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## CHEMICAL COMPOSITION AND OPTICAL PROPERTIES OF COMMON CLINOPYROXENES\*

### PART I.

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#### ABSTRACT

A study of common clinopyroxenes is presented including 40 new chemical analyses. The optical properties of these pyroxenes have been systematically determined with somewhat better accuracy than normally attained. Techniques for determination of these properties are discussed and their probable accuracy estimated. The results of the study are graphically presented on a series of curves. The recalculation of the chemical analyses in terms of a theoretical pyroxene formula and the distribution of various ions in the pyroxene structure are discussed.

#### INTRODUCTION

The present investigation is aimed at determining the chemical composition and optical properties of such common clinopyroxenes as the petrologist is likely to find in the course of his work. Only rarely do common pyroxenes occur as good crystals easily separable from their containing rocks. Partly for this reason the literature contains a large proportion of analyses of peculiar and unusual varieties of pyroxenes. Of the several hundred chemical analyses of pyroxenes available many are old and the great majority of poor quality by present standards. Aside from inaccuracies of the actual chemical analyses, the purity of the material analyzed is open to question. Furthermore, only a small percentage of those analyzed are accompanied by descriptions of optical properties and the accuracy of the optical work may be doubtful. After a study of the literature very little material was found which could be used in the present study.

Optical property curves for clinopyroxenes have been published by Winchell (1923, 1935) and by Tomita (1934).† The latter were revised

\* Princeton investigations of rock forming minerals, No. 4.

† Niggli (1943) has an exceedingly useful compilation of analyses of pyroxenes from igneous rocks with such optical data as was available.

by Wager and Deer (1938). All of these compilations are to a large extent based on data from synthetic pyroxenes which appear in the works of Bowen, Schairer and Posnjak of the Carnegie Geophysical Laboratory. Use of the same data has been made by the present writer to obtain the general trend of the curves into those areas where natural clinopyroxenes do not occur or have not been found.

#### ACKNOWLEDGMENTS

About three-quarters of this investigation was financed by research funds of the Department of Geology, Princeton University, and the remaining quarter by a grant from the Geological Society of America.

Almost all of the new chemical analyses are the work of Lee C. Peck and R. B. Ellestad. The skill and care with which these analyses have been made, in itself, represents a major contribution to the study of this mineral group. Acknowledgment is also due to the Rock Analysis Laboratory of the University of Minnesota, directed until recently by F. F. Grout, where Peck and Ellestad carried on their work. Without such a laboratory, this type of research work would not be possible.

Two samples for analysis from the Duluth area were obtained from F. F. Grout and one from A. N. Winchell. E. S. Larsen, Jr., supplied a small sample of the analyzed hedenbergite from the Percy Quadrangle, New Hampshire, previously described by Chapman and Williams (1935). H. E. Merwin gave the writer some of the hedenbergite analyzed by E. S. Shepherd (Wyckoff, Merwin and Washington, 1925). A. F. Hallimond sent the writer some of his analyzed "uniaxial augite" (1914).

A dozen of the Adirondack clinopyroxene analyses are a by-product of a study being carried on by A. F. Buddington and were kindly lent for the purposes of this study. These pyroxenes come from analyzed rocks representative of average rock types within given suites from that area and thus have a certain added geological significance. If, however, the purpose had been to pick the best material for pyroxene separations and analyses, some of these specimens would not have been chosen. Some of them are slightly altered and others have a minute amount of included impurities.

Five analyses of clinopyroxenes from skarn rocks are taken from the unpublished Ph.D. thesis of B. F. Leonard which deals with magnetite ore bodies of the Adirondacks. The writer is much indebted to Leonard for permission to use these analyses. Discussion of these analyses will be undertaken jointly with Leonard in a subsequent paper.

One augite analysis is from the unpublished thesis of Preston Hotz and another was contributed by A. W. Postel, both of which are gratefully acknowledged.

Thanks are due the U. S. Geological Survey for allowing the use of analysis number 37 by Norman Davidson and for the contributions to this work made by members of the Survey, Leonard, Hotz, and Postel.

The writer wishes to acknowledge his indebtedness to C. S. Hurlbut, C. Frondel, and B. F. Leonard for critical reading of the manuscript and for the many useful suggestions they made.

#### NOMENCLATURE

A nomenclature to describe common clinopyroxenes was outlined by the writer (1941) and is adhered to in this paper with the slight modifications indicated below. The term "endiopside," to describe clinopyroxenes with more magnesian and less calcic than diopside, should be dropped. The need for the term seems doubtful since pyroxenes of such a composition are rare; and since those that are found lie close to the augite field, they may as well be called augites with an appropriate adjectival modifier.

Benson (1944) suggested the term "subcalcic augite" to apply to that portion of the clinopyroxene composition field between augite ( $Wo < 25$ ) and pigeonite ( $Wo > 15$ ) which he correlated with optic angles of greater than  $45^\circ$  and less than  $30^\circ$ , respectively (Benson, Table IX). The writer would also adopt this term if pyroxenes are found which fall within the above composition range. Benson believes such pyroxenes are common, basing his estimate of  $Wo$  content on optic angle measurements. The present revision of the optic angle-composition curves indicates that the so-called subcalcic augites, which Benson was dealing with in his paper, all probably lie within his (Benson's) composition field of augite and are probably some 10%, or more, richer in  $Wo$  than he estimated. Though the writer believes that subcalcic augite is very rare or non-existent, it may occur, inasmuch as the optic angle-composition curves are not always reliable. Minor constituents or peculiarities in conditions of crystallization may affect the size of  $2V$ .

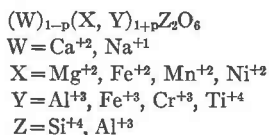
As a further modification it is proposed that the use of  $Wo$  (wollastonite),  $En$  (enstatite) and  $Fs$  (ferrosilite) be discontinued and  $Ca$ ,  $Mg$  and  $Fe$  (% atoms) be substituted at the three corners of the composition diagram. This changes the diagram in no way, but eliminates the concept of mixtures of end member "molecules" which is inconsistent with present ideas on the actual occurrence of the constituents in the crystal structure. It is also recommended because it is convenient to add  $Fe^{+3}$  to  $Fe^{+2}$  in the optical property-composition curves since this gives a better approximation of the bulk composition than curves which neglect  $Fe^{+3}$ . Inasmuch as  $Fe^{+3}$  would not be present in theoretical  $Fs$ , it is an additional argument in favor of dropping  $Wo$ ,  $En$  and  $Fs$ . Similarly the sub-

stitution of Al for Si, as well as other such replacements in the structure, is also better taken care of by eliminating the old molecule concept.

#### CHEMICAL CONSTITUTION AND THEORETICAL FORMULA OF CLINOPYROXENES

The structure of diopside was one of the first silicates to be worked out by *x*-ray methods (Warren and Lawrence, 1928) and its similarity to other clinopyroxenes was demonstrated by several investigators. The general formula for the pyroxene group suggested by Berman (1937) is here accepted with slight modification.

The formula for any pyroxene may be written as follows:



Four such units would be required by the monoclinic cell and eight by the orthorhombic. In the above formula *p* would be zero or close to it for the diopside-hedenbergite or acmite-jadeite series and would be 1, or close to it, for the orthorhombic pyroxenes and pigeonites.

No doubt many other less common ions enter the pyroxene structure and probably some could enter in large amounts if the geological environment provided them. The above-mentioned ions are the only important ones in the rock-forming pyroxenes. Though the orthorhombic pyroxenes have relatively few of the ions of the *W* and *Y* groups such ions are present in small but appreciable amounts so that the formula as given is readily adaptable to either the orthorhombic or monoclinic members of the group. The pyroxene, spodumene,  $LiAlSi_2O_6$ , may be mentioned in passing though it plays no part in the present study since varieties intermediate between it and the rock-forming clinopyroxenes are not known.

The *W*, *X* and *Y* ions are in octahedral positions (coordination number 6) with respect to surrounding  $O^{-2}$  ions. In the *Z* group the  $Si^{+4}$  and the  $Al^{+3}$  ions are in tetrahedral positions (coordination number 4) with respect to surrounding  $O^{-2}$  ions. There is no evidence suggesting that  $Fe^{+3}$  or any other ion than  $Al^{+3}$  may substitute for  $Si^{+4}$  in appreciable amounts.

The simplest clinopyroxene would be of the type  $Ca (Mg, Fe) Si_2O_6$ . The substitution of  $Ni^{+2}$  for  $Mg^{+2}$  or  $Mn^{+2}$  for  $Fe^{+2}$  represents an easily understandable degree of variation. Where ions of different charge enter into the structure, these must be balanced electrically by other ions with compensatory charges. The distribution of various sorts of ions must fulfill the requirements set forth in Table 1 below as governed by the following rules: (1) The sum of the ionic charges in groups *A* and *B* of

Table 1 must add up to +12 to balance the -12 charge of the six O<sup>-2</sup> ions. (2) *A* and *B* must each be represented by two ions to fill the required positions in the structure.

TABLE 1  
Distribution of electrical charge                      Examples

	A		B	Examples				
	W	X, Y	Z	O	W	X, Y	Z	O
(1)	+2	+2	+8	-12	Ca <sup>+2</sup>	Mg <sup>+2</sup>	2Si <sup>+4</sup>	O
(2)	+1	+3	+8	-12	Na <sup>+1</sup>	Fe <sup>+3</sup>	2Si <sup>+4</sup>	O
(3)	+2	+4	+6	-12	Ca <sup>+2</sup>	Ti <sup>+4</sup>	2Al <sup>+3</sup>	O
(4)	+2	+3	+7	-12	Ca <sup>+2</sup>	Al <sup>+3</sup>	Al <sup>+3</sup> , Si <sup>+4</sup>	O

The above examples are not to be construed as end members of pyroxene series though (1) and (2) happen to be. Al can only substitute for Si to a limited extent in the structure. Since the Al<sup>+3</sup> ion is much larger than the Si<sup>+4</sup> ion, this substitution is probably limited by the degree to which the pyroxene structure may be stretched or distorted to accommodate the larger ion. The largest amount of Al substituting for Si in any pyroxene thus far analyzed is 27.6% in a pyroxene from a xenolith described by Dixon and Kennedy (1933). Very few analyses have been made showing Al replacing Si to an extent greater than 12%. Recalculation of a large number of analyses of titaniferous pyroxenes indicates that example (3) above is the normal manner by which the +4 charge of the Ti ion is accommodated. The only other way by which it might be done is by substituting two monovalent ions such as Na for two divalent ions such as Ca for each Ti entering the structure. Search for analyses to substantiate such a relationship proved negative. Neptunite of the pyroxenoid group, however, might have such combination.

#### EXPLANATION OF CHEMICAL ANALYSIS TABLES

In handling the chemical analyses the weight per cents of the oxides were first converted to molecular ratios and then to ratios of ions. To save space in the tables the molecular ratios column was omitted since it could easily be derived from the atomic ratios by inspection if there were need therefor. The ions with +2 charge can readily be combined in a 2:2 ratio with the Si ions to form pyroxene molecules. However, the +1, +3 and +4 ions must be so distributed that the charges compensate and the correct proportion of ions is obtained in each group as explained above. This operation is performed in the tables and is accomplished in the following manner: (1) Na ions are combined with Cr ions if present to

form  $\text{NaCrSi}_2\text{O}_6$ ; (2) Remaining Na ions are combined with  $\text{Fe}^{+3}$  to form  $\text{NaFeSi}_2\text{O}_6$ ; (3) Na ions remaining after the above steps are combined similarly with Al ions; (4) For each Ti ion two Al ions are placed in the Z group substituting for Si; (5) If Cr ions are in excess of Na ions and are still to be accounted for, each Cr ion is combined with one Al ion placed in the Z group; (6) After these five steps some Al is almost invariably present. This is split into two equal parts one going into the Y group and one into the Z group. If the chemical analysis is accurate and the material analyzed pure, the total number of ions in the Z group (Si+Al) will come within about 2 per cent of equaling the total number of ions in the  $W+X+Y$  groups, and these will be in the ratio of 2:2:6 as compared to the total number of O ions. This is tested by dividing the total O ions by six and dividing the resulting figure into the number of ions in the Z group and into the sum of the ions in the  $W+X+Y$  groups. The result of these two divisions should equal  $2.00 \pm .02$  in a completely satisfactory analysis. The common practice in the literature of splitting the Al between the Z group and the  $W+X+Y$  groups in that proportion will make their ratio 2:2 if possible, conveniently compensates error in the analysis and is contrary to the rule which requires balancing of electrical charge.

Since the optical property curves are based on the ratio of Ca:Mg:Fe atoms, the three major variables in the pyroxenes under consideration, this ratio recalculated to 100% is given at the bottom of each table. In this calculation  $\text{Fe}^{+2}$  and  $\text{Fe}^{+3}$  are added together plus the small amount of Mn normally present. If Ni is present it is added to the Mg. The per cent Al replacing Si in the Z group is also indicated at the bottom of the table since this represents the fourth most important variable.

In the recalculation of the analyses  $\text{H}_2\text{O}$  is omitted since its constituents probably do not enter the pyroxene structure. In the few cases where  $\text{H}_2\text{O}$  is present in appreciable amount, it probably represents an alteration product and is best neglected in the recalculation.

#### SEPARATIONS

The major part of all separations was performed with the Frantz Iso-dynamic Magnetic Separator. In those cases where a completely pure separate was not obtained, heavy liquids were resorted to for final purification. If this was not successful the sample was discarded as being unsatisfactory.

Rocks containing the pyroxene to be separated were crushed to pass through a 100 mesh sieve or, for finer grained rocks, a 200 mesh sieve. The fines and adhering dust were removed by washing and decanting. In a few cases limonite stain or adhering grains of chlorite or serpentine

were removed by boiling for ten minutes in dilute acid (HCl). Magnetite, or grains including magnetite, and iron filings from the mortar were removed with an Alnico bar magnet before introducing the sample into the magnetic separator.

In slowly cooled rocks where crystals exhibit a minimum amount of zoning magnetic separations are as a rule excellent. In hypersthene gabbros, for example, the pyroxenes can be separated cleanly from the rock and the hypersthene and augite cleanly from one another. In the more quickly cooled diabbases, on the other hand, it is exceedingly difficult to separate the augite from the pigeonite since both of these minerals are zoned and their ranges of magnetic susceptibility overlap almost completely. Since the density ranges of these two minerals also overlap, the best that could be done was to produce an augite and a pigeonite concentrate, analyze both, and from the proportions present in each sample calculate the compositions of the pure minerals.

#### DETERMINATION OF PROPERTIES

About two weeks were spent on each of the analyzed pyroxenes, determining the various optical properties. A considerable portion of this time was used in attempts to develop better or easier methods of measurement. In the work thus far completed the accuracy of certain measurements could be improved, but it did not seem warranted to hold up publication any longer to effect further refinements. In many cases the measurements of  $Z/\wedge c$  are unsatisfactory and no reliable method was found for determining this value for many of the samples. Similarly, density determinations on powders showed so large a degree of fluctuation on repeated measurements that most of them were discarded as valueless. Measurements of dispersion gave promise of supplying usable criteria to distinguish the presence of, and possibly the amounts of, certain minor constituents but this study has not yet been completed. Observations on measurements of specific properties are summarized below.

##### (a) *Indices of refraction.*

All pyroxenes when crushed exhibit a small to moderate percentage of pinacoidal parting tablets. For all clinopyroxenes, except pigeonites, the {100} parting tablets were used to determine the  $V$  index accurately. These are easily recognized with practice and can be spotted quickly from among the large number of grains on the slide. They have low birefringence since an optic axis emerges from them at approximately  $20^\circ$  from the vertical. If bounded by cleavages, or other partings, they exhibit parallel extinction. The orientation of the grain is checked in convergent light. An off-center optic axis figure should result. The stage is rotated

until the isogyre is east-west. If it exactly splits the field in two then the optic plane is vertical and  $Y$ , the optic normal, is north-south. The grain is now in position to determine the  $Y$  index. For pigeonites with the optic plane  $\perp$   $\{010\}$  it is necessary to use the  $\{010\}$  parting tablets and determine  $Y$  or  $Z$ , checking orientation against the observation of a centered  $Bx_0$  figure, or either the  $\{100\}$  or  $\{001\}$  parting tablets and determine  $X$ .

