample from Lanark Co., Ontario, when reheated in hydrogen returned practically to the same value as in the original sample before heating, indicating that ferric iron has been reduced to ferrous iron.

TABLE VIII

Hornblende—Var. Edenite, Grenville Township, Argenteuil Co., Quebec.¹⁸

Unheated

Error¹⁹ ± .0002

	N_g	N_m	N_p	N_g-N_p	2V Calc.	2V Obs.	Z/\c	Pleochroism
F	1.6394	1.6252	1.6209	.0185	58° ± 4°	58° ± 3°		None
D	1.6331	1.6186	1.6143	.0188	57° ± 2°	58° ± 2°	27° ± 1°	
C	1.6300	1.6160	1.6117	.0183	58° ± 4°	58° ± 3°		

Heated

Error ± .0002

F	1.6369	1.6255	1.6221	.0148	57½° ± 6°	58° ± 3°		None
D	1.6317	1.6204	1.6170	.0147	57½° ± 3°	58° ± 2°	25° ± 1°	
C	1.6294	1.6178	1.6144	.0150	57° ± 6°	58° ± 3°		

Hornblende—Var. Edenite, Edenville, N. Y.

Unheated

Error ± .0005

F	1.6361	1.6245	1.6181	.0180	73° ± 8°	74° ± 3°		None
D	1.6307	1.6190	1.6125	.0182	73½° ± 4°	74° ± 2°	23° ± 1°	
C	1.6286	1.6166	1.6098	.0188	74½° ± 8°	74° ± 3°		

Heated

Error ± .0005

F	1.6375	1.6263	1.6198	.0177	74½° ± 8°	74° ± 3°		None
D	1.6311	1.6204	1.6138	.0173	76° ± 4°	74° ± 2°	25° ± 2°	
C	1.6288	1.6178	1.6112	.0176	75½° ± 8°	74° ± 3°		

Hornblende—Var., Pargasite, Edenville, N. Y.

Unheated

Error ± .0003

F	1.6464	1.6313	1.6245	.0219	67½° ± 6°	70° ± 3°		None
D	1.6410	1.6256	1.6188	.0222	67½° ± 3°	70° ± 2°	21° ± 1°	
C	1.6382	1.6231	1.6162	.0220	68½° ± 6°	70° ± 3°		

Heated

Error ± .0005

F	1.6492	1.6348	1.6279	.0213	69½° ± 6°	71° ± 3°		None
D	1.6430	1.6291	1.6221	.0209	71° ± 3°	71° ± 2°	21° ± 1°	
C	1.6406	1.6264	1.6197	.0209	69° ± 6°	71° ± 3°		

¹⁸ This sample was furnished by the Canadian Geological Survey, and is one of the most studied amphiboles, having been analyzed by three different people, Harrington, Johnston and Stanley, and studied optically by Ford and Kreutz.

¹⁹ This error refers only to the indices for the D line. For a fuller discussion of accuracy see text.

Hornblende—Var. Pargasite, Amity, New York

Unheated

Error $\pm .0005$

	N_g	N_m	N_p	$N_g - N_p$	2V Calc.	2V Obs.	$Z/\wedge c$	Pleochroism
F	1.6484	1.6338	1.6283	.0201	$63^\circ \pm 8^\circ$	$64^\circ \pm 3^\circ$		None
D	1.6416	1.6265	1.6206	.0210	$64^\circ \pm 4^\circ$	$64^\circ \pm 2^\circ$	$22^\circ \pm 1^\circ$	
C	1.6383	1.6233	1.6175	.0208	$66^\circ \pm 8^\circ$	$64^\circ \pm 3^\circ$		

Heated

Error $\pm .0005$

F	1.6476	1.6332	1.6262	.0214	$68^\circ \pm 8^\circ$	$70^\circ \pm 3^\circ$		None
D	1.6413	1.6265	1.6190	.0223	$71^\circ \pm 4^\circ$	$70^\circ \pm 2^\circ$	$28^\circ \pm 2^\circ$	
C	1.6378	1.6227	1.6148	.0230	$71\frac{1}{2}^\circ \pm 8^\circ$	$70^\circ \pm 3^\circ$		

Hornblende—Var. Pargasite, Warwick, N. Y.

