

FURTHER STUDIES IN THE AMPHIBOLE GROUP

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1. INTRODUCTION

At the time of an earlier study of the amphibole group¹ it was considered by the writer (and others) that experimental work carried out at the Geophysical Laboratory had demonstrated that the same molecule, namely, MgSiO_3 , could be made to crystallize either as a pyroxene or as an amphibole. The type-formula of the amphiboles being thus apparently established, formulas of the same type were deduced from the published analyses for the other amphiboles, disregarding their tenor of water. By a remarkable study of tremolite by *X*-ray methods, Warren² has recently demonstrated that the water cannot be neglected; since water is not a constituent of pyroxenes, it follows that the same molecules are not found in pyroxenes and amphiboles, and that the molecules of the amphibole group are more complicated than those of the pyroxenes. Warren has established the composition of tremolite as $\text{H}_2\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{24}$; starting with this type-formula, the laws of isomorphism, as modified by *X*-ray studies, lead to Warren's conclusion³ that other amphibole molecules include:

Actinolite	$\text{H}_2\text{Ca}_2\text{Fe}_5\text{Si}_8\text{O}_{24}$
Kupfferite	$\text{H}_2\text{Mg}_7\text{Si}_8\text{O}_{24}$
Grunerite	$\text{H}_2\text{Fe}_7\text{Si}_8\text{O}_{24}$
Hornblende	$\text{H}_2(\text{Ca, Na, K})_{2-3}(\text{Mg, Fe, Al})_5(\text{Si, Al})_8\text{O}_{24}$

The peculiar feature of the formula assigned to hornblende, namely, the variable number (2–3) of (Ca, Na, K) atoms is explained by Warren as follows:

"In the tremolite structure [space-lattice] there are seven metal atoms (2 Ca and 5 Mg), and in addition a vacant position where a single atom such as Na or K might find position. Replacements are of two types: (a) such that the number of metal atoms remains 7, $\text{Mg} = \text{Fe}$, $\text{Ca} = \text{Mg}$, $(\text{Mg, Si}) = (\text{Al, Al})$; (b) where the vacant position in the tremolite structure is filled by Na or K and the number

¹ *Am. Jour. Sci.*, **CCVII**, 1924, pp. 287–310; also "Elements of Optical Mineralogy, Part II," John Wiley and Sons, New York, 1927, pp. 198–216.

² *Zeit. Kryst.*, **LXXII**, pp. 42–57.

³ *Zeit. Kryst.*, **LXXII**, 1930, pp. 493–517.

of metal atoms is increased from 7 to 8, $\text{Si} = (\text{Al}, \text{Na})$, $\text{Ca} = (\text{Na}, \text{Na})$."

It is the purpose of this article to discuss the relations between variations in optic properties and variations in composition in various parts of the amphibole group on the basis of the newly established type-formula for the group. An attempt will be made, also, to deduce definite formulas for the chief molecules of hornblende to replace the indefinite formula proposed by Warren.

It is interesting to note that B. Gossner⁴ deduced the correct formula of tremolite as early as 1924, although he expressed it in the unfamiliar form: $2\text{SiO}_3 \cdot \text{Ca} \cdot 4\text{SiO}_3 \cdot \text{Mg} \cdot [2\text{SiO}_2 - \text{MgO}_2\text{H}_2]$. It is a pleasure to call attention to the fact that Schaller⁵ obtained the correct formula of tremolite as early as 1916. Still more important in relation to the present study is the recent article by W. Kunitz,⁶ who also deduced the correct formulas for tremolite, actinolite, kupfferite and grunerite, but considered that hornblende and arfvedsonite formulas have only 22 atoms of oxygen. Kunitz made numerous analyses of amphiboles on samples, some of whose optic properties he measured, so that his study adds much to our knowledge of the subject under consideration in this article. In some cases his graphs are almost unmodified by the present results; in other cases new results are obtained.

2. THE ANTHOPHYLLITE SERIES

The anthophyllite series differs from all other amphiboles, not only in simplicity of composition, due to the absence of Ca, Al, and Na atoms, but also in possessing orthorhombic symmetry. Kunitz⁷ regards the difference of symmetry as of little importance and unites the anthophyllite series with the cummingtonite series. The comparative *X*-ray study of anthophyllite, cummingtonite and tremolite made by K. Johansson⁸ shows clearly that the difference in symmetry is a fundamental property inherent in the space-lattices and should not be disregarded. *X*-ray patterns of anthophyllite and of tremolite made at the University of Wisconsin by the powder method are clearly different, while patterns of tremolite and hornblende are almost identical.

⁴ *Zeit. Kryst.*, **LX**, 1924, p. 368.

⁵ *U. S. Geol. Surv., Bull.* **610**, 1916, p. 133.

⁶ *N. Jahrb. Min., Bl. Bd.*, **LX**, A, 1930, pp. 171-250.

⁷ *Op. cit.*, p. 187.

⁸ *Zeit. Kryst.*, **LXXIII**, 1930, pp. 31.

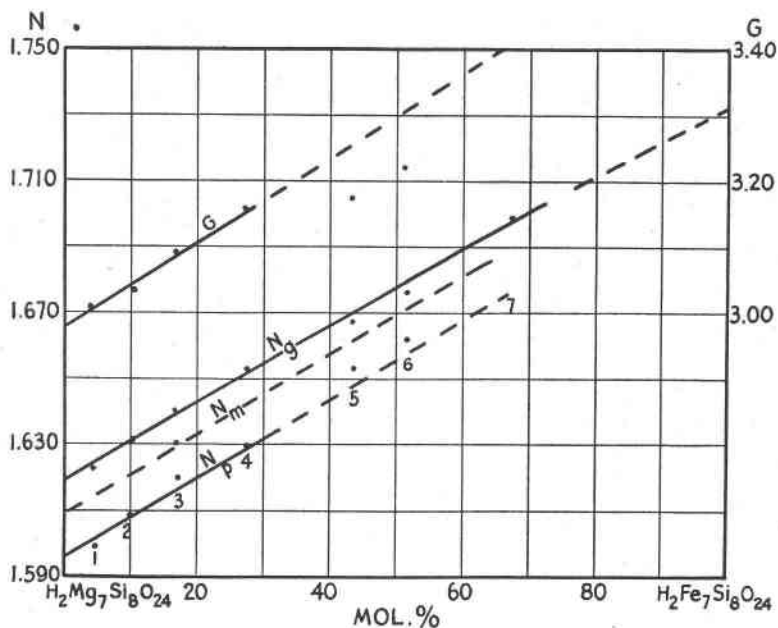


FIG. 1. Variations of composition and properties in the anthophyllite series.

