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THE FeSiO_3 - CaSiO_3 - MgSiO_3 - $\text{NaFeSi}_2\text{O}_6$ SYSTEM OF MONOCLINIC AMPHIBOLES

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Since the preparation of the article on the amphibole group,¹ further data have become available so that it is now possible to present a more complete account of the non-aluminous monoclinic amphiboles. The largest part of the new data was contributed by Sundius² in his valuable study of the grunerite-cummingtonite-kupfferite series. Additional optic data on rare minerals composed largely of MgSiO_3 and $\text{NaFeSi}_2\text{O}_6$ are given in the course of this article.

The diagram of the MgSiO_3 - FeSiO_3 series published by Sundius suggests³ that magnesia-rich anthophyllite is part of the same (discontinuous) series with cummingtonite and grunerite. This view seems improbable, since artificial MgSiO_3 is known in a monoclinic form, and the orthorhombic series beginning with MgSiO_3 is continuous, at least to types in which Fe is dominant and probably to pure FeSiO_3 . Furthermore, the optic properties of the artificial monoclinic MgSiO_3 correspond well with those of the rest of the series, as shown in Fig. 1.

The data on optic axial angle in the cummingtonite series require an S-shaped curve, which will perhaps be considered improbable; since the measures are on crystals which contain from 0 (artificial MgSiO_3) to 30 (Mansjö cummingtonite) molecular per cent of other molecules it is not certain that the double curve is correct, but the measures make a smooth curve much more nearly than the data on extinction angle. Of course, a double curve is not impossible as shown by the condition found in the plagioclase series.

The MgSiO_3 - FeSiO_3 series lies along the longest horizontal line

¹ *Am. Jour. Sci.*, CCVII, 1924, p. 287.

² *Geol. För. Förh. Stockholm*, XLVI, 1924, p. 154.

³ In a personal communication Dr. Sundius points out that his diagram (p. 164) shows that the index of refraction lines have a steeper slope for the orthorhombic than for the monoclinic series and states that he is "convinced that the optical properties of the two series are quite unlike."

of Fig. 2; the grunerite-riebeckite series⁴ lies along the right hand side above the $\text{MgSiO}_3\text{-FeSiO}_3$ series; the tremolite-actinolite⁵ series lies along a short line about half way below the ferromagnesian series. Pure $\text{CaMgSi}_2\text{O}_6$, like pure MgSiO_3 (as monoclinic amphibole) is unknown in nature, but was probably formed arti-

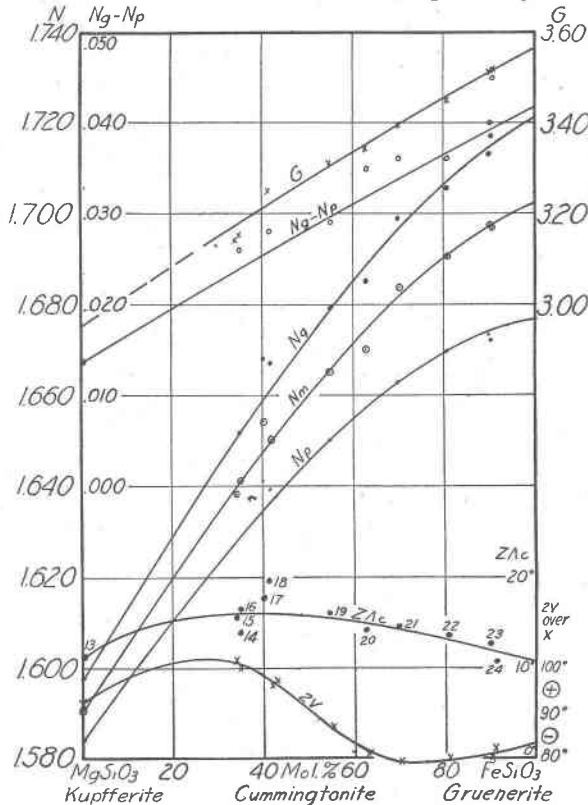


Fig. 1. Relations between optic properties and composition in the $\text{MgSiO}_3\text{-FeSiO}_3$ series of monoclinic amphiboles.

ficially by Bowen.⁵ Monoclinic amphiboles approaching $\text{CaFeSi}_2\text{O}_6$ in composition are unknown and probably unstable; the same is true of monoclinic amphiboles approaching CaSiO_3 and $\text{NaFeSi}_2\text{O}_6$ in composition; $\text{CaFeSi}_2\text{O}_6$ is included in the figure merely for convenience.