Unheated

Error $\pm .0002$

F	1.6480	1.6325	1.6259	.0221	$66^\circ \pm 4^\circ$	$66^\circ \pm 3^\circ$		X = Colorless
D	1.6429	1.6284	1.6218	.0211	$68^\circ \pm 2^\circ$	$66^\circ \pm 2^\circ$	$24^\circ \pm 1^\circ$	Y = Very light green
C	1.6411	1.6265	1.6203	.0208	$66^\circ \pm 4^\circ$	$66^\circ \pm 3^\circ$		Z = Very light brownish green

Heated

Error $\pm .0005$

F	1.6599	1.6472	1.6354	.0245	$88^\circ \pm 4^\circ$	$86^\circ \pm 3^\circ$		X = Very light green
D	1.6526	1.6402	1.6287	.0239	$88^\circ \pm 2^\circ$	$86^\circ \pm 2^\circ$	$21^\circ \pm 1^\circ$	Y = Light brownish green
C	1.6492	1.6370	1.6256	.0236	$88^\circ \pm 4^\circ$	$86^\circ \pm 3^\circ$		Z = Light brown

Hornblende—Var. Pargasite, Pargas, Finland

Unheated

Error $\pm .0005$

F	1.6511	1.6360	1.6318	.0193	$56^\circ \pm 8^\circ$	$56^\circ \pm 3^\circ$		None
D	1.6437	1.6286	1.6244	.0193	$55\frac{1}{2}^\circ \pm 4^\circ$	$56^\circ \pm 2^\circ$	$27^\circ \pm 1^\circ$	
C	1.6401	1.6250	1.6208	.0193	$56^\circ \pm 8^\circ$	$56^\circ \pm 3^\circ$		

Heated

Error $\pm .0003$

F	1.6510	1.6351	1.6314	.0196	$51\frac{1}{2}^\circ \pm 6^\circ$	$53^\circ \pm 3^\circ$		None
D	1.6451	1.6297	1.6260	.0191	$52\frac{1}{2}^\circ \pm 3^\circ$	$53^\circ \pm 2^\circ$	$27^\circ \pm 1^\circ$	
C	1.6427	1.6265	1.6228	.0199	$51^\circ \pm 6^\circ$	$53^\circ \pm 3^\circ$		

Hornblende, Ottawa, Canada

Unheated

Error $\pm .0002$

F	1.6600	1.6551	1.6423	.0177	$63^\circ \pm 4^\circ$	$62^\circ \pm 3^\circ$		X = Light bluish green
D	1.6522	1.6472	1.6341	.0181	$63^\circ \pm 2^\circ$	$62^\circ \pm 2^\circ$	$21^\circ \pm 1^\circ$	Y = Deep green
C	1.6490	1.6440	1.6311	.0179	$64^\circ \pm 4^\circ$	$62^\circ \pm 3^\circ$		Z = Deep bluish green

Heated

Error $\pm .0005$

F	1.7288	1.7095	1.6596	.0692	$64^\circ \pm 4^\circ$	$64^\circ \pm 3^\circ$		Y = Yellowish brown
D	1.7111	1.6978	1.6503	.0608	$55\frac{1}{2}^\circ \pm 2^\circ$	$56^\circ \pm 2^\circ$	$0^\circ \pm 1^\circ$	Y = Amber brown
C	1.7016	1.6917	1.6478	.0538	$51^\circ \pm 4^\circ$	$52^\circ \pm 3^\circ$		Z = Deep dark brown

Hornblende, Sandeled, near Risor, Norway

Unheated
Error $\pm .0005$

	N_g	N_m	N_p	$N_g - N_p$	2V Calc.	2V Obs.	$Z \setminus c$	Pleochroism
F	1.6642	1.6572	1.6421	.0221	$69^\circ \pm 8^\circ$	$72^\circ \pm 3^\circ$		X = Light green
D	1.6571	1.6490	1.6331	.0240	$71^\circ \pm 4^\circ$	$72^\circ \pm 2^\circ$	$16^\circ \pm 1^\circ$	Y = Yellowish green
C	1.6536	1.6457	1.6297	.0239	$70^\circ \pm 8^\circ$	$72^\circ \pm 3^\circ$		Z = Dark yellowish green

Heated
Error $\pm .0004$

F	1.6980	1.6838	1.6520	.0460	$66^\circ \pm 4^\circ$	$66^\circ \pm 3^\circ$		X = Light greenish brown
D	1.6862	1.6724	1.6406	.0456	$67^\circ \pm 2^\circ$	$66^\circ \pm 2^\circ$	$0^\circ \pm 1^\circ$	Y = Greenish brown
C	1.6798	1.6678	1.6367	.0431	$64^\circ \pm 4^\circ$	$66^\circ \pm 3^\circ$		Z = Deep brown

