A critical review of the data for a revision of the enstatite-hypersthene series.

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At the suggestion of Professor H. H. Read the optic axial angle and the refractive index γ were measured in four hypersthenes from Aberdeenshire norites. As the values obtained suggested that the minerals were iron-rich, it was decided to have chemical analyses made. These and the optical data are set out in table I below. At the same time the literature has been searched for analyses and optical data of enstatites and hypersthenes, in order to supplement those used by A. N. Winchell in his diagram of variation of the properties of the series.[1] The references given by Winchell have been examined, and it is found that some of the data is not reliable. A curve embodying what are considered to be superior values of 2V and γ is presented (fig. 1).

Hypersthene from Aberdeenshire.

Specimen (*a*) came from the norite of the Arnage mass, described by H. H. Read;[2] it takes the form of small (1·0 mm. diameter) subhedral grains, showing prismatic cleavages and a distinct pleochroism. It is accompanied by green hornblende and brown biotite, which sometimes show a reaction relationship to it, and is set in a base of plagioclase with a little quartz.

Specimen (*b*) was obtained from a 'micro-noritic' plagioclase-hypersthene xenolith in the norite of the Haddo mass.[3] The hypersthene forms clear, pale green to pink, rounded grains, about 0·07 mm. diameter, set in a base of plagioclase felspar, and makes up about 10 % of the volume of the xenolith.

[1] A. N. Winchell, Amer. Journ. Sci., 1923, ser. 5, vol. 6, p. 504 [M.A. 2-219]; and Optical mineralogy, 3rd edit., 1933, pt. 2, p. 218.

[2] H. H. Read, Quart. Journ. Geol. Soc. London, 1923, vol. 79, p. 454.

[3] H. H. Read, Quart. Journ. Geol. Soc. London (in the press).

TABLE I. *Hypersthene from Aberdeenshire.*

	(*a*)	(*b*)	(*c*)	(*d*)
SiO_2	51·96	49·52	49·85	45·98
TiO_2	0·37	0·59	0·44	0·55
Al_2O_3	0·01	3·60	2·82	2·95
Fe_2O_3	3·91	nil	1·90	6·27
FeO	19·48	26·47	27·41	28·95
NiO	nil	trace	0·01	trace
MnO	0·39	0·46	0·63	0·30
MgO	17·10	16·65	15·57	12·80
CaO	5·96	1·18	0·83	0·67
Na_2O	nil	0·12	0·13	0·03
K_2O	0·18	0·18	0·19	0·24
$H_2O(+110°\,C.)$ ...	0·28	0·79	0·39	1·01
$H_2O(-110°\,C.)$ ...	0·08	0·15	0·08	0·13
P_2O_5	0·51	0·30	trace	0·17
	100·23	100·01	100·25	100·05
Analyst, A. W. Groves.				
D_{20}^{20}	3·49	3·53	3·56	3·58
$\gamma_{Na}(\pm 0·001)$ ...	1·703	1·730	1·731	1·735
$2V(\pm 1°)$	71°	53°	55°	67°
Pleochroism α	pale red-brown	pale pink	pink	deep red
Pleochroism β	yellow-green	pale yellow-green	yellow-green	yellow-brown
Pleochroism γ	green	pale green	pale green	deep green

(*a*) Hypersthene, from norite of the Arnage mass, Railway Bridge Croft, Arnage, Aberdeenshire.

(*b*) Hypersthene from 'micro-noritic' xenolith in norite of the Haddo mass, Quilquox, Methlick, Aberdeenshire.

(*c*) Hypersthene from norite enclosing xenoliths, Quilquox, Methlick, Aberdeenshire.

(*d*) Hypersthene from contaminated rock of Insch mass, one-sixth of a mile south of Easter Saphock, Old Meldrum, Aberdeenshire.

The hypersthene of specimen (*c*) is from the norite enclosing the xenoliths. It occurs as larger subhedra, about 0·5 mm. diameter, showing prismatic cleavages and schiller plates. The mineral is associated with biotite and magnetite in a base of plagioclase (about $Ab_{44}An_{66}$).

Specimen (*d*) is from a norite of the Insch mass;[1] contaminated by the absorption of argillaceous material. It forms short prisms and is accompanied by brown biotite, much red garnet, plagioclase ($Ab_{35}An_{65}$), and quartz.

