THE CLASSIFICATION OF THE HORNBLENDES AND THE SOLID SOLUTION RELATIONS IN THE AMPHIBOLE GROUP

BY

N. SUNDIUS

Vapnö socken, Halland, Nr
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Contents.

When the standard formula of the amphiboles had been established (W. T. Schaller 1916, B. E. Warren 1929 and 1930, W. Kunitz 1930) and its validity also for the alkali- and sesquioxide-bearing hornblendes proved (Warren 1930), an attempt at a classification of the alkali-amphiboles on the basis of the formula was made by H. Berman and E. S. Larsen (1931), and a more general classification by Berman in 1937. The latter divided the elements present in hornblendes into four groups $W = Ca$, Na, K and sometimes Li; $X = Mg$, Fe'', Mn'', Al in part; $Y = Al$, Fe''', Ti, principally; and $Z = Si$ principally and Al in part. The species distinguished on this basis were the following.

X	Y	Z = Si : Al	
5	0	7 : 1	Hornblende-Edenite
4	1	6 : 2	Hastingsite
3	2	8 : 0	Glaucophane
4	1	8 : 0	Arfvedsonite

In the earlier paper of Berman and Larsen a formula styled soda-tremolite ($Na_2CaMg_5Si_8O_{22}(OH)_2$) had also been introduced, besides some formulas without OH or with one atom of hydroxyle.

In 1943 A. F. Hallimond published a list of no less than 196 analyses of lime-bearing hornblendes calculated at atomic ratios according to the standard formula, and showed that they can all be graphically reproduced if referred to the formulas 1) $Ca_2(MgFe'')_5Si_8O_{22}(OH)_2$ (tremolite), 2) $Ca_2(MgFe'')_3Al_4Si_6O_{22}(OH)_2$ (styled as Ts), 3) $Na_2Ca_2(MgFe'')_5Al_2Si_6O_{22}(OH)_2$ (styled as Ha). The third of these is not in accordance with the amphibole formula as shown

by Winchell, who proposes that it be exchanged for two formulas $NaCa_2(MgFe'')_5$ $AlSi_7O_{22}(OH)_2$ (hornblende-edenite) and $NaCa_2(MgFe'')_4Al_3Si_6O_{22}(OH)_2$ (hastings-ite).

The papers cited above prompt the conclusion that the seemingly complicated and confused relations in the hornblende group in reality can be expressed by a fairly small number of terms. Indeed all the formulas used in the following are contained in the works mentioned, though they contain some that are not necessary. Also most of the principles of the substitutions, on which a general classification must be founded, can be derived from the earlier papers. On the other hand the earlier works are incomplete, especially as regards the alkaline hornblendes, nor are the relations within the individual series treated. For this reason it has seemed justifiable to take up the matter in a somewhat broader connection.

A calculation of different types of hornblendes soon discloses that the chief type-forming kinds of substitution in the group are restricted to the introduction of alkalies and to the different manners in which this is accomplished and to the exchange of Si and (MgFe'') for Al. Upon applying this principle to tremolite or actinolite, we get a small number of formulas in which the substitution proper theoretically cannot proceed farther or in practice has not proceeded further than to a certain limit in the analysed amphiboles. Of these formulas the former correspond to what may be named end-members, the latter not. In the following both kinds are called standard types, from which all mixtures in the group can be derived.

In an additional chapter the solid solution relations within the whole amphibole group are briefly discussed. For the questions occurring here the optical relations play a conclusive rôle and for this reason and as the optical properties are a necessary means for the determination of the type of the specimens, they have to be included.

The general hornblende formula.

In its simplest form, as realized in tremolite-actinolite, the formula of lime-bearing amphiboles can be written $X_2Y_5Si_8O_{22}(OH)_2$. In the lattice the 24 O-atoms are linked together by eight Si-atoms to form chains of Si-O-tetra-hedrons, which are bound together by seven metal atoms. The latter are of two kinds, occupying positions with different size of the space rooms and with different co-ordination numbers (8-co-ordination for the X-atoms, 6-co-ordination for the Y-atoms). The X-atoms are large; the Y-atoms intermediate or smaller. Furthermore, the presence in the lattice of the so-called vacant spaces makes possible the introduction of further atoms in the frame-work of the hornblendes, and these may be of a size similar to that of the X-atoms. Remembering, too, that Si can be replaced partly by Al, the general formula of the hornblendes may be written: X_{2-3} $Y_5Z_8O_{22}(OH)_2$ where X = Mn'' (in part) Na, Ca, K and Ba and sometimes Li; Y = Al, Ti, Cr''', Fe''', Mn''', Mg, Ni, Li, Fe'', Zn, Mn'' (in part); Z = Si, Al and OH can be replaced by F or Cl. In the

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following X and Y are always taken in this sense.[1] For the sake of convenience alkalies will be referred to the vacant spaces when the sum of the elements in X is greater than 2.

Standard types of substitution in the hornblende group.

The introduction of alkalies into the hornblendes can occur in three different manners. If we start from the tremolite formula $Ca_2Mg_5Si_8O_{22}(OH)_2$ the common-est case is probably that alkalies occupy the vacant positions. In order to re-establish the balance of the valences a corresponding number of Si-atoms must be exchanged for Al. This process can proceed to the extent of 1 atom of Na and 1 atom of Al for 1 atom of Si, when the vacant spaces are filled. The resultant hornblende $NaCa_2Mg_5AlSi_7O_{22}(OH)_2$ may therefore be regarded as an end-member.

In the second case Ca is exchanged for Na. If one atom Ca is exchanged for the equivalent amount of Na, thus Ca for Na_2, no other change is necessary in the constitution of the tremolite. When this is accomplished the vacant spaces are filled and this kind of substitution cannot proceed farther. The re-sulting hornblende ($Na_2CaMg_5Si_8O_{22}(OH)_2$) may therefore be regarded as an end-member.

If the exchange of Ca for Na should continue further, it must be in the ratio Ca : Na. The balance of the valences is then disturbed and a surplus of negative valences arises which must be saturated by the exchange of a divalent atom of the group Y for a trivalent, i. e. Mg by Al (or Fe'' by Fe'''). When this sub-stitution is complete we get a new end-member ($Na_3Mg_4AlSi_8O_{22}(OH)_2$).

The same kind of substitution can also be realized under certain other circum-stances. If we start again from tremolite and substitute Na for Ca according to the ratio 1 : 1, but imagine that the vacant spaces are not filled, MgFe'' must be exchanged for Al or Fe'''. If the substitution is complete, we arrive at the formula $Na_2Mg_3Al_2Si_8O_{22}(OH)_2$, which also represents an end-member.

If Al is introduced in the tremolite formula without the introduction of al-kalies, the valence balance is maintained by a contemporaneous exchange of Mg and Si for Al Al. If this substitution occurs alone, we obtain the formulas $Ca_2Mg_4Al_2Si_7O_{22}(OH)_2$, $Ca_2Mg_3Al_4Si_6O_{22}(OH)_2$, and so on. This kind of substitu-tion is fairly common in the lime-bearing hornblendes, but practically it does not go farther than to the last-mentioned formula, which is not an end-member, but for practical reasons it will be chosen as a standard formula.

The last-mentioned kind of substitution can also be combined with the one first mentioned. If we substitute Al Al for Mg and Si in the formula $NaCa_2$ $Mg_5AlSi_7O_{22}(OH)_2$, we get the formula $NaCa_2Mg_4Al_3Si_6O_{22}(OH)_2$. This is not an end-member either as, theoretically, the exchange of Mg Si for Al Al can proceed further, and in nature it can be shown to have gone further, but it is fairly uncommon for the hornblendes to contain more Al, and therefore the formula may conveniently be set up as a standard formula.

[1] According to Machatschki (Zeitschr. f. Krist., 70, p. 214, 1929).

The application of these kinds of substitution to tremolite leads to the six formulas quoted in Table 1. They represent the standard types from which all other hornblendes can be derived. As Mg and Fe'' are unlimitedly exchangeable, there is one Mg- and one Fe''-member of each type, the name of the latter being quoted below that of the former. The table may conveniently be divided into two parts, corresponding to the alkaline and the lime-alkali hornblendes, which latter are also called lime-bearing hornblendes.

Table 1.

Tremolite
Actinolite
$Ca_2(MgFe'')_5Si_8O_{22}(OH)_2$

Richterite	Eckermannite	Glaucophane
Ferrorichterite	Arfvedsonite	Riebeckite
$Na_2Ca(MgFe'')_5Si_8O_{22}(OH)_2$	$Na_3(MgFe'')_4(AlFe''')Si_8O_{22}(OH)_2$	$Na_2(MgFe'')_3(AlFe''')_2$ $Si_8O_{22}(OH)_2$

Tremolite
Actinolite
$Ca_2(MgFe)_5Si_8O_{22}(OH)_2$

Edenite	Pargasite	Tschermakite
Ferroedenite	Hastingsite	Ferrotschermakite
$NaCa_2(MgFe'')_5AlSi_7O_{22}(OH)_2$	$NaCa_2(MgFe'')_4(AlFe''')Al_2$ $Si_6O_{22}(OH)_2$	$Ca_2(MgFe'')_3(AlFe''')_2$ $Al_2Si_6O_{22}(OH)_2$

As regards the table it is logical that those hornblendes in which Ca is exchanged for alkalies be termed alkali hornblendes. According to this principle, edenite, pargasite and hastingsite do not belong to this category, but are lime-alkali hornblendes, whereas richterite belongs to the alkaline group.

The species ferrorichterite and ferroedenite set up in the table lack analogies in the analyses. The former name is proposed here by the writer. The name tschermakite is used according to the proposal of Winchell (1945).

Tschermakite-ferrotschermakite and pargasite-hastingsite are not end-members; all other standard types are.

In the following some representative instances of the standard types of the table are quoted from the literature, and the relations within the separate series are discussed. A good many of the analyses reproduced here are from the valuable papers of S. Kreutz and W. Kunitz. As a summary of the numerous analyses of lime-bearing hornblendes the lists of Hallimond and Winchell have been very helpful.

The tremolite-actinolite series.

Two analyses with very different ratios FeO : MgO are shown in Table 2.

The optical relations in the series tremolite-actinolite will be discussed in connection with those of the lime-bearing hornblendes.

SiO_2	
Al_2O_3	
TiO_2	
Fe_2O_3	
MgO	
FeO	
MnO	
Na_2O	
CaO	
K_2O	
H_2O	
F	
$-O$	

[1] Plus 0.12 % CO_2

Spec. g:

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2. Actinolite (»ferr

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The formula is c two Na. This typ analyses, from an From richterite wit with decreasing ar.

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[2] Winchell, A. N. F

Table 2

	I	Numb. of atoms	2	Numb. of atoms	Atoms in the formula
SiO₂	58.38	7.90 } 7.97	49.30	7.82 {18} 8.00	8
Al₂O₃	0.44	0.07	1.30	0.24 {6}	
TiO₂	0.05	0.01			
Fe₂O₃	0.37	0.03	2.15	0.26	
MgO	25.01	5.07 } 5.11	0.66	0.16 } 4.98	5
FeO	—		30.50	4.03	
MnO	1.54	0.18	3.48	0.47	
Na₂O	0.76	0.19			
CaO	10.95	1.59 } 1.98	10.73	1.82	2
K₂O	0.07	0.02			
H₂O	2.17	1.97 } 2.08	2.13 } 2.25		2
F	0.27	0.11			
	100.01		100.25		
— O	0.11				
	¹99.90				

¹ Plus 0.12 % CO₂

	Spec. gr.	α	γ	$\gamma - \alpha$	$c : \gamma$	$2V_c$	Opt. orient.
1.	2.98	1.604	1.629	0.025	15°	79°20′	b = β
2.		1.668	1.685	0.017	10—12°¹	ca 74°¹	

1. Tremolite (»Hexagonite»), Edwards, N. Y., Anal. by A. Bygdén, T. M. P. M. 43, p. 437, 1933.

2. Actinolite (»ferroanthophyllite»), Tamarack Mine, Idaho, Shannon, ref. in N. J. 1924: 2.

As regards the nomenclature in the tremolite-actinolite series, the Fe-rich members of the series have also been named ferrotremolites.[2] As the name tremolite of old designates members with a very high MgO-content this term is inadequate. It seems appropriate to extend the term tremolite to about 15 mol % FeO and to name the Fe-richer members actinolites. If desirable the extremely Fe″-rich species can be separated as ferroactinolites. That the term actinolite has got so wide an extension is due to the fact that the Mg-rich members are quantitatively predominant and the older analyses only included varieties with a low Fe″-content.

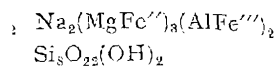### Richterite $Na_2CaMg_5Si_8O_{22}(OH)_2$.

The formula is derived from tremolite by exchange of one atom Ca against two Na. This type has also been named soda tremolite (cf. above). Three analyses, from an earlier paper by the writer (1945), are shown in Table 3. From richterite with about 2 atoms of Na(K) there is known a series of members with decreasing amounts of alkalies to about 0.7 atoms of Na(K).

[1] According to measurements by V. E. Barnes, cf. A. N. Winchell, 1931.
[2] Winchell, A. N. Elements of Optical Mineralogy, 1933.

(left margin column)

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Glaucophane
Riebeckite
Na₂(MgFe″)₃(AlFe‴)₂ Si₈O₂₂(OH)₂

Tschermakite
Ferrotschermakite
Ca₂(MgFe″)₃(AlFe‴)₂ Al₂Si₆O₂₂(OH)₂
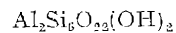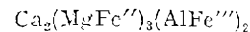
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e shown in Table 2. will be discussed in

Table 3.

	Numb. of atoms in the form.	1	Numb. of atoms	2	Numb. of atoms	3	Numb. of atoms
SiO₂	8	53.80	7.75 }7.97	56.01	7.89 }7.91	57.74	7.89} 7.95
Al₂O₃		1.37	0.22	0.14	0.02	0.37	0.06}
TiO₂		0.10	0.01	—		tr.	
Fe₂O₃		1.89	0.21	2.14	0.22	0.29	0.04}
MgO	5	18.45	3.98 }5.02	20.99	4.44 }5.00	23.67	4.64} 4.96
FeO		—		—		tr.	
MnO		8.69	1.05 {0.80 / 0.25}	5.81	0.69 {0.34 / 0.35}	2.40	0.28}
CaO	1	5.43	0.84 {1.09	8.29	1.25	9.01	1.32 1.32
Na₂O	2	5.63	1.57 }1.90	3.69	1.01 }1.09	3.14	0.83} 0.94
K₂O		1.72	0.31	0.47	0.08	0.64	0.11}
BaO		0.30	0.02				
H₂O < 105°		0.14					
H₂O > 105°	2	1.91	1.83 }2.01	1.94	1.83 }1.91	2.39	2.18} 2.21
F		0.36	0.16	0.18	0.08	0.37	0.03}
Cl		0.04	0.02				
		99.83		99.66		100.02	
— O for F and Cl.		0.16		0.07		0.16	
		¹99.67		99.59		99.86	

¹ Plus 0.19 SO₃. In a test for Li no greater amount of this metal was found than what was contained in the reagents used for the analysis.