Though  $\{110\}$  cleavage fragments are very common they give unreliable results since exact orientation cannot be checked by the interference figure, and many of them are tilted an unknown amount from the  $\{110\}$  plane.

The observations were made in white light and checked when close with a sodium vapor lamp. The light was passed through an infra-red filter to remove heat since errors resulting from not knowing the temperature of the immersion liquid are the largest potential source of error. Temperatures were checked by swinging a thermometer into position under the objective before and after observation.

Ordinary immersion methods were used with a closely spaced and carefully calibrated set of index liquids. Observations were made at different times on the same day or on different days when room temperature had changed sufficiently to split the spacing between index liquids. The index of the grain to be determined was bracketed between two oils about .001 apart. The normal accuracy for index determinations is estimated to be  $\pm .0005$  except for material of variable composition. For the latter it is  $\pm .001$ .

It was found to be both easier and more accurate to determine the other two indices by calculations from birefringence and optic angle determinations described below. For this purpose Wright's curve was used (1911, plate 9).

(b) *Birefringence.*

Birefringence was determined with a Berek compensator on specially prepared slides. These were made as follows: A small amount of the mineral was mixed with an equal amount of fine quartz sand. A bakelite mount such as commonly used for polished section work was then made in a press (150° C. and 4000 lbs./sq. in.)\* One end of the mount cylinder was ground on a very flat steel lap with fine abrasive so that a semi-polished, very flat surface resulted. This surface was cemented to a glass slide and ground to .06 mm. thickness and then flattened and cut to  $\pm .04$  mm. on the same steel lap as mentioned above. This gave two very flat surfaces which were almost if not quite parallel. Thicknesses of four or

\* Balsam mounts were not very satisfactory since it proved difficult to get a very flat surface on them. This is attributed to the relative softness of balsam.



five quartz grains surrounding the pyroxene to be measured were then determined by measuring path difference with the Berek compensator after the  $c$  axis had been made horizontal on the universal stage. Path difference in the quartz was converted directly to thickness by means of a curve. The thickness value was then multiplied by the cosine of angle of tilt of the stage corrected for indices of refraction of quartz and the hemispheres thus giving true thickness of the slide at the point of observation. The results give the thickness of the pyroxene grain to approximately  $\pm .0001$  mm. and birefringence of a pyroxene grain can ordinarily be measured to  $\pm .0002$ . This is more accurate and much less tedious than measuring the other indices of refraction. A number of the pyroxenes measured had somewhat variable birefringence necessitating from five to twenty observations to obtain a satisfactory average for the sample.

In choosing pyroxene grains for measurement only those were selected which happened to have the optic normal nearly vertical in the slide so that there would be only a small amount of correction for tilt. A fair number of such grains can be found since they represent the  $\{010\}$  parting tablets which were lying on this face when the mount was made.

The Berek compensator is of little practical use on an ordinary thin section because the thickness can normally not be measured within an accuracy of better than  $\pm 10\%$ . Ordinarily thin sections vary rather erratically in thickness from grain to grain as well as across the slide, as a whole, so that even if they contain quartz on which Berek measurements can be made, the accuracy nevertheless is low. Measuring thickness by various focusing methods commonly involves errors from  $10\%$  to  $40\%$ . Unless special slides are made the Berek compensator gives little better accuracy than merely estimating birefringence by observing the interference color.

### (c) Optic Angle.

All optic angle measurements were made on the universal stage on grains which had  $Bx_a$  near vertical and by direct rotation from one optic axis to the other. It appears that this observation for optic angles ranging from  $20^\circ$  to  $60^\circ$  is more accurate than most authors state. The accuracy after index corrections is certainly better than  $\pm 0.5^\circ$  and probably better than  $\pm 0.3^\circ$  judging from the variations obtained by repeated measurements on the same grain, or on numerous grains of uniform material. On the other hand, measurements of the optic angle by rotating from one optic axis to a bisectrix are apparently less accurate than one would suppose from the literature. Errors of five degrees are fairly common. In fact it appears that the orientation of a grain on the universal stage to bring  $X$ ,  $Y$  or  $Z$  to the vertical position cannot ordinarily be done with the

accuracy usually attributed to such orientation procedures (see Turner, 1942).

(d) *Dispersion.*

Dispersion of the optic axes was noted and recorded during the optic angle measurements. It is quite evident upon rotation of the stage through an optic axis even when not observable at all in the interference figure. Where the dispersion was just perceptible it was called weak, where quite obvious but too small to measure accurately, it was called moderate, and where greater than approximately  $0.5^\circ$ , it was called strong. In most cases the dispersion is inclined. The optic axis emerging in  $\{001\}$  not far from the  $c$  axis is labelled "B" and the other emerging in  $\{100\}$  is labeled "A". (Fig. 1A) The dispersion on each axis is given.

The dispersion of the indices of refraction, birefringence and  $Z \wedge c$  have not been measured but represent a fruitful field for further investigation.

(e)  $Z \wedge c$ .

Since most common clinopyroxenes have an extinction angle,  $Z \wedge c$ , between  $40^\circ$  and  $46^\circ$ , an accuracy of at least  $\pm 1^\circ$  is necessary if the observations are to have any determinative value. Even so their value is comparatively small. Reasonably reliable values can be obtained on twinned crystals by following a procedure such as suggested by Nemoto (1938) and Turner (1940). Analogous methods were used by the writer and are described below. On untwinned clinopyroxene, as a rule, the value cannot be determined with the required accuracy.

To escape the comparatively large possible errors in bringing  $X$  or  $Z$  to coincidence with the microscope axis, these positions were, as a rule, not measured nor were such physical discontinuities as cleavages or twinning planes. Choosing only twinned crystals which had their optic planes nearly vertical ( $\pm 20^\circ$ ) by rotation about  $Y (=b)$ , the angles between two optic axes of one twin and one of the second twin were measured as well as the positions equivalent to the pole of  $\{100\}$  and the direction of the  $c$  axis. The latter two positions can be found by rotation about  $Y$  to the point where the birefringence of the twins exactly matches. Thus the angles  $A_1 \wedge B_1 (=2V)$ ,  $B_1 \wedge B_2$  or  $A_1 \wedge A_2$  and either the angles  $A_1 \wedge \{100\}$ ,  $A_2 \wedge \{100\}$  or  $B_1 \wedge c$ ,  $B_2 \wedge c$  can be measured on almost any such favorably oriented grain. In the special case where  $Bx_a$  is vertical, the angles  $B_1 \wedge c$ ,  $A_1 \wedge B_1$  and  $A_1 \wedge \{100\}$  can be observed. Three of these angles will ordinarily require tilts of  $0^\circ$ – $45^\circ$  and the one or perhaps two other angles will require tilts of  $45^\circ$ – $55^\circ$ . Higher tilts result in unacceptable errors particularly if the index of the mineral is greatly different than

the index of the glass hemispheres. Those angles between  $45^\circ$  and  $55^\circ$  should be marked as having lower accuracy than those below  $45^\circ$ . Normally about ten such twinned crystals were measured and the results averaged giving greater weight to the angles with lower tilt. From such a series of measurements all angles in the plane  $\parallel \{100\}$  can be observed

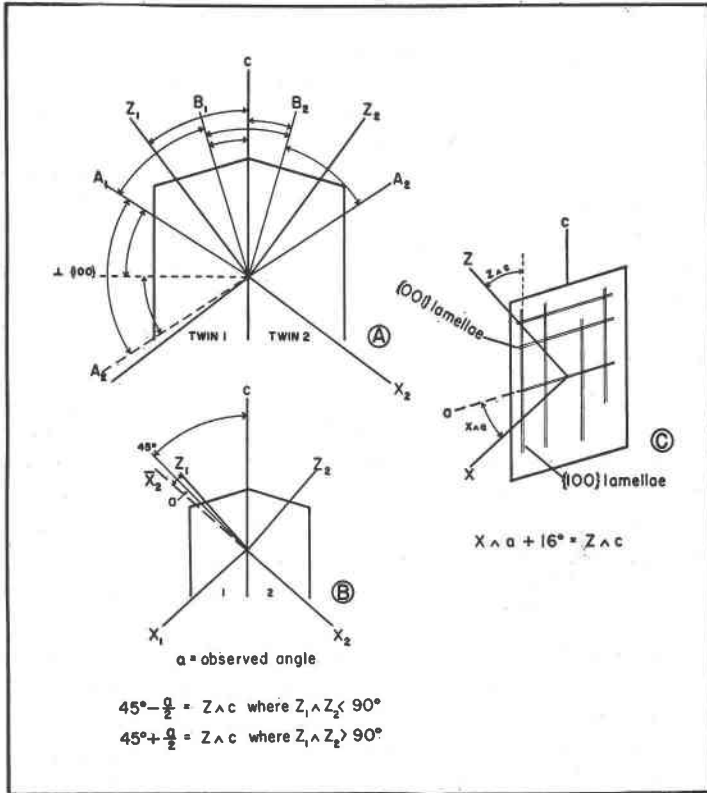


FIG. 1. Measurement of  $Z/c$ .

or calculated with accuracy estimated to be better than  $1^\circ$  and probably good to  $\pm 0.5^\circ$ .  $Z/c$  and  $2V$  are thus determined simultaneously.

In powders twinned  $\{010\}$  parting tablets can be found in rare cases. In such cases  $Z/c$  can be determined fairly well by measuring  $Z_1 \wedge X_2$  as shown in Fig. 1B. This angle is normally less than  $10^\circ$ .

In untwinned clinopyroxenes exhibiting very fine, sharp exsolution lamellae of orthopyroxene parallel to either  $\{100\}$  or  $\{001\}$ , the angle  $Z/c$  or  $X/a$  may be measured on  $\{010\}$  parting tablets in powders

(Fig. 1C). This is not as satisfactory as the other two methods suggested above.

(f) *Pleochroism.*

The absorption indicatrix does not coincide with the optical indicatrix ( $X, Y, Z$ ) in most clinopyroxenes. The colors observed can more readily be related to the directions paralleling the  $b$  and  $c$  axes and the direction at right angles to the  $bc$  plane. It is evident from the analyses that the color of those pyroxenes herein described may be directly related to the  $\text{Fe}^{+3}$  ion (predominantly greens) and to Ti (purplish tints). No other ions have thus far been identified as affecting the transmitted color of clinopyroxenes either by themselves or in conjunction with the above. Where no data are given on pleochroism the mineral appeared to be virtually colorless in thin section. Faintly colored specimens were examined in relatively thick sections or grains to determine the pleochroism.

(g) *Density.*

Accurate density determinations on mineral grains are difficult to make. The numerous pitfalls are adequately pointed out by Mason (1944). The most successful measurements were made with the Berman balance. This has the great advantage of permitting rapid measurements so that in an hour or two a number of observations can be made (10 to 15 minutes per grain). In this manner the results can be compared, extremes discarded, and a group of fairly consistent values averaged. It is assumed that the aberrant values are grains with unseen cavities or inclusions. Unfortunately, this method is only applicable when pure grains of at least 10 milligrams can be obtained. It is preferable to use a 20–25 milligram sample\*.

Toluene was used in the Berman balance determinations. The accuracy is thought to be better than  $\pm 0.01$ . All observations were made at room temperature (density of toluene at that temperature being used in the calculation) and are uncorrected for atmospheric pressure. (Plate IX)

A large number of pycnometer determinations on powders were made but these are considered to be too unreliable to report. Some determina-

\* It seems likely that if further experimentation were undertaken on powders that a method using a rather large volume of heavy liquid would be the most satisfactory for routine determinations. Large volume of liquid would minimize the errors resulting from measuring the volume of the liquid and weighing it to obtain its density. This might be coupled with calibration of the liquid for thermal expansion and density comparison to the powders in a cell with variable controlled temperature thereby eliminating the need for diluting the liquid and having to measure its density along with each sample determined. Mason suggests measuring volume by displacing a gas, a method which also has promise of greater accuracy than current methods.

tions were made at the Rock Analysis Laboratory on Buddington's Adirondack pyroxenes presumably by pycnometer and these are attributed to the Laboratory in the tables. The writer has no basis for judging their accuracy.

#### EXPLANATION OF OPTICAL PROPERTY CURVES

The coordinates of the curves are in per cents of atoms of Ca, Mg and total Fe. These ions plus their associated Si and O make up the great bulk of the pyroxenes under consideration. There are, however, five or six weight per cents of other metallic oxides normally present in the

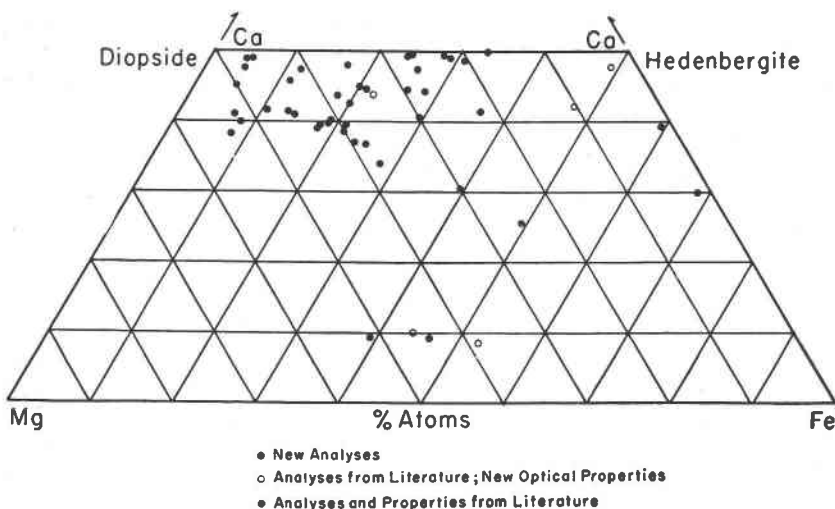
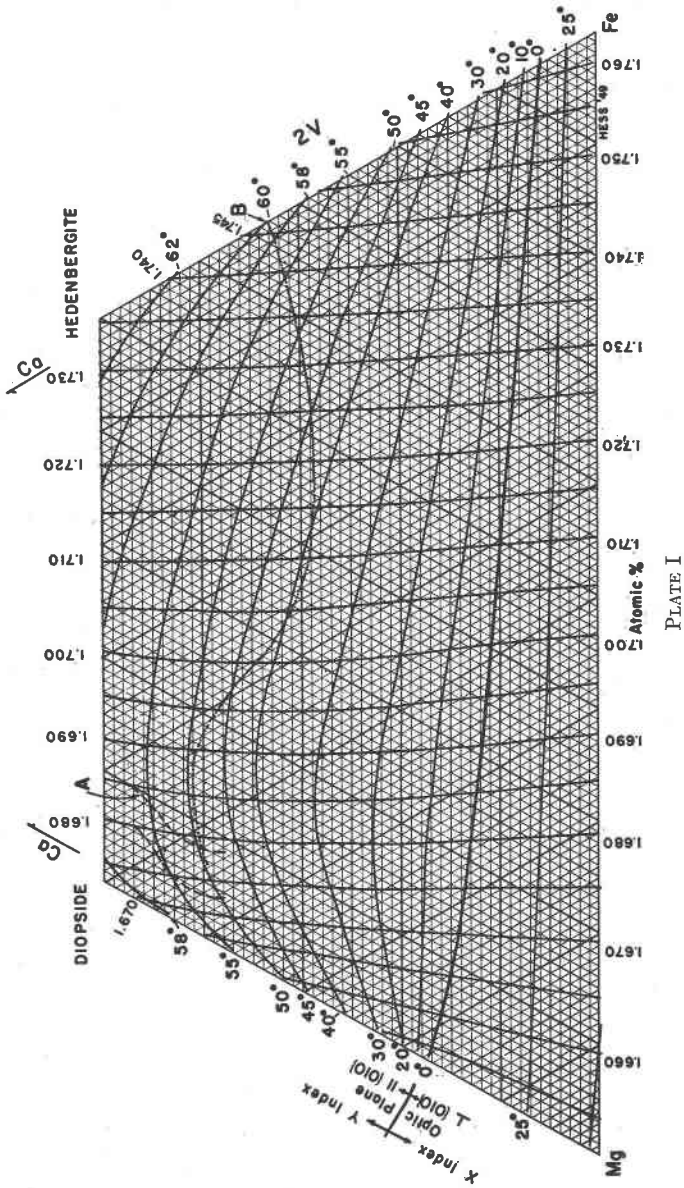


FIG. 2

chemical analyses. As a rule, these other constituents are present in fairly uniform proportions in naturally occurring Ca-Mg-Fe clinopyroxenes. It is assumed in drawing the curves that the following amounts of these other constituents are present:  $\text{Al}_2\text{O}_3$  3%;  $\text{Fe}_2\text{O}_3^*$  1.5%;  $\text{Na}_2\text{O}$  0.4%;  $\text{TiO}_2$  0.4%;  $\text{MnO}$  0.3% but higher in more ferriferous samples;  $\text{Cr}_2\text{O}_3^\dagger$  1.1% in highly magnesian augites of igneous rocks but negligible after Fe atoms reach 13% (of total Ca+Mg+Fe); other oxides negligible amounts. If these minor constituents are present in considerably different amounts than assumed, this can in most cases be recognized by failure

\* Though the  $\text{Fe}^{+3}$  ions are included in the total Fe of the curves, the effect of  $\text{Fe}^{+3}$  on optical properties is not exactly the same as  $\text{Fe}^{+2}$ , so it has to be dealt with in the same way as other minor constituents.