Hornblende, Tyrol

Unheated
Error $\pm .0005$

F	1.6713	1.6585	1.6445	.0268	$87^\circ \pm 4^\circ$	$86^\circ \pm 3^\circ$		X = Very light green
D	1.6640	1.6510	1.6370	.0271	$88^\circ \pm 2^\circ$	$86^\circ \pm 2^\circ$	$10^\circ \pm 1^\circ$	Y = Light grayish green
C	1.6618	1.6494	1.6347	.0371	$85\frac{1}{2}^\circ \pm 4^\circ$	$86^\circ \pm 3^\circ$		Z = Grayish green

Heated
Error $\pm .0010$

F	1.7411	1.7152	1.6623	.0788	$70^\circ \pm 4^\circ$	$70^\circ \pm 3^\circ$		X = Light amber
D	1.7175	1.6980	1.6507	.0668	$65\frac{1}{2}^\circ \pm 2^\circ$	$65^\circ \pm 2^\circ$	$1^\circ \pm 1^\circ$	Y = Amber brown
C	1.7093	1.6928	1.6473	.0620	$62^\circ \pm 4^\circ$	$62^\circ \pm 3^\circ$		Z = Deep brown

Hornblende, Lanark Co., Ontario²⁰

Unheated
Error $\pm .0002$

F	1.6732	1.6668	1.6608	.0124	$88^\circ \pm 4^\circ$	$88^\circ \pm 3^\circ$		X = Very light green
D	1.6665	1.6589	1.6511	.0154	$89\frac{1}{2}^\circ \pm 2^\circ$	$88^\circ \pm 2^\circ$	$23^\circ \pm 2^\circ$	Y = Brownish green
C	1.6641	1.6557	1.6473	.0168	$90^\circ \pm 4^\circ$	$88^\circ \pm 3^\circ$		Z = Green

Heated
Error $\pm .0005$

F	1.7243	1.7083	1.6726	.0517	$68^\circ \pm 4^\circ$	$76^\circ \pm 3^\circ$		X = Light greenish brown
D	1.7100	1.6961	1.6626	.0474	$66^\circ \pm 2^\circ$	$66^\circ \pm 3^\circ$	$5^\circ \pm 2^\circ$	Y = Amber brown
C	1.7014	1.6890	1.6581	.0433	$65^\circ \pm 4^\circ$	$64^\circ \pm 3^\circ$		Z = Deep brown

Reheated in hydrogen
Error $\pm .0004$

F	1.6737	1.6659	1.6581	.0156	$90^\circ \pm 4^\circ$	$88^\circ \pm 3^\circ$		X = Very light green
D	1.6670	1.6583	1.6493	.0177	$89^\circ \pm 2^\circ$	$88^\circ \pm 2^\circ$	$24^\circ \pm 2^\circ$	Y = Brownish green
C	1.6650	1.6562	1.6464	.0186	$87^\circ \pm 4^\circ$	$88^\circ \pm 3^\circ$		Z = Green

²⁰ Analysis by R. B. Ellestad, University of Minnesota.

Hornblende, Eganville, Ontario

Unheated

Error $\pm .0003$

	N_g	N_m	N_p	$N_g - N_p$	2V Calc.	2V Obs.	$Z/\wedge c$	Pleochroism
F	1.6786	1.6735	1.6614	.0172	$66^\circ \pm 4^\circ$	$63^\circ \pm 3^\circ$		X = Light green
D	1.6702	1.6656	1.6539	.0163	$64^\circ \pm 2^\circ$	$63^\circ \pm 2^\circ$	$32^\circ \pm 1^\circ$	Y = Deep green
C	1.6660	1.6616	1.6499	.0161	$63^\circ \pm 4^\circ$	$63^\circ \pm 3^\circ$		Z = Deep blue green

Heated

Error $\pm .0010$

F	1.7311	1.7168	1.6741	.0570	$60^\circ \pm 8^\circ$	$61^\circ \pm 3^\circ$		X = Greenish brown
D	1.7193	1.7060	1.6666	.0527	$61^\circ \pm 4^\circ$	$61^\circ \pm 2^\circ$	$4^\circ \pm 2^\circ$	Y = Dark greenish brown
C	1.7148	1.7017	1.6635	.0513	$62^\circ \pm 8^\circ$	$61^\circ \pm 3^\circ$		Z = Opaque brown