	Sp. gr.	a	β	γ	$\gamma-a$	c : γ	$2V_a$	Opt. orient.
1.	3.08	1.622	1.635	1.641	0.019	19°	66°30'	b = β
2.	3.044	1.6151	1.6294	1.6367	0.0216	16°55'	68°34'	»
3.	2.99	1.605		1.627	0.022	17°	medium	»

1. Richterite, Långban, anal. R. Blix, opt. determ. by N. Sundius 1945.
2. » , » » and opt. determ. by S. Kreutz.
3. » , » » A. Bygdén, opt. determ. by N. Sundius 1945.

The high content of Mn is noteworthy in the analyses. This is due to the fact that the occurrences of richterites known are Fe-Mn-deposits. To judge from the atomic ratios Mn may partly enter in group X. It is possible that part of the amount in group Y may be present in the form of Mn''', but the relations in the modern analyses make it appear improbable that the whole content of Mn should be threevalent, as supposed by J. Jakob.

The substitution of Na₂ for Ca in tremolite has had but little influence on the optical properties, except that the axial angle has diminished from about 82° in tremolite to 66—68°. This may be due partly to the presence of Mn, but it is not likely that this should be the only cause, among other things because the difference in Mn between analyses 1 and 2 is considerable, whereas the variation in 2V is small.

Below are shown the calculated figures of another five richterites representing the more recently published analyses. The numbers refer to the list in the author's earlier paper. Ru refers to an analysis by Kreutz of hornblende from Russel,

N. Y. (p. 930), a t substitution of ed

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The formula ass at the same time exchange for a diva its theoretically hi seldom surpasses th analyses.

X. Y. (p. 930), a tremolite with admixture of richterite molecules and a slight substitution of edenitic type (Na Al for Si).

	Si	Al	Fe'''	Fe''	Mg	Mn''	Ca	Na	K	H	F
6.	7.97			0.02	4.65	0.58 + 0.20	0.83	1.69	0.28	1.46	0.06
7.	7.84			0.02	3.83	1.15 + 0.39	0.89	1.11	0.30	2.64	0.04
9.	7.87	0.04	0.50		4.32	0.82	1.68	0.08	0.62	1.28	
10.	7.72	0.06	0.05		5.12	0.69 + 0.04	1.46	0.83	0.16	1.22	
11.	7.40	0.48	0.46		4.92	0.19 + 0.18	1.02	1.36	0.25	1.36	
Ru	7.60	0.36	0.09	0.17	4.61	0.02	1.72	0.68	0.23	1.90	0.37

Where double figures are quoted for Mn the second one shows the amounts that are to be united in the formula with Ca. The principle for the division is that 2 Na should substitute Ca. The amount of Mn to be included with Ca is therefore 2.0—a, a being equal to the sum of Ca and half of Na + K. But in no case is more Mn transported to group X than what corresponds to the sum of at least 5.00 in the atom group Y.

As the substitution occurring in the richterites is restricted to the exchange of Ca for alkalies the analyses can be reproduced in a diagram with the two kinds of atoms as coordinates as shown in fig. 1. The positions of the formulas of richterite and tremolite are marked with the letters R and Tr. The richterites form a series extending from R to somewhat more than half of the distance to Tr. The diagram also shows the position of the Russel tremolite (Ru), plotted according to its content of Ca and the amount of NaK that can be calculated to substitute Ca (the small amount of Na corresponding to edenite molecules being neglected). The nature of this hornblende is clearly tremolitic ($2V = 86°14'$). As the axial angle of the richterites remains similar at least from point 1 to 2 (for 9 no optical determinations are available) the change to the angle of tremolite may be rather sudden.
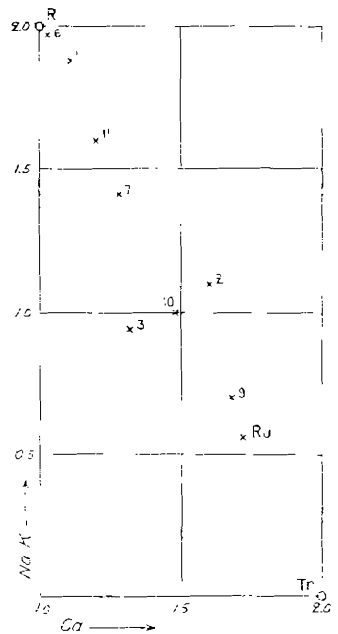
Fig. 1.

Eckermannite, $Na_3Mg_4AlSi_8O_{22}(OH)_2$.

The formula assumes a further replacement in richterite of Ca by Na and at the same time the introduction of a threevalent atom in the Y-group in exchange for a divalent. When the index of Na has arrived at 3, it has attained its theoretically highest possible value in an amphibole, and in reality it only seldom surpasses this figure and then by inconsiderable amounts in the modern analyses.

imb. atoms | 3 | Numb. of atoms

7.91 | 57.74 / 0.37 / tr. | 7.89 / 0.06 } 7.95

5.20 | 0.29 / 23.67 / tr. / 2.40 | 0.04 / 4.64 / 0.28 } 4.96

0.34 / 0.35 } 1.60 | 9.01 / 3.14 / 0.64 | 1.32 / 0.85 / 0.11

1.09 | | 1.32 / 0.94

1.91 | 2.39 / 0.37 | 2.18 / 0.03 } 2.21

| 100.02
| 0.16
| 99.86

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Only two representatives of this species seem to be known, namely the imerinite described by Lacroix from contact-metamorphosed limestone in Madagascar and the Li-bearing eckermannite from the nepheline syenite at Norra Kärr in southern Sweden. Both the analyses are quoted in Table 4.

Table 4.

	Numb. of atoms in the formula	I	Numb. of atoms	2	Numb. of atoms		
SiO$_2$	8	57.10	8.02	53.73	7.58	0.42	8.00
Al$_2$O$_3$	1	6.19	1.02	2.72	0.46	0.04	
TiO$_2$		0.35	0.04	0.41	0.04		
Fe$_2$O$_3$		8.01	0.84	4.72	0.51		
MgO	4	9.13	1.92	20.60	4.36	4.91	
Li$_2$O		1.15	0.65				
FeO		2.69	0.31	4.70	0.55		
ZnO		0.59	0.06				
MnO		0.34	0.04				
CaO		0.31	0.05	2.73	0.41		
Na$_2$O	3	9.77	2.66 (3.14)	7.42	2.03	2.76	
K$_2$O		2.38	0.43	1.82	0.32		
H$_2$O $<$ 105°		[1] 0.08					
H$_2$O $>$ 105°	2	0.50	0.47 (1.66)	0.85	0.80	1.62	
F		2.69	1.19	0.92	0.82		
		101.28		100.62			
— O for F		1.13					
		100.15		100.62			

Sp. gr.	α	β	γ	$\gamma - \alpha$	c : α	2V$_\alpha$	Opt. orient.
1. 3.16	1.636	1.644	1.649	0.013	25—53°	75°	b = β
2. 3.02	1.638	1.650	1.653	0.015	45°	[2]55°	»

[1] of which 0.02 in H$_2$SO$_4$-exsiccator
[2] Calc. by the author from 2 E about 100°

Pleochroism: α bluish green, β light bluish green or blue-violet, γ pale yellowish green.

1. Eckermannite, Norra Kärr, Sweden.
2. Imerinite, Ambatoharina, Madagascar.

Of the two amphiboles the eckermannite accords well with the formula. The high Fe''' content in the Y-group is caused by the presence of Li$_2$O and partly also by the presence of O instead of OH (oxidation of Fe''). The imerinite shows some departures from the theoretical ratios of the metal groups but evidently belongs to the same substitution type. In the choice of the type name preference may be given to the former.

Optically the eckermannites are most closely allied with the arfvedsonites, their iron analogues, though the colour is more similar to that found in glaucophane.

1

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SiO$_2$ ....
Al$_2$O$_3$ ....
Fe$_2$O$_3$ ....
MgO ....
FeO ....
CaO ....
Na$_2$O ....
K$_2$O ....
H$_2$O ....

Sp. gr.

1. 3.085
2. 3.126

1. Glaucophane,
2. »

Pleochroism γ blu
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Holmquistite ....
Gastaldite ....

†2—462066. S. G. U.,

Glaucophane, $Na_2Mg_3Al_2Si_8O_{22}(OH)_2$.

Table 5.

	No. of atoms in the formula	1	Numb. of atoms			2	Numb. of atoms		
SiO_2	8	57.73	7.79	0.21	8.00	56.97	7.86	0.14	8.00
Al_2O_3	2	12.04	1.91	1.70		10.83	1.75	1.61	
Fe_2O_3		1.16	0.11		1.81	2.92	0.30		1.91
MgO	3	13.02	2.64			10.43	2.16		
FeO		5.41	0.61		3.25	8.27	0.95		3.11
CaO		1.04	0.15			0.68	0.10		
Na_2O	2	6.98	1.83		2.09	6.79	1.82		2.03
K_2O		0.68	0.11			0.65	0.11		
H_2O	2	2.27	2.04			2.23	2.05		
		100.33				99.77			

	Sp. gr.	α	γ	$\gamma-\alpha$	$c:\gamma$	$2V_a$	Opt. orient.
1.	3.085	1.606	1.627	0.021	8°		$b=\beta$
2.	3.126	1.615	1.634	0.019	6—8°	41°	»

1. Glaucophane, Zermatt (Matterhorn), Kunitz.
2.   » , Champ de Praz, ibidem

Pleochroism γ blue, β violet blue, α colourless or yellowish green.

Besides by their characteristic colour the glaucophanes are optically characterized also by the small extinction angle $c:\gamma$ (0—8°) and a relatively small negative axial angle.

Kunitz succeeded in deducing from the analyses the right formulas for tremolite-actinolite, glaucophane and riebeckite. From the ratios of the formulas he concluded that there must exist isomorphic series between these three compounds. On the other hand, a calculation of the different molecules contained in the intermediate members of the series glaucophane-actinolite compiled by Kunitz (Tab IV), discloses them to be quite impure. Only No. 2 (glaucophane Mt. Saléve) and No. 7 (Winchite, Piz Valesa), lying fairly near to glaucophane resp. tremolite, can strictly speaking be referred to this series. Of the others, the analyses show No. 3 (glaucophane, Berkeley) to be an intermediate member between eckermannite and tremolite, and 6 (Winchite, Lanjaron) a pargasite with some admixture chiefly of richterite. Also the other amphiboles quoted are more or less admixed with foreign compounds. Furthermore, the sparse optical determinations (essentially $c:\gamma$) do not indicate a continual transition.

To the glaucophane group belong also the Li-bearing holmquistite from Utö, Sweden, and the gastaldite from St. Marcel, whose calculated atom numbers are quoted below.

	Si	Al	Fe‴	Mg	Fe″	Ca	Li	Na	K	H	F
Holmquistite	8.00	1.21	0.97	2.41	0.48	—	1.12	0.29	0.10	2.02	0.18
Gastaldite	8.03	3.45		0.81	1.04	0.30		1.27			

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l in Table 4.

Numb. of atoms		
.58	0.42	8.00
.46	0.04	
.04		
.51		
.36	4.91	
.55		
.41		
.03	2.76	
.32		
.80	1.62	
.82		

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Osann gives the following data for holmquistite: $C : \gamma = 2\text{—}3°$, $2E_a = 68°56'$, γ = skyblue, β violet, a light greenish yellow. The properties of gastaldite have been studied by Rosenbusch[1] and Kreutz: $c : \gamma = 6°$ and $4\text{—}8°$, $2V_a$ (Na) = $= 43°58'$ and (gr) $42°02'$, $\gamma\text{—}a = 0.018$, though the determinations were not made on the material analysed.

Unfortunately the analysis of gastaldite is rather old (1875) and incomplete. However, both minerals have in common the optical properties of glaucophane but a fairly low content of atoms in group X, amounting in holmquistite to I,5I, if Li is included, in gastaldite to I.57. The two amphiboles are accordingly exceptions from the rule that the sum of the X-atoms in a hornblende must not be less than 2, and they seem to be unique in this respect. It should further be noted that the place of Na and K in holmquistite is largely taken by atoms of Li, which has a small radius similar to that of Mg. If the two hornblendes should be interpreted as transitional members they would chemically most likely belong to a series glaucophane-cummingtonite or -gedrite, but with close connection to glaucophane.

Arfvedsonite, $Na_3Fe''_4Fe'''Si_8O_{22}(OH)_2$.

In the iron-rich amphiboles we meet the complications occasioned by the introduction of large amounts of Fe_2O_3. This oxide is generally present in excess over the ratio required by the formula and by the quantity of alkalies. Furthermore the iron-rich alkali hornblendes often contain essential amounts of TiO_2. The agreement with the theoretical formula is often therefore poorer for these members than for the Mg-rich ones. A contributing factor is also a certain replacement of Si by Al (admixture of hastingsite), which is rather common.

Two analyses which are fairly consistent with the theoretical formula are quoted in Table 6.

Table 6.

	Numb. of atoms in the formula	I	Numb. of atoms	2	Numb. of atoms
SiO_2	8	48.76	7.69⎫ 7.95	49.36	7.49⎫ 7.99
Al_2O_3		I.41	0.26⎰	2.78	0.50⎰
Fe_2O_3	I	10.70	1.32	8.24	0.95
TiO_2		1.03	0.12	2.12	0.24
MgO		0.30	0.08	5.92	1.34
FeO	4	25.52	3.35⎱ 3.51	18.23	2.32⎱ 4.01
MnO		0.43	0.06⎰	0.86	0.11⎰
CaO		1.02	0.17⎱	1.83	0.30⎱
Na_2O	3	7.12	2.18⎱ 2.65	7.88	2.32⎱ 2.79
K_2O		1.53	0.30⎰	0.89	0.17⎰
H_2O	2	2.07	2.18	2.05	2.09
		99.89		100.16	

[1] Mikr. Physiogr. d. Mineralien und Gesteine, 4th ed. p. 240, 1905.