†  $\text{Cr}_2\text{O}_3$  content is taken care of by an extra set of dashed curves for Mg-rich augites in Plates I, II and III.



of the optical properties to group together in such a manner that they fit the curves. In a succeeding part of this series of papers the specific effects on optical properties of each of the above mentioned minor oxides will be evaluated.

Two end members of the curves, diopside and hedenbergite, tend to occur as relatively pure Ca-Mg or Ca-Fe clinopyroxenes, though the intermediate varieties rarely if ever do. The optical property curves take into account this normal decrease in "impurities" upon approaching these two corners of the diagrams.

The distribution of analyses on which the curves are based is shown in Fig. 2. Since there are no natural clinopyroxenes along the side of the diagram from clinoenstatite to a point quite close to diopside, the terminations of the curves along this side are taken from the synthetic pyroxenes described by Bowen and Schairer (1935). Similarly use is made of the synthetics from hedenbergite towards ferrosilite by Bowen, Schairer, and Posnjak (1933). The curves are most reliable for those areas where natural clinopyroxenes are commonest such as, for example, from diopside to  $\text{Ca}_{38}\text{Mg}_{40}\text{Fe}_{22}$  or in the salite area. Conversely, they are least reliable where natural clinopyroxenes are very rare or do not exist, so that the writer does not feel too much concern for most of the area where the data are poor. One area, however, does cause him concern and that is in the region from ferroaugite with 30% Ca toward hedenbergite. These ferroaugites are not too rare for they occur in ferrogabbros, syenites, and some granites as well as probably in the ground mass of ferri-ferrous lavas. The curves here depend very largely on only two analyses of Skaergaard pyroxenes (Wager and Deer, 1939).

Plate I presents curves for variation of the optic angle with composition. It also shows curves for the  $Y$  index of refraction for the area above  $2V=0^\circ$  and the  $X$  index for the area below  $2V=0$ . The reasons for shifting from  $Y$  to  $X$  index upon crossing  $2V=0^\circ$  are: (1) The  $X$  and  $Y$  curves come together at  $2V=0^\circ$  so that  $Y$  of the augite field is continued in a smooth curve as  $X$  in the pigeonite field thus making this combination easier to construct than a broken curve; and (2)  $Y$  of the augite field and  $X$  of the pigeonite field are respectively the easiest indices to determine accurately in each case. Thus this becomes not only the simplest but also the most useful combination to present on one diagram.

At "A" near the upper left hand corner of Plate I are two dashed lines diverging at a sharp angle from the  $Y$  index curves of this area. These dashed lines in this Plate and Plates II and III should be used for *igneous rock* clinopyroxenes rather than the solid lines if the determined optic angle and indices indicate pyroxenes falling within this area. The cause of this divergence of the index of refraction in igneous pyroxenes is

related to the rapid increase of  $\text{Cr}^{+3}$  with high Mg which seems to occur in practically every case and in a regular manner.  $\text{Cr}_2\text{O}_3$  amounts to 1.1% when Fe is 7%\* and decreases abruptly to almost zero at Fe equal to 13%\*, thus the 1.69  $Y$  curve is not at all displaced by this effect. Further consideration will be given to this point in the part of this series of papers which will deal with clinopyroxenes of gabbros, norites, peridotites, etc.

"B" on the center right-hand side of Plate I indicates a dotted curve representing the normal trend of crystallization of clinopyroxenes from common mafic magmas as previously outlined by the writer (1941). It is often convenient to estimate the composition of such a clinopyroxene rapidly by determining the  $Y$  index and noting its point of intersection with the crystallization curve. It is also a convenient check on compositions inferred from  $2V$  and  $Y$  index.

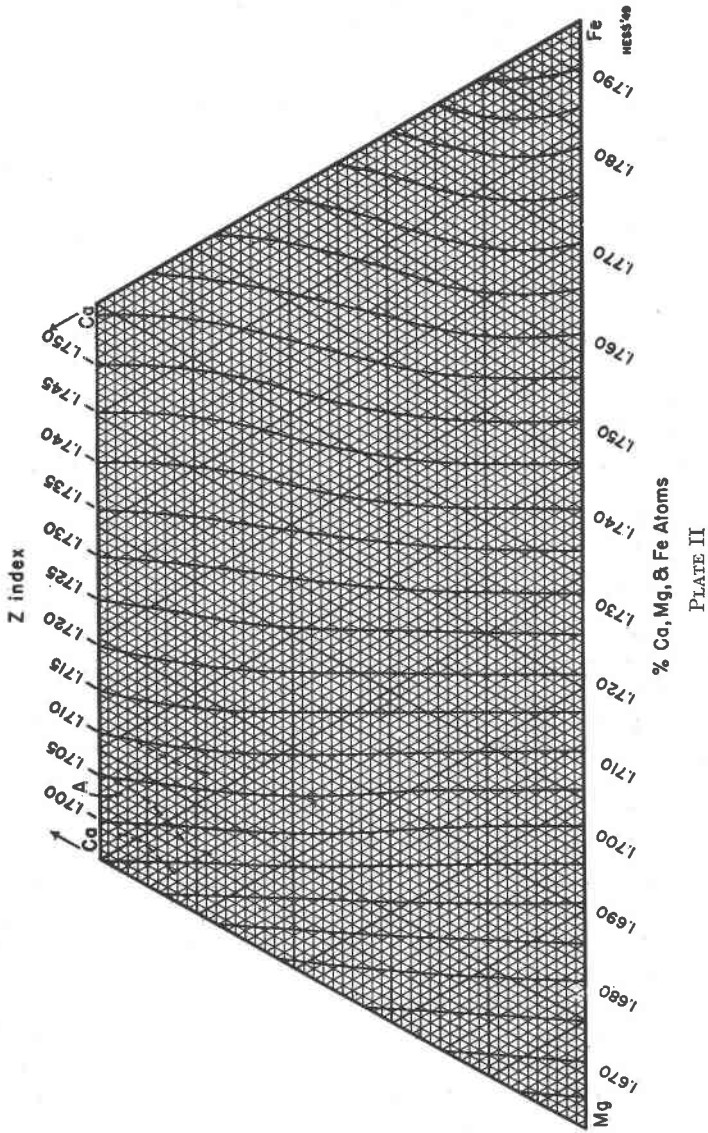
The optic angle curves were drawn by first making rough curves to fit 30 analyzed clinopyroxenes and using a smoothed curve for the synthetic pyroxenes from clinoenstatite to diopside. These rough curves were then smoothed to make an even distribution of the variation of  $2V$  over the field. The smooth curves were then compared to the points for analyzed pyroxenes with the following results. The maximum departure for any one point from the curves was  $4^\circ$ . The average departure with respect to sign was  $-1.25^\circ$  and without regard to sign  $1.5^\circ$ . Ninety-four per cent of the observed values depart from the curves by  $3^\circ$  or less, 80% by  $2^\circ$  or less, and 60% by  $1^\circ$  or less. The distribution of points over those areas where natural clinopyroxenes occur is good except in the ferroaugite area, though even in this area the curves cannot depart far from being correct unless an abrupt change in slope of the general family of curves takes place which seems unlikely.

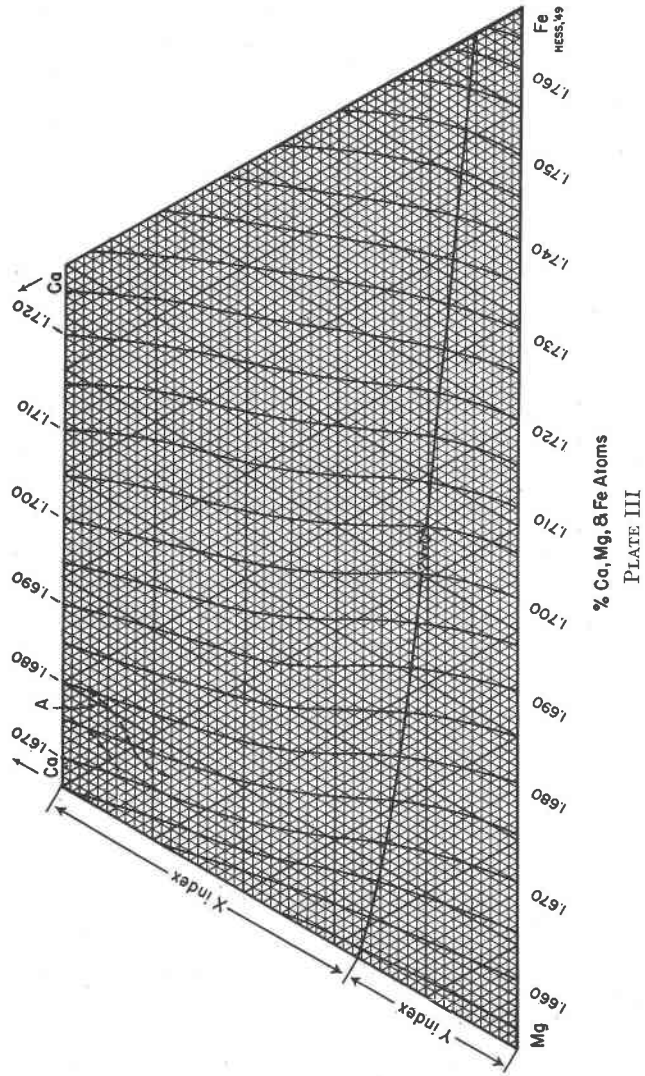
Where exsolution of lamellae of hypersthene has taken place in augites (or any clinopyroxenes) the optic angle of the host material will increase by about  $3^\circ$ . Thus if the bulk composition of the host plus lamellae is desired, about  $3^\circ$  should be subtracted from the observed value before entering the curves.

Plate II presents the  $Z$  index of refraction, and Plate III the  $X$  index above  $2V=0^\circ$  and  $Y$  index below  $2V=0^\circ$ . These curves were calculated by superimposing the birefringence curves (Plate III) on Plate I, and calculating the remaining two indices of refraction by use of Wright's curves relating optic angle, birefringence and partial birefringence. While these curves are not strictly correct, the errors amount to only about 2 in the fourth decimal place as rule for the birefringences, indices, and

\* Of total number of Ca+Mg+Fe ions.







% Co, Mg, & Fe Atoms  
PLATE III

optical angles here encountered (see Larsen and Berman 1934, p. 6-7). Considering the larger uncertainty in the measured values, this error is acceptable.

Plate IV gives the birefringence variation with changes in Ca, Mg, and Fe concentration. Birefringence is markedly decreased by Al substituting for Si in the Z group. After determining the composition of the clinopyroxene on Plate I, a comparison of observed vs. normal birefringence as given on Plate IV will indicate deviations in Al concentration from the assumed amount. Exsolution of hypersthene lamellae from augites will generally increase the birefringence of the host material by

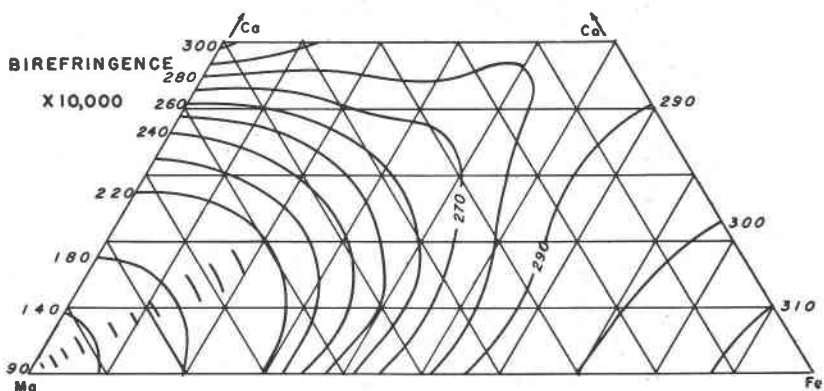


PLATE IV

a small but appreciable amount. Several of the analyzed titanaugites show birefringence about .0015 above the normal values indicated by the curves. Other titanaugites are normal. It has not been possible thus far to correlate this abnormality with variation in the amount of Ti or amount of any of the minor constituents. Possibly it is related to conditions of crystallization.

In succeeding parts of this study the following subjects will be considered: Skarn clinopyroxenes from the Adirondacks (with B. F. Leonard). The diopside-hedenbergite series and related clinopyroxenes. Augites and pigeonites from crystallization of basaltic magmas. The effects  $Ti^{+4}$ ,  $Al^{+3}$ ,  $Fe^{+3}$ ,  $Cr^{+3}$ ,  $Mn^{+2}$ ,  $Na^{+1}$  on optical properties. The optical property curves for skarn pyroxenes (Plate V), the diopside hedenbergite series (Plate VI), Mg-rich igneous augites (Plate VII), and pigeonites (Plate VIII) are all included in this paper in order to present the main body of the descriptive material as one unit. Discussion of these plates will be undertaken in the subsequent papers.