[1] H. H. Read, Mem. Geol. Surv. Scotland, Explanation of Sheets 86 & 96, 1923, p. 135; and Geol. Mag., 1921, vol. 58, pp. 177–183.

In separating the mineral for analysis, the rock was crushed in a diamond mortar with frequent sieving, until microscopic examination of the powder showed the absence of compound grains. The bulk of

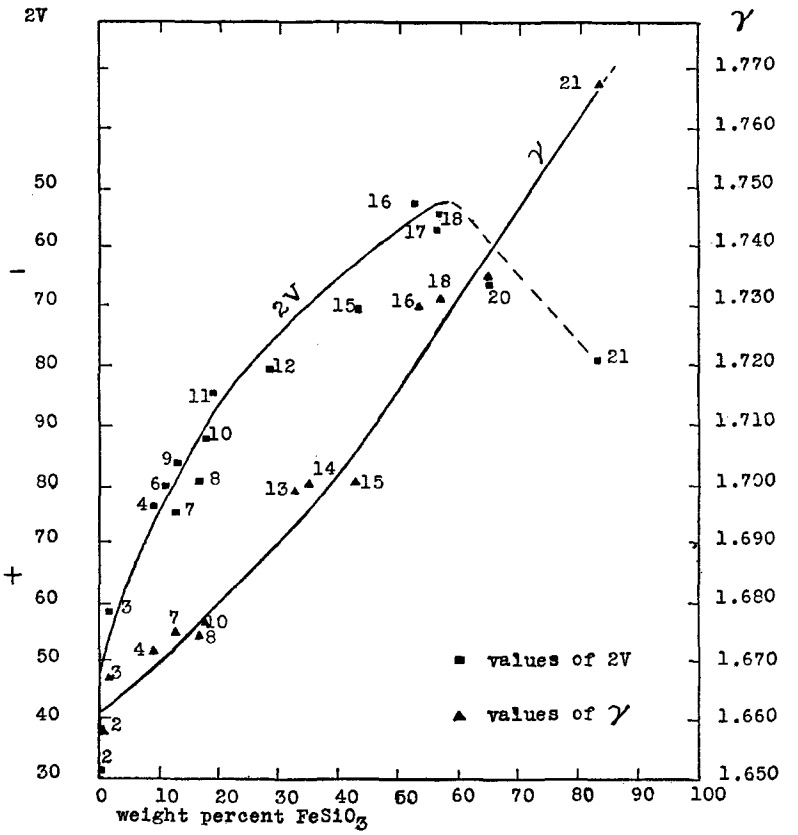

FIG. 1. Variation of the optic axial angle (2V) and the refractive index (γ) with $FeSiO_3$ content in the orthorhombic pyroxenes. The numbers refer to table II.

the felspar and quartz was removed by a preliminary separation in bromoform. The heavy crop, containing the hypersthene with some magnetite, garnet, hornblende, apatite, and zircon, was suspended in Clerici's solution (sp. gr. about 4·0). By careful addition of small quantities of distilled water, the density of the liquid was so lowered that successive crops of minerals sank and were removed. Those crops consisting principally of hypersthene were repeatedly subjected

to this process, until examination under the microscope revealed them to be uncontaminated. The hypersthene was washed with distilled water until free from all trace of thallium. Quantities varying from 2¾ to nearly 4 grams were available for chemical analysis.

The refractive indices were determined by the immersion method in sodium-light at room-temperature, using mixtures of α-bromonaphthalene and methylene iodide. An Abbe refractometer with hemisphere n 1·7497 was used to measure the refractive index of the mixture. At least five determinations were made on each specimen.

In measuring 2V a Leitz universal-stage with segments n 1·649 was employed. The direct method of observing the emergence of an optic axis was followed with all the precautions against error detailed in the textbooks.[1] The values quoted in table I are the mean of at least six determinations in each case.