REFERENCES FOR FIG. 1—ANTHOPHYLLITE SERIES

1. Anthophyllite (Valleite), Edwards, N. Y. W. Kunitz: *N. Jahrb. Min. Bl.-Bd.*, **LX**, 1930, pp. 188, 189 and 244. Pale yellowish thin-lamellar crystals.
2. Anthophyllite, Miask. W. Kunitz: *loc. cit.* Brownish and greenish crystals.
3. Anthophyllite, Franklin, N. C. S. L. Penfield: *Am. Jour. Sci.*, **CXL**, 1890, p. 394.
4. Anthophyllite, Kjerfverud. W. Kunitz: *loc. cit.* Brown elongated crystals.
5. Anthophyllite (Gedrite), Träskböle, Orijarvi. P. Eskola: *Bull. Com. Geol. Finlande*, **XL**, 1915, p. 176. Brown crystals. N_g as corrected on p. 279.
6. Anthophyllite (Gedrite), Träskböle, Orijarvi. P. Eskola: *loc. cit.* Brown crystals. N_g as corrected on p. 279.
7. Anthophyllite, Mesabi Range, Minn. Incomplete analysis by C. R. Wise: $\text{SiO}_2=42.98$, $\text{Al}_2\text{O}_3=2.14$, $\text{Fe}_2\text{O}_3=1.50$, $\text{FeO}=37.82$, $\text{MgO}=5.91$, $\text{CaO}=1.50$, $\text{H}_2\text{O}=5.23$, Total=97.08. Parallel extinction and $N_g=1.698$ as measured by A. N. Winchell.

The relations between composition and optic properties (and density) in the anthophyllite series are shown in Fig. 1. The two samples described by Eskola from Finland show clearly that about 7.5 per cent Al_2O_3 lowers the specific gravity of anthophyllite about 0.8 and the indices of refraction from 0.004 (N_g) to nearly 0.01 (N_m). Unfortunately no member of this series very high in iron has

been studied as yet, since the "ferroanthophyllite" of Shannon⁹ must be assigned to actinolite,¹⁰ as shown by the following facts. It contains about 11 per cent CaO, a fact confirmed by test made by Sidney Schafer on a small fragment of the original material kindly supplied through the courtesy of Dr. Wetmore of the U. S. National Museum. It shows parallel extinction between crossed nicols of groups of fibers in any position and also of single fibers in the usual position, but V. E. Barnes reports that a single tiny fiber when turned on its axis to a suitable position shows an extinction angle of about 10° , although it shows parallel extinction in some positions. He also reports an approximate value of the optic angle, $2V$, as 74° about X . Finally, the X-ray pattern given by the sample is practically identical with that given by tremolite and distinctly different from that given by anthophyllite as shown by the patterns reproduced in Fig. 2.

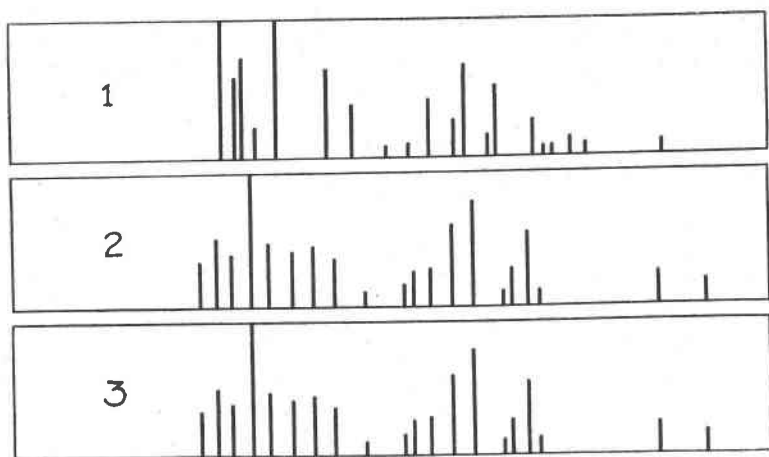


FIG. 2. X-ray patterns of: (1) anthophyllite from Medway, Mass., (2) "ferroanthophyllite," Idaho=type material as described by E. V. Shannon: *Proc. U. S. Nat. Mus.*, **LIX**, 1921, p. 397, (3) tremolite, No. 1310, Univ. Wis.

3. THE CUMMINGTONITE SERIES

The cummingtonite series is chemically equivalent to the anthophyllite series, but crystallographically it is monoclinic instead of orthorhombic. The series consists of kupferite ($H_2Mg_7Si_8O_{24}$),

⁹ *U. S. Nat. Mus. Proc.*, **LIX**, 1921, pp. 397-401.

¹⁰ It was referred to actinolite by Kunitz because of its tenor of CaO: *loc. cit.*, pp. 193, 194.

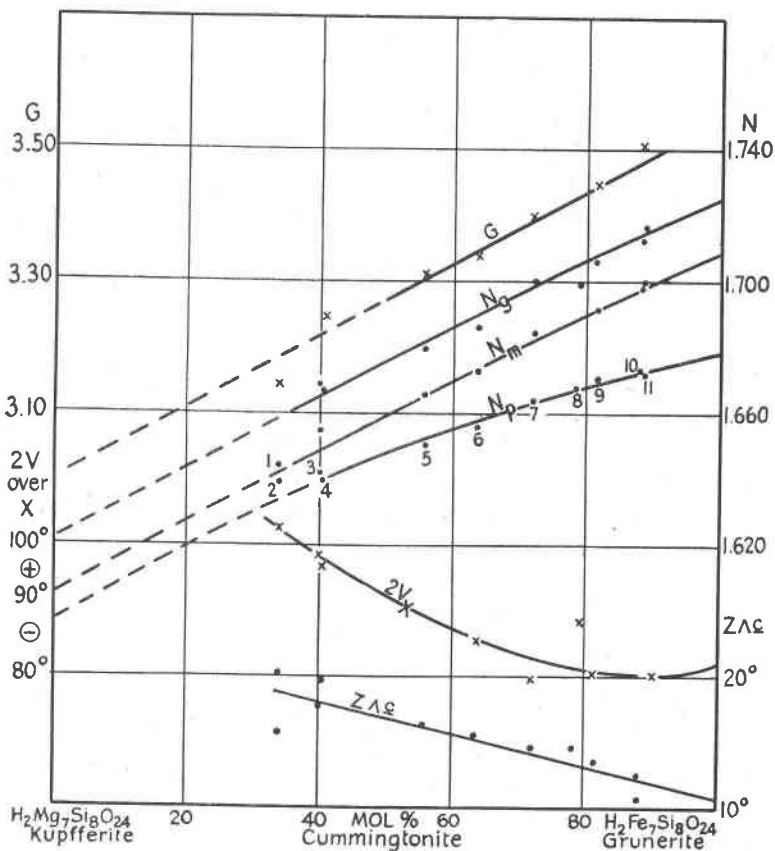


FIG. 3. Variations of composition and optic properties in the cummingtonite series.