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TH:

• *Arfvedsonites*

✗ *Katophorites*

× *Eckermannites*
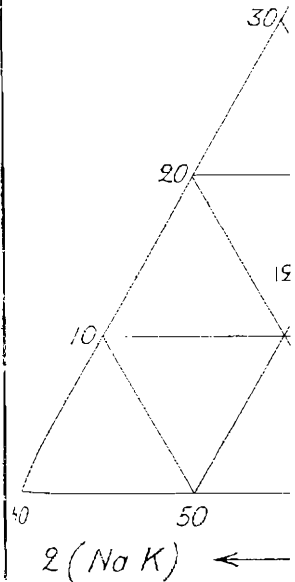
Fig. 2. E = ecl

Sp. gr.

1. 3.421
2. 3.332

1. Arfvedsonite, Kange:
2. » , Los A:

Between arfvedsc styled by the resp katophorite, anoph guished by high con of Fe_2O_3 and low A sonite. As in the la admixture of hastin mannites, is shown coordinates Si, AlF

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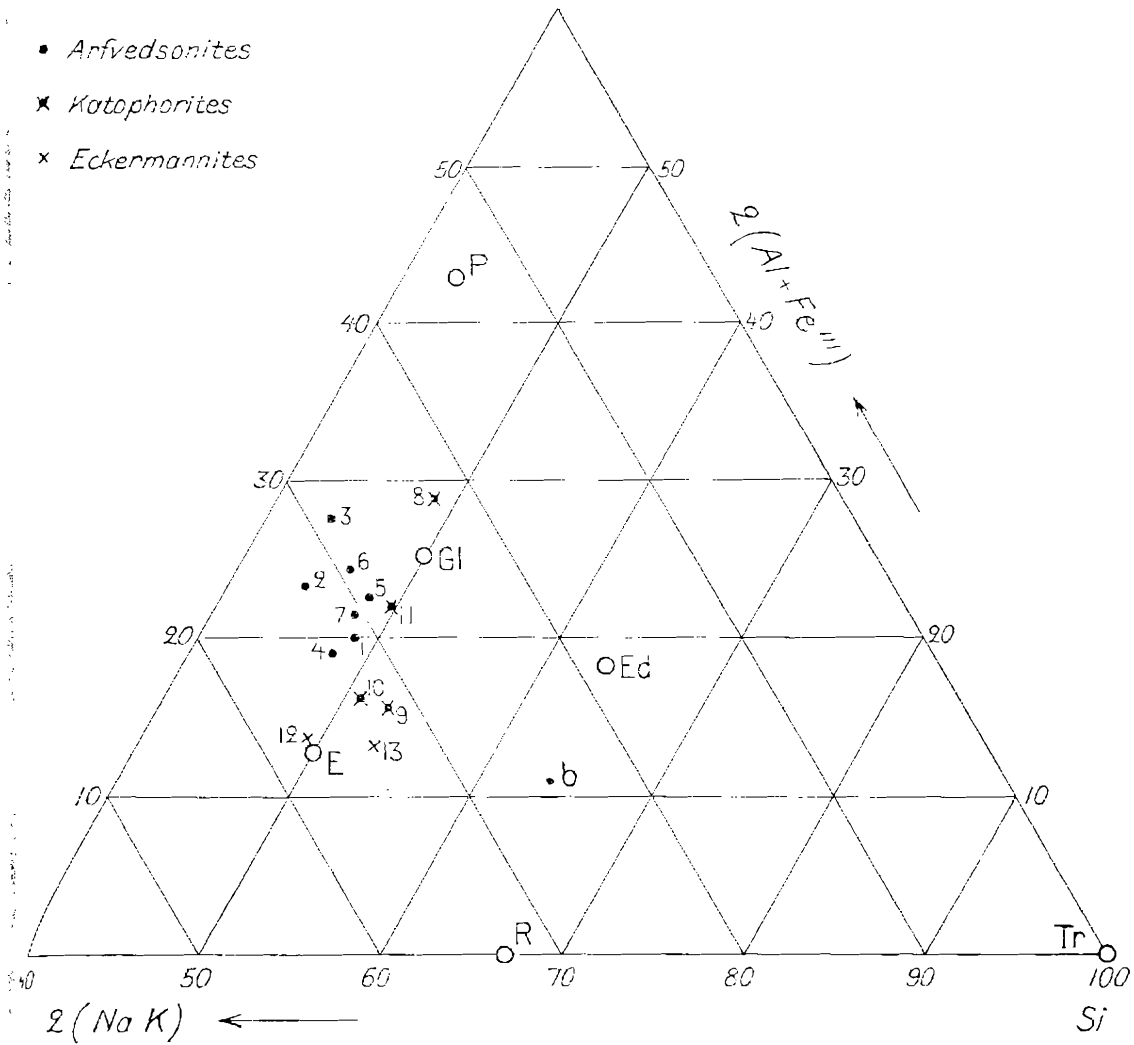r is also a certain
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Fig. 2. E = eckermannite, Gl. = glaucophane, R = richterite, Tr = tremolite,
P = pargasite, Ed = edenite.

	Sp. gr.	α	β	β—α	Opt. ch.	c : γ	Opt. orient.
1.	3.421	1.695	1.698	0.003	—	8°	b = γ
2.	3.332	1.683	1.687	0.004	—	15°	»

1. Arfvedsonite, Kangerdluarsuk. Kunitz, pp. 219 and 245
2.   »   , Los Archipel.   »   »   »   »   »

Between arfvedsonite and eckermannite there are a number of hornblendes,
styled by the respective authors by different names, such as arfvedsonite,
katophorite, anophorite, riebeckite, taramite. Chemically they are all distin-
guished by high contents of alkalies (index of X = 2.6—2.9), moderate amounts
of Fe$_2$O$_3$ and low Al$_2$O$_3$ contents, thus the same characteristics as of arfved-
sonite. As in the latter some Al enters in the Si group and causes a restricted
admixture of hastingsite. A collection of such species, arfvedsonites and ecker-
mannites, is shown in fig. 2, where they have been plotted according to the
coordinates Si, AlFe‴, NaK, the two latter being multiplied by 2 to give a

2	Numb. of atoms	
49.36	7.49	
2.78	0.50	7.99
8.24	0.95	
2.12	0.24	
5.92	1.34	
18.23	2.32	4.01
0.86	0.11	
1.83	0.30	
7.88	2.32	2.79
0.89	0.17	
2.05	2.09	
100.16		

clearer picture. The localities corresponding to the points in the diagram are shown in the following list where also the atomic ratios of Fe''Mn : Mg (calcul. on 100), the extinction angle and the optical orientation have been included.

	Mg	Fe'' + Mn	c : α	opt. orient.
1) Arfvedsonite, Kangardluarsuk, Kunitz	2	98	8°	b = γ
2) »Riebeckite», Pikes Peak, Kunitz	5	95	13°	»
3) Arfvedsonite, Sinai, Kunitz	7	93	7°	»
4) » , Loparsky pass, Kunitz	28	72	28°	»
5) » , Kakasujujakok, »	28	72	30°	»
6) » , Hackmanschlucht, »	33	67	27°	»
7) » , Los Archipel, »	36	64	15°	»
8) Katophorite, Fuente Vaca, »	39	61	36°	»
9) Taramite, Mariupol, Morozewicz	57	43	[2]12—15°	»
10) Anophorite, Katzenbuckel, Freudenberg	69	31	20—27°	»
11) Katophorite, Chibinpaehk, Kunitz	71	29	56°	b = β
12) Eckermannite, Norra Kärr, Bygdén........	86	14	25—55°	»
13) Imerinite, Ambatoharina, Lacroix	89	11	45°	»

[1] c : β or α because b = γ and AE = (010) (Kunitz, Table III, p. 198).
[2] c : β

It seems appropriate to place the intermediate members from about 70 per cent Fe'' + Mn to about 70 per cent Mg in one group and to use the name katophorite for these members. The name arfvedsonite should accordingly be restricted to iron-rich members, optically distinguished by a small extinction angle c : α. The name katophorite was originally proposed by Brögger for amphiboles in tinguaite dykes in the Oslo region, which were considered by him to be intermediate members between arfvedsonite and barkevikite. Unfortunately no analysis was given in the original paper but the optical properties stressed by Brögger are found in the amphiboles belonging to the transition series of the table above.

The diagram in fig. 2 discloses that the points of the whole series are rather scattered and spread out in the direction of and beyond the position of glaucophane. However, this is not merely the consequence of admixtures of glaucophane-riebeckite molecules but is chiefly due to the presence of hastingsite molecules and to the excess of Fe_2O_3.

The chemical composition of the katophorites is somewhat complicated, for instance TiO_2 is present in an amount of 0.6—2 per cent (in anophorite 5.37). This makes the optical relations somwehat variable, but a characteristic feature, besides the strong absorption colours and the low double refraction, properties, which they have in common with arfvedsonite, is a relatively large extinction angle c : α. A normal symmetrical position of the axial plane with b = γ is a common feature, though not always present. The variation of the position of the axial plane is reasonable when considering the low double refraction, on account of which only small differences in the chemical composition may be necessary to bring about a change in the mutual size of the chief indices.

Transition membe: molecules seem to b amphibole from Be Table IV, No 3). The marked b.

In comparison wit allied members, the examples of riebeck

SiO_2		
Al_2O_3		
Fe_2O_3		
TiO_2		
MgO		
FeO		
MnO		
CaO		
Na_2O		
K_2O		
H_2O		
F		
— O		

Sp. gr.

1. 3.35[2]
2. 3.39[1]

1. Rie
2.

Optically the rieb extinction angle of difference is only s

The crossites m glaucophane and ri an intermediate rat the series glaucoph in Table III p. 198 3), and the ratios F Al I is the quantit

[1] with the exception

the diagram are
"Mn : Mg (calcul.
ve been included.

c : α	opt. orient.
8°	b = γ
13°	»
7°	»
28°	»
30°	»
27°	»
15°	»
36°	»
²12—15°	»
20—27°	»
56°	b = β
25—53°	»
45°	»

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Transition members with a considerable content of tremolite and actinolite molecules seem to be uncommon. One instance of this kind is probably the amphibole from Berkeley, analysed by Blasdale (quoted by Kunitz p. 202, Table IV, No 3). The position of it is shown in the diagram in fig. 2 by the point marked b.

Riebeckite, $Na_2Fe''_3Fe'''_2Si_8O_{22}(OH)_2$.

In comparison with arfvedsonites and katophorites the riebeckites and their allied members, the crossites, form a chemically more distinct series. Two examples of riebeckite are quoted in Table 7.

Table 7.

	Numb. of atoms in the formula	1	Numb. of atoms	2	Numb. of atoms
SiO₂	8	49.55	7.82 8.01	51.79	8.20
Al₂O₃		0.97	0.19	0.68	0.13 1.82
Fe₂O₃	2	16.52	1.95	14.51	1.69
TiO₂		0.34	0.04	1.28	0.15
MgO		0.16	0.04	0.10	0.03
FeO	3	20.38	2.68 2.93	21.43	2.70 3.03
MnO		1.30	0.17	1.15	0.15
CaO		0.90	0.15	1.28	0.21
Na₂O	2	6.53	1.99 2.31	6.16	1.84 2.27
K₂O		0.85	0.17	1.10	0.22
H₂O	2	1.85	1.93	1.30	1.32 1.42
F				0.20	0.10
		99.35		100.98	
—O				0.09	
				100.89	

	Sp. gr.	α	β	β—α	2V	c : α	opt. orient.
1.	3.352	1.693	0.003	great	o—5°	b = γ
2.	3.391				»	4—5°

1. Riebeckite (»Osannite»), Cevadaes, Portugal, Hlavatsch.
2. » , Quincy, Ch. Palache and Ch. H. Warren.

Optically the riebeckites are difficult to distinguish from arfvedsonites. The extinction angle of the former is somewhat smaller than of the latter but the difference is only some few degrees.

The crossites may be characterized as intermediate members between glaucophane and riebeckite with an intermediate to high ratio Fe''': Al and an intermediate ratio Fe'' : Mg. In order to give a summary of the relations in the series glaucophane-crossite-riebeckite all the analyses compiled by Kunitz in Table III p. 198[1] have been reproduced in the NaK-AlFe'''-Si-diagram (fig. 3), and the ratios Fe'' : Mg and Fe''' : Al I (calc. on 100) are quoted in Table 8. Al I is the quantity of Al entering in the atom-group Y. The table has been

[1] with the exception of 13, Pikes Peak, which may be referred to the arfvedsonitic series.

Table 8.

Glaucophane—Crossite—Riebeckite.

	% Fe″	% Mg	% Al I	% Fe‴	c : γ	Opt. orient.
1) Gl. Matterhorn	18.15	81.5	93.9	6.1	8°	b = β
2) » Cyklades	51.0	49.0	91.4	8.6	5—6°	»
3) » Smyrna	40.7	59.3	89.4	10.6	4°	»
4) » Rocca Bianca	32.4	67.6	87.9	12.1		»
5) » Champ de Praz	30.5	69.5	84.3	15.7	6—8°	»
6) » Isle Groix	17.2	82.8	65.0	35.0	4°	»
7) Cr. Berkeley	48.0	52.0	61.2	38.8	3°	»
					c : β	
8) » »	36.0	64.0	40.9	59.1	ab. 13°[1]	b = γ
9) » Ternowsky mine	33.3	66.7	15.8	84.2		b = β
					c : α	
10) » Askyss river	34.7	65.3	1.1	98.9	2—3°	b = γ
11) R. Krokydolith	84.3	15.7	7.6	92.4		
12) R. Quincy	99.0	1.0	7.1	92.9	< 4—5°	b = β and γ
13) Cr. Payerb. Graben	94.2	5.8	0	100	0°	
14) R. Cevadaes	98.6	1.4	0	100	0—5°	b = γ