⁴ This series was shown in terms of weight per cent in Fig. 4 of the amphibole article. (*Am. Jour. Sci.*, CCVII, 1924, p. 307.)

⁵ See *Am. Jour. Sci.*, CCVII, 1924, p. 301.

⁶ *Am. Jour. Sci.*, CLXXXVIII, 1914, p. 207.

The optic properties change very rapidly in the upper part of Fig. 2, as illustrated previously in the case of the grunerite-riebeckite series. It is worthy of note that the unusual optic orientation, which seems to the writer to be common to all compositions in the upper part of the figure, has in many cases required special and repeated study for its determination. This orientation in monoclinic amphiboles seems to be caused by $\text{NaFeSi}_2\text{O}_6$; it is

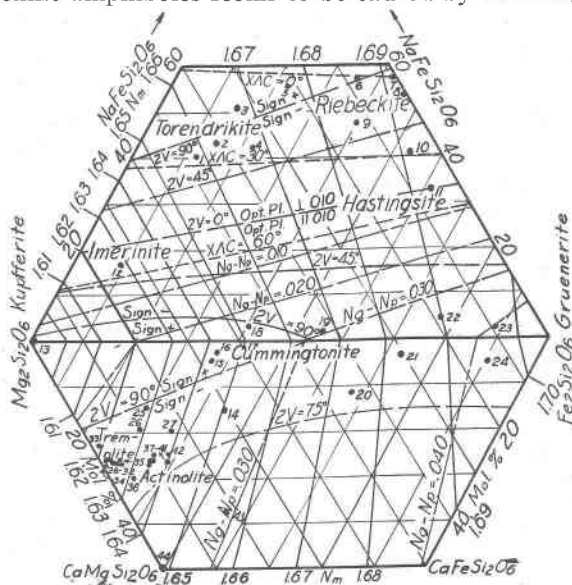


Fig. 2. Relations between optic properties and composition in the $\text{FeSiO}_3\text{-CaSiO}_3\text{-MgSiO}_3\text{-NaFeSi}_2\text{O}_6$ system of monoclinic amphiboles

found in all such minerals containing an important tenor of this molecule, and in no others. The same molecule causes very marked absorption and pleochroism in blue, green and yellow, and also very strong dispersion, resulting in incomplete extinction in white light and abnormal interference colors. Such minerals are probably stable only under a very limited range of conditions; they are rare and confined (except for riebeckite) to contact zones. In them small changes of composition cause such large changes in optic properties that the data seem somewhat discordant. This condition is believed to be due to the fact that in a single small occurrence, only the average composition of which can be obtained, the optic properties vary very considerably; and these variations

are doubtless due to variations in composition. At the same time the diagram expresses the main facts correctly; the mean index of refraction is correct within $\pm .01$ in all cases; the birefringence is correct within $\pm .005$ in nearly all cases; the position of the optic plane is believed to be correct in all cases; but the extinction angle and optic axial angle are only approximately correct for imerinite (No. 12) and crossite (No. 4).

The lower part of the figure includes richterite, tremolite and actinolite, as well as the artificial $\text{CaMgSi}_2\text{O}_6$; the last substance is the only one in the diagram whose optic sign is not correctly given by the diagram. No reason for the anomaly is known. In this part of the system the optic properties do not vary so rapidly, and they are indicated with reasonable accuracy by the diagram, though the optic angle of richterite is smaller than given by the drawing.

In both figures molecular percentages are used; the small amounts of MnO found in some analyses have been calculated as equivalent to FeO; $\text{NaFeSi}_2\text{O}_6$ is computed, if possible, after forming the MgSiO_3 , FeSiO_3 , and CaSiO_3 molecules. Those analyses which show the presence of both CaSiO_3 and $\text{NaFeSi}_2\text{O}_6$ are plotted in the (partial) triangle above the MgSiO_3 - FeSiO_3 line if $\text{NaFeSi}_2\text{O}_6$ is in excess⁷ of CaSiO_3 and in the (partial) triangle below that line in the reverse case. All other molecules are omitted from consideration in plotting these analyses; the molecular percentages thus neglected are given after the references in each case.