REFERENCES FOR FIG. 3—CUMMINGTONITE SERIES

1. Cummingtonite, Orijarvi, Finland. P. Eskola: *Bull. Com. Geol. Finlande*, **XL**, 1915, pp. 112, 222.
2. Cummingtonite, Kongsberg, Norway. A. Des Cloizeaux: *Nouv. Rech. Mem.*, **XVIII**, 1867, from Dana: *System Mineralogy*, 1892, p. 390.
3. Cummingtonite, Träskböle, Finland. P. Eskola: *op. cit.*, p. 182.
4. Cummingtonite, Röberggruvan, Sweden. N. Sundius: *Geol. För. Förh.*, Stockholm, **XLVI**, 1924, p. 154.
5. Cummingtonite, Ö. Silvergruvan, Sweden. N. Sundius: *loc. cit.*, p. 154.
6. Cummingtonite, Tunaberg, Sweden. K. Johansson: *Zeit. Kryst.*, **LXXIII**, 1930, p. 31.
7. Grunerite, Strömshult, Sweden. J. Palmgren: *Bull. Geol. Inst. Univ. Upsala*, **XIV**, 1917, p. 109.
8. Grunerite, ("Cummingtonite") Krivoi Rog, Russia. Polovinkina: *Mem. Soc. Russe Mineral.*, **LIII**, 1924, p. 179, from *N. Jahrb. Mineral.*, A, 1927, I. p. 39.

9. Grunerite ("Silvbergite"), Silvberg, Sweden. N. Sundius: *op. cit.*, p. 154.
10. Grunerite (Dannemorite), Dannemora, Sweden. N. Sundius: *op. cit.*, p. 154.
11. Grunerite, Collobrières, France. S. Kreutz: *Sitzb. Akad. Wiss. Wien*, CXVII, 1908, p. 875.

cummingtonite $[H_2(Mg, Fe)_7Si_8O_{24}]$ and grunerite $(H_2Fe_7Si_8O_{24})$; a variety containing considerable manganese has been called dannemorite. Samples from nature containing more than 70 per cent of the magnesium molecule are very rare and no careful studies have been made on such material. Furthermore, the only careful study¹¹ made of an artificial product supposed to be the pure magnesian monoclinic amphibole includes no analysis of the product, which was so fine-grained that accurate optical measurements were impossible. Consequently, the properties of kupfferite can only be inferred by extrapolation. As stated in the discussion of the anthophyllite series the writer can see no justification for disregarding crystallographic differences and combining the anthophyllite and cummingtonite series, even though it may be true that they are very nearly the same in their refractive indices. These two series seem to furnish a good example of isodimorphism; an example in which the magnesian member is more stable in the orthorhombic phase, while the ferrous iron member is more stable in the monoclinic phase. The relations between composition and properties are shown in Fig. 3.

It is worthy of note that 10.95 per cent MnO found in the mineral from Dannemora, Sweden (No. 10) makes no appreciable differences in the physical characters, as shown by the graph. On the other hand, about 5 per cent CaO (which means about 40 per cent of the actinolite molecule), found in cummingtonite from Mansjö Mt. by H. von Eckerman (*Geol. För. Förh.*, XLIV, 1922, p. 303) and in cummingtonite from Brunsjögruvan by N. Sundius (*op. cit.*, p. 154) decreases the indices of refraction nearly .01, and apparently decreases the optic angle measured about X considerably.

4. THE TREMOLITE-ACTINOLITE SERIES

The writer has given elsewhere¹² the evidence available in 1924 which tends to show that Mg and Fe may be replaced by Ca in monoclinic amphiboles in any amount from 0 to 50 molecular per cent. However, although such a possibility seems to exist, it is

¹¹ *Am. Jour. Sci.*, CLXXII, 1906, pp. 403, 431.

¹² *Am. Jour. Sci.*, CCVIII, 1924, p. 287.

clear that the usual condition is that Ca is either absent (or negligible) or present in about the ratio of 2 to 5, with the important exception that this ratio is commonly changed to about 2 to 4 in hornblende by the replacement of one atom of Mg by one atom of Al (with simultaneous replacement of one atom of Si by one atom of Al).

Accordingly, there is a fairly definite tremolite molecule the formula of which is $H_2Ca_2Mg_5Si_8O_{24}$, as shown by Warren.¹³ Since the magnesium may be replaced in any proportion by ferrous iron there is a definite and continuous series from tremolite, to actinolite, $H_2Ca_2Fe_5Si_8O_{24}$. Analyses indicate that minerals of this series usually contain a moderate tenor (20–30 mol. per cent) of other amphibole molecules, including $H_2NaCa_2Mg_5AlSi_7O_{24}$ and the molecules of the cummingtonite series, but a higher tenor is rare. On account of these other molecules, the diagram (Fig. 4) expressing the relations between composition and properties in the tremolite-actinolite series shows a range of possible variation in the properties for any given molecular percentage of the chief molecules. The accessory molecules seem to be especially important in determining the extinction angle ($Z \wedge c$). Johansson¹⁴ reports measuring the extinction angle in "grammatite" (=tremolite No. 6) in the acute angle β ; this is plotted with the other results on the assumption that it is a misstatement.

About 15 molecular per cent of the glaucophane molecule lowers the indices of refraction about 0.005, as shown in sample No. 18.

The reasons for including Shannon's "ferroanthophyllite" as actinolite (No. 19) have been given in the discussion of the anthophyllite series.