[1] According to E. S. Larsen c: β = 7°

● Riebeckites

✱ Crossites

× Glaucophanes
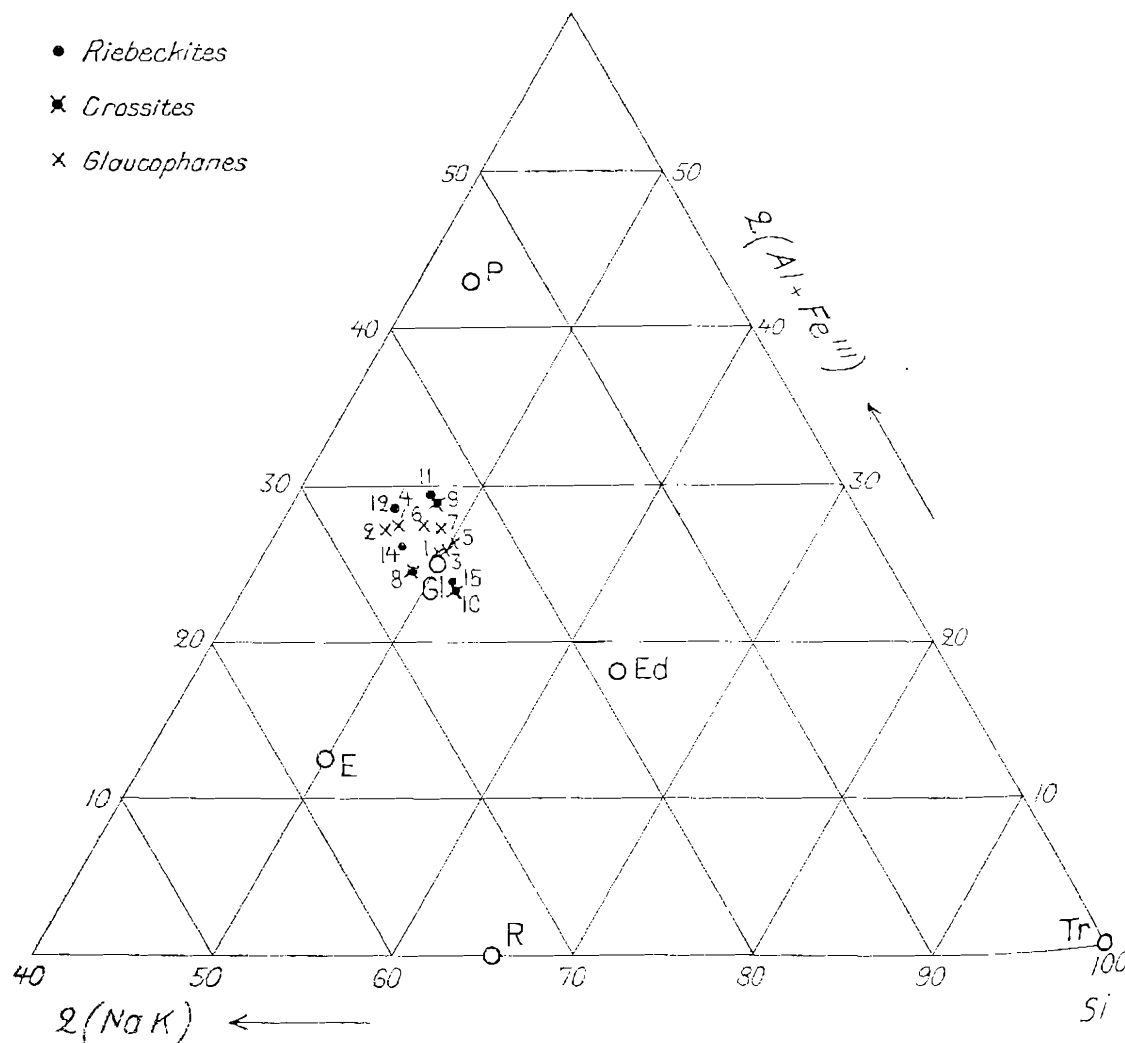
Fig. 3.

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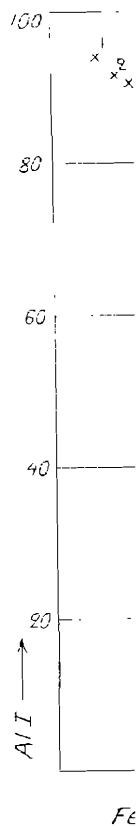
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c : γ	Opt. orient.
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5—6°	»
4°	»
6—8°	»
4°	»
3°	»
c : β b. 13°1	b = γ
	b = β
c : α 2—3°	b = γ
4—5° 0°	b = β and γ
0—5°	b = γ

made to include the determinations of the extinction angle and of the optical orientation.

In the triangle in fig. 3 all the analyses are concentrated around the point of the standard formula, though they are somewhat displaced towards the corner of Al Fe‴, a result of the surplus of Fe‴. Table 8 shows that a difference occurs in the series at about 40—60 per cent Al I (between 7 and 8). All members richer in Al I have b = β, whereas the members richer in Fe‴ show varying relations as regards the orientation of the axial plane, though a normal symmetrical position is predominant. At the same time the birefraction changes from 0.018—0.021 in glaucophane to lower values in the crossites and riebeckites. The axial angle is comparatively small in the glaucophanes (42—45°) but is stated to be fairly great to very great in the crossites and riebeckites. On the other hand, there are no signs of a break in the series. Fig. 4 shows the points of the series plotted according to the ratio Al I : Fe‴.

Fig. 4.

Judging from these relations it would seem convenient to distinguish as glaucophanes the members with an Al I : Fe‴ ratio greater than 1 : 1. The relations between crossites and riebeckites are more diffuse. The latter may be designated as the most iron-rich members of the series in which the ratio Fe″ + Mn : Mg exceeds 80 : 20. At the same time the ratio Al I : Fe‴ is low, but it can reach similar values in both riebeckites and crossites.

The lime-bearing hornblendes.

The lime-bearing hornblendes represent the bulk of the amphiboles. It is therefore reasonable that most of the analyses published should belong here and that several surveys of the relations within the series have been made. Of the works published during the last few years that of Hallimond has especially contributed to giving a survey of the chemical relations.

The substitutions characteristic of the the series are: NaAl for Si and AlAl for MgSi. In the lime-bearing series, therefore, the silica content is always less than 8. The type formulas arising from the two kinds of substitution are $NaCa_2$ $Mg_5AlSi_7O_{22}(OH)_2$ = edenite. $NaCa_2Mg_4Al_3Si_6O_{22}(OH)_2$ = pargasite, and Ca_2 $Mg_3Al_4Si_6O_{22}(OH)_2$ = tschermakite, and their iron analogies.

In order to give a survey of the chemical relations in the series Hallimond used a graphical method of reproduction of the calculated analyses, based upon the two chief quantities introduced by the substitutions, namely the amount of Al in the silica tetrahedrons (8.oo less the calculated number of Si) and the quantity of alkali atoms in the vacant spaces (Ca + Na — K less 2.oo). In a triangular diagram this leads to a third component with the formula $Na_2Ca_2Mg_5Al_2Si_6O_{22}(OH)_2$ (cf. fig. 5), in which should occur the double substitu-
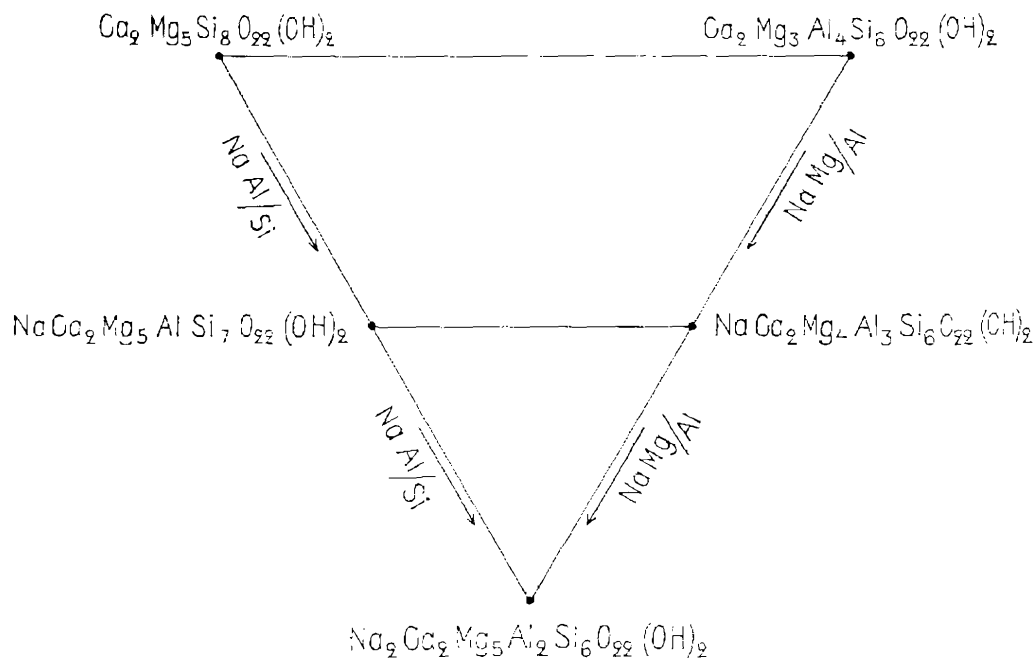
Fig. 5.

tion of the kind occurring in edenite. This component is not consistent with the amphibole formula and the possible hornblende mixtures are therefore restricted to the area between the four upper points of the triangle and to its vicinity.

As the characteristic substitutions occurring in the series are NaAl for Si and AlAl for MgSi, a graphical reproduction can also be achieved by using as
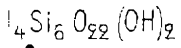

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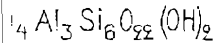amphiboles not inc
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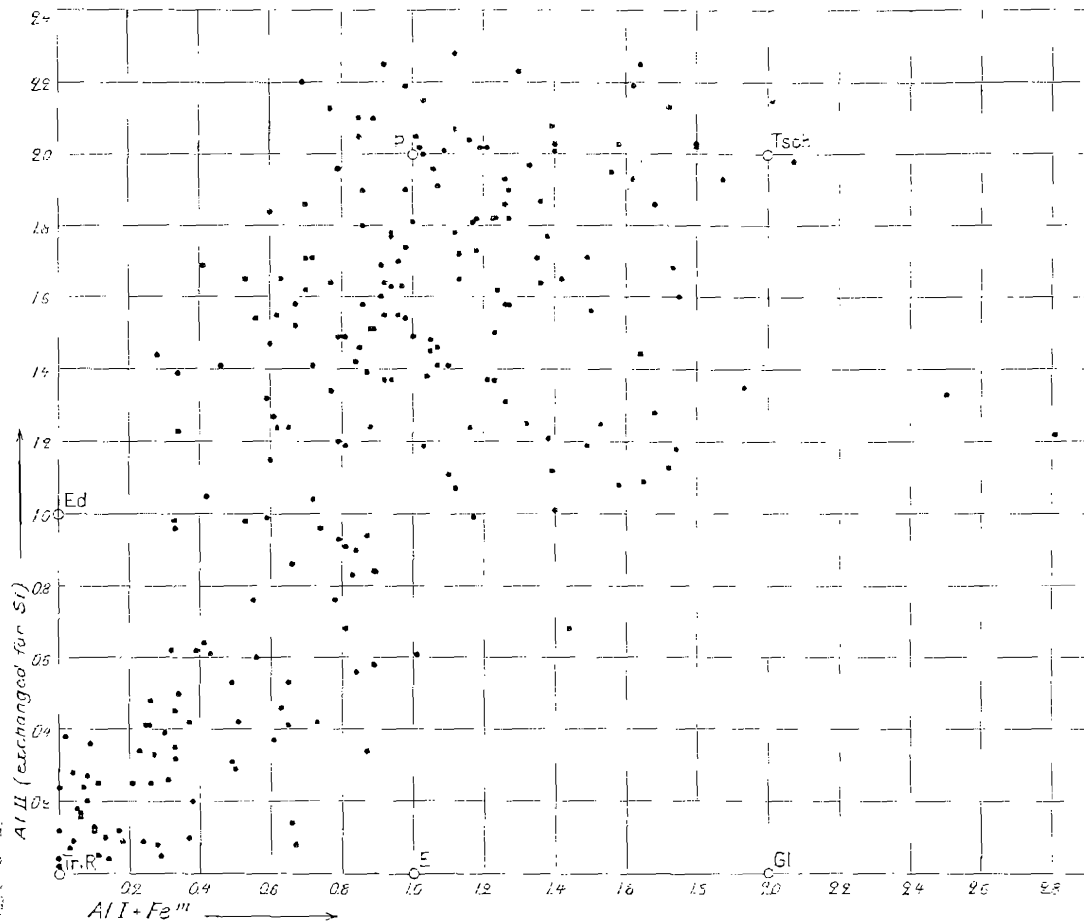
Fig. 6.

coordinates the amount of Al that replaces Si (the same as the one coordinate
of Hallimond) and the amount of Al + Fe''' that enters in the atom-group Y.
Fe''' should also be included in the latter figure, because it compensates Al.
A diagram of this kind was recently employed by St. Foslie in his interesting
paper on common hornblendes and hastingsites, although he did not include
Fe'''. In the present paper the amount of Al that replaces Si is designated as
Al II (8.00 less the calculated number of Si-atoms) and the amount of Al
present in the atom-group Y as Al I. A number of calculated analyses have
been plotted according to these principles in the two-axial diagram in fig. 6. The
loc. of the standard types have been indicated in the usual way by open circles
and by the initial letters of their Mg-representatives. As the alkaline hornblendes
all have a full Si-content (Al II = 0), they are all situated on the bottom line
of the diagram. Richterite has the same position as tremolite. For the diagram
all the analyses in Hallimond's list have been used, 188 in number (hydrous
amphiboles not included), 22 analyses from the list of optically determined
hornblendes by Winchell (1945), 10 analyses from Foslie's paper,[1] and 4 ana-
lyses, not included in these works, quoted below.

---

[1] Nine of these analyses are calculated from rock analyses.

	Si	Al	Ti	Fe'''	Fe''	Mn	Mg	Ca	Na	K	H	F
1...	6.04	2.14	0.02	0.88	0.12	0.27	3.51	1.70	1.14	0.05	2.32	
2...	6.51	1.61	0.15	0.69	2.77	0.07	1.30	1.91	0.62	0.26	1.40	0.11
3...	7.90	0.07	0.01	0.03		0.18	5.07	1.59	0.19	0.02	1.97	0.11
4...	7.87	0.08		0.07	0.67	0.07	4.42	1.72			2.30	

1. Tibergite, Långban, N. H. Magnusson. The following determinations were made by the present writer on the material used for the analysis: $\alpha = 1.662$, $\gamma = 1.674$, $c : \gamma = 30°$, $2V_\alpha = 78°$.

2. Isol. fr. granite, Rönne, Bornholm, K. Callisen. Sp. v. $= 3.338$, $\alpha = 1.676$, $\gamma = 1.702$, $2V_\alpha = $ ca 42°, $c : \gamma = 15°$.

3) »Hexagonite», Edwards, N. Y. Cf. p. 7 in this paper.

4. Actinolite, Ö. Silvergruvan, Sweden. G.F.F., 46: 157, 1924.

It should be observed that all the analyses collected have in common a calculated Ca-quantity > 1.5 and small to moderate amounts of alkalies, seldom exceeding $NaK = 1$.