Arfvedsonite and cossyrite are composed largely of FeSiO_3 , NaSiO_2OH , and $\text{NaFeSi}_2\text{O}_6$; by adding another (partial) triangle at the right of the upper part of Fig. 2 they could be included in the diagram. However, the number of analyses is very small, and optic data are almost entirely lacking; the only measures of indices of refraction ever made on supposed arfvedsonite were actually made on barkevikite, according to Hintze.⁸ Therefore, these minerals have been omitted; it may be noted that, as compared

⁷ Of course, in calculating molecular percentages, molecules of comparable size are considered, so that $\text{NaFeSi}_2\text{O}_6$ is compared with $\text{Ca}_2\text{Si}_2\text{O}_6$, etc. Also CaSiO_3 is probably present in these amphiboles, not as an independent variable, but as part of $\text{CaFeSi}_2\text{O}_6$ or $\text{CaMgSi}_2\text{O}_6$. Recent analyses by Walker (*Univ. Toronto Stud. Geol. Ser.*, 17, 1924, p. 58) of "hastingsite" and by Shannon (*Am. Jour. Sci.*, CCVIII, 1924, p. 323) of "HUDSONITE" include too much CaO to belong to the system here studied, though closely related to it.

⁸ HDB, MINERAL. II., 1897, p. 1254.

with grunerite, arfvedsonite shows that NaSiO_2OH causes a rapid change in the extinction angle, but has little effect on the optic angle; the tenor of $\text{NaFeSi}_2\text{O}_6$ is small and not sufficient to produce much effect on the optic angle in arfvedsonite.

REFERENCES AND DATA FOR FIGS. 1 AND 2; NOS. 13 TO 24 ON FIG. 1; ALL THE NUMBERS ON FIG. 2.

1. Torendrikite, Ambahy, Madagascar. A. Lacroix: *Comp. Rend.*, **CLXXXI**, 1920, p. 594. In addition to the constituents shown in the diagram it contains also 7.7 molecular percent CaSiO_3 , 3.1 KAlSi_2O_6 , 2.1 AlAlO_3 , 0.5 H_2SiO_3 . $2V$ = very large, $Z \wedge c = 40^\circ \pm$, $Y = b$, $X = \text{sea blue}$, $Y = \text{violet}$, $Z = \text{straw yellow}$. (The writer would exchange Y and Z in this description.)
2. Torendrikite, Ambatofinendrahana, Madagascar. A. Lacroix: *loc. cit.