Hornblende, Millford, Massachusetts

Unheated

Error $\pm .0005$

F	1.6856	1.6788	1.6663	.0193	$73^\circ \pm 6^\circ$	$72^\circ \pm 3^\circ$		X = Yellowish green
D	1.6792	1.6715	1.6578	.0214	$74^\circ \pm 3^\circ$	$72^\circ \pm 2^\circ$	$20^\circ \pm 1^\circ$	Y = Dark yellow green
C	1.6766	1.6686	1.6549	.0217	$74\frac{1}{2}^\circ \pm 6^\circ$	$72^\circ \pm 3^\circ$		Z = Dark bluish green

Heated

Error $\pm .0008$

F	1.7729	1.7450	1.6884	.0845	$70^\circ \pm 6^\circ$	$72^\circ \pm 3^\circ$		X = Yellowish green
D	1.7477	1.7288	1.6759	.0718	$62^\circ \pm 3^\circ$	$65^\circ \pm 2^\circ$	$0^\circ \pm 1^\circ$	Y = Dark amber brown
C	1.7399	1.7206	1.6719	.0680	$64\frac{1}{2}^\circ \pm 6^\circ$	$63^\circ \pm 3^\circ$		Z = Deep brown

Hornblende, Frankfort, Pennsylvania

Unheated

Error $\pm .0004$

F	1.7073	1.7043	1.6900	.0173	$49^\circ \pm 12^\circ$	$45^\circ \pm 3^\circ$		X = Light yellow green
D	1.6980	1.6950	1.6801	.0179	$48^\circ \pm 6^\circ$	$45^\circ \pm 2^\circ$	$22^\circ \pm 1^\circ$	Y = Yellowish green
C	1.6960	1.6930	1.6765	.0195	$47^\circ \pm 12^\circ$	$45^\circ \pm 3^\circ$		Z = Bluish green

Heated

Error $\pm .0012$

F	1.8068	1.7759	1.7137	.0931	—————	$70^\circ \pm 3^\circ$		X = Yellow green
D	1.7825	1.7564	1.7003	.0822	—————	$69^\circ \pm 2^\circ$	$0^\circ \pm 1^\circ$	Y = Opaque yellow green
C	1.7706	1.7483	1.6962	.0744	—————	$66\frac{1}{2}^\circ \pm 3^\circ$		Z = Opaque

Hornblende, Renfrew Co., Ontario²¹

Unheated

Error $\pm .0005$

F	1.7110	1.7090	1.6908	.0202	$37^\circ \pm 14^\circ$	$35^\circ \pm 3^\circ$		X = Light green
D	1.7000	1.6980	1.6804	.0196	$38^\circ \pm 7^\circ$	$38^\circ \pm 4^\circ$	$20^\circ \pm 1^\circ$	Y = Dark green
C	1.6948	1.6930	1.6758	.0190	$36^\circ \pm 14^\circ$	$40^\circ \pm 3^\circ$		Z = Very dark green

Heated

Error $\pm .0012$

F	1.8275	1.7857	1.7145	.1130	—————	$75^\circ \pm 3^\circ$		X = Light brown
D	1.7960	1.7690	1.7020	.0940	—————	$65^\circ \pm 2^\circ$	$0^\circ \pm 1^\circ$	Y = Dark brown
C	1.7838	1.7608	1.6973	.0865	—————	$62^\circ \pm 3^\circ$		Z = Very dark brown

²¹ Analysis by L. C. Hurd, University of Wisconsin.

Tremolite, Russell, New York

Unheated

Error $\pm .0002$

	N_g	N_m	N_p	$N_g - N_p$	2V Calc.	2V Obs.	$Z \wedge c$	Pleochroism
F	1.6342	1.6230	1.6096	.0246	$85^\circ \pm 4^\circ$	$81^\circ \pm 3^\circ$		None
D	1.6278	1.6178	1.6042	.0236	$81\frac{1}{2}^\circ \pm 2^\circ$	$81^\circ \pm 2^\circ$	$20^\circ \pm 1^\circ$	
C	1.6252	1.6154	1.6016	.0236	$80\frac{1}{2}^\circ \pm 4^\circ$	$81^\circ \pm 3^\circ$		