An inconvenience in the reproduction is caused by the contents of Fe_2O_3 in the analyses. A study of the figures calculated discloses that also here the amounts of Fe''' are often greater than what is demanded by the balance of the valences. This lack of agreement may be due partly to analytical errors, in that the chance of getting too much Fe_2O_3 in the analytical work is greater than that of getting too little, Another source of trivalent iron may be the reduction of OH by Fe'', occurring at or after the formation of the minerals. A fair calculation of the extent to which the latter reaction may have advanced in the individual specimens would be possible if reliable determinations of H_2O and F were available, but in most cases this is not the case. On the other hand the two possible sources of the excess of Fe_2O_3 do not fully explain the surplus found in some cases, and in reality an exact balance of the O-valences does not seem to be quite necessary. The surplus of Fe''' may be of some importance in the iron-rich mixtures and cause some displacement of the points towards the right, but this will not disturb the general aspect of the diagram.

As shown in fig. 6 the majority of the hornblendes fall in a zone between tremolite and pargasite-tschermakite. Above the line pargasite-tschermakite there are scattered points up to Al II $= 2.27$, showing that substitution of Si above the adopted boundary value Si $= 6.00$ is possible though uncommon. In the diagram there are points situated in the immediate vicinity of pargasite and also in the neighbourhood of tschermakite. On the other hand, no points are found along the line tremolite-edenite above Al II $= 0.6$ and none in the vicinity of edenite. Hornblendes of purer edenitic composition may thus be rare in nature. The distribution of the points shows no gap, though an evident concentration of the points is displayed in the neighbourhood of tremolite and in the upper part of the diagram around and beneath pargasite. It should also be observed that there is no special aggregation of the analyses around the

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mixtures, is evident i
Below are quoted
the type formulas.

Si	7.0:
Al	1.1:
Fe'''	0.1(
Ti	0.1(
Fe''	1.5:
Mg	2.8(
Mn	
Ca	1.9(
Na	0.8:
K	
OH	1.9?
F	

Si	6.0(
Al	2.0(
Fe'''	0.9:
Ti	0.1(
Fe''	3.4:
Mg	0.3:
Mn	0.1:
Ca	1.6(
Na	0.6:
K	0.4(
OH	2.1:
F	

1. Brown hornblende fr(
2. Iron Hill, E. S. Lars
3. Almunge, P. Quensel
4. Hornblende, isol. fro

K	H	F
0.05	2.32	
0.26	1.40	0.11
0.02	1.97	0.11
	2.30	

terminations were
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points of the standard types. This is due to the fact that the members selected as standard types are not true end-members but only represent a fair upper boundary for the substitution of Si by Al and of MgFe'' by Al and Fe''' occurring in nature. Hence all hornblendes shown in the diagram of the fig. 6 may be regarded as mixed compounds with the exception of the purer tremolites and actinolites.

The distribution of the points is similar to that shown in the earlier diagrams of Foslie and Hallimond. The separation of the analyses into two groups, one in the neighbourhood of tremolite, the other comprising the sesquioxide-richer mixtures, is evident in both and is also more pronounced in Hallimond's triangle.

Below are quoted some examples of species that show a fair agreement with the type formulas.

Table 9.

	Edenite			Pargasite		
	1		Formula	2		Formula
Si	7.02 } 1.0		7	5.98 } 2.02		6
Al	1.15 } 0.15		1	2.51 } 0.49		2
Fe'''	0.16	} 0.31		0.53	} 1.02	1
Ti	0.10			0.20		
Fe''	1.52			0.72		
Mg	2.89	} 4.51	5	3.30	} 4.25	4
Mn				0.03		
Ca	1.99		2	2.03		2
Na	0.83			0.64		
K		} 1		0.35	} 0.99	1
OH	1.98			0.60		
F		} 2		0.35	} 0.95	2

	Hastingsite			Tschermakite		
	3		Formula	4		Formula
Si	6.09 } 1.91		6	6.03 } 1.97		6
Al	2.06 } 0.15		2	3.25 } 1.28		2
Fe'''	0.92	} 1.07	1	0.80	} 2.08	2
Ti	0.10			0.12		
Fe''	3.42			1.30		
Mg	0.33	} 3.98	4	1.83	} 3.29	3
Mn	0.13			0.04		
Ca	1.69		2	1.61		2
Na	0.65			0.52		
K	0.40	} 1.05	1	0.19	} 0.71	
OH	2.17			0.99		
F		} 2			} 2	

1. Brown hornblende from Usumbura, Urundi. R. Van de Putte.
2. Iron Hill, E. S. Larsen
3. Almunge, P. Quensel
4. Hornblende, isol. from amphibolite, Titianul, Hungary, Vendl.

The nomenclature of the lime-bearing hornblendes is at present somewhat confused. Of the many special and local names given to different and in some cases similar species, the following have acquired a broader meaning: Common hornblende, hastingsite, pargasite, edenite, barkevikite and basaltic (or oxy-) hornblendes. Of these the two last-mentioned are generally distinguished by similar optical and chemical properties and may be included in one and the same sub-group, which may be called basaltic or oxy-hornblendes. The definition of the term edenite was given above. In its present meaning it was first used by Berman (1937). Because of its frequent content of AlFe''' substituting MgFe'', edenite may practically be included in the sub-group of the common hornblendes. Of the other names, hastingsite originally had a distinct meaning, namely that of a hornblende rich in iron and aluminium with moderate amounts of alkalies, and it was optically distinguishable by *inter alia* a very small axial angle. Later experience has proved that properties of this very kind are characteristic of hornblendes of the chemical composition corresponding to the hastingsite formula. Billings later proposed the use of the name also for Mg-rich members and divided the relevant series into subgroups named magnesio-hastingsites, femag-hastingsites and ferro-hastingsites, though he does not seem to have realized the similarity of the Mg-rich members to pargasite. Berman, on the other hand, extended the term hastingsite to comprise all members with Si : Al = 6 : 2, independent of their ratio of Mg and Fe''. Foslie recently accepted Billings's nomenclature.

The term pargasite, dating from 1815 (Steinheil), was at first rather diffuse but through the works of Laitakari and von Eckermann it gained a more distinct meaning, an Al_2O_3-rich hornblende with a high Mg-content, the quantity of alkalies at the same time being moderate. A considerable content of F seems to be common but is by no means constitutional. The formulas of the analyses published from Pargas and Mansjön correspond fairly well to $NaCa_2$ $Mg_{1.5}Al_2Si_{6.5}O_{22}(OH, F)_2$, but in analyses published from other localities there are instances of sesquioxide-richer mixtures with an Mg-content corresponding to the atom number of Fe'' in hastingsite. For this reason it seems appropriate to retain both the names pargasite and hastingsite as expressions for the Mg- and Fe''-extreme members of the hornblende series with a content of Al II approaching 2. The numerous members with intermediate ratios Mg: Fe'' may according to Billings's proposal be named femag-hastingsites. The lower boundary of the Al II content against the common hornblendes may be placed at about Al II = 1.4—1.5. The boundary against the tschermakites is quite diffuse. It would seem convenient to restrict the term tschermakite to comprise members in the neighbourhood of the formula proper and outside and on the conjuntion line tschermakite-tremolite.

The optical relations in the lime-bearing hornblendes.

Rather much has been written on this subject. W. E. Ford (1914) was the first to show that a connection existed between the refraction power and the

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$Ca_2Mg_5Si_8O_{22}(OH)_2$.
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$Ca_2Mg_3Al_3Si_6O_{22}(OH$
$Ca_2Fe''_5Si_8O_{22}(OH)_2$
$NaCa_2Fe''_5AlSi_7O_{22}(O$
$NaCa_2Fe''_4Fe'''Al_3Si$
$Ca_2Fe''_3Fe_2'''Al_2Si_6O$
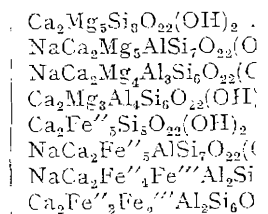
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ratio of Mg and total iron. Other properties were found to be of less diagnostic value. The latter was verified also by N. H. Kolderup and R. Van de Putte. Billings could show a connection between ferrous iron , on the one hand, and refraction, specific gravity and optic axes, on the other, in the series named by him ferro-hastingsite, femag-hastingsite and magnesio-hastingsite. Kunitz was the first to realize that the refraction is not due entirely to the ratio of iron and magnesia but is influenced by the amount of Al_2O_3 replacing SiO_2. In consequence of this he distinguished two series of hornblendes, the green ones and the basaltic hornblendes. In the latter the molecule $H_2Ca_2(MgFe'')_4 Al_2Si_6O_{22}$, named by him syntagmatite, was predominant. Both series were found to lie above that of tremolite-actinolite with respect of the refraction. Similar results were gained by Van de Putte, and recently Foslie has shown that amphiboles with a lower quantity of Al II have a lower mean refraction than those with hastingsitic ratio.

A. N. Winchell has tried in several works to establish the components in the amphibole group and to determine the optical relations of them. In his latest paper (1945) he has a very useful list of no less than 104 calculated analyses of optically determined hornblendes, containing most of the chemically and optically studied members belonging to the series, with the exception of basaltic hornblendes. On the basis of Hallimond's triangle and a fourth vertical axis — the relation Mg + Al I : Fe'' — Fe''' — Mn + Ti — a graphical reproduction was made showing the connection between physical properties and chemical variation. The quantity chosen for the fourth axis of the prism is an approximation to the ratio used by Ford and later authors, but the inclusion of Al I is a not unimportant difference. If, as would appear probable, the influence of a substitution of Al for Mg is of no great importance at least not for certain optical properties, the ratio chosen by Winchell for the fourth coordinate is less appropriate than the older one. From the space model thus erected and the sites of the analyses in it Winchell arrived at the following figures for the mixtures, styled by him as end-members.

	Sign.	2V	γ	$\gamma-\alpha$	c : γ	Sp. gr.
$Ca_2Mg_5Si_8O_{22}(OH)_2$	—	88°	1.625	0.03	18°	2.98
$NaCa_2Mg_5AlSi_7O_{22}(OH)_2$	-	50°	1.63	0.02	25°	3.06
$NaCa_2Mg_4Al_3Si_6O_{22}(OH)_2$	-	85°	1.64	0.02	28°	3.15
$Ca_2Mg_3Al_4Si_6O_{22}(OH)_2$	-	80°	1.657	0.02	20°	3.15
$Ca_2Fe''_5Si_8O_{22}(OH)_2$	—	75°	1.735	0.025	12°	3.40
$NaCa_2Fe''_5AlSi_7O_{22}(OH)_2$	—	20°	1.73	0.02	15°	3.42
$NaCa_2Fe''_4Fe'''Al_2Si_6O_{22}(OH)_2$	---	35°	1.74	0.02	18°	3.45
$Ca_2Fe''_3Fe_2'''Al_2Si_6O_{22}(OH)_2$	—	70°	1.75	0.03	18°	3.42

According to Winchell the figures can only be regarded as approximate because of the complex character of the individual hornblendes. As regards the table it may also be observed that several of the figures do not agree very well with the determinations made by different authors directly on specimens whose composition closely resembles those of the »end-members». It should

also be mentioned that the rather great difference between tschermakite and ferro-tschermakite, on the one hand, and pargasite-hastingsite, on the other, found by Winchell is not consistent with that found recently by Foslie and by the present writer.

Apart from these reservations Winchell's table also prompts the conclusion that the properties of the calciferous amphiboles are not merely a function of the ratio Fe : Mg or Fe + Mn − Ti : Mg, but that the introduction of sesquioxides exercises notable modifications.

In order to study the question last mentioned we can use a two-axial diagram of the same type as in fig. 6 and divide the points in it into different groups with different contents of Al II, then erecting separate diagrams for the separate groups and choosing as axes certain properties and the ratio of selected elements. Accordingly all optically determined lime-bearing amphiboles known to the writer, with the exception of the basaltic ones, have been compiled in the diagram in fig. 7. It contains 127 numbers, namely 103 numbers from Winchell's list, the four analyses quoted on p. 20, the following numbers from Hallimond's list: 123, 128, 143, 165, 184, and furthermore all analyses published by Foslie and an analysis from a paper by O. Kulling. For the study of the optical properties the points have been divided into three groups with boundaries at Al II = 0.6 and 1.4. The three groups correspond fairly well to what has been distinguished above as Strahlsteins (group I), common hornblendes (group II), and pargasites-hastingsites (group III). In order to test the influence of greater amounts of sesquioxides in the atom group Y (AlI + Fe''') only the analyses to the left of the broken line indicated in fig. 7 have been used for the construction of the curves. These analyses have been marked with points, whereas the sesquioxide-richer ones to the right of the line are marked with crosses. A similar distinction to the left of the connecting line pargasite-tremolite is hardly necessary, as the content of Al I − Fe''' is only small in the members belonging to the tremolite-actinolite series. The properties of the pure edenite therefore remain unaccessible. The properties tested in this way are the refraction of γ and the axial angle. The horizontal axis of the diagrams is the ratio Fe'' + Fe''' + Mn − Ti : Mg, the elements known most greatly to influence the properties mentioned.

As regards the *refraction of* γ (fig. 8) it is obvious that the introduction of Al into the Si-O-chains causes an increase in the index. The points are somewhat scattered along the curves, but the scattering is not very great, especially when considering the unheterogeneity of the material used. Some small uncertainty cannot be avoided when drawing the curves, but the material available leaves no doubt about the relatively higher position in the diagram of the curves when passing from I to II and III. On the other hand, there is no regular difference in the distribution of the points and the crosses in relation to the individual curves. Thus the introduction of Al into the atom-group Y as compensation for Mg does not to seem exercise any noteworthy influence on the refraction.