¹³ *Zeit. Kryst.*, **LXXII**, 1929, p. 42.

¹⁴ *Zeit. Kryst.*, **LXXIII**, 1930, p. 31.

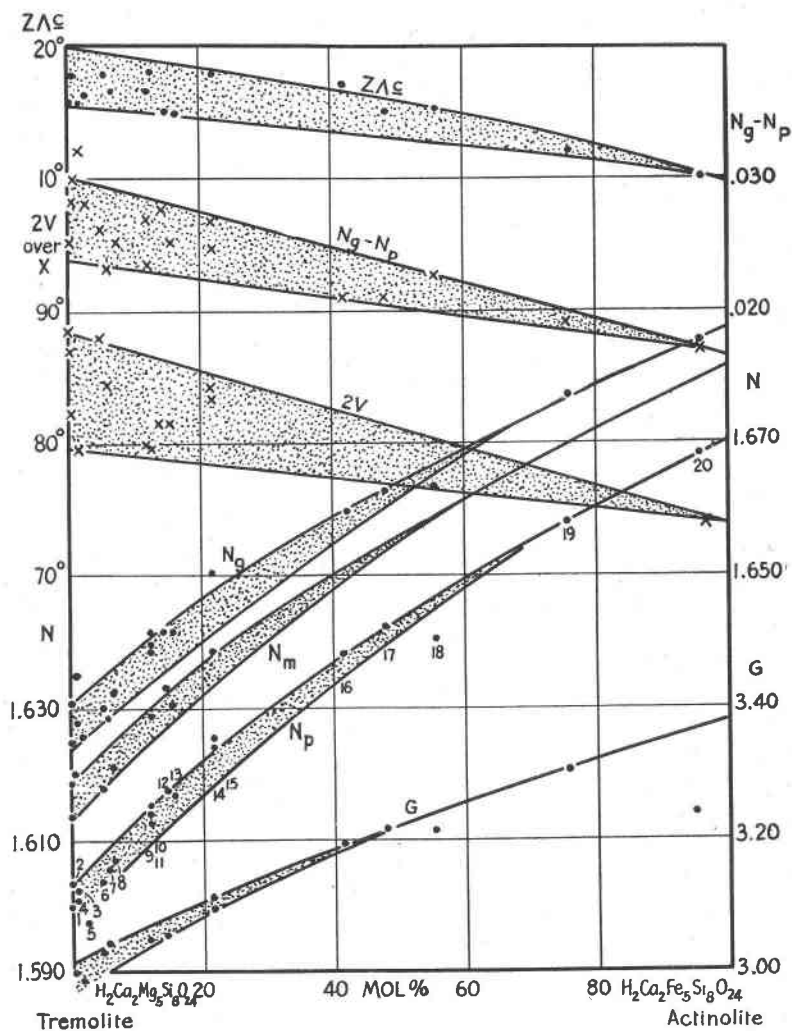


FIG. 4. Variations of composition and properties in the tremolite-actinolite series.

REFERENCES FOR FIG. 4—TREMOLITE-ACTINOLITE SERIES

1. Tremolite, Richville, N. Y. Optic data given by W. E. Ford: *Am. Jour. Sci.*, **CLXXXVII**, 1914, p. 179; analysis given by S. L. Penfield and F. C. Stanley: *Am. Jour. Sci.*, **CLXXXIII**, 1907, p. 31. Optic data also given by S. Kreutz: *Sitzb. Akad. Wiss. Wien.*, **CXVII**, 1908, p. 928.
2. Tremolite, Ossining, N. Y. Analysis given by E. T. Allen and J. K. Clement: *Am. Jour. Sci.*, **CLXXVI**, 1908, p. 101. On fragments of the original material kindly supplied by Dr. H. E. Merwin of the Geophysical Laboratory, Virgil E. Barnes has

obtained by the double variation method of Emmons the following indices: $N_o = 1.6307$ D, $N_m = 1.6183$, $N_p = 1.6024$; $N_o - N_p = 0.0273$, $(-)\angle V = 83^\circ$ calc.; $F - C = 0.009$ (N_m); also $Z \wedge c = 15\frac{1}{2}^\circ$, $2V = 82^\circ$ obs.

3. Tremolite, Lee, Mass. Analysis by Penfield and Stanley: *op. cit.* Optic data by W. E. Ford: *op. cit.*

4. Tremolite, Switzerland. S. Kreutz: *Sitz. Akad. Wiss. Wien.* **CXVII**, 1908, p. 925.

5. "Nephrite," Bahia, Brazil. Optic data by H. E. Merwin and analysis by H. S. Washington: *Pan-Amer. Geol.*, **XXXVII**, 1922, p. 198.

6. "Grammatite," Kaveltorp. Sweden. K. Johansson: *Zeit. Kryst.*, **LXXIII**, 1930, p. 31.

7. Tremolite, Edwards, N. Y. W. Kunitz: *N. Jahrb. Min.*, Bl. Bd., **LX**, 1930, p. 171. A very similar analysis of tremolite from Edwards, N. Y., given by E. T. Allen and J. K. Clement: *op. cit.*

8. Actinolite, Pierrepont, N. Y. S. Kreutz: *op. cit.* (Analysis by Haefcke). Virgil E. Barnes has obtained on actinolite from Pierrepont, N. Y. the following data: $N_o = 1.6301$ D, $N_m = 1.6201$, $N_p = 1.6067$; $N_o - N_p = 0.0237$; $2V = 82^\circ$ calc., 82° obs. $Z \wedge c = 18^\circ$.

9. Actinolite, Greiner, Switz. S. Kreutz: *op. cit.*

10. Actinolite, Japan. *Jour. Pet. Mineral. Ore Dep.*, **I**, 1929, p. 73. From an abstract.

11. Actinolite, Arendal. W. Kunitz: *op. cit.*

12. Actinolite, Greiner, Tyrol. Analysis by Penfield and Stanley: *op. cit.* Optic data by W. E. Ford: *op. cit.*

13. Actinolite, Russell, N. Y. Analysis by Penfield and Stanley: *op. cit.* Optic data by W. E. Ford: *op. cit.*

14. Actinolite, Pierrepont, N. Y. Analysis by Penfield and Stanley: *op. cit.* Optic data by W. E. Ford: *op. cit.* Birefringence given by Ford ($N_o - N_p = 0.0236$) does not check values of $N_o - N_p$; probably should be 0.0266.