Heated

Error $\pm .0004$

F	1.6488	1.6350	1.6105	.0383	$74^\circ \pm 4^\circ$	$72^\circ \pm 3^\circ$		X = Colorless
D	1.6367	1.6262	1.6058	.0309	$71\frac{1}{2}^\circ \pm 2^\circ$	$72^\circ \pm 2^\circ$	$13^\circ \pm 1^\circ$	Y = Very light green
C	1.6323	1.6228	1.6047	.0276	$72^\circ \pm 4^\circ$	$72^\circ \pm 3^\circ$		Z = Very light brown

Tremolite, Natural Bridge, New York

Unheated

Error $\pm .0004$

F	1.6303	1.6218	1.6076	.0227	$75\frac{1}{2}^\circ \pm 4^\circ$	$77^\circ \pm 3^\circ$		None
D	1.6267	1.6181	1.6041	.0226	$76^\circ \pm 2^\circ$	$77^\circ \pm 2^\circ$	$16^\circ \pm 1^\circ$	
C	1.6247	1.6161	1.6020	.0227	$76^\circ \pm 4^\circ$	$77^\circ \pm 3^\circ$		

Heated

Error $\pm .0005$

F	1.6335	1.6224	1.6061	.0274	$79^\circ \pm 6^\circ$	$83^\circ \pm 3^\circ$		None
D	1.6284	1.6175	1.6014	.0270	$79^\circ \pm 3^\circ$	$83^\circ \pm 2^\circ$	$15^\circ \pm 1^\circ$	
C	1.6258	1.6147	1.5991	.0267	$80^\circ \pm 6^\circ$	$83^\circ \pm 3^\circ$		

Tremolite, Ossining, New York²²

Unheated

Error $\pm .0002$

F	1.6367	1.6245	1.6086	.0283	$83^\circ \pm 4^\circ$	$82^\circ \pm 3^\circ$		None
D	1.6307	1.6183	1.6024	.0283	$83^\circ \pm 2^\circ$	$82^\circ \pm 2^\circ$	$15\frac{1}{2}^\circ \pm 1^\circ$	
C	1.6278	1.6155	1.5996	.0282	$83^\circ \pm 4^\circ$	$82^\circ \pm 3^\circ$		

Heated

Error $\pm .0004$

F	1.6355	1.6228	1.6080	.0275	$85\frac{1}{2}^\circ \pm 4^\circ$	$82^\circ \pm 3^\circ$		None
D	1.6308	1.6178	1.6026	.0282	$85\frac{1}{2}^\circ \pm 2^\circ$	$82^\circ \pm 2^\circ$	$18^\circ \pm 1^\circ$	
C	1.6282	1.6152	1.6002	.0280	$86^\circ \pm 4^\circ$	$82^\circ \pm 3^\circ$		

Actinolite, Pierrepont, New York

Unheated

Error $\pm .0004$

F	1.6367	1.6271	1.6131	.0236	$79^\circ \pm 4^\circ$	$82^\circ \pm 3^\circ$		None
D	1.6301	1.6201	1.6067	.0234	$82^\circ \pm 2^\circ$	$82^\circ \pm 2^\circ$	$18^\circ \pm 1^\circ$	
C	1.6276	1.6169	1.6037	.0239	$84^\circ \pm 4^\circ$	$82^\circ \pm 3^\circ$		

Heated

Error $\pm .0004$

F	1.6443	1.6328	1.6106	.0337	$71\frac{1}{2}^\circ \pm 4^\circ$	$70^\circ \pm 3^\circ$		X = Colorless
D	1.6377	1.6270	1.6053	.0324	$70^\circ \pm 2^\circ$	$70^\circ \pm 2^\circ$	$12^\circ \pm 1^\circ$	Y = Very light green
C	1.6343	1.6242	1.6032	.0311	$69\frac{1}{2}^\circ \pm 4^\circ$	$70^\circ \pm 3^\circ$		Z = Very light brown

²² Analysis by Allen and Clement: *Amer. Jour. Sci.*, 4th Ser., Vol. 26, 101, 1908. The material studied is a portion of the original sample that was analyzed.