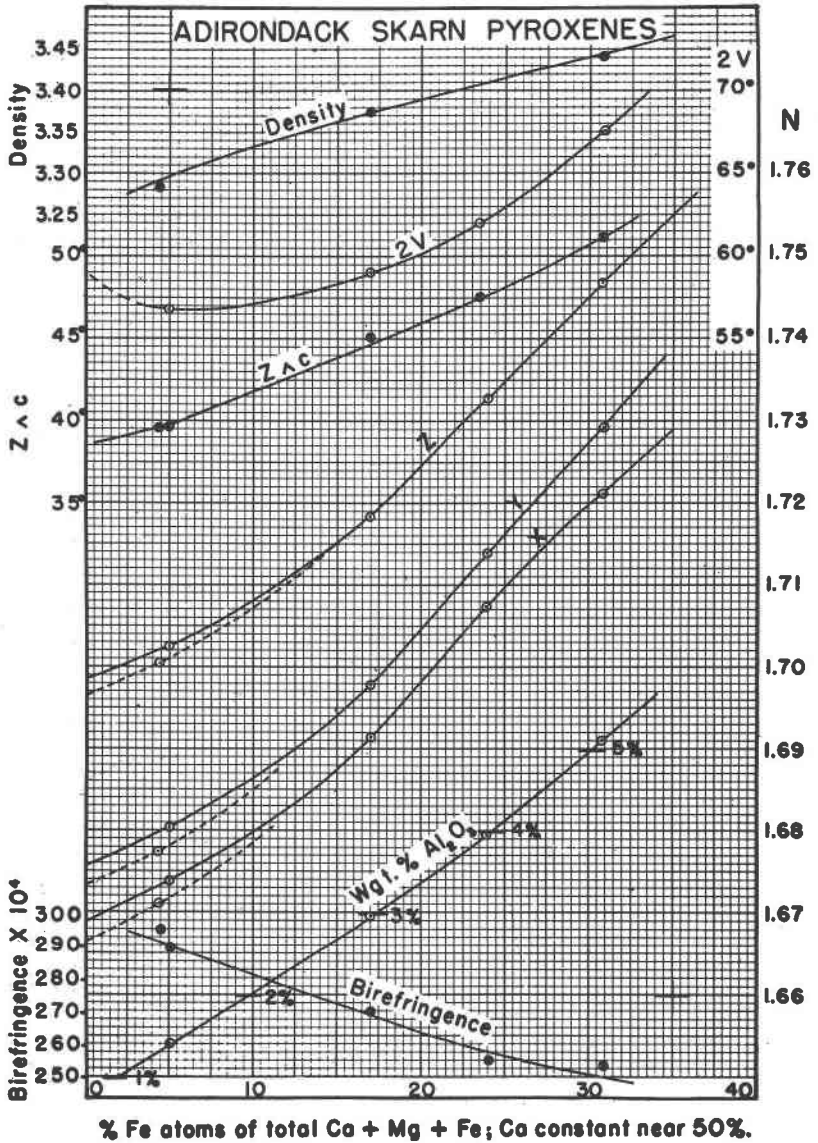


PLATE V

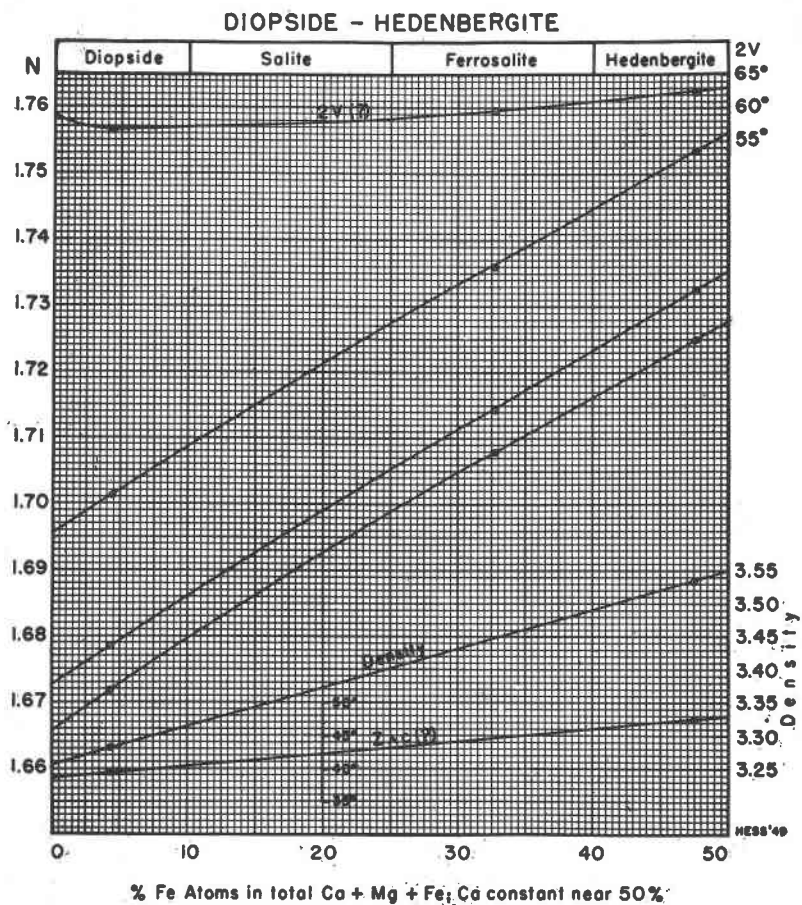


PLATE VI

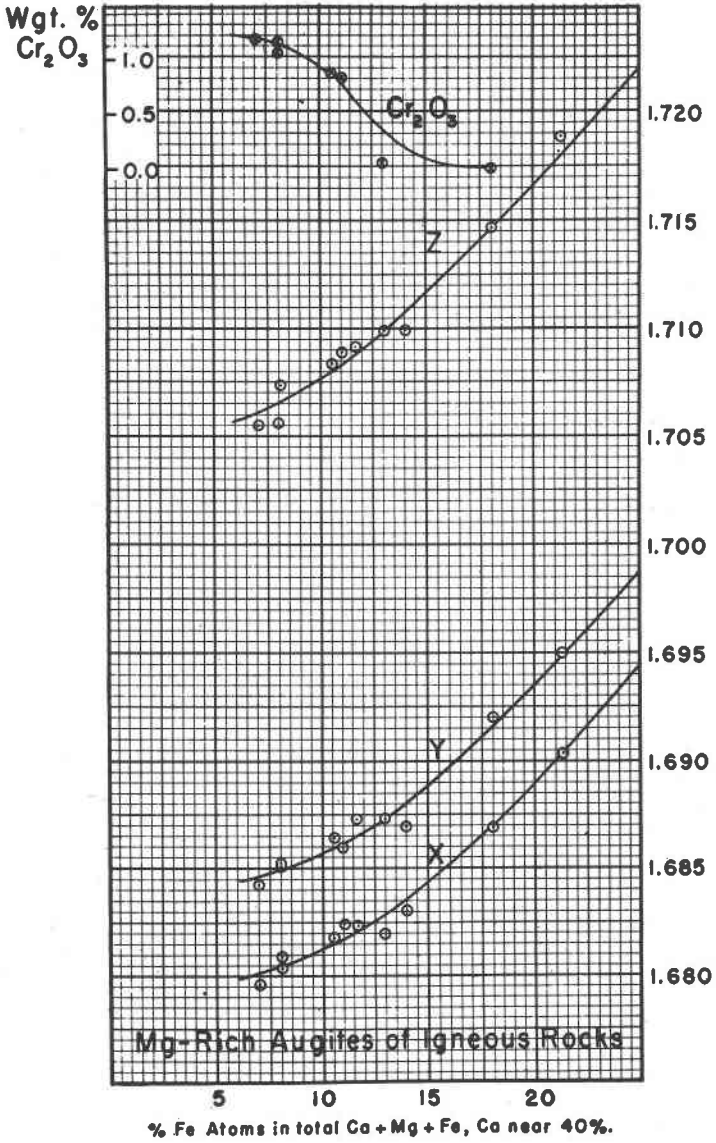


PLATE VII

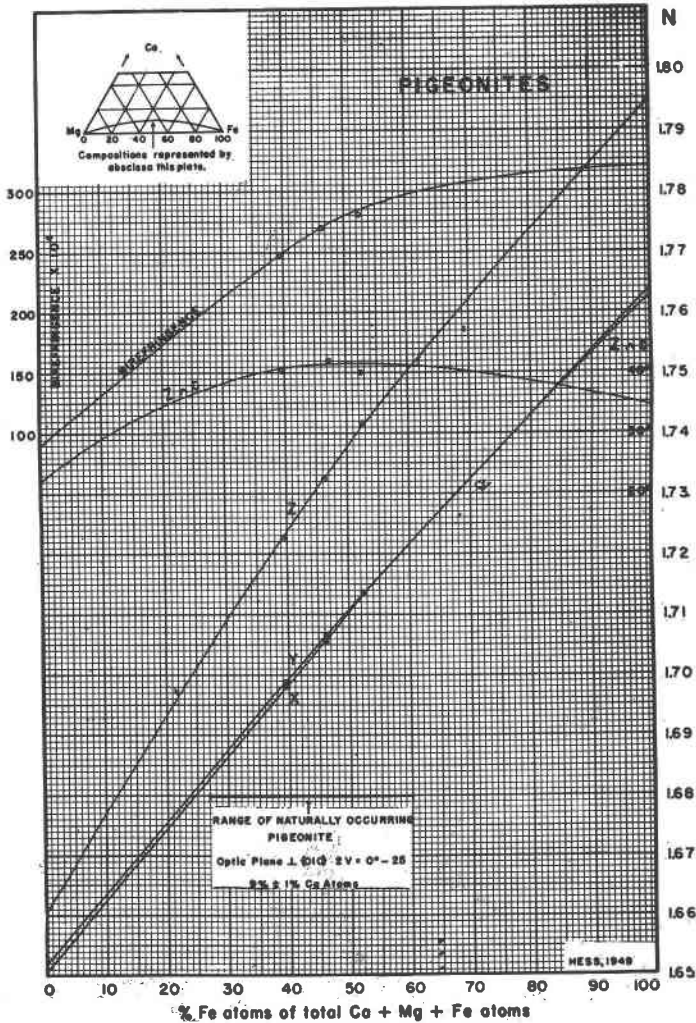


PLATE VIII

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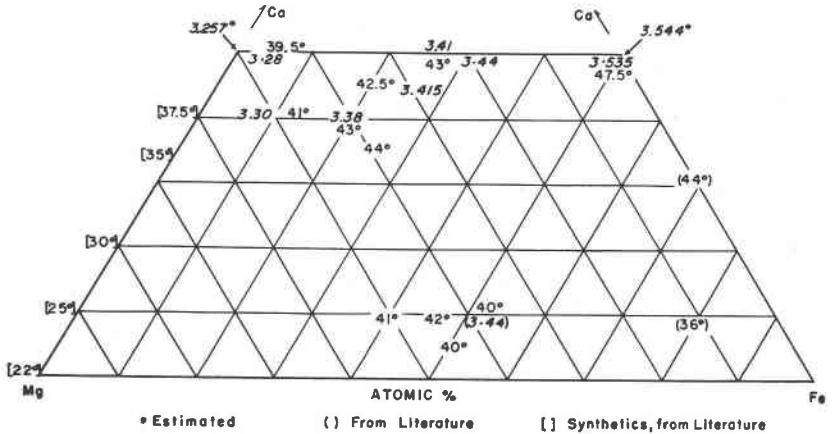


PLATE IX. Density variation.

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TABLES OF ANALYSES

abbreviations

R.A.L. = Rock Analysis Laboratory, University of Minnesota.  
A.F.B. = A. F. Buddington (1939).

ANALYSIS 1

Specimen No. WEB. Chrome Diopside. Webster, North Carolina, from Websterite

	Atomic Ratios	Cations to Six O								Indices of Refraction n <sub>X</sub> 1.6715 n <sub>Y</sub> 1.6782 n <sub>Z</sub> 1.7007	Pleochroism Colorless in section
		Fe <sup>''</sup>	Al	Cr	2Al	Fe <sup>'''</sup>	Al	Al	Z		
		Na	Na	Na					W		
SiO <sub>2</sub>	54.38	Si	905½								Birefringence, x10 <sup>4</sup> aver. 292 287, 290, 293, 297, 298  2V aver. 57½° 57°, 57½°, 58½°, 58½°  Dispersion, Opt. Ax. {B none } r > v {A weak }  Z∧c aver. 39°  Extinction Lamellae, rare    {001}
Al <sub>2</sub> O <sub>3</sub>	1.29	Al	25½							} Z 930½	
Fe <sub>2</sub> O <sub>3</sub>	2.19										
FeO	.94										
MgO	16.96	Fe <sup>'''</sup>	27½	3			24½				
CaO	23.71	Cr	3½		3½						
Na <sub>2</sub> O	.14	Fe	13								
K <sub>2</sub> O	.08	Mn	1½								
H <sub>2</sub> O+	.14	Ni	—								
H <sub>2</sub> O-	.08	Mg	420½						WXY	} 1.95 893	
TiO <sub>2</sub>	.04	Ca	423								
Cr <sub>2</sub> O <sub>3</sub>	.28	Na	4½	1	2		3½				
MnO	.09	K	—								
NiO	.00	Ti	2½				3				
P <sub>2</sub> O <sub>5</sub>	.10	O	2757								
	100.42										

Analyst: A. H. Phillips  
Density: 22°/4° 3.32(?)  
Color hand specimen: Emerald green

Ca<sub>1.2</sub>Mg<sub>1.1</sub>Fe<sub>1.7</sub>  
% Al in Z = 2.7

Remarks:  
Chemical analysis good but not of superior quality.

ANALYSIS 2

Specimen No. 7666. Chrome Diopside. From bronzitite, Malips Drift Camp, Bushveld Complex. Analyzed mineral only present in minute amounts in this rock. Collected by E. Sampson

	Atomic Ratios	Cations to Six O								Indices of Refraction n <sub>X</sub> 1.6742 n <sub>Y</sub> 1.6800 n <sub>Z</sub> 1.7019	Pleochroism Colorless in section
		Fe <sup>''</sup>	Al	Cr	2Al	Fe <sup>'''</sup>	Al	Al	Z		
		Na	Na	Na					W		
SiO <sub>2</sub>	54.07	Si	900								Birefringence, x10 <sup>4</sup> aver. 277 254, 272, 272, 276, 278, 280, 288, 291 highly variable  2V aver. 55½° 54½, 55, 55½, 56½°  Dispersion, Opt. Ax. {B weak } r > v {A weak }  Z∧c aver. 40½° 39½, 39½, 40, 40, 40½, 41°  Extinction Lamellae, rare, if any.
Al <sub>2</sub> O <sub>3</sub>	2.08	Al	40								
Fe <sub>2</sub> O <sub>3</sub>	.56										
FeO	2.55										
MgO	17.39	Fe <sup>'''</sup>	8				8				
CaO	22.12	Cr	14		12			2			
Na <sub>2</sub> O	.41	Fe	35								
K <sub>2</sub> O	.00	Mn	1								
H <sub>2</sub> O+	.04	Ni	1								
H <sub>2</sub> O-	.06	Mg	431						WXY	} 1.98 911	
TiO <sub>2</sub>	.21	Ca	394								
Cr <sub>2</sub> O <sub>3</sub>	.98	Na	12		12						
MnO	.09	K	—								
NiO	.04	Ti	3				3				
	100.58	O	2767								

Analyst: R. B. Ellestad  
Color hand specimen: Emerald green

Ca<sub>1.2</sub>Mg<sub>1.0</sub>Fe<sub>1.5</sub>  
% Al in Z = 3.0

Remarks:

## ANALYSIS 3

Specimen No. PG 50. Chrome augite. Cayogan chromite deposit, Moa district, Oriente, Cuba. Rock a medium coarse feldspathic peridotite which grades into gabbro pegmatite cutting chromite ore.

	Atomic Ratios	Cations to Six O							Indices of Refraction $n_X$ 1.6797 $n_Y$ 1.6844 $n_Z$ 1.7058	Pleochroism Colorless in section	
		Fe <sup>'''</sup>	Al	Cr	Ti	Fe <sup>'''</sup>	Cr	Al			Z
		Na	Na	Na	2Al	Al	Al	Al			Y
SiO <sub>2</sub> 51.98	Si 865½									Cations to Six O	Birefringence, $\times 10^4$ aver. 261 255, 258, 261, 263, 269
Al <sub>2</sub> O <sub>3</sub> 3.67	Al 72			4	8	9	25	911½	1.99		
Fe <sub>2</sub> O <sub>3</sub> .62											2V aver. 50°
FeO 3.62	Fe <sup>'''</sup> 8			7							Dispersion, Opt. Ax. {B weak} <sub>r</sub> > v {A weak}
MgO 18.28	Cr 16				8		9				
CaO 20.13	Fe 50										Z $\wedge$ c aver. 40½°
Na <sub>2</sub> O .17	Mn 2										Ezsolution Lamellae,   {100}
K <sub>2</sub> O .08	Ni —										
H <sub>2</sub> O+ .11	Mg 453										Remarks:
H <sub>2</sub> O- .03	Ca 359										
TiO <sub>2</sub> .15	Na 5			2 ½							
Cr <sub>2</sub> O <sub>3</sub> 1.21	K 2										
MnO .14	Ti 2										
NiO .03	O 2747										
100.22											

Analyst: Lee C. Peck  
Color hand specimen: light green

Ca<sub>41</sub>Mg<sub>59</sub>Fe<sub>7</sub>  
% Al in Z=5.0

## ANALYSIS 4

Specimen No. MVL 101/2. Chrome augite. From pegmatitic olivine plagioclase rock below chromite horizon, Mountain View Lake, west side. Stillwater Valley. Stillwater Complex, Montana.