15. Actinolite ("black hornblende"), Snarum. S. Kreutz: *op. cit.*

16. Actinolite, New Hampshire. W. Kunitz: *op. cit.*

17. Actinolite, Rhode Island. W. Kunitz: *op. cit.*

18. Actinolite ("Winchite"), Piz Valesa. W. Kunitz: *op. cit.*

19. Actinolite, Nordmark. W. Kunitz: *op. cit.*

20. "Ferroanthophyllite," Idaho. E. V. Shannon: *Proc. U. S. Nat. Mus.*, **LIX**, 1921, p. 397.

The only known modern data combining analyses with optic measures omitted from the diagram are the following:

"Hornblende" (= Tremolite), Russell, N. Y. S. Kreutz: *op. cit.* Calculations into amphibole molecules not satisfactory.

Actinolite, Kupferberg. W. Kunitz: *op. cit.* The published weight analysis does not check the published molecular analysis as to iron.

Actinolite, Kragerö, Norway. Analysis by Penfield and Stanley: *op. cit.* Optic data by W. E. Ford: *op. cit.* Indices are high (because of TiO_2 ?).

Actinolite, Kragerö, Norway. Analysis by H. S. Washington and optic data by H. E. Merwin: *Am. Mineral.*, **VIII**, 1923, p. 66. Indices are high (because of TiO_2 ?).

Actinolite, Berkeley, Calif. W. C. Blasdale: *Bull. Dept. Geol. Univ. Calif.*, II, 1902, p. 327. No determination of Fe_2O_3 , MnO nor TiO_2 .

"Hornblende" (= Actinolite), Hebrides. L. Duparc and F. Pearce: *Bull. Soc. Fr. Min.*, XXXI, 1908, p. 109. Calculations into amphibole molecules not satisfactory.

5. THE $\text{H}_2\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{24} - \text{H}_2\text{NaCa}_2\text{Mg}_5\text{AlSi}_7\text{O}_{24}$ SERIES

Several of the samples studied optically by V. E. Barnes¹⁵ have been analyzed recently by R. B. Ellestad of the Rockefeller Laboratories with results as follows:

	1	2	3	4	5	6
SiO_2	56.87	46.46	46.22	46.03	54.54	47.16
Al_2O_3	1.26	13.70	4.13	12.03	1.40	6.19
Fe_2O_3	0.11	0.38	0.36	1.18	5.03	5.64
FeO	2.26	0.99	0.85	2.22	8.17	11.64
MgO	22.47	20.48	20.27	20.16	16.40	12.75
CaO	14.09	12.57	12.73	12.84	8.33	9.53
Na_2O	0.75	2.84	2.75	2.66	2.93	3.05
K_2O	0.15	0.57	0.58	0.80	0.66	1.41
H_2O	1.53	1.35	1.36	0.99	1.65	1.16
F	0.21	0.26	0.33	0.25	0.16	0.20
TiO_2	0.13	0.04	0.05	0.48	0.31	0.37
MnO	0.13	0.05	0.06	0.05	0.32	0.38
Total	99.76	99.69	99.69	99.69	99.90	99.48
$\text{O}=\text{F}_2$	0.09	0.11	0.14	0.11	0.07	0.08
Sum	99.87	99.58	99.55	99.58	99.83	99.40

1. "Edenite," Edenville, N.Y.
2. "Pargasite," Edenville, N.Y.
3. "Pargasite," Amity, N.Y.
4. "Pargasite," Warwick, N.Y.
5. "Hornblende," Ottawa, Canada.
6. "Hornblende," Eganville, Ont.

A study of these analyses revealed that one of them (the pargasite from Amity, N. Y.) represents a chemically rare type of amphibole which consists very largely of one molecule; indeed, it contains about 80 molecular per cent of $\text{H}_2\text{NaCa}_2\text{Mg}_5\text{AlSi}_7\text{O}_{24}$ with about 14 per cent of $\text{H}_2\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{24}$. It may therefore serve to establish approximately the optical characters of a molecule which is not ordinarily present in hornblende, but is a possibility in every case. The discovery of other samples of amphibole representing ap-

¹⁵ *Am. Mineral.*, XV, 1930, p. 393.