* Contains also 7.6 CaSiO_3 , 4.4 KAlSi_2O_6 , 3.1 H_2SiO_3 . $2V$ = very large, $Y = b$, $Z \wedge c = 40^\circ \pm$, strong dispersion. A sample of the analyzed material, very kindly supplied by Professor Lacroix, was tested by the writer with the following results. The index is $1.665 \pm .005$; cleavage fragments in oil show vertical elongation distinctly; on the cleavage face the elongation is negative, but after careful search a fragment with positive elongation was found. A fragment with parallel extinction, and therefore parallel to 100, is not normal to an optic axis, but is normal to a plane of symmetry of the triaxial ellipsoid. The optic angle is large and dispersion is so great as to prevent complete extinction in fragments parallel to 010. It seems that the optic plane must be normal to 010 with $Z = b$ and $Y \wedge c$ rather large. The data published by Lacroix (*Mineral. Madagascar*, **III**, 1923, p. 295), namely, $N_g = 1.67$, $N_p = 1.65$, were found later.
3. Crocidolite, Golling, Salzburg. R. Doht and C. Hlawatsch: *Verh. geol. Reichsanst. Wien*, **1913**. Contains also 21.7 H_2SiO_3 , 2.4 AlAlO_3 . (Since quartz is reported as an impurity the per cent of H_2SiO_3 may be less.) $N_m < 1.692$, $N_g - N_p = .006$, $Z = b$, $X \wedge c = 8^\circ - 11^\circ$, $\rho < \nu$ strong, $X = \text{blue}$, $Y = \text{yellow}$, $Z = \text{violet}$.
4. Crossite, Coast Range, Calif. C. Palache: *Bull. Geol. Dept. U. Calif.*, **I**, 1894, p. 181. Contains also 19.8 $\text{NaAlSi}_2\text{O}_6$, 5.0 CaSiO_3 . $X \wedge c = 13^\circ$. Rosenbusch (*Mikr. Phys.*, **I**, 1, p. 246) proved that this is really $Y \wedge c = 13^\circ$ (to 30°) and $Z = b$. Larsen gives for crossite: $(-)$ $2V$ = rather large, $N_g = 1.663$, $N_m = 1.659$ (1.670), $N_p = 1.657$, $N_g - N_p = .006$, $Y \wedge c = 10^\circ$.
5. Crocidolite, Berks Co., Pa. E. T. Wherry and Earl Shannon: *Jour. Wash. Acad. Sci.*, **XII**, 1922, p. 242. Contains also 18.7 H_2SiO_3 , 1.9 FeFeO_3 , 1.6 TiTiO_3 , 1.0 AlAlO_3 . First described (*Am. Mus. Nat. Hist.*, **XXXII**, 1913, p. 517, as having $(-)$ $2V$ = large and $Z \wedge c = 3^\circ$ to 15° , but Wherry and Shannon give $X \wedge c = 3^\circ$ to 15° with $N_g = 1.66$, $N_m = 1.65$, $N_p = 1.64 - 1.65$, $N_g - N_p$ = variable but weak, dispersion strong.
6. Crocidolite, So. Africa. A. H. Chester and F. J. Cairns: *Am. Jour. Sci.*, **CXXXIV**, 1887, p. 116. Contains also 19.5 H_2SiO_3 , 3.9 FeFeO_3 , 1.5 CaSiO_3 . A. Johnsen (*Cent. Mineral.*, **1910**, p. 353) gives for crocidolite from So. Africa, but not for analyzed material: $(+)$ $2V > 56^\circ$, $X = b$, strong dispersion; this is not in harmony with other results.