Table II below sets out the optic data of the enstatite-hypersthene

TABLE II. *Collected data for enstatite-hypersthene series.*

No.	Locality.	(Fe, Mn) SiO_3 %.	Opt. sign.	2V.	α.	β.	γ.	Sp. gr.
1.	Synthetic 'enstatite' ...	0	+	44–70°	1·640	1·646	1·652	3·174–3·876
2.	Bishopville, South Carolina (meteorite)	0	+	31	1·650	1·653	1·658	—
3.	Blithfield, Ontario (meteorite)	1·8	+	58	1·657	1·660	1·667	—
4.	Almeklovdal, Norway ...	9·4	+	76	1·660	1·665	1·671	3·274
5.	Diamond washings, S. Africa	9·2	+	74	—	1·669	1·675	3·20
6.	Fiskernäss, Greenland ...	10·8	+	79	—	1·650	—	3·21
7.	Espedalen, Norway ...	12·4	+	*c.* 75	1·666	1·670	1·675	3·254
8.	Loderio, Tessin, Switzerland	16·4	+	*c.* 80	1·662	1·667	1·674	3·232
9.	Kapfenstein, Styria ...	12·7	+	83	—	1·67	—	3·436
10.	Stora Ålke, Västerbotten, Sweden	17·9	+	*c.* 87	1·665	1·670	1·676	3·301
11.	Lauterbach, Hesse ...	19·2	−	85	—	1·685	—	3·34
12.	Farsund, Norway	28·8	−	81	—	1·695	—	3·351
13.	Franklin, North Carolina ...	33·3	−	—	1·685	1·696	1·699	—
14.	Nain, Labrador	34·2	−	—	1·690	—	1·700	3·415
15.	Arnage, Aberdeenshire (*a*)	43·7	−	71	—	—	1·703	3·49
16.	Quilquox, Aberdeenshire (*b*)	52·8	−	53	—	—	1·730	3·53
17.	Mt. Pelée, Martinique ...	56·7	−	58	—	—	—	3·54
18.	Quilquox, Aberdeenshire (*c*)	57·2	−	55	—	—	1·731	3·56
19.	Warrambu, W. Australia ...	66·5	−	—	1·654	1·664	1·678	3·45
20.	Easter Saphock, Aberdeenshire (*d*)	65·7	−	67	—	—	1·735	3·58
21.	Tunaberg, Sweden ...	83·5	−	80	1·750	1·760	1·768	3·85

[1] e.g. M. Berek, Universaldrehtischmethoden. Berlin, 1924, pp. 31–36, 50–64.

1. E. T. Allen, F. E. Wright, and J. K. Clement, Amer. Journ. Sci., 1906, ser. 4, vol. 22, p. 385. The synthetic material here described as enstatite has been shown not to yield the X-ray powder pattern of that material (N. L. Bowen and J. F. Schairer, Amer. Journ. Sci., 1935, ser. 5, vol. 29, p. 165).
2. E. T. Allen, F. E. Wright, and J. K. Clement, loc. cit., p. 385. The optic axial angle determined by Becke's method. The mineral contained inclusions of metallic iron.
3. R. A. A. Johnston and M. F. Connor, Trans. Roy. Soc. Canada, 1922, vol. 16, sect. 4, p. 187. The limits of the optical determinations are rather wide.
4. K. Johannson, Zeits. Kryst. Min., 1894, vol. 23, p. 152. The analysed material contained some amphibole.
5. H. L. Bowman, Min. Mag., 1900, vol. 12, p. 349. Clear grains from the diamond washings, probably from the Kimberley district. The analysis sums high.
6. J. Lorenzen, Medd. om Grønland, 1893, vol. 7, p. 24. Material analysed and described by this writer as 'kupfferite' was optically investigated by N. V. Ussing (Zeits. Kryst. Min., 1889, vol. 15, p. 615) and shown to be enstatite. The analysed material contained clinopyroxene.
7. H. S. Washington and H. E. Merwin, Amer. Min., 1923, vol. 8, p. 63 [M.A. 2–305]. The optic axial angle is given as approximate, the probable error not being stated.
8. F. de Quervain, Schweiz. Min. Petr. Mitt., 1934, vol. 14, p. 447 [M.A. 6–119]. Two analyses are given; the second, on pure material, does not show Al_2O_3, Fe_2O_3, CaO, or H_2O. The optic axial angle is approximate.
9. J. Schiller, Tsch. Min. Petr. Mitt., 1905, vol. 24, p. 307. The optic axial angle was measured in Schneider's rotation apparatus, assuming β of the mineral to be 1·67.
10. E. Grip, Bull. Geol. Inst. Univ. Upsala, 1932, vol. 23, p. 171 [M.A. 5–137]. The enstatite, which is often altered, occurs in serpentine lenses in a zoisite-amphibolite. Fresh material was used for the analysis.
11. A. Des Cloizeaux, Manuel de Minéralogie, Paris, 1874, vol. 2, pt. 1, p. xvi. The optic data are for red light.
12. A. Des Cloizeaux, Mém. Acad. Sci. Paris, 1867, vol. 18, p. 576. The optic data are for red light. The high (9·11) percentage of alumina shown in the analysis is remarkable.
13. E. P. Henderson, Amer. Min., 1931, vol. 16, p. 563 [M.A. 5–76]. No optic axial angle is given. The material contained small inclusions of biotite.
14. H. S. Washington and H. E. Merwin, loc. cit., 1923, p. 63. The analysed mineral contained intergrowths of augite, estimated at 5–10 % volume.
15. See (*a*) table I above.
16. See (*b*) table I above.
17. A. Lacroix, La Montagne Pelée et ses éruptions, Paris, 1904, p. 506. The hypersthene was separated by heavy liquids and hydrofluoric acid from an andesite.
18. See (*c*) table I above.
19. E. S. Simpson, Journ. Roy. Soc. W. Australia, 1930, vol. 16, p. 25 [M.A. 4–346]. The large cleavage pieces of hypersthene contained about 10 % of impurities, chiefly magnetite, not removed before analysis.