	Atomic Ratios	Cations to Six O							Indices of Refraction $n_X$ 1.6810 $n_Y$ 1.6853 $n_Z$ 1.7057	Pleochroism Colorless in section	
		Fe <sup>'''</sup>	Al	Cr	Ti	Fe <sup>'''</sup>	Cr	Al			Z
		Na	Na	Na	2Al	Al	Al	Al			Y
SiO <sub>2</sub> 51.43	Si 856									Cations to Six O	Birefringence, $\times 10^4$ aver. 247 230, 238, 238, 242, 248, 248, 250, 252, 259 268, (2807).
Al <sub>2</sub> O <sub>3</sub> 3.00	Al 58			7	17	5	15	900	1.99		
Fe <sub>2</sub> O <sub>3</sub> 1.37											2V aver. 48½°
FeO 4.23	Fe <sup>'''</sup> 17			9		17		5			Dispersion, Opt. Ax. {B moderate} <sub>r</sub> > v {A moderate}
MgO 19.44	Cr 14										
CaO 17.86	Fe 59										Z $\wedge$ c aver. 40½° 39½, 39½, 40½, 41, 41°
Na <sub>2</sub> O .28	Mn 2										Ezsolution Lamellae,   {100}
K <sub>2</sub> O .02	Ni 482										
H <sub>2</sub> O+ .70	Mg 319										Remarks:
H <sub>2</sub> O- .10	Na 9			9							
TiO <sub>2</sub> .27	K —										
Cr <sub>2</sub> O <sub>3</sub> 1.09	Ti 3½										
MnO .14	O 2719										
NiO —											
99.93											

Analyst: R. B. Ellestad  
Color hand specimen: Emerald green

Ca<sub>37</sub>Mg<sub>56</sub>Fe<sub>7</sub>  
% A in Z=4.9

ANALYSIS 5

Specimen No. I 52. Chrome augite. From pegmatitic gabbro below chromite horizon. Stillwater Complex. Montana.

Atomic Ratios									Z	Cations to Six O	Indices of Refraction n <sub>X</sub> 1.6805 n <sub>Y</sub> 1.6852 n <sub>Z</sub> 1.7075	Pleochroism Colorless in section	
		Fe <sup>'''</sup>	Al	Cr	Ti	Fe <sup>'''</sup>	Cr	Al					Al
		Na	Na	Na	2Al	Al	Al	Al	W	Y	Z	2.00	Birefringence, x10 <sup>4</sup> aver. 270 249, 254, 258, 272, 272, 276, 282, 295 (variable).
SiO <sub>2</sub>	52.55	Si	875										
Al <sub>2</sub> O <sub>3</sub>	2.98	Al	58										Dispersion, Opt. Ax. {B moderate} r > v {A moderate} r > v
Fe <sub>2</sub> O <sub>3</sub>	1.17												
FeO	3.98	Fe <sup>'''</sup>	14										Ezsolution Lamellae,   {100} well developed
MgO	18.21	Cr	16										
CaO	19.23	Fe	55		10								
Na <sub>2</sub> O	.32	Mn	2										
K <sub>2</sub> O	.00	Ni	1										
H <sub>2</sub> O+	.14	Mg	451½										
H <sub>2</sub> O-	.08	Ca	344										
TiO <sub>2</sub>	.24	Na	10										
Cr <sub>2</sub> O <sub>3</sub>	1.18	K	3										
MnO	.12	Ti	3										
NiO	.05	O	2746½										
100.25													

Analyst: R. B. Ellestad  
Density: 20°/4° 3.299  
Color hand specimen: Emerald green

Ca<sub>4.0</sub>Mg<sub>0.2</sub>Fe<sub>3</sub>  
% Al in Z=4.6

ANALYSIS 6

Specimen No. 7503. Chrome augite. From gabbro above Merensky reef, Rustenburg Platinum Mine, Bushveld Complex. Collected by E. Sampson.

Atomic Ratios									Z	Cations to Six O	Indices of Refraction n <sub>X</sub> 1.6818 n <sub>Y</sub> 1.6865 n <sub>Z</sub> 1.7085	Pleochroism Colorless in section	
		Fe <sup>'''</sup>	Al	Cr	Ti	Fe <sup>'''</sup>	Cr	Al					Al
		Na	Na	Na	2Al	Al	Al	Al	W	Y	Z	2.01	Birefringence, x10 <sup>4</sup> aver. 267 253, 262, 267, 273, 274, 274
SiO <sub>2</sub>	52.92	Si	881										
Al <sub>2</sub> O <sub>3</sub>	2.80	Al	54										Dispersion, Opt. Ax. {B moderate} r > v {A weak} r > v
Fe <sub>2</sub> O <sub>3</sub>	.85												
FeO	5.57	Fe <sup>'''</sup>	10										Ezsolution Lamellae,   {100}
MgO	16.40	Cr	12										
CaO	19.97	Fe	78										
Na <sub>2</sub> O	.35	Mn	2										
K <sub>2</sub> O	.01	Ni	1										
H <sub>2</sub> O+	.10	Mg	407										
H <sub>2</sub> O-	.07	Ca	356										
TiO <sub>2</sub>	.50	Na	11										
Cr <sub>2</sub> O <sub>3</sub>	.88	K	—										
MnO	.15	Ti	6										
NiO	.10	O	2737										
100.67													

Analyst: R. B. Ellestad  
Color hand specimen: green

Ca<sub>4.15</sub>Mg<sub>0.6</sub>Fe<sub>1.55</sub>  
% Al in Z=4.2

## ANALYSIS 7

Specimen No. PG 10. Chrome titanaugite. Gabbro pegmatite dike in chromite ore.  
Moa district, Oriente, Cuba

Atomic Ratios									Cations to Six O	Indices of Refraction $n_X$ 1.6825 $n_Y$ 1.6860 $n_Z$ 1.7090	Pleochroism Colorless in section		
		Fe'''	Al	Cr	Ti	Fe'''	Al	Al				Z	
		Na	Na	Na								Y	
SiO <sub>2</sub>	50.90	Si	847										
Al <sub>2</sub> O <sub>3</sub>	3.83	Al	74				24	4		23	} Z 898	2.00	Birefringence, $\times 10^4$ aver. 265 262, 265, 269
Fe <sub>2</sub> O <sub>3</sub>	1.29												
FeO	5.49	Fe'''	16	12				4					2V aver. 48° 45½, 48½, 52½°
MgO	16.07	Cr	11										Dispersion, Opt. Ax. {B moderate A weak} $r > v$
CaO	18.92	Fe	76										
Na <sub>2</sub> O	.69	Mn	3										Z $\wedge$ c aver. 40½°
K <sub>2</sub> O	.06	Ni	—										
H <sub>2</sub> O+	.71	Mg	399										} WXY 901
H <sub>2</sub> O-	.20	Ca	338										
TiO <sub>2</sub>	.94	Na	22	11									} Z
Cr <sub>2</sub> O <sub>3</sub>	.84	K	1										
MnO	.19	Ti	12										} Z
NiO (.034)	.03	O	2697										
	100.16												

Analyst: Lee C. Peck  
Color hand specimen: brown

$Ca_{40.7}Mg_{68.3}Fe_{11}$   
% Al in Z=5.7

Remarks:

Resolution Lamellae, ||{100}

## ANALYSIS 8

Specimen No. EB 175. Augite. From feldspathic pyroxenite, East Boulder plateau, Stillwater Complex, Montana

Atomic Ratios									Cations to Six O	Indices of Refraction $n_X$ 1.6823 $n_Y$ 1.6874 $n_Z$ 1.7093	Pleochroism Colorless in section		
		Fe'''	Al	Ti	Fe'''	Al	Al	Z					
		Na	Na					Y					
SiO <sub>2</sub>	52.61	Si	876										
Al <sub>2</sub> O <sub>3</sub>	2.72	Al	53				11	8	17		} Z 912	2.01	Birefringence, $\times 10^4$ aver. 270 266, 268, 269, 270, 274, 279
Fe <sub>2</sub> O <sub>3</sub>	1.36												
FeO	5.85	Fe'''	17	9				8					2V aver. 51½° 48½, 50½, 51½, 51½, 52½, 52½, 53°
MgO	15.97	Fe	81										Dispersion, Opt. Ax. {B weak A very weak} $r > v$
CaO	20.50	Mn	2½										
Na <sub>2</sub> O	.28	Mg	396										} WXY 894
K <sub>2</sub> O	.02	Ca	366										
H <sub>2</sub> O+	.19	Na	9	9									Z $\wedge$ c aver. 41° 39, 39½, 40, 40½, 41, 41½, 41½, 41½, 41½, 41½, 42½°
H <sub>2</sub> O-	.04	K	—										
TiO <sub>2</sub>	.44	Ti	5½										} Z
MnO	.18	O	2718										
	100.16												

Analyst: R. B. Ellestad  
Color hand specimen: greenish brown

$Ca_{41.2}Mg_{66}Fe_{11.7}$   
% Al in Z=3.9

Remarks: Twinned on {100}

Resolution Lamellae, ||{100}, 2V lamellae orthopyroxene = 66° ± 2° = Mg<sub>72</sub>Fe<sub>28</sub>

## ANALYSIS 9

Specimen No. 7648. Augite, from norite, Sekukuni, Fighting Kop, Bushveld Complex.  
Collected by E. Sampson

Atomic Ratios									Cations to Six O	Indices of Refraction $n_X$ 1.6820 $n_Y$ 1.6875 $n_Z$ 1.7101	Pleochroism Colorless in section
		Fe <sup>'''</sup>	Al	Cr	Ti	2Al	Fe <sup>'''</sup>	Al			
		Na	Na	Na					W	Y	
SiO <sub>2</sub>	52.47	Si	873½							Z	2.01
Al <sub>2</sub> O <sub>3</sub>	2.28	Al	46			12	9	12½		907	
Fe <sub>2</sub> O <sub>3</sub>	1.49										
FeO	6.61										
MgO	15.71	Fe <sup>'''</sup>	18	9			9				
CaO	20.28	Cr	1		1						
Na <sub>2</sub> O	.31	Fe	92								
K <sub>2</sub> O	.02	Mn	3								
H <sub>2</sub> O <sup>+</sup>	.20	Ni	½						WXY	1.90	
H <sub>2</sub> O <sup>-</sup>	.04	Mg	390						894		
TiO <sub>2</sub>	.46	Ca	361								
Cr <sub>2</sub> O <sub>3</sub>	.08	Na	10	0		1					
MnO	.20	K	—				6				
NiO	.04	Ti	6								
	100.19	G	2708								

Analyst: R. B. Ellestad  
Color hand specimen: greenish brown

$Ca_{41.5}Mg_{35.4}Fe_{13}$   
% Al in Z=3.7

Birefringence  $\times 10^4$  aver. 281  
272½, 281, 283, 287½ (margin one grain 254)

2V aver. 51½°  
50½, 51½, 52, 52½°

Dispersion, Opt. Ax. {B moderate}  $r > v$   
{A moderate}

Z  $\wedge$  c aver. 42½°

Resolution Lamellae, a few coarse  $\{001\}$ ,  
fine, numerous  $\{100\}$

Remarks: Twinned on  $\{100\}$ . Contains a small amount of impurity as follows: hypersthene 0.4%, plagioclase 0.3%, biotite 0.2%.

## ANALYSIS 10

Specimen No. EB 43. Augite. From gabbro at base of upper gabbro zone,  
Stillwater Complex, Montana. East Boulder Plateau area

Atomic Ratios									Cations to Six O	Indices of Refraction $n_X$ 1.6832 $n_Y$ 1.6870 $n_Z$ 1.7100	Pleochroism Colorless in thin section
		Fe <sup>'''</sup>	Al	Ti	Fe <sup>'''</sup>	Al	Al	Z			
		Na	Na					W	Y		
SiO <sub>2</sub>	51.83	Si	863							Z	2.007
Al <sub>2</sub> O <sub>3</sub>	3.07	Al	60			12	8	20		903	
Fe <sub>2</sub> O <sub>3</sub>	1.38										
FeO	7.21										
MgO	16.00	Fe <sup>'''</sup>	17	9			8				
CaO	19.21	Fe	100								
Na <sub>2</sub> O	.27	Mn	2½								
K <sub>2</sub> O	.02	Mg	397								
H <sub>2</sub> O <sup>+</sup>	.47	Ca	342½						WXY	1.987	
H <sub>2</sub> O <sup>-</sup>	.11	Na	9	9					894		
TiO <sub>2</sub>	.49	K	—								
MnO	.17	Ti	6			6					
	100.23	O	2700								

Analyst: R. B. Ellestad  
Color hand specimen: dark greenish brown

$Ca_{41}Mg_{34}Fe_{14}$   
% Al in Z=4.4

Birefringence,  $\times 10^4$  aver. 268  
266, 268, 269

2V aver. 52°. Average of 16 values

Dispersion, Opt. Ax. {B weak}  $r > v$   
{A none}

Z  $\wedge$  c aver. 42.1°. Average of 16 values

Resolution Lamellae,  $\{100\}$

Remarks: Twinned on  $\{100\}$

ANALYSIS 11

Specimen No. EB 41. Augite. From gabbro near uppermost exposure.  
Stillwater Complex, Montana. East Boulder Plateau area

Atomic Ratios		Cations to Six O						Z	Y	W	Cations to Six O										
		Fe <sup>'''</sup>	Al	Cr	2Al	Fe <sup>'''</sup>	Al					Al	Al								
SiO <sub>2</sub>	51.86	Si	863																		
Al <sub>2</sub> O <sub>3</sub>	2.33	Al	44																		
Fe <sub>2</sub> O <sub>3</sub>	1.60																				
FeO	9.45																				
MgO	14.50	Fe <sup>'''</sup>	20	8																	
CaO	18.92	Cr																			
Na <sub>2</sub> O	.23	Fe	131																		
K <sub>2</sub> O	.00	Mn	3½																		
H <sub>2</sub> O+	.37	K																			
H <sub>2</sub> O-	.09	Ni																			
TiO <sub>2</sub>	.55	Mg	360																		
Cr <sub>2</sub> O <sub>3</sub>	.01	Ca	338																		
MnO	.24	Na	8	8																	
NiO	.02	Ti	7																		
	100.17	O	2674½																		

Analyst: R. B. Ellestad	Ca <sub>33.5</sub> Mg <sub>42.5</sub> Fe <sub>13</sub>
Color hand specimen: dark greenish brown	% Al in Z=3.9

<p><i>Indices of Refraction</i>  <i>n</i>X 1.6870  <i>n</i>Y 1.6921  <i>n</i>Z 1.7149</p> <p><i>Birefringence</i>, x10<sup>4</sup> aver. 279                  275, 278, 283</p> <p>2V aver. 50½°. Average of 22 values.</p> <p><i>Dispersion</i>, Opt. Ax. {B moderate} <i>r</i> &gt; <i>v</i>                  {A weak}</p> <p>Z∧c aver. 42°. Average of 22 values.</p> <p><i>Extinction Lamellae</i>,   {001} and   {100}</p>	<p><i>Pleochroism</i>                  Not perceptibly pleochroic in thin section</p>
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ANALYSIS 12

Specimen No. 7493. Augite. Bushveld Complex, Pretoria district, The Pyramids norite.  
Collected by E. Sampson