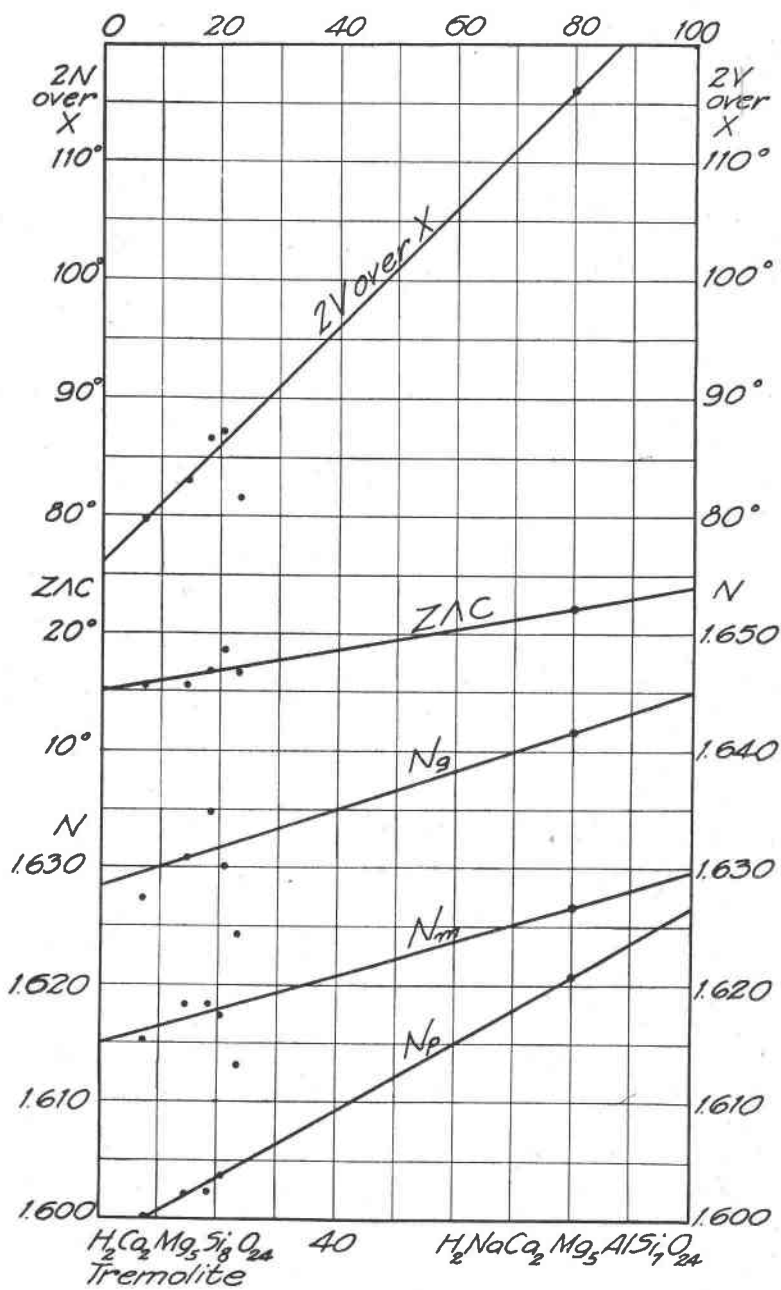


FIG. 5. Variations of composition and properties in the tremolite, $\text{H}_2\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{24}$ – $\text{H}_2\text{NaCa}_2\text{Mg}_5\text{AlSi}_7\text{O}_{24}$ series.

proximately pure molecules may be expected to gradually disclose the full relations between the composition and the optical properties in this extremely complex system. The relations between properties and composition in the tremolite — $\text{H}_2\text{NaCa}_2\text{Mg}_5\text{AlSi}_7\text{O}_{24}$ series are shown in Fig. 5. It is clear that the substitution of Al, Na for Si has a very marked effect upon the optic properties. It raises the indices of refraction, and increases the extinction angle, but the most remarkable effect is on the optic angle which is changed from about 75° to more than 120° about X , thus changing the optic sign. It is clear from a study of the optic properties of amphiboles moderately rich in the molecule $\text{H}_2\text{NaCa}_2\text{Mg}_4\text{Al}_3\text{Si}_6\text{O}_{24}$ that this molecule produces similar effects. It seems that the substitution of Al, Na for Si produces much more effect on the optic properties than does the substitution of Al, Al for Mg, Si.

6. THE COMMON HORNBLENDE SYSTEM

In an earlier study¹⁶ of the amphibole group it was shown that the ratio between Ca and $\text{Mg} + \text{Fe}$ is not the same in the hornblende as in the tremolite-actinolite system. This difference seems to be due to the replacement of some Mg atoms by Al atoms, the total valencies remaining balanced by means of the simultaneous replacement of Si atoms by Al atoms. Expressed in groups containing oxygen, MgSiO_3 may be replaced by AlAlO_3 in hornblende just as in pyroxene, biotite and chlorite. This relationship between tremolite and hornblende is not easily derived from analyses because there seems to be no simple gradation from the tremolite molecule, $\text{H}_2\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{24}$, to a corresponding hornblende molecule, $\text{H}_2\text{Ca}_2\text{Mg}_4\text{Al}_2\text{Si}_7\text{O}_{24}$, representing only the replacement of MgSiO_3 by AlAlO_3 ; on the contrary, a different type of replacement, first discovered and explained by Warren,¹⁷ seems to accompany the replacement of MgSiO_3 by AlAlO_3 in hornblende with surprising frequency; this is the replacement of Si by $(\text{Na})\text{Al}$, the extra Na atom taking a place in the space lattice which is otherwise unoccupied. Thus it comes about that the gradation from tremolite to magnesian hornblende is not from $\text{H}_2\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{24}$ to $\text{H}_2\text{Ca}_2\text{Mg}_4\text{Al}_2\text{Si}_7\text{O}_{24}$, but from $\text{H}_2\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{24}$ to $\text{H}_2\text{NaCa}_2\text{Mg}_4\text{Al}_3\text{Si}_6\text{O}_{24}$. A sample of hornblende from Montville, N. J., analyzed by L. G. Eakins¹⁸ is composed of this molecule to the extent of

¹⁶ *Am. Jour. Sci.*, CCVII, 1924, p. 287.

¹⁷ *Op. cit.*

¹⁸ *U. S. Geol. Surv. Bull.* 64, 1890, p. 40.

83 per cent and has also 10 per cent of $\text{H}_2\text{Ca}_2\text{Mg}_4\text{Al}_2\text{Si}_7\text{O}_{24}$. Many analyses of common hornblende show the presence of 60 to 70 per cent of $\text{H}_2\text{NaCa}_2(\text{Mg}, \text{Fe})_4\text{Al}_3\text{Si}_6\text{O}_{24}$, so that this (double) molecule may be considered the dominant component of the chief amphibole. (It should be understood that F is considered equivalent to OH, K to Na, Mn to Fe'' and Fe''' to Al.)

Using the tremolite-actinolite series as one coordinate and the gradation from $\text{H}_2\text{Ca}_2(\text{Mg}, \text{Fe})_5\text{Si}_8\text{O}_{24}$ to $\text{H}_2\text{NaCa}_2(\text{Mg}, \text{Fe})_4\text{Al}_3\text{Si}_6\text{O}_{24}$ as the other coordinate, a diagram can be constructed which shows the chief variations in composition in common hornblende, as illustrated in Fig. 6. It should be clearly understood that this diagram does not show all the variations in composition in common hornblende; in spite of this fact it is possible to show approximately the relation between variations in composition and variations in refringence, as is done by the diagonal lines of the diagram. Unfortunately the writer has not been able to show graphically the relations between other optic properties and the composition. It is possible at present only to make certain general statements regarding these relationships.

1. The optic angle ($2V$) decreases rapidly with increase of the riebeckite molecule, $\text{H}_2\text{Na}_2\text{Fe}_3'''\text{Fe}_2'''\text{Si}_8\text{O}_{24}$; it seems to increase rapidly with increase in the pargasite molecule which is probably $\text{NaCa}_2(\text{Mg}, \text{Fe})_4\text{Al}_3\text{Si}_6\text{O}_{22}\text{F}_2$; according to the data secured by Barnes,¹⁹ the optic angle ($2V$) changes to about 65° no matter what its former value may have been when oxidation changes common hornblende to "basaltic hornblende," whose chief molecule seems to be $\text{NaCa}_2(\text{Mg}, \text{Fe})_3\text{Fe}'''\text{Al}_3\text{Si}_6\text{O}_{24}$.