20. See (*d*) table I above.
21. N. SUNDIUS, Årsb. Sveriges Geol. Undersök., 1932, vol. 26, p. 1 [M.A. 6-118]. The high iron content and refractive indices with large optic axial angle are noteworthy.

series collected from the literature, as having been determined upon analysed specimens. In collecting the optical data, only 2V and γ have been considered, and any publication not giving at least one of these quantities has been ignored. The petrographer who desires to know the approximate composition of an enstatite or hypersthene can determine the index γ rapidly by the immersion method, while a search for fragments yielding the other principal indices would take much time.

In addition to the foregoing there are several analyses extant which have been made on material reported from the same locality as that on which optical determinations have been made. As some of these have been used in constructing diagrams of variation, it is necessary to consider them, although none have been employed in fig. 1. They are set out in table III, and some notes on them are offered below.

TABLE III. *Uncertain data for enstatite-hypersthene series.*

No.	Locality.	(Fe,Mn) SiO_3 %.	Opt. sign.	Optic axial angle.	α.	β.	γ.
22.	Zdjar Berg, Moravia ...	5·6	+	(*a*) 2V 69°		1·639	—
				(*b*)	1·656	1·659	1·665
23.	Kupferberg, Bavaria ...	13·3	+	2V 82	—	1·668	—
24.	Balsfjord, Norway	15·0	+	2H 112	—	—	—
25.	Kraubat, Styria	18·6	—	2H 106			
26.	Labrador	31·9	—	(*a*) 2V 50	1·692	1·702	1·705
				(*b*) 2V 72	—	1·69	—
27.	St. Paul's Island, Labrador	41·0	—		1·715	—	1·727
28.	Aranyer Berg, Hungary ...	23·9	—	2H 84	—	—	—
29.	Krakatoa	56·7	—	2H 79	—	—	—
30.	Mt. Dore, France	56·0	—	(*a*) 2E 101			
				(*b*) 2H 59			
				(*c*) 2V 62 ± 5	1·696	1·709	1·712
				(*d*) ...	1·704–1·707		1·720–1·723

22. A. KENNGOTT, Sitzungsber. Akad. Wiss. Wien, 1855, vol. 16, p. 162, gave a chemical analysis but no optical data when he established the new species enstatite on material from this locality. Des Cloizeaux (Man. Min., 1862, vol. 1, p. 540) determined 2V and $\beta(a)$, while C. Hintze (Handbuch Min., 1897, vol. 2, p. 964) quotes the indices obtained by Mallard (*b*).

23. C. W. GÜMBEL, Geogn. Beschr. Bayern, 1879, vol. 3, p. 157, published an analysis by von Ammon of material occurring in serpentine. Optical data for red light are by Des Cloizeaux (Mém. Acad. Sci. Paris, 1867, vol. 18, p. 555).

24. H. ROSENBUSCH, Neues Jahrb. Min., 1884, vol. 1, p. 195. 2H is given for yellow light. An analysis was made on 0·82 g. of somewhat impure material.

25. H. ROSENBUSCH, Mikr. Phys., 1905, vol. 1, pt. 2, p. 147, associated G. Tschermak's determination of 2H with an analysis by Regnault, Ann. Mines, 1838, vol. 14, pt. 3, p. 147. Another analysis is by H. Höfer, Jahrb. Geol. Reichsanstalt, Wien, 1866, vol. 16, p. 445.