Atomic Ratios		Cations to Six O						Z	Y	W	Cations to Six O										
		Fe <sup>'''</sup>	Al	Ti	2Al	Fe <sup>'''</sup>	Al					Al									
SiO <sub>2</sub>	51.39	Si	855½																		
Al <sub>2</sub> O <sub>3</sub>	2.45	Al	48																		
Fe <sub>2</sub> O <sub>3</sub>	1.26																				
FeO	11.63																				
MgO	14.21	Fe <sup>'''</sup>	16	9																	
CaO	18.12	Fe	162																		
Na <sub>2</sub> O	.27	Mn	4½																		
K <sub>2</sub> O	.02	Mg	352																		
H <sub>2</sub> O+	.03	Ca	323																		
H <sub>2</sub> O-	.07	Na	9	9																	
TiO <sub>2</sub>	.41	K																			
MnO	.32	Ti	5																		
	100.18	O	2663																		

Analyst: R. B. Ellestad	Ca <sub>33.7</sub> Mg <sub>41</sub> Fe <sub>21.3</sub>
Color hand specimen: brownish green	% Al in Z=3.7

<p><i>Indices of Refraction</i>  <i>n</i>X 1.6905  <i>n</i>Y 1.6951  <i>n</i>Z 1.7190</p> <p><i>Birefringence</i>, x10<sup>4</sup> aver. 285                  283, 284, 285, 285, 286</p> <p>2V aver. 47½°                  41, 43½, 45, 45, 45½, 46½, 46½, 46½, 47, 48, 48½, 48½, 48½, 48½, 49½, 49½, 49½, 50½, 51, 51½, 53°</p> <p><i>Dispersion</i>, Opt. Ax. {B strong} <i>r</i> &gt; <i>v</i>                  {A moderate}</p> <p>Z∧c aver. 44° (average 25 observations)</p> <p><i>Extinction Lamellae</i>,   {100} and {001}</p>	<p><i>Pleochroism</i>                  Pale smoky green with a purplish tint in most directions but ⊥bc yellowish brown</p>
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ANALYSIS 13

Specimen No. 4015. Augite. From mafic gabbro dike in anorthosite, 2 miles S.E. of Gates Corners, Antwerp Quadrangle, Adirondacks. Chemical Analysis of rock A.F.B. no. 47, p. 52

Atomic Ratios								Z	Cations to Six O
		Fe <sup>+++</sup>	Al	Ti	2Al	Al	Al		
		Na	Na					Y	
		Na	Na					W	
SiO <sub>2</sub>	51.01	Si	849					Z	2.001
Al <sub>2</sub> O <sub>3</sub>	2.69	Al	52½		10	8½	17	884½	
Fe <sub>2</sub> O <sub>3</sub>	1.86								1.997
FeO	10.07	Fe <sup>+++</sup>	23½	15		8½	17	882½	
MgO	12.41	Fe	140					WXY	
CaO	20.59	Mn	7					882½	
Na <sub>2</sub> O	.47	Mg	308						
K <sub>2</sub> O	.02	Ca	367						
H <sub>2</sub> O+	.19	Na	15	15					
H <sub>2</sub> O-	.06	K							
TiO <sub>2</sub>	.40	Ti	5		5				
MnO	.48	O	265½						
	100.25								

Analyst, L. C. Peck  
Density, 3.394 (R. A. L.)  
Color hand specimen:

Ca<sub>41.5</sub>Mg<sub>20.5</sub>Fe<sub>25</sub>  
% Al in Z=4. 2

*Indices of Refraction*  
n<sub>X</sub> 1.6924  
n<sub>Y</sub> 1.6973  
n<sub>Z</sub> 1.7193

*Pleochroism*  
X faint green  
Y pink  
Z faint green  
||c axis faint green  
⊥bc pink

*Birefringence*, x10<sup>4</sup> aver. 270  
268, 270, 271, 273

2V aver. 50½°  
48½, 48½, 49½, 51½, 52, 52½

*Dispersion*, Opt. Ax. {B very weak} r > v  
{A moderate}

Z∧c aver. 42½°

*Extinction Lamellae*, ||{100}

*Remarks*: Rare twinning on {100}

ANALYSIS 14

Specimen No. 5641b. Augite. From metagabbro; garnet-augite-oligoclase-granulite. Dike one mile west of Elizabethville, N. Y. Chemical analysis of rock A.F.B. 64-L, p. 62

Atomic Ratios								Z	Cations to Six O
		Fe <sup>+++</sup>	Al	Ti	2Al	Al	Al		
		Na	Na					Y	
		Na	Na					W	
SiO <sub>2</sub>	50.54	Si	841½					Z	2.011
Al <sub>2</sub> O <sub>3</sub>	2.74	Al	54		6	4	22	873½	
Fe <sub>2</sub> O <sub>3</sub>	2.42								1.979
FeO	12.80	Fe <sup>+++</sup>	30	26		4	22	859½	
MgO	9.65	Fe	178					WXY	
CaO	20.16	Mn	2						
Na <sub>2</sub> O	.75	Mg	239						
K <sub>2</sub> O	.07	Ca	359½						
H <sub>2</sub> O+	.17	Na	24	24					
H <sub>2</sub> O-	.04	K	2	2					
TiO <sub>2</sub>	.25	Ti	3		3				
MnO	.15	O	2606½						
	99.74								

Analyst: Lee C. Peck  
Density 3.414 (R. A. L.)  
Color hand specimen: dark green

Ca<sub>41.5</sub>Mg<sub>29.5</sub>Fe<sub>25</sub>  
% Al in Z=3.7

*Indices of Refraction*  
n<sub>X</sub> 1.6985  
n<sub>Y</sub> 1.7055  
n<sub>Z</sub> 1.7270

*Pleochroism*  
X pale bluish green  
Y brownish green  
Z pale bluish green  
with a trace of pink

*Birefringence*, x10<sup>4</sup> aver. 280  
277, 282, 284. Y-X=215

2V aver. 57½°  
55½, 56, 57½, 58, 59°

*Dispersion*, Opt. Ax. {B very weak} r > v  
{A moderate}

Z∧c aver. 43°

*Extinction Lamellae*, a few ||{001}

*Remarks*: Slightly purplish anomalous dispersion.  
Small amount of garnet and plagioclase included in above analysis. Possibly 2% impurities.

## ANALYSIS 15

Specimen No. 5977. Ferroaugite. Ilmenite-magnetite pyroxenite band in syenite,  $1\frac{1}{4}$  miles west of Kalurah, Oswegatchie quadrangle, Adirondacks. Rock analysis A.F.B. to appear in USGS report on geology of St. Lawrence County magnetite district

Atomic Ratios								Ca to Six O	Indices of Refraction $n_X$ 1.6995 $n_Y$ 1.7083 $n_Z$ 1.7280	Pleochroism X, Y and Z pale bluish green, └ bc pink
		Fe'''	Al	Ti	2Al	Al	Al			
		Na	Na					W		
SiO <sub>2</sub>	51.53	Si	858						1.982	Birefringence, $\times 10^4$ aver. 284 278, 278, 285, 288, 290  2V aver. $48\frac{1}{2}^\circ$ $47\frac{1}{2}, 47\frac{1}{2}, 48\frac{1}{2}, 48\frac{1}{2}, 49\frac{1}{2}, 50\frac{1}{2}^\circ$  Dispersion, Opt. Ax. {B weak* } $r > v$  Z $\wedge$ c aver. $42\frac{1}{2}^\circ$ variable  Resolution Lamellae, many    {100} and {001} Lamellae are ferrosphenene Mg <sub>72</sub> Fe <sub>73</sub> estimated from 2V = $77^\circ$ negative. Remarks: * Peculiar purplish rather than normal bluish dispersion on B optic axis. Margins of crystals have higher birefringence and lower Z $\wedge$ c than cores.
Al <sub>2</sub> O <sub>3</sub>	1.50	Al	20 $\frac{1}{2}$		5	12 $\frac{1}{2}$	6	Z		
Fe <sub>2</sub> O <sub>3</sub>	2.72							881 $\frac{1}{2}$		
FeO	13.13									
MgO	8.92	Fe'''	34	21 $\frac{1}{2}$		12 $\frac{1}{2}$	6			
CaO	20.17	Fe	183							
Na <sub>2</sub> O	.67	Mn	12							
K <sub>2</sub> O	.00	Mg	221					WXY		
H <sub>2</sub> O+	.36	Ca	360					859 $\frac{1}{2}$		
H <sub>2</sub> O-	.06	Na	21 $\frac{1}{2}$	21 $\frac{1}{2}$						
TiO <sub>2</sub>	.19	K	—							
MnO	.82	Ti	2 $\frac{1}{2}$		2 $\frac{1}{2}$					
	100.07	O	2602							

Analyst: L. C. Peck  
Color hand specimen: medium green

$Ca_{33.4}Mg_{27.23}Fe_{28.25}$   
% Al in Z = 2.7

## ANALYSIS 16

Specimen No. 1197a. Ferrosalite. From marble layer in Whiteface anorthosite, Adirondacks, N. Y. Pokamoonshine Quarry, Ausable Quadrangle

Atomic Ratios								Ca to Six O	Indices of Refraction $n_X$ 1.7080 $n_Y$ 1.7140 $n_Z$ 1.7360	Pleochroism Faint green not appreciably pleochroic
		Fe'''	Al	Ti	2Al	Al	Al			
		Na	Na					W		
SiO <sub>2</sub>	50.71	Si	844						1.964	Birefringence, $\times 10^4$ aver. 280 275, 277, 277, 283, 287 X - Y = 69  2V aver. $59\frac{1}{2}^\circ$ $59, 59\frac{1}{2}, 59\frac{1}{2}, 60\frac{1}{2}^\circ$  Dispersion, Opt. Ax. {B weak } $r > v$  Z $\wedge$ c aver. $43\frac{1}{2}^\circ$  Resolution Lamellae, none  Remarks:
Al <sub>2</sub> O <sub>3</sub>	1.06	Al	21		2	9 $\frac{1}{2}$	9 $\frac{1}{2}$	Z		
Fe <sub>2</sub> O <sub>3</sub>	.53							855 $\frac{1}{2}$		
FeO	18.57									
MgO	5.70	Fe'''	6	6						
CaO	22.86	Fe	258 $\frac{1}{2}$							
Na <sub>2</sub> O	.16	Mn	2 $\frac{1}{2}$							
K <sub>2</sub> O	.02	Mg	141 $\frac{1}{2}$					WXY		
H <sub>2</sub> O+	.08	Ca	407 $\frac{1}{2}$					832 $\frac{1}{2}$		
H <sub>2</sub> O-	.04	Na	6	6						
TiO <sub>2</sub>	.07	K	—							
MnO	.18	Ti	1		1					
	99.98	O	2543 $\frac{1}{2}$							

Analyst: Lee C. Peck  
Density: 3.413 (R. A. L.)  
Color hand specimen: light green

$Ca_{36}Mg_{17}Fe_{30}$   
% Al in Z = 1.4



ANALYSIS 17

Specimen No. 5657a. Ferroaugite. Inclusion in granoblastic melanocratic augite syenite; quarry NE of Moody Lake, Saranac Quadrangle, Adirondacks. Chemical analysis of rock A.F.B. #109, p. 120

Atomic Ratios		Cations to Six O									
		Fe <sup>'''</sup>	Al	Ti	Fe <sup>'''</sup>	Al	Y				
SiO <sub>2</sub>	50.33	Si	838								
Al <sub>2</sub> O <sub>3</sub>	2.32	Al	45½								
Fe <sub>2</sub> O <sub>3</sub>	1.88										
FeO	18.23										
MgO	6.92	Fe <sup>'''</sup>	23½	21½							
CaO	18.39	Fe	254								
Na <sub>2</sub> O	.61	Mn	12								
K <sub>2</sub> O	.07	Mg	175½								
H <sub>2</sub> O+	.16	Ca	328								
H <sub>2</sub> O-	.09	Na	20	20							
TiO <sub>2</sub>	.28	K	1½	1½							
MnO	.83	Ti	3½								
		O	2567								
	100.11										

Indices of Refraction  
*n*X 1.7080  
*n*Y 1.7145  
*n*Z 1.7350

Pleochroism  
 X, Y, Z pale bluish green  
 1 bc plane, pink

Birefringence, x10<sup>4</sup> aver. 270  
 289, 261, 275, 277; X-Y=65.

2V aver. 57°  
 56½, 56½, 56½, 57½, 58½°

Dispersion, Opt. Ax. {B none }r>v  
 {A weak }

Z∧c aver. 47½°

Exsolution Lamellae, ||{001} and {100}

Analyst: Lee C. Peck  
 Density: 3.397 (R. A. L.)  
 Color hand specimen: dark green

Ca<sub>41.5</sub>Mg<sub>22</sub>Fe<sub>36.5</sub>  
 % Al in Z=3.2

Remarks: Twinned on {100}

ANALYSIS 18

Specimen No. HER. Hedenbergite, Herault, California. Analysis quoted from Wyckoff, Merwin and Washington. *Amer. Journ. Sci.*, 4 ser., 10, p. 389, 1925. Sample of original material obtained from Merwin. Optical properties determined on this material

Atomic Ratios		Cations to Six O									
		Fe <sup>'''</sup>	Al	Ti	Fe <sup>'''</sup>	Al	Y				
SiO <sub>2</sub>	48.34	Si	805								
Al <sub>2</sub> O <sub>3</sub>	.30	Al	6								
Fe <sub>2</sub> O <sub>3</sub>	1.50										
FeO	22.94										
MgO	1.06	*Fe <sup>'''</sup>	19	5							
CaO	21.30	Fe	319								
Na <sub>2</sub> O	.14	Mn	53								
K <sub>2</sub> O	.03	Mg	26								
H <sub>2</sub> O+	.46	Ca	350								
H <sub>2</sub> O-	.08	Na	5	5							
TiO <sub>2</sub>	.08	K	—								
MnO	3.70	Ti	1								
		O	2430								
	99.85										

Indices of Refraction  
*n*X 1.7225  
*n*Y 1.7300  
*n*Z 1.7505

Pleochroism  
 Colorless in section or faint brown nonpleochroic

Birefringence x10<sup>4</sup> aver. 280  
 268, 270, 272, 273, 274, 280, 295, 287, 289, 300

2V aver. 62½°  
 Range 61°-67°

Dispersion, Opt. Ax. {B none }r>v  
 {A strong }

Z∧c aver. 47½°  
 Range 46°-49°

Exsolution Lamellae, rare ||{001}

Analyst: E. S. Shepherd  
 Density: 22°/4° 3.535  
 Color hand specimen: dark brown

Ca<sub>47.7</sub>Mg<sub>2.2</sub>Fe<sub>19.1</sub>  
 % Al in Z=0.8

Remarks: Pair and multiple twins with {100} composition plane. Good {100} and {010} partings.