2. The extinction angle ($Z \wedge c$) increases rapidly with increase in the riebeckite molecule, $\text{H}_2\text{Na}_2\text{Fe}_3\text{Fe}_2\text{Si}_8\text{O}_{24}$; it decreases rapidly to about 0° with increase of the "basaltic hornblende" molecule.

3. The dispersion ($F-C$) increases with increase of the "basaltic hornblende" molecule and probably also with increase of the riebeckite molecule.

4. The refringence increases markedly with increase in the "basaltic hornblende" molecule; it increases much more slowly in most types of common hornblende with increase of the riebeckite molecule; it decreases with increase in the pargasite molecule.

¹⁹ *Am. Mineral.*, **XV**, 1930, p. 393.

5. The birefringence increases considerably with increase in the "basaltic hornblende" molecule; it decreases with increase in the riebeckite molecule.

The diagram (Fig. 6) shows that common hornblende averages about 70 molecular per cent of the aluminous (double) molecule, $\text{H}_2\text{NaCa}_2(\text{Mg,Fe})_4\text{Al}_3\text{Si}_6\text{O}_{24}$, and about 40 molecular per cent of the ferrous iron molecules. It also shows that there is a continuous gradation from the tremolite-actinolite series to the most highly aluminous hornblendes and also a continuous gradation from iron-free magnesian hornblende to magnesium-free ferrous iron hornblende.

In plotting analyses on the diagram (Fig. 6) only two ratios are used. The vertical coordinate gives the ratio between aluminous molecules [dominantly $\text{H}_2\text{NaCa}_2(\text{Mg,Fe})_4\text{Al}_3\text{Si}_6\text{O}_{24}$, but also including $\text{H}_2\text{Ca}_2(\text{Mg,Fe})_4\text{Al}_2\text{Si}_7\text{O}_{24}$] and non-aluminous molecules. The horizontal coordinate expresses the ratio between magnesian molecules and iron molecules, all the iron being included, as well as manganese. The ferric iron, for the purpose of obtaining this ratio, is converted to its equivalent as ferrous iron; this is done because: (1) some analyses are not very accurate in the separation of ferrous and ferric iron, (2) it is now known that the state of oxidation of the iron can be changed in hornblende without destroying the crystal, and (3) it is impractical to try to represent both ferrous and ferric iron molecules separately in a diagram for hornblende.

No attempt has been made to plot all known analyses on the diagram; those have been selected which show that all parts of the diagram correspond with known samples of hornblende (including gradations to the tremolite-actinolite series). Some samples of hornblende include important amounts of molecules not used in the diagram; they are not shown and usually do not fit the diagram well.

The writer regrets that he is not yet able to present diagrams using the correct formulas for alkaline amphiboles nor for basaltic hornblende. He would urge that results given above should be considered as approximations only.

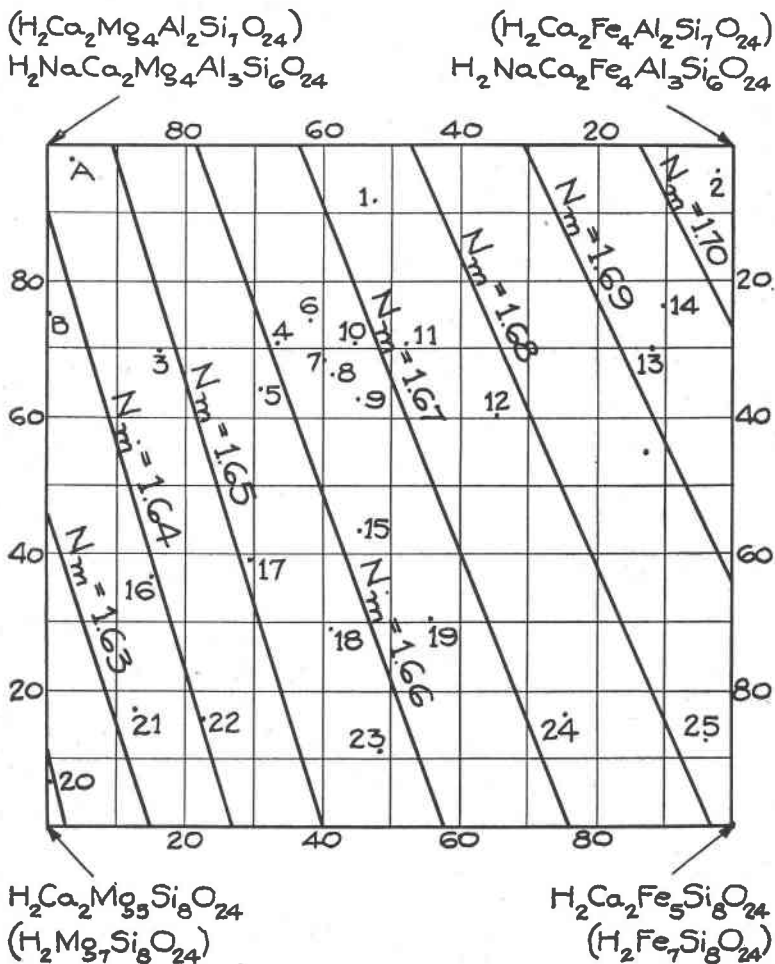


FIG. 6. Variations of composition and refringence in the common hornblende system.

REFERENCES FOR FIG. 6. HORNBLLENDE SYSTEM

- A. Hornblende, Montville, N. J. Analysis by L. G. Eakins: *U. S. Geol. Surv., Bull.* **64**, 1890, p. 40. No optic data.
- B. Hornblende, Ceylon. Analysis by A. K. Coomaraswamy: *Q. Jour. Geol. Soc.*, **LVIII**, 1902, p. 399. No optic data.
1. Hornblende, Monte Somma, Italy. Analysis by F. C. Stanley: *Am. Jour. Sci.*, **CLXXIII**, 1907, p. 41. Optic data by W. E. Ford: *Am. Jour. Sci.*, **CLXXXVII**, 1914, p. 179. $N_m = 1.68$.
2. Amphibole, Babbitt, Minn. S. Richarz: *Am. Mineral.*, **XV**, 1930, p. 65. About 50% $\text{H}_2\text{NaCa}_2\text{Fe}_4\text{Al}_3\text{Si}_6\text{O}_{24}$ and 46% $\text{H}_2\text{Ca}_2\text{Fe}_4\text{Al}_2\text{Si}_7\text{O}_{24}$; the latter lowers

the index (N_m) about .02 as compared with the diagram. Richarz gives: $N_m = 1.690$.