26. M. LÉVY and A. LACROIX, Minéraux des roches, 1888, p. 261, publish optic data for a hypersthene from Labrador (*a*). In A. N. Winchell, loc. cit., p. 507, fig. 1, no. 15, the index β of this determination is used with a 2V differing from Lévy and Lacroix's value, and is coupled with A. Remele's analysis of hypersthene from St. Paul's Island (Ber. Deutsch. Chem. Gesell., 1868, vol. 1, p. 143).

27. J. E. WOLFF, in Rosenbusch, Mikr. Phys., 1905, vol. 1, pt. 2, p. 147, gives values for α and γ for hypersthene from St. Paul's Island, Labrador. A. N. Winchell, loc. cit., fig. 1, no. 17, uses a value (1·723) for γ ascribed to J. E. Wolff, and 2V obtained by Des Cloizeaux on material from Labrador (26*b*) (Mém. Acad. Sci. Paris, 1867, vol. 18, p. 573). These are joined with the analysis by A. Damour (Ann. Mines, 1844, vol. 4, p. 157).

28. A. KOCH, Zeits. Kryst. Min., 1879, vol. 3, p. 307, gave an analysis of a new mineral 'szaboite', which showed a high content of Fe_2O_3. J. A. Krenner, Zeits. Kryst. Min., 1884, vol. 9, p. 255, considered the analysis to be in error, and gave a value for 2H. F. Koch, Zeits. Kryst. Min., 1885, vol. 10, p. 99, published a new analysis, showing the presence of FeO, MgO, and CaO, and suggested the identity of the mineral with hypersthene. The iron silicate content given here is calculated from F. Koch's analysis.

29. J. A. KRENNER, Zeits. Kryst. Min., 1885, vol. 10, p. 101. This determination of 2H and the analysis (J. W. Retgers, Zeits. Kryst. Min., 1886, vol. 11, p. 418) were made on material isolated from volcanic dust falling in different localities.

30. A. DES CLOIZEAUX, Man. Min., 1874, vol. 2, pt. 1, p. xviii, gives values of 2E for three wave-lengths (*a*). J. A. Krenner, Zeits. Kryst. Min., 1884, vol. 9, p. 262, gives 2H (*b*). Recent determinations by B. E. Warren and D. I. Modell, Zeits. Krist., 1930, vol. 75, p. 1 (*c*), and by N. L. Bowen and J. F. Schairer, Amer. Journ. Sci., 1935, ser. 5, vol. 29, p. 151 (*d*), give different values. The only analysis is an old one by Laurent showing 5·2% MnO.

A consideration of the above notes shows that much of the data which we possess is not of the first quality. In six out of the twenty undoubted orthorhombic pyroxenes of table II impurities were present in the material analysed. In five cases γ and in three cases 2V were not determined, while in a further four 2V is doubtful. Several analyses do not show Fe_2O_3, MnO, or CaO, although it is probable

that these oxides occur to some extent in all natural enstatites and hypersthenes.

In constructing the diagram (fig. 1) it was found that more regularity was obtained when all the iron in the analyses was calculated as FeO, and MnO, if present, added. $MgSiO_3$ and $CaSiO_3$ were calculated separately and combined. Alumina, titania, alkalis, &c., were neglected; it is certain that their influence on the optical properties is small.

From the figure it is seen that three considerable ranges of iron silicate content are unrepresented by optical measurements, i.e. between about 20–30, 34–44, and 65–84 % $FeSiO_3$. While determinations in the lower parts would give more precision to the curves, yet additional data for iron-rich hypersthenes would be of the greatest interest. In the case of the curve of 2V, it is probable that a minimum is reached at about 55–60 % $FeSiO_3$, after which 2V tends once more toward 90°, although until more data becomes available it is not possible to draw any definite line.

In view of the imperfect state of the data it is clear that no high degree of accuracy can be claimed for these curves. It seems probable that, until synthetic material suitable for accurate optical investigation can be prepared, considerable uncertainty will attach to our knowledge of the variation of the series.

In conclusion, I wish to thank Professor H. H. Read, who suggested this study, Dr. A. W. Groves who made the chemical analyses, and the Government Grant Committee of the Royal Society for a grant defraying the cost of the analyses.