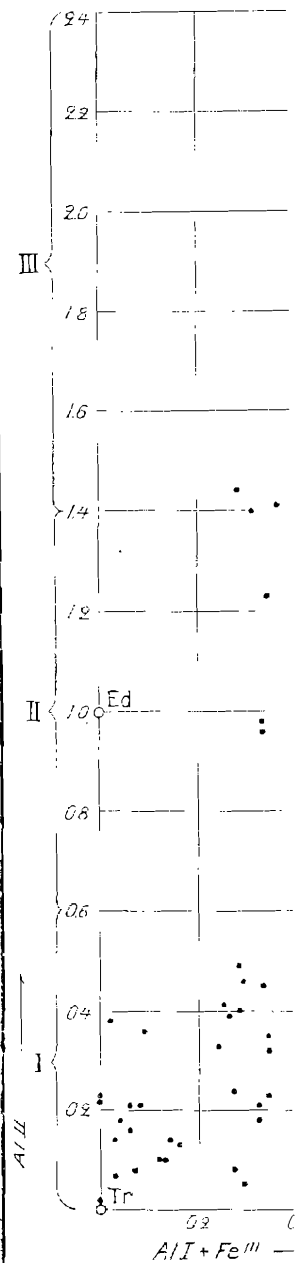It remains to investigate to what extent the positions of the curves in the

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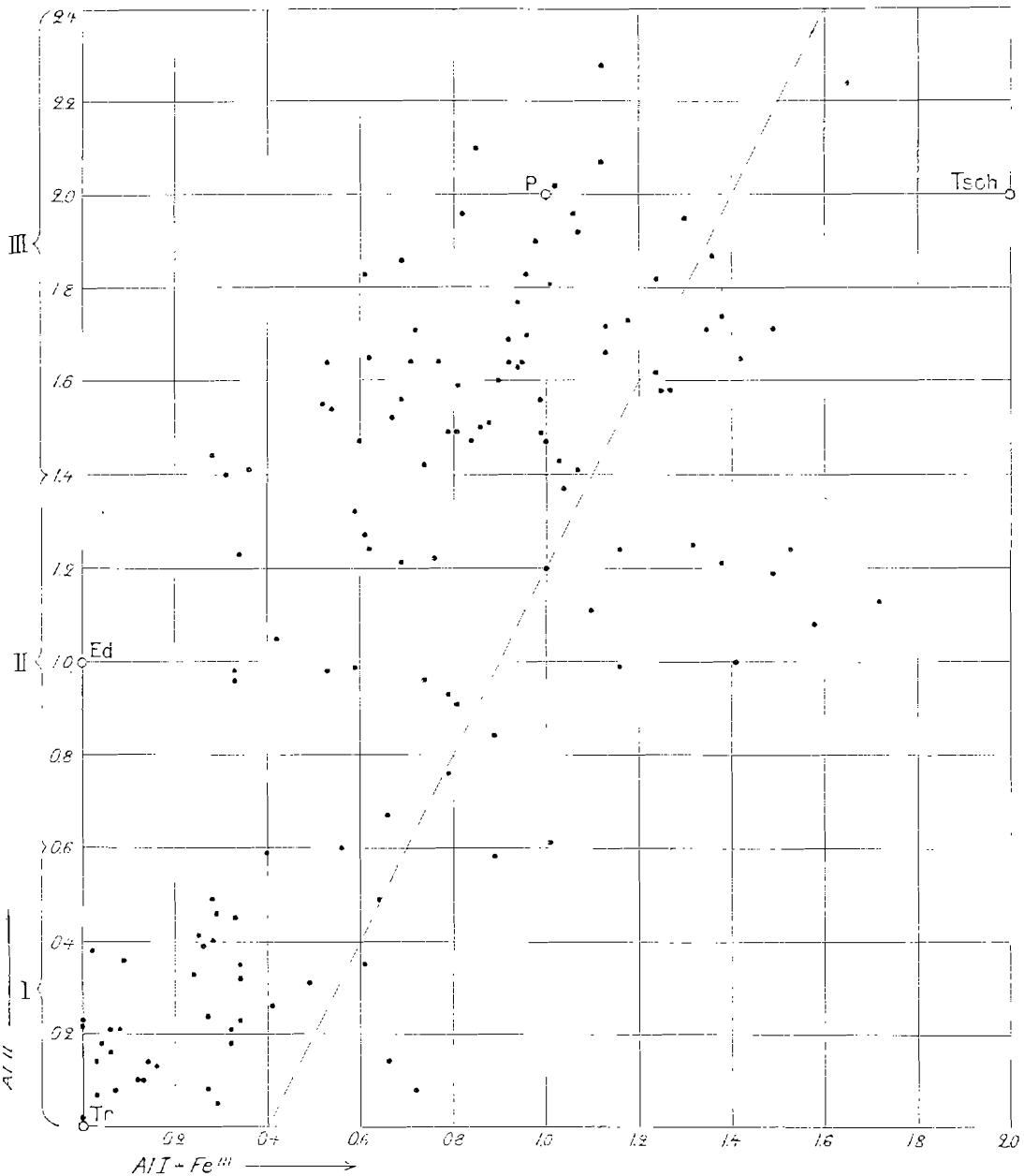
Fig. 7.

diagram can be influenced by the varying content of Fe''' and Ti. Both are
regarded as strong agents in raising the refraction power. As regards the first
due regard is paid to its greater refracting power as compared with Fe'' when
using the calulated atom numbers for the construction of the diagram, for the
atoms in Fe_2O_3 are calculated twice. In the analyses reproduced Ti is generally
present in subordinate amounts, only in a few cases surpassing 0.3 (about
2.5 per cent TiO_2). On the other hand, it is a fact that on the whole Fe''' and
Ti increase when passing from the Strahlsteins to groups II and III. A calcula-
tion of the mean figures for Ti alone in the different groups gives 0.02 in group
I, 0.08 in group II, and 0.14 in III. If Fe''' alone is considered, the upper limit

K. SUNDIUS.

III (Al'''=1.40)

II (Al'''=0.60–1.40)

I (A'.II = 0–0.60)

Mg

Fe'' + Fe''' + Mn + Ti
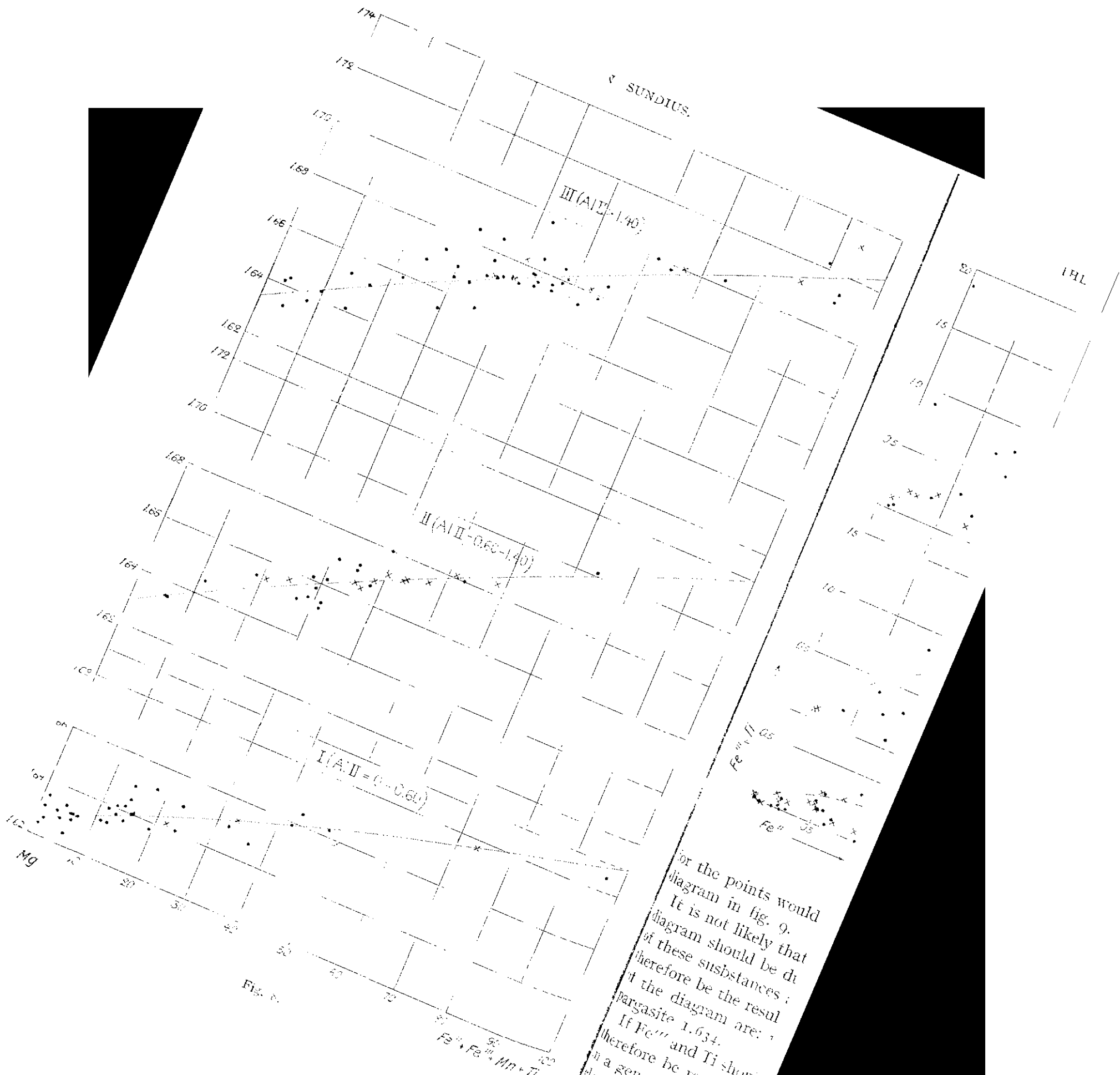
Fig. 8.

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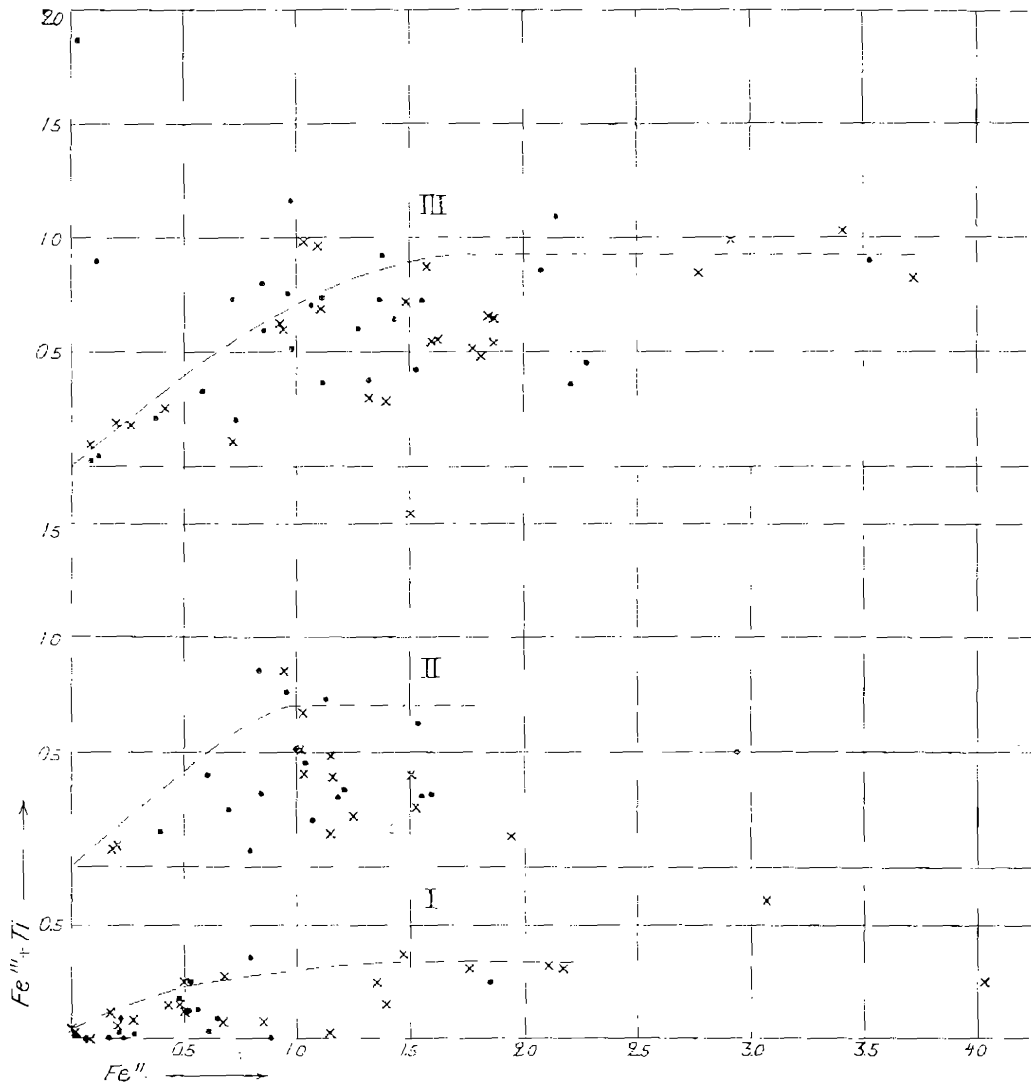
Fig. 9.

for the points would be approximately the broken lines shown in the special diagram in fig. 9.

It is not likely that the differences in γ found at the Mg-extreme side of the diagram should be due to different amounts of Fe''' and Ti, for the amounts of these susbstances are very small here. The differences appearing here may therefore be the result of the exchange of Si for Al. The indices at the Mg-side of the diagram are: tremolite 1.625, Mg-extreme common hornblende 1.629, pargasite 1.634.

If Fe''' and Ti should have an influence on the position of the curves it would therefore be restricted to the iron-richer parts of them and become apparent in a generally higher position of the analyses with larger amounts of these two elements. On the other hand, the relations shown in fig. 9 do not tally with this, as is demonstrated by the irregular distribution of points and crosses, the former referring to analyses situated above the γ-curves in fig. 8 and the latter to those on or beneath the curves. This fact may be interpreted to indicate that Fe'''

is fairly well compensated when calculated twice, and no perceptible influence of the probably more strongly active Ti becomes apparent on account of the restricted amounts of this metal. It would therefore seem reasonable to conclude that the relatively higher position of curves II and III is also in the iron-richer parts of the diagram chiefly due to the higher amounts of Al II in groups II and III. The values of γ read at the right side of the diagram are actinolite 1.69, ferro-extreme common hornblende 1.720, hastingsite 1.725. However, the second of these is rather approximate.

A noteworthy feature in the diagram is the different course of curve I as compared with the others. Whereas II and III run about parallel, I has a distinctly flatter course. The same thing reappears in Foslie's diagram. This fact will be discussed further on.

The relations of the *axial angle* have been studied less than those of the refraction. A diagram by Winchell from 1931 may be mentioned and also his recent figures for the »end-members» of the series quoted above. Other contributions are Billings's paper on the hastingsitic group of amphiboles and a diagram published by S. Gavelin. In the present paper the same horizontal coordinate (Fe'' + Fe''' $\div$ Ti) is used as in the case of the refraction, as the axial angle is a function of the chief indices. The attendant diagram is shown in fig. 10. As in the case of the refraction, the analyses with high contents of Al I $\div$ Fe''' are marked with crosses, those with lower amounts of those substances with points. Both kinds are irregularly distributed here, too, so the presence of varying amounts of tschermakite does not seem to influence the size of the axial angle very greatly.