3. "Karinthine," Alps. S. Kreutz: *Sitz. Akad. Wiss. Wien.*, **CXVII**, 1908, p. 875. Analysis by Rammelsberg; optic data by Kreutz. $N_m = 1.643$.

4. Hornblende, Baranaschka Kudnik. W. Kunitz: *N. Jahrb. Min., Bl. Bd.* **LX**, A, 1930, p. 171. $N_g = 1.671$, $N_m = ?$, $N_p = 1.652$.

5. Hornblende, Lanark Co., Ont. V. E. Barnes: *Am. Mineral.*, **XV**, 1930, p. 393. Analysis by R. B. Ellestad; optic data by Barnes. $N_m = 1.6589$.

6. Hornblende, Senftenberg, Austria. A. Marchet: *Tsch. Min. Pet. Mit.*, **XXXVIII**, 1925, p. 494. Analysis by J. Morozewicz; optic data by Marchet. $N_m = 1.663$.

7. Hornblende, Beerberg. W. Kunitz: *op. cit.* $N_g = 1.678$, $N_m = ?$, $N_p = 1.658$.

8. Hornblende, Plauen. W. Kunitz: *op. cit.* $N_g = 1.678$, $N_m = ?$, $N_p = 1.658$.

9. Hornblende, Edenville, N. Y. Analysis by F. C. Stanley: *op. cit.* Optic data by W. E. Ford: *op. cit.* $N_m = 1.6701$.

10. Hornblende, Arendal. W. Kunitz: *op. cit.* $N_g = 1.677$, $N_m = ?$, $N_p = 1.658$.

11. Hornblende, Pulang, N. Celebes. W. Kunitz: *op. cit.* $N_g = 1.681$, $N_m = ?$, $N_p = 1.661$.

12. Hornblende, Renfrew Co., Ont. V. E. Barnes: *op. cit.* Analysis by L. C. Hurd. Optic data by Barnes. $N_m = 1.6980$.

13. Amphibole, Mt. Monadnock, Vt. J. E. Wolff: *Jour. Geol.*, **XXXVII**, 1929, p. 1. $N_m = 1.71$.

14. "Hudsonite," Cornwall, N. Y. Analysis by J. L. Nelson: *Am. Jour. Sci.*, **CLXV**, 1903, p. 227. Optic data by W. E. Ford: *op. cit.* $N_m = 1.71$.

15. Hornblende, Signal Peak, Calif. A. Pabst: *Univ. Calif. Publ. Geol.*, **XVII**, 1928, p. 363. N_1 on cleavage = 1.674, N_2 on cleav. = 1.661.

16. Hornblende, Radautal. W. Kunitz: *op. cit.* $N_g = 1.654$, $N_m = ?$, $N_p = 1.633$.

17. Hornblende, San Felix. W. Kunitz: *op. cit.* $N_g = 1.661$, $N_m = ?$, $N_p = 1.641$.

18. Actinolite, New Hampshire. W. Kunitz: *op. cit.* $N_g = 1.659$, $N_m = ?$, $N_p = 1.638$.

19. Actinolite, Piz Valeza. W. Kunitz: *op. cit.* $N_g = 1.663$, $N_m = ?$, $N_p = 1.640$.

20. Tremolite, Ossining, N. Y. Analysis by E. T. Allen and J. K. Clement: *Am. Jour. Sci.*, **CLXXVI**, 1908, p. 101. Optic data by V. E. Barnes: *op. cit.* $N_m = 1.6183$.

21. Actinolite, Greiner, Switzerland. S. Kreutz: *op. cit.* $N_m = 1.6297$.

22. Actinolite, Pierrepont, N. Y. Analysis by F. C. Stanley: *op. cit.* Optic data by W. E. Ford: *op. cit.* $N_m = 1.6382$.

23. Actinolite, Rhode Island. W. Kunitz: *op. cit.* $N_g = 1.663$, $N_m = ?$, $N_p = 1.642$.

24. Actinolite, Nordmark. W. Kunitz: *op. cit.* $N_g = 1.677$, $N_m = ?$, $N_p = 1.658$.

25. Amphibole, Idaho. E. V. Shannon: *Proc. U. S. Nat. Mus.*, **LIX**, 1921, p. 397. $N_g = 1.685$, $N_m = ?$, $N_p = 1.668$.

POSTSCRIPT. The preceding discussion of the amphiboles was presented to the Mineralogical Society of America at Toronto, Ont., on December 30, 1930. Since that time other studies of the amphiboles have been published, notably:

H. Berman and E. S. Larsen: Composition of the Alkali Amphiboles. *Am. Mineral.*, **XVI**, 1931, p. 140.

H. V. Warren: An Occurrence of Grunerite at Pierrefitte, Hautes-Pyrénées, France, *Mineral. Mag.*, **XXII**, 1931, p. 477.

N. Sundius: The Optical Properties of Manganese-poor Grunerites, etc., *Am. Jour. Sci.*, **XXI**, 1931, p. 330.

The article by Berman and Larsen deals with the alkali amphiboles, whereas the writer's discussion is confined almost wholly to the non-alkali amphiboles.

The article of Warren gives the composition and optic properties of a grunerite²⁰ containing 2.23 MnO, 3.12 MgO, 1.51 CaO, 0.70 Na₂O and 0.43 K₂O. The lime and alkalis decrease the birefringence and also the refringence (except for N_p) as compared with the writer's Fig. 3.

The article of Sundius presents an attempt to obtain greater precision regarding the relations between variations in composition and in optical properties. Sundius has succeeded in showing graphically the influence of manganese, of iron and of magnesium on the optic properties of part of the ternary system. He concludes that the pure magnesian end-member would have the optic plane normal to (010). This conclusion is based solely upon the idea that the indices of refraction (especially N_m and N_p) vary along straight lines; such a rectilinear variation for N_p is not demonstrated by the data and seems improbable to the writer.

²⁰ Warren states that the name of the iron amphibole is properly grunerite, not grünerite.