\* Insufficient Al<sup>+++</sup> to balance electrical charge Fe<sup>+++</sup> by substitution Al<sup>+++</sup> for Si<sup>+++</sup>

## ANALYSIS 19

Specimen No. 4785. Ferroaugite. From quartz syenite, quarry  $\frac{7}{8}$  mile NE Ausable Forks, N. Y. Chemical analysis of rock A.F.B. #113, p. 120

	Atomic Ratios	Cations to Six O						Cations to Six O	Indices of Refraction $n_X$ 1.7355 $n_Y$ 1.7450 $n_Z$ 1.7650	Pleochroism X blue green Y yellow green Z yellow green c axis blue green bc brownish yellow green
		Fe <sup>'''</sup>		Al		Z				
		Na	Na	Al	Al	Y	W			
SiO <sub>2</sub>	48.28	Si	804							
Al <sub>2</sub> O <sub>3</sub>	1.45	Al	28	7	9 $\frac{1}{2}$	9 $\frac{1}{2}$	Z 820 $\frac{1}{2}$	2.02	Birefringence, $\times 10^4$ aver. 295 283, 295, 297, 297, 299	
Fe <sub>2</sub> O <sub>3</sub>	3.96									
FeO	27.02									
MgO	.32	Fe <sup>'''</sup>	50	50					2V aver. 70 $\frac{1}{2}$ °	
CaO	16.18	Fe	376						Dispersion, Opt. Ax. {B strong $v$ } > r {A strong $r$ } > v	
Na <sub>2</sub> O	1.51	Mn	10 $\frac{1}{2}$							
K <sub>2</sub> O	.14	Mg	8				WXY 800	1.97	Z $\wedge$ c aver. 56 $\frac{1}{2}$ (?)°	
H <sub>2</sub> O+	.15	Ca	188 $\frac{1}{2}$							
H <sub>2</sub> O-	.15	Na	49	47					Ezsolution Lamellae,   {001} coarse	
TiO <sub>2</sub>	.28	K	3	3						
MnO	.76	Ti	3 $\frac{1}{2}$						Remarks:	
		O	2441							
	100.20									

Analyst: L. C. Peck  
Color hand specimen: medium green

$Ca_{35.4}Mg_{21}Fe_{95.5}$   
% Al in Z=2.0

## ANALYSIS 20

Specimen No. TrM 2. Augite. From contaminated granite gneiss, Lyon Mt. Quadrangle, N. Y. Collected by and published by permission of A. W. Postel

	Atomic Ratios	Cations to Six O						Cations to Six O	Indices of Refraction $n_X$ 1.6977 $n_Y$ 1.7055 $n_Z$ 1.7240	Pleochroism X blue green Y brownish green Z pale green bc nearly colorless
		Fe <sup>'''</sup>		Al		Z				
		Na	Na	Al	Al	Y	W			
SiO <sub>2</sub>	52.11	Si	867 $\frac{1}{2}$							
Al <sub>2</sub> O <sub>3</sub>	1.86	Al	36 $\frac{1}{2}$	2	5 $\frac{1}{2}$	14 $\frac{1}{2}$	Z 889 $\frac{1}{2}$	2.01	Birefringence, $\times 10^4$ aver. 263 263, 263, 264	
Fe <sub>2</sub> O <sub>3</sub>	4.59									
FeO	7.93									
MgO	11.32	Fe <sup>'''</sup>	57 $\frac{1}{2}$	52					2V aver. 66° variable 61°, 69°, 73°, 75±°	
CaO	20.16	Fe	110 $\frac{1}{2}$						Dispersion, Opt. Ax. {B weak $r$ } > v {A moderate $v$ } > r	
Na <sub>2</sub> O	1.61	Mn	3							
K <sub>2</sub> O	.06	Mg	281				WXY 879 $\frac{1}{2}$	1.99	Z $\wedge$ c aver. 50° variable	
H <sub>2</sub> O+	.12	Ca	360							
H <sub>2</sub> O-	.05	Na	52	52					Ezsolution Lamellae, probably   {100}	
TiO <sub>2</sub>	.06	K	—							
MnO	.23	Ti	1						Remarks:	
		O	2650							
	100.10									

Analyst: Lee C. Peck  
Color hand specimen: green

$Ca_{41.5}Mg_{31.5}Fe_{21}$   
% Al in Z=2.5

ANALYSIS 21

Specimen No. 6072. Augite. From anorthositic gabbro, Keene Valley road, 1 mile WNW intersection with main N-S highway. Elizabethtown quadrangle, N. Y. Chemical analysis rock A.F.B. #25. p. 36

Atomic Ratios		Cations to Six O									
		Fe <sup>'''</sup>	Al	Ti	2Al	Al	Al	Z			
SiO <sub>2</sub>	49.96	Si	832								
Al <sub>2</sub> O <sub>3</sub>	4.30	Al	84								
Fe <sub>2</sub> O <sub>3</sub>	1.96										
FeO	8.87										
MgO	12.00	Fe <sup>'''</sup>	24½	17			17	7½	29½		
CaO	20.43	Fe	123½								
Na <sub>2</sub> O	.52	Mn	3								
K <sub>2</sub> O	.00	Mg	297½					7½			
H <sub>2</sub> O+	.64	Ca	364								
H <sub>2</sub> O-	.10	Na	17	17							
TiO <sub>2</sub>	.67	K	—								
MnO	.22	Ti	8½								
	99.67	O	2640								

*Indices of Refraction*  
*n*X 1.6892  
*n*Y 1.6950  
*n*Z 1.7164

*Pleochroism*  
 Absorption Z>X>Y.  
 All olive green in thick sections. Y slightly yellowish tint and ||c axis slightly bluish tint

*Birefringence*, x10<sup>4</sup> aver. 272  
 263, 265, 269, 273, 277, 283

2V aver. 55½°  
 55, 55½, 55½, 55½

*Dispersion*, Opt. Ax. {B weak / A moderate} r>v

Z∧c aver. 43(?)°

*Extinction Lamellae*, ||{100}

Analyst: R. B. Ellestad  
 Density 25°/4° 3.315 (R. A. L.)  
 Color hand specimen: medium green

Ca<sub>43.76</sub>Mg<sub>38.76</sub>Fe<sub>18</sub>  
 % Al in Z=6.1

*Remarks*: Lamellae altered to cloudy opaque material  
 Not twinned.

ANALYSIS 22

Specimen No. 5915. Augite. From coarse anorthosite, Mt. Marcy, road cut S.W. end of outlet Lake Clear, St. Regis quadrangle. Chemical analysis of rock A.F.B. #7, p. 24

Atomic Ratios		Cations to Six O									
		Fe <sup>'''</sup>	Al	Ti	2Al	Al	Al	Z			
SiO <sub>2</sub>	50.13	Si	834½								
Al <sub>2</sub> O <sub>3</sub>	4.71	Al	92								
Fe <sub>2</sub> O <sub>3</sub>	2.67										
FeO	9.66										
MgO	10.98	Fe <sup>'''</sup>	17	17							
CaO	19.54	Fe	134½								
Na <sub>2</sub> O	.81	Mn	3								
K <sub>2</sub> O	.14	Mg	272								
H <sub>2</sub> O+	.91	Ca	348½								
H <sub>2</sub> O-	.05	Na	27	14	13						
TiO <sub>2</sub>	.58	K	3	3							
MnO	.23	Ti	7								
	100.41	C	2619½								

*Indices of Refraction*  
*n*X 1.6925  
*n*Y 1.6980  
*n*Z 1.7195

*Pleochroism*  
 X yellow green  
 Z blue green

*Birefringence*, x10<sup>4</sup> aver. 265  
 238, 242, 257, 260, 260, 266, 267, 272, 280, 287, 291

2V aver. 54½°

*Dispersion*, Opt. Ax. {B weak / A weak} r>v

Z∧c aver. 45½(?)°

*Extinction Lamellae*, coarse ||{100}

Analyst: R. B. Ellestad & L. C. Peck  
 Density: 25°/4° 3.285  
 Color hand specimen: medium green

Ca<sub>34.6</sub>Mg<sub>38</sub>Fe<sub>20</sub>  
 % Al in Z=5.3

*Remarks*:

## ANALYSIS 23

Specimen No. 6102. Salite. Skarn inclusion in gabbroic anorthosite magma. From quarry 2.5 miles SSW of Upper Jay, Lake Placid Quadrangle, N. Y. Chemical analysis of rock A.F.B. #30, p. 36

Atomic Ratios								Cations to Six O	Indices of Refraction $n_X$ 1.6990 $n_Y$ 1.7048 $n_Z$ 1.7260	Pleochroism X pale gray green Y pale brownish green Z pale gray green bc pink	
		Fe'''	Al	Ti	2Al	Al	Al				Z
		Na	Na								Y
SiO <sub>2</sub>	48.81	Si	812							Birefringence, $\times 10^4$ aver. 270 268, 269, 270, 274	
Al <sub>2</sub> O <sub>3</sub>	4.37	Al	85½		18	9½	28½	Z	868		2V aver. 56° 55½, 55½, 55½, 56½, 56½, margins 1° higher than cores
Fe <sub>2</sub> O <sub>3</sub>	2.12	Fe'''	26½	17		9½	29	WXY	870½	Dispersion, Opt. Ax. {B strong } <sub>r&gt;v</sub> {A moderate}	
FeO	12.70	Fe	181								Z∧c aver. 457°
MgO	8.79	Mn	3							Exsolution Lamellae, none	
CaO	21.70	Mg	218								Remarks: not twinned.
Na <sub>2</sub> O	.53	Ca	387								
K <sub>2</sub> O	.00	Na	17	17							
H <sub>2</sub> O+	.10	K	—								
H <sub>2</sub> O-	.03	Ti	—		9						
TiO <sub>2</sub>	.70	O	2607½								
MnO	.23										
	100.08										

Analyst: R. B. Ellestad  
Density: 24°/4° 3.445 (R. A. L.)  
Color hand specimen: black

Ca<sub>47.5</sub>Mg<sub>26.76</sub>Fe<sub>25.76</sub>  
% Al in Z=6.1

## ANALYSIS 24

Specimen No. 6053. Salite. From granoblastic Whiteface gabbroic anorthosite. Quarry 0.3 miles east of Stickney Bridge, Ausable Quadrangle. Chemical analysis of rock A.F.B. #10, p. 24

Atomic Ratios								Cations to Six O	Indices of Refraction $n_X$ 1.7087 $n_Y$ 1.7140 $n_Z$ 1.7339	Pleochroism Z=X olive green Y brownish green bc pink Colors very faint in thin section	
		Fe'''	Al	Ti	2Al	Al	Al				Z
		Na	Na								Y
SiO <sub>2</sub>	45.80	Si	762½							Birefringence, $\times 10^4$ aver. 247 245, 245, 248, 251	
Al <sub>2</sub> O <sub>3</sub>	7.06	Al	138½		36	17	42½	Z	858		2V aver. 56° 55, 55½, 55½, 56, 56½, 57°
Fe <sub>2</sub> O <sub>3</sub>	3.14	Fe'''	39	22		17	43	WXY	862	Dispersion, Opt. Ax. {B strong } <sub>r&gt;v</sub> {A weak}	
FeO	10.29	Fe	143								Z∧c aver. 44(?)°
MgO	8.42	Mn	3							Exsolution Lamellae, none	
CaO	21.58	Mg	209								Remarks: not twinned.
Na <sub>2</sub> O	.68	Ca	385								
K <sub>2</sub> O	.01	Na	22	22							
H <sub>2</sub> O+	.30	Na	—								
H <sub>2</sub> O-	.10	Ca	22								
TiO <sub>2</sub>	1.42	K	—								
MnO	.20	Ti	18		18						
	99.00*	O	2578								

Analyst: R. B. Ellestad  
Density: 25°/4° 3.389 (R. A. L.)  
Color hand specimen: black

Ca<sub>40.1</sub>Mg<sub>26.76</sub>Fe<sub>25.76</sub>  
% Al in Z=11.2

\* Low summation, probably some carbonate alteration decreasing SiO<sub>2</sub>. CO<sub>2</sub> not determined.

ANALYSIS 25

Specimen No. 6020A. Ferrosalite. From skarn inclusion in gabbroic anorthosite, 1.9 miles SW of Willsboro bridge, Willsboro Quadrangle, N. Y. Chemical analysis of rock A.F.B. #38, p. 44

	Atomic Ratios	Cations to Six O						Indices of Refraction nX 1.7154 nY 1.7208 nZ 1.7402	Pleochroism X purplish green Y pinkish purple Z yellowish green   c axis bluish green ⊥bc pinkish brown
		Fe'''	Al	2Al	Al	Al	Z		
		Na	Na	Ti	Fe'''	Al	Al		
SiO <sub>2</sub> 45.30	Si 754						Z	Birefringence, x10 <sup>4</sup> aver. 245 237, 239, 247, 247, 250, 252	
Al <sub>2</sub> O <sub>3</sub> 7.74	Al 152			32	10	55	851		
Fe <sub>2</sub> O <sub>3</sub> 3.36								2V aver. 57½° 56½, 57½, 57½, 57½°	
FeO 12.27	Fe''' 42	32			10	55			
MgO 7.04	Fe 171						WXY 876	Dispersion, Opt. Ax. {B strong }r > v {A weak }r > v	
CaO 21.74	Mn 2								
Na <sub>2</sub> O .88	Mg 175						ZΛc aver. 46½(?)°	Resolution Lamellae, fine   (100) a few   (001)	
K <sub>2</sub> O .16	Ca 383								
H <sub>2</sub> O+ .39	Na 28	28					Remarks: Some sphene inclusions, probably ex- solution products.		
H <sub>2</sub> O- .06	K 4	4							
TiO <sub>2</sub> 1.30	Ti 16		16						
MnO .15	O 2578								
100.39									

Analyst: R. B. Ellestad & L. C. Peck  
Density: 27°/4° 3.449 (R. A. L.)  
Color hand specimen: black

Ca<sub>41.2</sub>Mg<sub>22.5</sub>Fe<sub>25</sub>  
% Al in Z=11.4

ANALYSIS 26

Specimen No. 6101a. Ferrosalite. From gabbro pegmatite in Mt. Marcy anorthosite. Quarry 3 miles east of Wilmington on south shoulder of Hamlin Mt., Lake Placid Quadrangle, N. Y. Chemical analysis of rock A.F.B. #26, p. 36

	Atomic Ratios	Cations to Six O						Indices of Refraction nX 1.7095 nY 1.7153 nZ 1.7350	Pleochroism X pale bluish green Y pale green with pink tint Z pale yellowish green ⊥bc pink Weakly colored in thin section
		Fe'''	Al	2Al	Al	Al	Z		
		Na	Na	Ti	Fe'''	Al	Al		
SiO <sub>2</sub> 46.85	Si 780						Z	Birefringence, x10 <sup>4</sup> aver. 255 250, 256, 257	
Al <sub>2</sub> O <sub>3</sub> 5.03	Al 98½			37	21½	20	858½		
Fe <sub>2</sub> O <sub>3</sub> 2.91								2V aver. 54½° 53½, 54½, 54½, 54½	
FeO 13.63	Fe''' 36½	15			21½	20			
MgO 7.03	Fe 190						WXY 848	Dispersion, Opt. Ax. {B strong }r > v {A moderate }r > v	
CaO 21.90	Mn 3								
Na <sub>2</sub> O .46	Mg 174½						ZΛc aver. 44(?)°	Resolution Lamellae, none	
K <sub>2</sub> O .24	Ca 390½								
H <sub>2</sub> O+ .00	Na 15	15					Remarks: Much exsolved sphene as mi- nute blebs or rods (checked by x-ray). Not twinned Host material minus sphene =Ca <sub>41.8</sub> Mg <sub>22.5</sub> Fe <sub>25.5</sub> . 7.3% Al in Z.		
H <sub>2</sub> O- .05	K —								
TiO <sub>2</sub> 1.47	Ti 18½		18½						
MnO .20	O 2567								
99.77									

Analyst: R. B. Ellestad  
Density: 23°/4° 3.449  
Color hand specimen: black

Ca<sub>41.8</sub>Mg<sub>22.5</sub>Fe<sub>25.5</sub>  
% Al in Z=9.1

## ANALYSIS 27

Specimen No. Percy (19258, Harvard No.). Ferroaugite. From syenite, White Mountain magma series, Percy Quadrangle, New Hamp. Quoted from Chapman and Williams. *Amer. Min.* 20, p. 512, 1935. Optical properties redetermined

	Atomic Ratios	Cations to Six O						Indices of Refraction $n_X$ 1.7258 $n_Y$ 1.7327 $n_Z$ 1.7550	Pleochroism X, Y, Z yellow green bc yellow Weakly pleochroic
		Fe <sup>+++</sup>	Al	2Al	Al	Al	Z		
		Na	Na	Ti	Fe <sup>+++</sup>	Al	Y		
SiO <sub>2</sub> 47.58	Si 797							Birefringence, $\times 10^4$ aver. 292 286, 287, 290, 291, 294, 295	
Al <sub>2</sub> O <sub>3</sub> 1.16	Al 222½			9	13½		Z 819½		2V aver. 58½° 56½, 58½, 59½, 59½°
Fe <sub>2</sub> O <sub>3</sub> 2.60								Dispersion, Opt. Ax. {B moderate} $v > r$ {A strong} $r > v$	
FeO 24.21	Fe <sup>+++</sup> 32½	19			13½		WXY 819½		Z $\wedge$ c aver. 48(?)°
MgO 3.34	Fe 337							Ezsolution Lamellae, none	
CaO 18.80	Mn 8½								
Na <sub>2</sub> O .47	Mg 83							Remarks:	
K <sub>2</sub> O .21	Ca 335	15							
H <sub>2</sub> O+ .34	Na 15	4							
H <sub>2</sub> O- .37	K 4			4½					
TiO <sub>2</sub> .59	Ti 4½								
MnO .59	O 2456½								
99.67									