The points of the analyses are more scattered than in the case of the refraction and the uncertainty when drawing the lines is greater. The distribution of the points could also invite to the construction of an S-shaped curve at the groups II and III. However for the following discussion the right choice among the two possibilities is not of conclusive importance. In any case, the diagram leaves no doubt but that a sudden change in 2 V occurs in the interval between tremolite-actinolite and common hornblendes. The diagram shows that the axial angle is similar in groups II and III, which is reasonable in view of the similar course of the γ-lines found above. In the series pargasite-hastingsite there is a marked decrease in 2 V_a, extending from about 125° in pargasite to about 10° in hastingsite, and as far as analyses are available the relations are similar in the common hornblendes. In strong contrast hereto 2 V is little altered in the tremolite-actinolite series, only changing from about 83° in tremolite to about 74° in actinolite. It is true there is but one point on the actinolite side but the relations in the Mg-richer part of the diagram are in palpable accordance with the position of the actinolite point.

This is a remarkable fact, which corresponds to the difference in the courses of the γ curves I and II—III found in fig. 8.

The influence of Al II on the properties of the hornblendes will be seen more distinctly if we confine ourselves to the Mg-extreme members with 90—100 parts of Mg and construct diagrams with Al II as the one axis and the respective
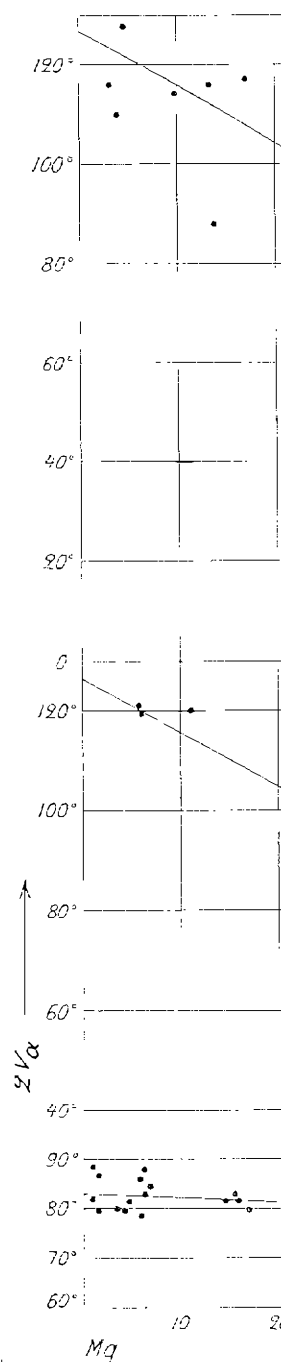
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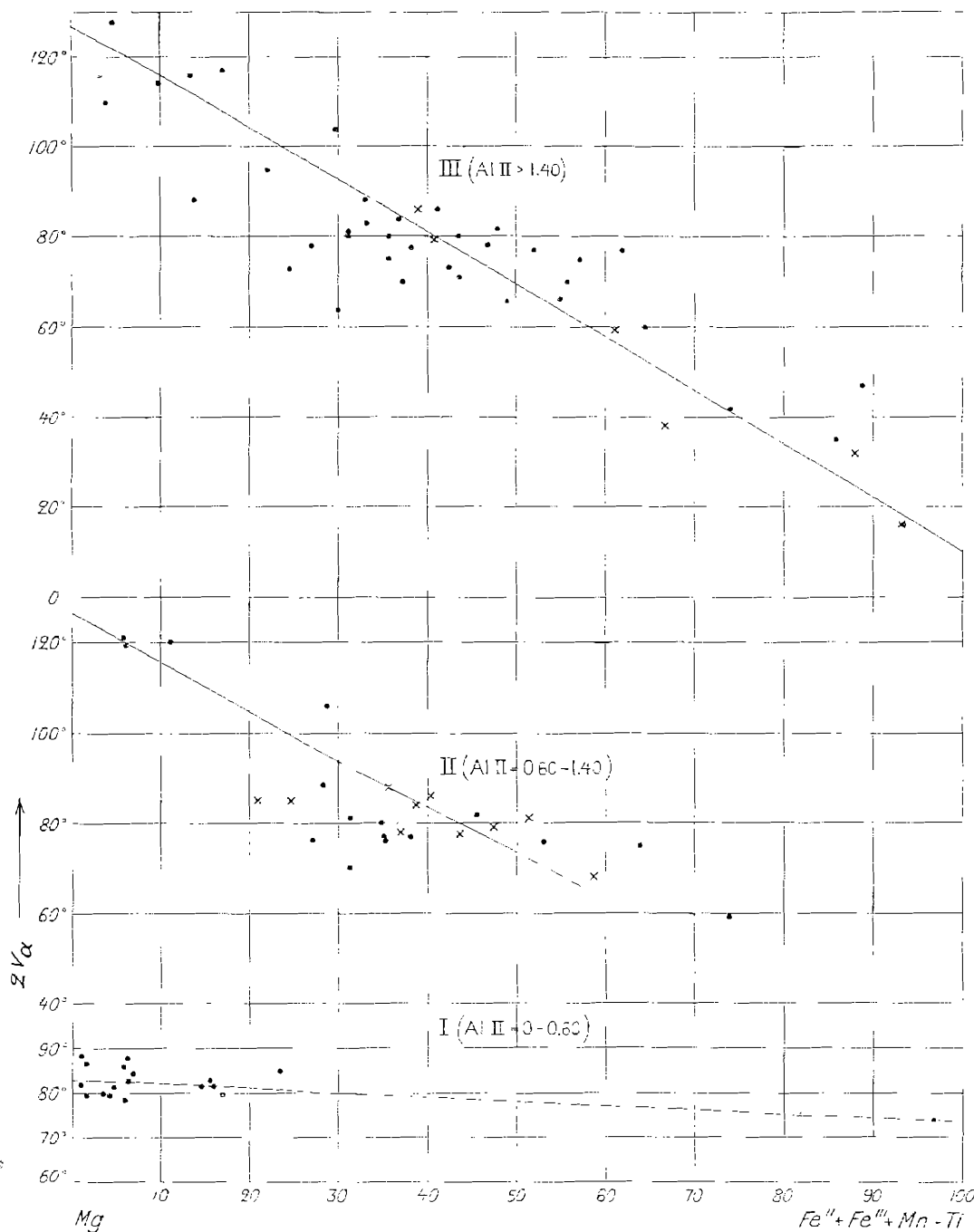
Fig. 10.

optical property as the other. Similar diagrams could be erected for other vertical sections of the diagrams in figs. 8 and 10, but the axial angle is more alike in all curves for the intermediate mixtures, and in the iron-extreme section, where the difference in 2V grows greater again and the difference in refraction is greatest, the number of determinations is small. The section along the Mg-side of diagrams 8 and 9 is shown in fig. 11. It will be noticed that there is a break in the series somewhere between about 0.6 and 1.2 Al II. The discontinuity is most marked for 2V but is evident also for γ.
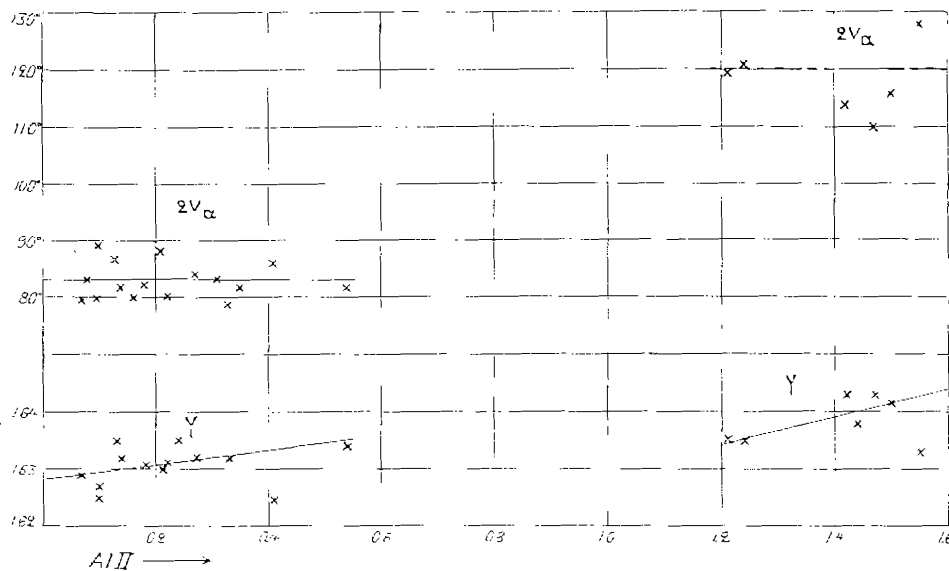
Fig. 11.

The relations of the axial angle aid us in distinguishing the Mg- and Fe''-richer mixtures of common hornblendes, pargasite and tschermakite from tremolite and actinolite, but the numerous intermediate mixtures cannot be distinguished by this means. In fact for these members the only difference seems to be the generally deeper absorption colours of the former.

It would thus seem justifiable to conclude that the members of the tremolite-actinolite series optically behave as a separate group as compared with the sesquioxide-richer hornblendes. The boundary between the two groups lies somewhere between Al II = 0.6 and Al II = 1.2 where the general diagrams also have a zone with few or no points.

Basaltic hornblendes.

Basaltic hornblendes are generally understood to be species distinguished by deep brownish colours, relatively small extinction angles of $c : \gamma$ and high refracting and birefracting power. Chemically they should be characterized by high contents of $Al Fe_2O_3$, generally also of TiO_2, and a relatively low percentage of H_2O. The barkevikites may conveniently be included in the same group. The members of the group have also been named oxyhornblendes because of their high content of Fe_2O_3 being ascribed to a reduction of OH and a contemporaneous oxidation of Fe''.[1] However, the term oxyhornblendes has a wider extension than that of basaltic hornblendes, as every amphibole containing Fe'' can show a corresponding reduction of OH. The latter term has therefore been preferred here.

In Table 10 are collected a number of hornblendes, stated in the literature to be basaltic or barkevikitic, showing their content of Ti, the atomic numbers of Fe'' and Fe''', OH, and the extinction angle. The members called barkevi-

[1] As regards the literature on oxyhornblendes see the papers of Hallimond and Winchell (1945).
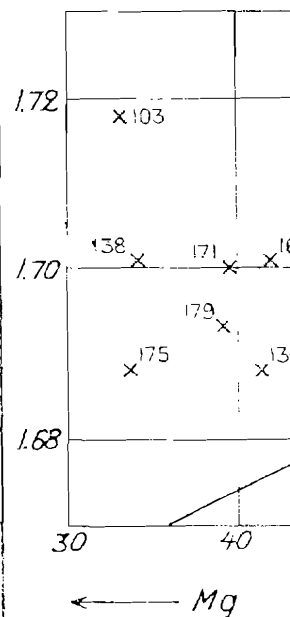
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11) H 187 Fue
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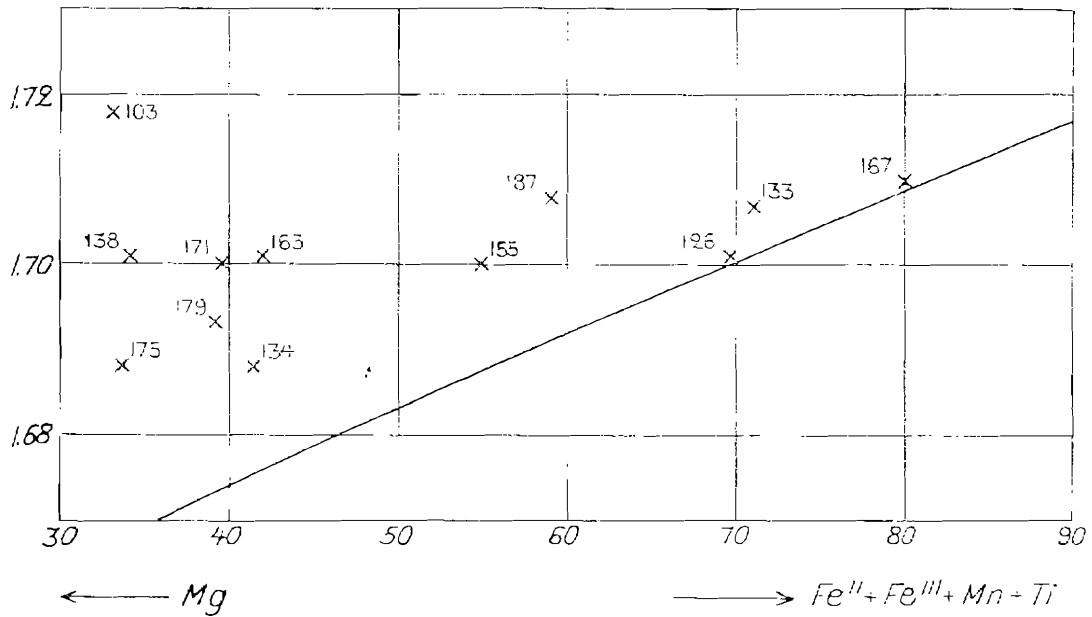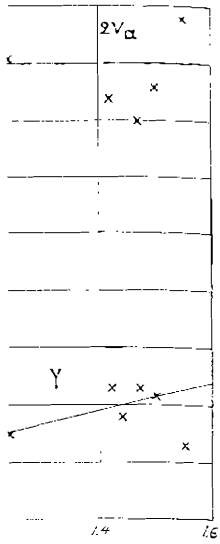are members of the
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kite are marked with B. The figures before the names refer to the lists of Hal-
limond and Winchell (W). The sequence in the table has been determined by the
increasing content of Ti. In fig. 12 the points of the analyses have been plotted
according to the refraction of γ and the ratio Fe'' — Fe''' — Mn — Ti : Mg.
The curve shown is that of the normal pargasites and hastingsites (III in fig. 8).

Table 10.