Actinolite, Zillerthal, Tyrol

Unheated

Error $\pm .0005$

	N_g	N_m	N_p	$N_g - N_p$	2V Calc.	2V Obs.	Z/\(\angle c	Pleochroism
F	1.6463	1.6332	1.6142	.0321	$79^\circ \pm 4^\circ$	$78^\circ \pm 3^\circ$		X = Very light green
D	1.6403	1.6278	1.6085	.0318	$77\frac{1}{2}^\circ \pm 2^\circ$	$78^\circ \pm 2^\circ$	$16^\circ \pm 1^\circ$	Y = Yellowish green
C	1.6380	1.6253	1.6060	.0320	$78^\circ \pm 4^\circ$	$78^\circ \pm 3^\circ$		Z = Green

Heated

Error $\pm .0010$

F	1.6679	1.6594	1.6283	.0396	$55^\circ \pm 10^\circ$	$56^\circ \pm 3^\circ$		X = Light green
D	1.6617	1.6532	1.6220	.0397	$55^\circ \pm 5^\circ$	$56^\circ \pm 2^\circ$	$11^\circ \pm 1^\circ$	Y = Greenish brown
C	1.6581	1.6496	1.6183	.0398	$55^\circ \pm 10^\circ$	$56^\circ \pm 3^\circ$		Z = Mottled brown

Actinolite, Val Malenco, Italy²³

Unheated

Error $\pm .0004$

F	1.6490	1.6384	1.6214	.0276	$76\frac{1}{2}^\circ \pm 4^\circ$	$73^\circ \pm 3^\circ$		X = Light green
D	1.6413	1.6313	1.6133	.0280	$73\frac{1}{2}^\circ \pm 2^\circ$	$73^\circ \pm 2^\circ$	$15^\circ \pm 1^\circ$	Y = Bluish green
C	1.6379	1.6280	1.6108	.0271	$74\frac{1}{2}^\circ \pm 4^\circ$	$73^\circ \pm 3^\circ$		Z = Green

Heated

Error $\pm .0005$

F	1.6848	1.6743	1.6380	.0468	$56\frac{1}{2}^\circ \pm 6^\circ$	$57^\circ \pm 3^\circ$		X = Greenish brown
D	1.6728	1.6634	1.6301	.0427	$56^\circ \pm 3^\circ$	$56^\circ \pm 2^\circ$	$10^\circ \pm 1^\circ$	Y = Deep brown
C	1.6680	1.6586	1.6278	.0402	$58^\circ \pm 6^\circ$	$55^\circ \pm 3^\circ$		Z = Dark brown

Kreutz²⁴ mentions that for common hornblende the birefringence in red is greater than for violet and that for basaltic hornblende the opposite is true. The results obtained in this study bear out, in general, the results obtained by Kreutz for common hornblende and entirely for brown hornblende. The heated hornblende also shows a marked rhombic dispersion as indicated by the difference of the optic angle for F and C calculated from the indices and observed directly.

In dehydration of amphiboles hydrogen is given off and not water (except water which is not a constituent part of the space lattice). This is substantiated by the difference between the weight percentage loss on heating and the water content by analysis. The percentage loss in weight of the Lanark County hornblende upon heating was 0.27% and the analysis for water gave 0.74%. The sample from Argenteuil Co., Quebec, shows a weight loss of 0.04% and the water content by analysis is 0.58%. Kôzu²⁵ and associates show a weight-percent loss for common hornblende of 0.13% and for soretite of 0.28% at a temperature of 800°C., which compares

²³ No. 11453 of the Milwaukee Museum.

²⁴ Kreutz, S.: *Sitz. Akad. Wiss. Wien.*, **117**, I, 875, 1908.

²⁵ Kôzu, S., Yoshiki, B., and Kani, K.: *Science Reports of the Tôhoku Imperial University*, Ser. 3, Vol. III, No. 2, 143, 1927.

with the temperature used here, and at 1000° the weight-percent loss is 0.18% and 0.49%, respectively. The water analysis is not given for either of these samples, but it is reasonable to assume that as in other amphiboles the analyses would show about 1% or more of water. The reason it is thought that hydrogen is given off and not water given off and oxygen taken on is that the sample from Argenteuil Co., Quebec, which is very low in iron shows a weight percentage loss that is only a small fraction of the water contained, and since little iron is present there would be no reason for oxygen to enter the mineral. The oxygen which remains in the mineral must (if ferrous iron is available) oxidize the ferrous iron to ferric iron, and when no ferrous iron is present must be held in the mineral by its size and consequently its inability to move through the space lattice.