7. Osannite; Cevadaes, Portugal. C. Hlawatsch: *Festsch.*, H. Rosenbusch, 1906, p. 74. Contains also 7.1 H₂SiO₃, 4.3 KAlSi₂O₆, 1.9 CaSiO₃. (-)2*V*=large, Ng-Np=.003-.004, *Z*=*b*, *X*∧*c*=0° red, 5° blue; *X*=blue, *Y*=yellow, *Z*=green.
8. Riebeckite, Quincy, Mass. C. Palache and C. H. Warren: *Am. Jour. Sci.*, **CLXXXI**, 1911, p. 547. Contains also 9.8 H₂SiO₃, 2.8 excess SiO₂, 3.3 NaAlSi₂O₆, 2.7 CaSiO₃, 0.9 TiTiO₃. (-) 2*V*=large, Nm=1.695, Ng-Np=weak. *Z*=*b*, *X*∧*c*=4±, *X*=blue to green, *Y*=yellow, *Z*=green to black.
9. Osannite, Alemtejo, Portugal. A. Osann and O. Umhauer: *Sitz. Akad. Wiss. Heidelberg*, A. 1914, Abh. 16. Contains also 5.7 H₂SiO₃, 4.5 CaSiO₃, 3.8 KSiO₂OH. (-)2*V*=large, Ng-Np=weak, *Z*=*b*, *X*∧*c*=3°-5°, extinction on 110=2.5°, *X*=blue, *Y*=yellow, *Z*=dark green.
10. Hastingsite, Hastings Co., Ont. F. D. Adams and B. J. Harrington: *Am. Jour. Sci.*, **CLI**, 1896, p. 210. Contains also 21.7 CaAlO₂(OH), 3.1 AlAlO₃, 2.3 FeFeO₃. Nm=1.69, Ng-Np=weak, (-) 2*V*=30°-45°, *ρ*>*ν* strong, *Z*∧*c*=25°-30° in obtuse angle β. But Graham (*Am. Jour. Sci.*, **CLXXVIII**, 1909, p. 540) has shown that the optic plane is normal to 010, at least in green, with 2*V*=very small.
11. Hastingsite, Almunge, Sweden. P. Quensel: *Bull. Geol. Inst. U. Upsala*, **XII**, 1913. Contains also 16.5 CaAlO₂(OH), 5.1 CaSiO₃, 4.9 AlAlO₃, 1.5 KSiO₂(OH). 2*V*=0°±, optic plane parallel and normal to 010, *Z* or *Y*∧*c*=35°-41°, *X*=yellowish green, *Y*=bluish green, *Z*=green.
12. Imerinite, Ambatoharina, Madagascar. A. Lacroix: *Mineral. France*, **IV**, 1910, p. 787. Contains also 16.3 NaSiO₂(OH) 5.7 (Na,K)AlO₂F₂, 5.1 CaSiO₃. (-)2*V*=small, *Z*∧*c* is near 45° with strong dispersion, zonal. A sample kindly supplied by Prof. Lacroix gives N=1.650±.005, Ng-Np=.020±.005, *X*∧*c*=23°±3° (red), 13°±3° (blue), but this has *X*=bluish green, *Y*=slate blue, *Z*=pale green, and therefore probably is not exactly of the same composition as the sample described by Lacroix, which has *X*=pale yellowish green, *Y*=violet blue, *Z*=pale bluish green. The data published by Lacroix (*Mineral. Madagascar III*, 1923, p.295), namely Ng=1.653, Np=1.638 were found later.
13. Artificial. F. E. Wright: *Am. Jour. Sci.*, **CLXXII**, 1906, p. 403, and A. N. Winchell, *Am. Jour. Sci.*, **CCVII**, 1924, p. 295. (+)2*V*=88°, Ng=1.597, Nm=1.590, Np=1.582, Ng-Np=.015, *X*∧*c*=79°.
14. Cummingtonite, Mansjö Mt., Sweden. H. v. Eckerman: *Geol. För. Förh. Stockholm*, **XLIX**, 1922, p. 303. Contains also 17.3 H₂SiO₃, 9.8 AlAlO₃, 4.3 NaFeSi₂O₆, 1.3 NaSiO₂(OH), 0.8 TiTiO₃. (-) 2*V*=79°58', Ng=1.6519, Nm=1.6410, Np=1.6259, Ng-Np=.026, *Z*∧*c*=13.8°.
15. Cummingtonite, Kongsberg, Norway. A. Des Cloizeaux: *Nouv. Rech. Mem.*, **XVIII**, 1867, Dana: *Syst. Mineral.* p. 390. Contains also 5.6 H₂SiO₃. Nm=1.638. (+) 2*V*=77°58', *ρ*<*ν*, *Z*∧*c*=15°-16°.
16. Cummingtonite, Greenland. A. Des Cloizeaux: *loc. cit.* Contains also 12.2 H₂SiO₃. (+)2*V*=77°±, *Z*∧*c*=16°-17°.
17. Cummingtonite, Orijarvi, Finland. P. Eskola: *Bull. Com. Geol. Finlande*. **XL**, 1915, p. 183. (Analysis incomplete.) Nm=1.642, Ng-Np=.026, (+) 2*V*>80°, *Z*∧*c*=20°.
18. Cummingtonite, Robergsgruvan, Sweden, N. Sundius: *Geol. För. Förh. Stockholm*, **XLVI**, 1924, p. 154. Contains also 2.0 CaSiO₃ (incomplete analysis). (+)2*V*=84°, Ng=1.667, Nm=1.650, Np=1.639, Ng-Np=.028, *X*∧*c*=70.5°.