			Ti	Fe'''	Fe''	H	c : γ
1)	H 133	Skudesundskjaer B	0.03	0.88	2.25	1.20	16°
2)	H 126	Stavaernsjö B ...	0.05	0.77	2.34	1.49	18°
3)	H 175	St. Vincent B ...	0.14	1.37	2.17	1.28	20°
4)	H 167	St. Vincent	0.20	0.97	0.80	0.63	n. d.
5)	H 134	Grosspriessen	0.29	0.86	0.47	0.59	3°
6)	H 155	Tejedatal	0.30	1.37	1.03	0.47	0
7)	H 179	Balaton	0.41	0.60	0.73	2.05	8°
8)	H 163	Isleta-Krater	0.46	0.84	0.80	0.72	n. d.
9)	H 138	Kilimandjaro	0.47	0.52	0.73	0.20	11—12°
10)	H 171	Madeira	0.48	0.76	0.74	0.67	6°
11)	H 187	Fuente Ventura B	0.56	1.12	1.35	1.06	10°
12)	W 103	Lockkow	0.57	0.78	0.29	0.43	13°

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A comparison between the figures for Fe''' and the relations in fig. 9, curve
III, demonstrates that all the hornblendes in the list with the exception of the
two first (133 and 126) really contain relatively higher amounts of Fe''' than
is generally the case in the pargasite-hastingsite series. These two hornblendes
are not basaltic but ordinary members of the series mentioned. The others
are members of the basaltic group, though Nos. 179 and 138 may be considered
to lie on the boundary. A study of the diagram in fig. 12 and of the figures for
Ti would seem to justify the conclusion that the most active agent in the in-

crease in the refraction is the content of Ti, though greater amounts of Fe''' may possibly have some contributing effect. A similar conclusion has earlier been drawn by Kunitz. The few determinations of $2 V_\alpha$ available (138, 179, 103) agree with the normal relations.

The miscibility relations in the amphibole group.

The data available are not sufficient to settle all questions pertaining to the solid solution relations in the very differentiated amphibole group, but some conclusions can be drawn.

Table 11.

	β	$a_0:b_0:c_0$	a_0	b_0	c_0	$110:110$
Anthophyllite		1.027 : 1 : 0.292	18.52	18.04	5.27	54°23'
Cummingtonite	109°34'	0.545 : 1 : 0.293	9.93	18.22	5.33	54°20'
Grünerite		0.525 : 1 : 0.294	9.4 ?	17.9	5.27	
Tremolite	106°02'	0.55? : 1 : 0.295	9.78	17.8	5.26	55°36'
Karinthine (Actin.)	106°02'	0.5511 : 1 : 0.2938				
Common hornblende ...	105°45'	0.541 : 1 : 0.292	9.94(?)	18.38	5.36	
Kaersutite	105°45'	0.542 : 1 : 0.297	9.85(?)	18.17	5.39	55°25'—
Basalt. hornblende	105°45'	0.541 : 1 : 0.292	9.94(?)	18.38	5.36	—55°50'
Barkevikite	105°45'	0.542 : 1 : 0.291	9.92(?)	18.30	5.33	
Richterite	104°14'?	0.5499 : 1 : 0.2854				
Arfvedsonite	104°15,5'	0.539 : 1 : 0.291	9.87(?)	18.31	5.33	56°2'
Glaucophane	104°10'	0.543 : 1 : 0.300	9.72(?)	17.98	5.37	54°55'——55°30'
Riebeckite	103°30'	0.546 : 1 : 0.293	9.88(?)	18.10	5.31	56°
Osannite (Riebeckite)...	107°34'	0.554 : 1 : 0.296	9.98	18.02	5.33	

In Table 11 are collected the values of the constants of the unit cells and of β, as compiled by H. Struntz, and the measured cleavage angles. As will be seen from the table the ratios and dimensions of the axes of the unit cells display but small and irregular variations and do not permit of any distinction between the separate groups except in the case of anthophyllite. As regards the cleavage angle a distinction can be made between the lime-poor monoclinic species and all other monoclinic amphiboles, but the difference is not great. The most instructive relations are found in the figures for β. A study of the species in groups discloses that the value of β in the monoclinic Ca-poor group is 109°34', in the tremolite actinolite series 106°02', in the group of common hornblende-pargasite-hastingsite 105°45', and in the alkaline hornblende group 103°30'—104°15'. The only exception found is osannite with $\beta = 107°34'$, which differs from all other amphiboles. From these relations no conclusion can be drawn as to the degree of miscibility between the various subgroups, but the relations found indicate that if a restricted miscibility does exist in the hornblende group, it may be found between the four sub-

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b_0	c_0	110:1̄10
18.04	5.27	54°23'
18.22	5.33	54°20'
17.9	5.27	
17.8	5.26	55°36'
18.38	5.36	
18.17	5.39	55°25'—
18.38	5.36	—55°50'
18.30	5.33	
18.31	5.33	56°2'
17.98	5.37	54°55'—
18.10	5.31	—55°30' 56°
18.02	5.33	

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groups just mentioned. Chemical-statistical and optical researches are neces-
sary to throw further light upon the matter.

As regards the Ca-poor amphiboles it has long been known that a rather
marked area of immiscibility separates them from tremolite-actinolite.[1] In
no case does the calculated figure for the X-group (NaCaK) in the lime-alkali-
group seem to be less than 2, and with the exception of holmquistite and
gastaldite (p. 12) the same is true of the alkaline hornblendes. If the two horn-
blendes mentioned be understood to represent the lowest possible number of
atoms in group X in the alkaline group, the boundary should lie at about 1.5.
At the same time the content of the corresponding elements in the Ca-poor
group is very small. Between the general formula of the latter $Y_7Si_8O_{22}(OH)_2$
and that of tremolite-actinolite and hornblendes $X_{2-3}Y_5Z_8O_{22}(OH)_2$ no inter-
mediate forms seem to be known.

In the Ca-poor group there is a distinction between the Fe''Mn-richer mono-
clinic members and the antohophyllites, the dividing zone lying at about
37—40 mol. per cent $MgSiO_3$. Only when greater amounts of sesquioxides are
present in the rhombic amphiboles does their content of Fe and Mn exceed
the limit given above.

The relations between the Strahlsteins and the hornblendes are more un-
certain. In a paper of 1929 G. Beskow published a general diagram on the
amphiboles and concluded that there may exist considerable gaps between the
Strahlsteins, the alkaline and the lime-bearing hornblendes, whereas at about
the same time (1930) Kunitz supposed transition relations to exist between
Strahlsteins and lime-bearing hornblendes and also between the former and
glaucophane and between basaltic hornblendes and arfvedsonite, though with
the modification that may be attributable to the temperature. Foslie seems to
be of the same opinion as Kunitz as regards the relations of Strahlsteins to
common hornblendes and pargasite-hastingsite. Berman's conclusion was that
within each of the four series recognized by him (anthophyllite, cumming-
tonite, tremolite-actinolite and hornblendes) there is isomorphism to the extent
indicated in the formulae, but between these series little overlapping is found
(p. 387).

Leaving aside, to begin with, the relations of the Strahlsteins to alkaline
hornblendes, it is apparent from the diagram in fig. 6 in the present paper
that if an unmixing area exists between tremolite-actinolite, on the one hand,
and common hornblendes, pargasite-hastingsite and tschermakite, on the other,
it cannot be very great. The relations of refraction and axial angle as demon-
strated above are incompatible with the existence of transition relations. What
has been said in this paper seems to prompt the conclusion that the pattern
corresponding to tremolite-actinolite cannot continuously change to that of
the sesquioxide-richer hornblendes. But as the unmixing area is small the con-
temporaneous formation of the two amphiboles may occur fairly seldom in
nature. They may also easily be overlooked in a specimen, unless the optical
properties are carefully studied. Especially in the quantitatively predominant

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[1] For literature on this subject see Sundius, 1944.

$Al + Fe'''$

× Eckermannites
× Arfvedsonites
× Kataphorites
→ Glaucophanes
• Crossites
✗ Riebeckites
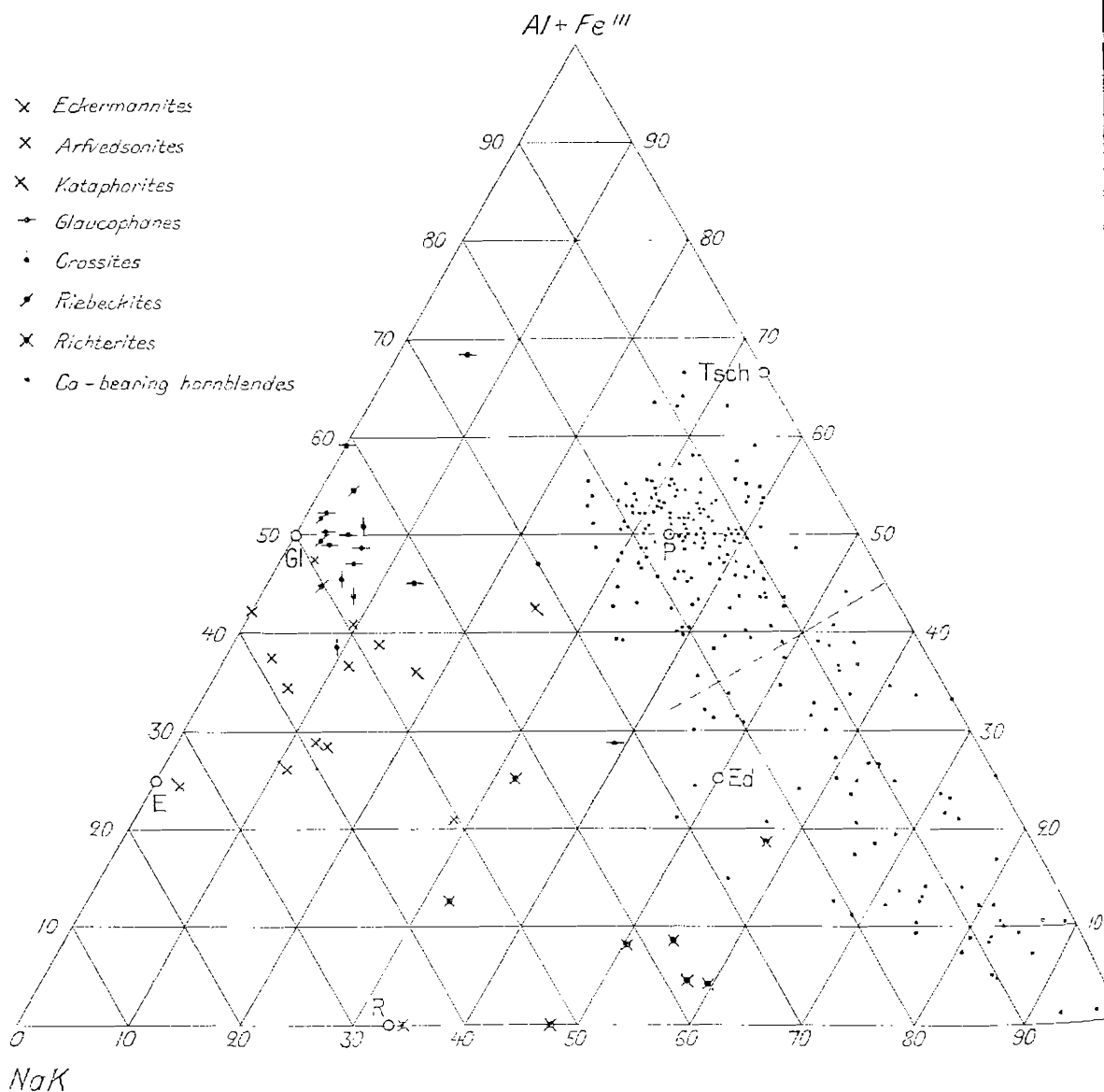× Richterites
• Ca - bearing hornblendes

NaK

Fig. 13.

mixtures with an intermediate content of Mg and Fe the two kinds of hornblende will be fairly similar and difficult to distinguish.

In the alkaline hornblendes the relations are more complicated and the number of analysed specimens is smaller. There is not available any complete series of mixtures between the end-members which could settle the question. Consequently no definite conclusion can be drawn regarding the solid solution relations within this group; it can only be said that the similar values of β found for the different standard types do not indicate unmixing. It is doubtful how the abnormal value of β in the riebeckitic osannite should be interpreted.

Fig. 13 is a compilation of all the amphiboles treated in this paper in a triangular diagram with the coordinates Ca, Na + K and Al + Fe'''. As the atom number of Si theoretically remains similar in all alkaline hornblendes, the coordinates chosen should be appropriate for a graphical reproduction of the

members of this group. In reality a slight replacement of Si by Al occurs. In the lime-bearing group the replacement of Si by Al is the most characteristic feature. In the diagram this is evident by the equally raised values of $Al + Fe'''$. The greatest shortcoming of the present as of all hornblende diagrams that include Fe is the already discussed excess of Fe''' in the analyses, which has caused many of the points to be dislocated towards the top corner. Chiefly for this reason most of the points of the eckermannite-arivedsonite series and of the richterite group have moved upwards, so that the former partly mix with glaucophane-riebeckites. But this is of minor importance as regards the relations between the alkaline and the lime-bearing hornblendes.

A study of the diagram shows that the two chief groups mentioned do not mix with each other, their points clustering along different sides of the triangle. This is most conspicuous in the case of the lime-bearing hornblendes, the pargasitic, hastingsitic and tschermakitic members of which form a rather dense aggregation round the theoretical point of pargasite, whereas common hornblendes and tremolites-actinolites form a more sparsely occupied zone toward the Ca-corner. The broken line marks the approximate position of the unmixing zone between the Strahlsteins and the sesquioxide-richer hornblendes. The alkaline hornblendes tend to aggregate along the other sides of the triangle. As regards the richterites this should become even more noticeable if regard could be taken to the excess of Fe''' in the calculation for the diagram. Practically all the dislocations of the points from the bottom line — the theoretical site of the richterites — are attributable to this. In any case there are only few points in the central part of the triangle and the only instance where a hornblende referred to the alkaline group comes in touch with the lime-bearing series is the point of richterite (No. 9 in the table on p. 9), which is situated in the outermost zone of the area occupied by tremolite-actinolite. Its position may be influenced by an excess of Fe''' and furthermore its optical properties, whether tremolitic or not, are undetermined (cf. p. 9).

It should be noted that also the amphiboles corresponding to the outermost points of the alkaline group always behave as members of that group when optical determinations are available, and the corresponding points of the lime-bearing series behave optically as members of this series. The change in the optical properties may therefore also generally be fairly sudden, as is shown to be probable in the individual case of richterite-tremolite.

These facts rather support the supposition that there exists an unmixing zone between the alkaline and the lime-alkaline hornblendes, though the unmixing area may be restricted.
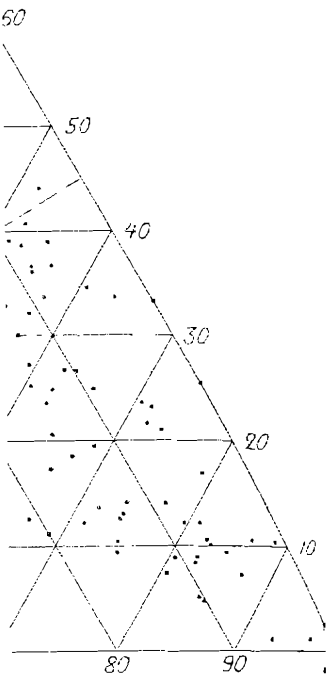
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