To establish oxidation definitely we may turn to the analyses of the Renfrew and Lanark hornblendes, before and after heating, in Table IX. In both samples it is very apparent that a large share of the ferrous iron has been converted into ferric iron and that

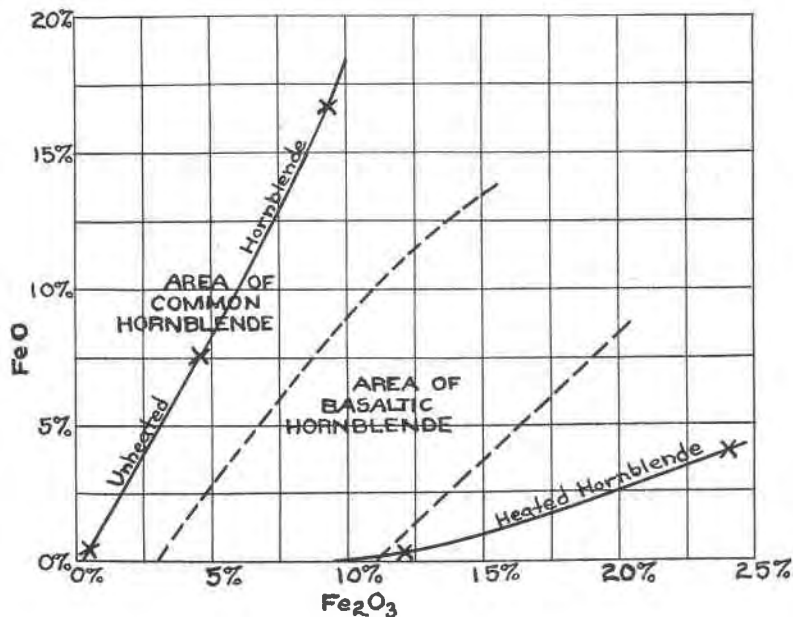


FIG. 2. Relations between ferrous and ferric iron in analyzed samples of common, basaltic, and heated hornblende.

water has been lost. Two other analyses of iron-poor amphiboles that show very little optical change on heating are included in the table. Analyses after heating were not made because the small optical change indicates practically no chemical change.

The total iron is stated for the unheated and heated phases of the Lanark and Renfrew hornblendes. The total iron for the Lanark sample checks within 0.04% and from all appearances the analysis is excellent. The total iron in the Renfrew sample is over twice that in the Lanark sample. The analyses before and after heating show a discrepancy of 0.28% for total iron and the accuracy given for the fluorine indicates that it is little better than an estimate, so this analysis should be used with discretion.

TABLE IX

	1	2	3	4	5	6
SiO ₂	43.59		41.02		45.79	57.35
TiO ₂	0.86		1.02		0.63	0.07
Al ₂ O ₃	11.17		9.69		12.18	1.21
Fe ₂ O ₃	4.60	12.42	9.23	23.40	0.50	0.11
FeO	7.48	0.39	16.51	4.12	0.39	0.23
MnO	0.29		tr.		0.29	0.01
MgO	14.59		7.20		20.85	23.87
CaO	11.60		10.65		12.98	14.02
K ₂ O	1.95		1.33		1.76	0.19
Na ₂ O	2.49		2.72		2.54	0.42
H ₂ O	0.74	0.05	0.92	0.08	0.58	2.21
F ₂	0.29	0.34	0.40 ± .20	0.30 ± .20	2.80	0.11
Total	99.65		100.68		101.29	99.80
O=F ₂	.12		.18		1.17	.05
	99.53		100.50		100.12	99.75
Total						
Fe	9.03	8.99	19.29	19.57		

1. Unheated hornblende, Lanark Co., Ont. Analyzed by R. B. Ellestad, University of Minnesota.

2. Heated, otherwise the same as 1.

3. Unheated hornblende, Renfrew Co., Ont. Analyzed by L. C. Hurd, University of Wisconsin.

4. Heated, otherwise the same as 3.

5. Edenite, Argenteuil Co., Quebec. Average of analyses by Harrington, B. J.: *Am. Jour. Sci.*, **XV**, 392, 1903; Johnston, R. A. A.: *Geol. Sur. Canada*, Vol. **XIII**; and Stanley, F. C.: *Am. Jour. Sci.*, **XXIII**, 49, 1907.