19. Cummingtonite, O. Silvergruvan, Sweden. N. Sundius: *loc. cit.* Contains also 13.6 H₂SiO₃, 0.6 CaSiO₃, 0.4 FeFeO₃, 0.3 AlAlO₃. (-)2V=87°, Ng=1.679, Nm=1.665, Np=1.650, Ng-Np=.029, X∧c=74°.
20. Cummingtonite, Brunsjögruvan, Sweden, N. Sundius: *loc. cit.* Contains also 12.6 H₂SiO₃, 0.4 AlAlO₃, 0.2 FeFeO₃. (-)2V=81°, Ng=1.685, Nm=1.670; Np=1.650, Ng-Np=.035, X∧c=75°.
21. Gruenerite, Stromshult, Sweden. J. Palmgren: *Bull. Geol. Inst. U. Upsala*, XIV, 1917, p. 109, and N. Sundius: *loc. cit.* Contains also 13.3 H₂SiO₃, 0.6 FeFeO₃, 0.6 AlAlO₃. (-)2V=79.2°, Ng=1.699, Nm=1.6835, Np=1.663, Ng-Np=.036 (.040), X∧c=75.5°.
22. Silbbergite, Silbberg, Sweden. N. Sundius: *loc. cit.* Contains also 2.5 CaSiO₃, 2.2 AlAlO₃ (incomplete analysis). (-)2V=80°, Ng=1.7057, Nm=1.6904, Np=1.6696, Ng-Np=.0361, X∧c=75.6°.
23. Dannemorite, Dannemora, Sweden. N. Sundius: *loc. cit.* Contains also 2.3 CaSiO₃, 0.6 AlAlO₃ (incomplete analysis). (-)2V=80°, Ng=1.713, Nm=1.697, Np=1.673, Ng-Np=.040, X∧c=77.5°.
24. Gruenerite, Collobrières, France. S. Kreutz: *Sitz. Akad. Wiss. Wien*, CXVII, 1908, p. 875. Contains also 6.4 H₂SiO₃, 4.0 NaFeSi₂O₆, 1.3 AlAlO₃ (-)2V=82° ±, Ng=1.717, Nm=1.697 (1.695), Np=1.672, X∧c=79°-80°.
25. Richterite, Langban, Sweden. Lévy and Lacroix: *Minér. Roches*, 1888, p. 144. Analysis by Michaelson. Contains also 14.9 KSiO₂(OH), 4.8 NaFeSi₂O₆, 1.1 NaAlO(OH)₂. (-) Ng=1.64, Nm=1.63, Np=1.62, Ng-Np=.024, X∧c=70° (73°).
26. Richterite, Sweden. S. Kreutz: *loc. cit.* Contains also 11.1 (Na,K)SiO₂(OH), 5.6 NaFeSiO₆, 2.4 H₂SiO₃. (-)2V=70°33', Ng=1.6367, Nm=1.6294, Np=1.6151, Ng-Np=.0215, X∧c=73°5'.
27. Richterite, Langban, Sweden. See No. 25. Analysis by Engstrom. See Dana: *Syst. Mineral.* Contains also 13.7 NaSiO₂(OH), 4.9 NaAlO(OH)₂.
- 28-32. Tremolite, See *Am. Jour. Sci.*, CCVII, 1924, p. 306.
33. Tremolite, Edwards, N. Y., E. T. Allen and J. K. Clement: *Am. Jour. Sci.*, CLXVI, 1908, p. 101. Contains also 4.9 H₂SiO₃, 4.9 (K,Na)SiO₂OH, 3.7 Na(Al,Fe)Si₂O₆. No optic measures.
34. Nephrite, Bahia, Brazil. H. S. Washington: *Pan-Amer. Geol.*, XXXVII, 1922, p. 198. Contains also 12.2 H₂SiO₃, 2.8 NaAlSi₂O₆, 0.2 AlAlO₃, 0.2 FeFeO₃. Ng=1.625, Np=1.597, X∧c=74°.
35. "Hornblende," Russel, N. Y., S. Kreutz: *loc. cit.* Contains also 9.8 NaSiO₂(OH), 2.4 AlAlO₃, 2.1 NaFeSi₂O₆, 1.2 H₂SiO₃. (-)2V=86°14', ρ>ν weak. Ng=1.6244, Nm=1.6134, Np=1.6017, Ng-Np=.0227, X∧c=70°29'.
36. Tremolite, Nordmark, Sweden: G. Flink: *Zeit. Kryst.*, XV, p. 90. (Analysis incomplete.) (-)2V=84°9', Nm=1.618, X∧c=72°42'.
- 37-41. Actinolite, see *Am. Jour. Sci.*, CCVII, 1924, p. 306.
42. Actinolite, Berkeley, Calif., W. C. Blasdale: *Bull. Geol. Dept. Univ. Calif.*, II, p. 328. Contains also 14.8 NaAlSi₂O₆, 4.1 H₂SiO₃. Ng=1.6529, Np=1.6267, X∧c=75°26'.
43. Actinolite, Dubostica, Bosnia. M. Kispatic: *Zeit. Kryst.*, XXXVI, 1902, p. 649. Contains also 12.4 CaAlO₂(OH), 0.8 AlAlO₃. No optic measures.
44. Artificial monoclinic amphibole not certainly of composition indicated, but made from 85% CaMgSi₂O₆ and 15% SiO₂. N. L. Bowen: *Am. Jour. Sci.*, CLXXXVIII, 1914, p. 207, and CCVII, 1924, p. 296. (+) 2V=45°, Ng=1.638, Nm=(1.623) Np=1.620, X∧c=23°.