6. Tremolite, Ossining, N.Y. Analysis by Allen and Clement, *Am. Jour. Sci.*, 4th Ser., Vol. **26**, 101, 1908.

The optical properties were plotted against the content of iron oxides and also against the ratio of combined iron oxides to magnesia. In both cases the resulting diagrams were almost exactly the same as obtained in Plate I in which the average index of the heated hornblendes were plotted as a straight line variation. In Fig. 2, ferrous iron is plotted on the ordinate and ferric iron on the abscissa. The areas of common hornblende and of basaltic hornblende are shown as obtained from many analyses. The analyses from Table IX are indicated by crosses, and it will be noticed that for the heated samples the crosses fall outside of the basaltic hornblende area. It is probable that most basaltic hornblendes are not fully oxidized. This view is supported by Schneider, previously quoted, who heated basaltic hornblendes and found in most of them an increase in pleochroism, absorption and double refraction, and a decrease in extinction angle ($Z \wedge c$).

The density of the heated hornblende is greater than that of the unheated hornblende. Using Clerici solution the density of the Lanark Co., sample was determined to be 3.175 in the unheated state and 3.215 afterwards, and for the Renfrew Co. sample the density was determined to be 3.258 for the unheated sample and 3.320 for the one that was heated. Graham²⁶ states that, "The diffraction-angles of the heated sample are slightly greater than in the unheated one, indicating that in the heated hornblendes the planes of atomic structure are a trifle closer together and the mineral is slightly denser." Kôzu and associates, previously quoted, found a contraction between the temperatures of 750° and 790° C., which is additional evidence that the heated hornblendes are denser. Kôzu attributed this change to inversion. Many substances do show this phenomenon at the inversion point, but with inversion there is only a rearrangement of the material present and no change in chemical composition by either addition or expulsion. It may be argued that the effects of the chemical changes taking place are subordinate as shown by the lack of change of the iron-poor amphiboles upon the loss of water, but at the same time there is no change to indicate inversion. Inversion should take place without regard to the atmosphere in which it is heated. As found in the present study the high-iron hornblendes when heated in hydrogen do not change. If inversion were the chief factor the change of mean index should be related

²⁶ Graham, W. A. P.: *Am. Mineral.*, Vol. XI, No. 5, 118, 1926.

to the change in density. This was tested with the aid of the formula of Gladstone & Dale:²⁷ $n-1/d=\text{constant}$, where n is the index and d is the density. The constant obtained for the unheated sample was used with the density of the heated sample to obtain the index. The Lanark Co. sample gives an increase of mean index of .0083 due to density increase, whereas, the measured increase of mean index is .0308. Following the same procedure for the Renfrew Co. sample .0132 is obtained for the increase in mean index due to density and .0625 is the mean index increase observed. The increase of index due to the increase of density is only about one-quarter of the increase actually found. The accuracy of this formula for solids is seriously questioned, so these results cannot be regarded as more than approximations.

Oxidation is by far the most important factor in the change from green to brown hornblende and in fact if it were not for oxidation there would be no increase in density and consequently no increase in index from this cause.

SUMMARY

The facts obtained in this study may be enumerated as follows:

1. Green hornblende, when heated in air, changes to brown hornblende, which has the same optical properties as basaltic hornblende.
2. The iron-poor hornblendes do not change on heating.
3. Upon heating tremolite behaves like the iron-poor hornblendes and actinolite like the iron-containing hornblendes.
4. The changes obtained in the iron-rich varieties upon heating are as follows: Increase in density, indices of refraction, birefringence, and dispersion; decrease in extinction angle; and change in optic angle to about 65° , and in pleochroism and color from greens to browns.
5. Brown hornblende when heated in hydrogen changes back to green hornblende.
6. The weight-percent loss on heating is only a fraction of the water obtained by analysis.
7. The birefringence of brown hornblende in violet is greater than for red and the opposite is true in general for common hornblende.

²⁷ Gladstone and Dale: *Phil. Trans.*, 153, 317, 1863.

8. The heated, iron-rich hornblendes show a marked rhombic dispersion.

9. The analyses show a marked conversion of ferrous to ferric iron on heating and a loss in water.

10. The optical properties change almost in proportion to the change in the total iron oxides, with ferric iron being the most influential upon the optical properties.

11. Dehydration has little effect upon the optical properties.

12. Heated hornblendes in general have a more complete change of ferrous to ferric iron than basaltic hornblendes.

The conclusions drawn from these facts are as follows:

1. Oxidation of ferrous to ferric iron causes the changes in optical properties observed upon heating common hornblende.

2. Dehydration is of no importance except that it allows oxidation to proceed.

3. Inversion is not present as proved by the lack of change when heated in hydrogen.

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