Analyst: F. A. Gonyer  
Color hand specimen: medium green

Ca<sub>42</sub>Mg<sub>103</sub>Fe<sub>17.5</sub>  
% Al in Z = 2.7

## ANALYSIS 28

Specimen No. 9639. Titanaugite. Duluth gabbro, collected by E. Sampson. From fine grained biotite gabbro in city of Duluth. 150 yds. NE of top of inclined railway at small quarry

	Atomic Ratios	Cations to Six O						Indices of Refraction $n_X$ 1.6930 $n_Y$ 1.6968 $n_Z$ 1.7215	Pleochroism Pale purplish brown not appreciably pleochroic	
		Fe <sup>+++</sup>	Al	Cr	2Al	Al	Al			Z
		Na	Na	Na	Ti	Fe <sup>+++</sup>	Cr			Al
SiO <sub>2</sub> 50.79	Si 845							Birefringence, $\times 10^4$ aver. 285 282, 285½, 287		
Al <sub>2</sub> O <sub>3</sub> 3.48	Al 68				26	5	3		17	
Fe <sub>2</sub> O <sub>3</sub> 1.37									2V aver. 43½° 42½, 42½, 43½, 44½, 45°	
FeO 9.41	Fe <sup>+++</sup> 17	12				5		17		
MgO 14.64	Cr 3								Dispersion, Opt. Ax. {B strong} $r > v$ {A weak} $r > v$	
CaO 18.55	Fe 131									
Na <sub>2</sub> O .36	Mn 5½								Z $\wedge$ c aver. 43½°	
K <sub>2</sub> O .03	Ni 3									
H <sub>2</sub> O+ .03	Mg 363								Ezsolution Lamellae, none	
H <sub>2</sub> O- .04	Ca 331									
TiO <sub>2</sub> 1.03	Na 12	12								
Cr <sub>2</sub> O <sub>3</sub> .25	K 13				13					
MnO .24	Ti 13									
NiO .03	O 2682½									
100.25										

Analyst: R. B. Ellestad  
Color hand specimen: dark brown

Ca<sub>232</sub>Mg<sub>52</sub>Fe<sub>19</sub>  
% Al in Z = 5.7

ANALYSIS 29

Specimen No. D3. Titanaugite. Coarse diabase pegmatite. Bluff east of Dutchmans Lake. Sec. 7, T 63 N, R 6 E. Cook Co., Minn. Supplied by F. F. Grout

Atomic Ratios		Cations to Six O							
		Fe <sup>'''</sup>	Al	Cr	Ti	Fe <sup>'''</sup>	Al	Al	Z
		Na	Na	Na				Y	W
SiO <sub>2</sub>	50.76	Si	845						
Al <sub>2</sub> O <sub>3</sub>	2.83	Al	56						
Fe <sub>2</sub> O <sub>3</sub>	1.35								
FeO	10.23								
MgO	14.22	Fe <sup>'''</sup>	16	8					
CaO	19.08	Cr	2						
Na <sub>2</sub> O	.32	Fe	142						
K <sub>2</sub> O	.00	Mn	3½						
H <sub>2</sub> O+	.02	Ni	—						
H <sub>2</sub> O-	.01	Mg	352½						
TiO <sub>2</sub>	.99	Ca	—						
Cr <sub>2</sub> O <sub>3</sub>	.19	Na	—	8					
MnO	.25	K	—						
NiO	.02	Ti	—						
		O	2669						
	100.27								

*Indices of Refraction*  
*n<sub>X</sub>* 1.6941  
*n<sub>Y</sub>* 1.6984  
*n<sub>Z</sub>* 1.7218

*Pleochroism*  
 Faint purplish brown  
 not perceptibly pleochroic in thin sections.

*Birefringence*, x10<sup>4</sup> aver. 277  
 272, 275½, 277, 281, 282

2V aver. 46½°  
 46½, 47½°

*Dispersion*, Opt. Ax. {B moderate} <sub>{A weak}</sub> *r* > *v*

Z∧c aver. 44°

*Exsolution Lamellae*, none

Analyst: R. B. Ellestad  
 Color hand specimen: dark brown, almost black

Ca<sub>29.7</sub>Mg<sub>61.4</sub>Fe<sub>18.9</sub>  
 % Al in Z=5

Remarks:

ANALYSIS 30

Specimen No. D2. Titanaugite. From pegmatitic zone in gabbro sill, shore of Lake Superior; Sec. 35, T 63 N, R 5 E. Cook Co., Minn. Supplied by F. F. Grout

Atomic Ratios		Cations to Six O							
		Fe <sup>'''</sup>	Al	Cr	Ti	Fe <sup>'''</sup>	Al	Al	Z
		Na	Na	Na				Y	W
SiO <sub>2</sub>	50.85	Si	846						
Al <sub>2</sub> O <sub>3</sub>	2.70	Al	52						
Fe <sub>2</sub> O <sub>3</sub>	1.11								
FeO	10.36								
MgO	14.09	Fe <sup>'''</sup>	14	8					
CaO	19.20	Cr	2						
Na <sub>2</sub> O	.30	Fe	144						
K <sub>2</sub> O	.00	Mn	3½						
H <sub>2</sub> O+	.01	Ni	—						
H <sub>2</sub> O-	.09	Mg	349						
TiO <sub>2</sub>	1.05	Ca	343						
Cr <sub>2</sub> O <sub>3</sub>	.13	Na	10	8					
MnO	.25	K	—						
NiO	.02	Ti	13						
		O	2666½						
	100.16								

*Indices of Refraction*  
*n<sub>X</sub>* 1.6937  
*n<sub>Y</sub>* 1.6982  
*n<sub>Z</sub>* 1.7221

*Pleochroism*  
 Z, X faint purplish brown color  
 Y pink

*Birefringence*, x10<sup>4</sup> aver. 284  
 279, 283½, 284, 285, 287½

Z-Y=239, 241, 241

2V aver. 47°  
 46½, 46½, 46½, 47, 47½, 48½°

*Dispersion*, Opt. Ax. {B moderate} <sub>{A weak}</sub> *r* > *v*

Z∧c aver. 44°

*Exsolution Lamellae*, none

Analyst: R. B. Ellestad  
 Density: 24°/4° 3.383  
 Color hand specimen: dark brown almost black

Ca<sub>29</sub>Mg<sub>61.4</sub>Fe<sub>18.9</sub>  
 % Al in Z=4.7

Remarks:

ANALYSIS 31

Specimen No. W. Titanautgite, gabbro sill vicinity of Pigeon Point, Minn. (?)  
Supplied by A. N. Winchell

	Atomic Ratios								Cations to Six O	Indices of Refraction <i>n</i> X 1.6954 <i>n</i> Y 1.7005 <i>n</i> Z 1.7250	Pleochroism Faint pleochroism in pale purplish brown X=Y=Z, $\perp$ bc lighter colored yellowish brown			
		Fe'''	Al	Cr	2Al	Al	Al	Z						
		Na	Na	Na	Ti	Fe'''	Cr	Al				Y		
SiO <sub>2</sub>	50.85	Si	840½											
Al <sub>2</sub> O <sub>3</sub>	2.38	Al	48											
Fe <sub>2</sub> O <sub>3</sub>	.96													
FeO	11.92													
MgO	13.50	Fe'''	12	9										
CaO	18.80	Cr	—											
Na <sub>2</sub> O	.28	Fe	165											
K <sub>2</sub> O	.00	Mn	4											
H <sub>2</sub> O+	.04	Ni	—											
H <sub>2</sub> O-	.04	Mg	335											
TiO <sub>2</sub>	1.03	Ca	336											
Cr <sub>2</sub> O <sub>3</sub>	.03	Na	9	9										
MnO	.29	K	—											
NiO	.01	Ti	13											
P <sub>2</sub> O <sub>5</sub>	.00	O	2653½											
	100.13													

Analyst: R. B. Ellestad  
Color hand specimen: dark brown or black  
C<sub>33.2</sub>Mg<sub>32.7</sub>Fe<sub>23.1</sub>  
% Al in Z=4.3

Indices of Refraction  
*n*X 1.6954  
*n*Y 1.7005  
*n*Z 1.7250

Pleochroism  
Faint pleochroism in pale purplish brown  
X=Y=Z,  $\perp$  bc lighter colored yellowish brown

Birefringence,  $\times 10^4$  aver. 296  
289, 293, 297, 297½, 300, 300

2V aver. 49°  
44, 47, 47½, 48½, 48½, 48½, 51½, 53, 53½°

Dispersion, Opt. Ax. {B moderate }<sub>r</sub>><sub>v</sub>  
                          {A none }

Z $\wedge$ c aver. 44(?)°

Exsolution Lamellae, rare ||{001}

Remarks:

ANALYSIS 32\*

Specimen No. LAM 12A. Augite. From diabase sill in Triassic, south of Lambertville, N. J. From wall of quarry 750 feet above base of sill approximately and 1000 feet below, roof

	Atomic Ratios								Cations to Six O	Indices of Refraction <i>n</i> X 1.6950 <i>n</i> Y 1.6990 <i>n</i> Z 1.7220	Pleochroism Barely pleochroic Range X=Y=Z purplish brown $\perp$ bc light brown			
		Fe'''	Al	Ti	2Al	Al	Al	Z						
		Na	Na					Y						
SiO <sub>2</sub>	50.74	Si	845											
Al <sub>2</sub> O <sub>3</sub>	3.21	Al	63											
Fe <sub>2</sub> O <sub>3</sub>	.70													
FeO	13.07													
MgO	13.45	Fe'''	9	9										
CaO	17.40	Fe	182											
Na <sub>2</sub> O	.30	Mn	4½											
K <sub>2</sub> O	.06	Mg	353½											
H <sub>2</sub> O+	.28	Ca	310											
H <sub>2</sub> O-	.01	Na	9	8										
TiO <sub>2</sub>	.46	K	1	1										
MnO	.32	Ti	6											
	100.00*	O	2645											

Analyst: Lee C. Peck  
Color hand specimen: brown with slight purple tint  
C<sub>33.7</sub>Mg<sub>33.7</sub>Fe<sub>23.3</sub>  
% Al in Z=4.2

Indices of Refraction  
*n*X 1.6950  
*n*Y 1.6990  
*n*Z 1.7220

Pleochroism  
Barely pleochroic  
Range X=Y=Z purplish brown  
 $\perp$  bc light brown

Birefringence,  $\times 10^4$  aver. 270  
267, 270, 271, 273

2V aver. 43½°  
41½, 42½, 43, 43½, 43½, 43½, 44½, 45½°  
Rims about 6° higher than cores

Dispersion, Opt. Ax. {B moderate }<sub>r</sub>><sub>v</sub>  
                          {A weak }

Z $\wedge$ c aver. 43½(?)°

Exsolution Lamellae, numerous ||{001}

Remarks: Twinned on {100}.

\* Impurity 6% pigeonite LAM 12 P. Pigeonite also analyzed and appropriate correction has been applied to above analysis by subtracting pigeonite and calculating to 100%.



ANALYSIS 33

Specimen No. TR-1-A. Augite. Coarse diabase pegmatite. Goose Creek, Va.  
(Triassic) Pigeonite TR-1-P also analyzed

Atomic Ratios		Fe <sup>'''</sup>		2Al		Al		Al		Z	Cations to Six O	Indices of Refraction nX 1.6972 nY 1.7005 nZ 1.7240	Pleochroism Light purplish brown Pleochroism not evident in thin section
		Na	Na	Ti	Fe <sup>'''</sup>	Al	Al	Y					
SiO <sub>2</sub> 50.53	Si 841										1.999	Birefringence, x10 <sup>4</sup> aver. 285	
Al <sub>2</sub> O <sub>3</sub> 2.49	Al 49			22	13½					Z 876½			
Fe <sub>2</sub> O <sub>3</sub> .59											2.002	2V aver. 40°	Dispersion, Opt. Ax. {B moderate} r > v A weak
FeO 14.25	Fe <sup>'''</sup> 7½	7½	½							WXY 878			
MgO 13.08	Fe 198										2.002	ZΛc aver. 44°	
CaO 17.38	Mn 5½												
Na <sub>2</sub> O .23	Mg 324½										2.002	ZΛc aver. 44°	
K <sub>2</sub> O .03	Ca 310												
H <sub>2</sub> O+ .25	Na 8	7½	½								2.002	ZΛc aver. 44°	
H <sub>2</sub> O- .09	K 8												
TiO <sub>2</sub> .87	Ti 11			11							2.002	ZΛc aver. 44°	
MnO .38	O 2631												
100.17													

Analyst: Lee C. Peck  
Color hand specimen: brown with slight purplish tint

Ca<sub>22</sub>Mg<sub>21</sub>Fe<sub>21</sub>  
% Al in Z=4.1

Remarks: Twinned on {100}

ANALYSIS 34\*

Specimen No. Dil 3. Augite. Diabase dike, Dillsburg Quadrangle, Pa.  
(Triassic). Collected by P. Hotz

Atomic Ratios		Fe <sup>'''</sup>		2Al		Al		Al		Z	Cations to Six O	Indices of Refraction nX 1.6950 nY 1.7010 nZ 1.7240	Pleochroism Faint purplish brown not appreciably pleochroic
		Na	Na	Ti	Fe <sup>'''</sup>	Al	Al	Y					
SiO <sub>2</sub> 50.72	Si 843										2.01	Birefringence, x10 <sup>4</sup> aver. 265 258, 261, 261, 263, 264, 265, 268, 269, 270, 271	
Al <sub>2</sub> O <sub>3</sub> 2.28	Al 44			21	1½	10				Z 875½			
Fe <sub>2</sub> O <sub>3</sub> .84											1.98	2V aver. 44°	Dispersion, Opt. Ax. {B weak} r > v A none
FeO 16.32	Fe <sup>'''</sup> 10½	9			1½					WXY 860½			
MgO 12.63	Fe 227										1.98	ZΛc aver. 43½°	
CaO 15.46	Mn 4½												
Na <sub>2</sub> O .28	Mg 313										1.98	ZΛc aver. 43½°	
K <sub>2</sub> O .00	Ca 275½												
H <sub>2</sub> O+ .22	Na 9	9									1.98	ZΛc aver. 43½°	
H <sub>2</sub> O- .08	K 9												
TiO <sub>2</sub> .84	Ti 10½			10½							1.98	ZΛc aver. 43½°	
MnO .33	O 2613												
100.00*													

Analyst: Lee C. Peck  
Color hand specimen: brown

Ca<sub>22</sub>Mg<sub>21</sub>Fe<sub>21</sub>  
% Al in Z=3.7

Remarks: Twinned on {100}

\* Estimated impurity 10% pigeonite. Analysis corrected by subtraction of 10% pigeonite of appropriate composition and recalculated to 100%.

## ANALYSIS 35

Specimen No. BH 1.23. Diopside. Skarn rock, Brunner Hill magnetite deposit near Colton, Stork Quadrangle, St. Lawrence Co. N. Y.; 2.8 miles WNW of Catamount Mt. Collected by B. F. Leonard

Atomic Ratios		Fe <sup>+++</sup>		2Al	Al		Z	Cations to Six O	Indices of Refraction n <sub>X</sub> 1.6718 n <sub>Y</sub> 1.6785 n <sub>Z</sub> 1.7013	Pleochroism Colorless
		Na	Na	Ti	Fe <sup>+++</sup>	Al	Al			
		Na	Na				W			
SiO <sub>2</sub> 54.51	Si 908½							2.00	Birefringence, x10 <sup>4</sup> aver. 295 289, 295, 299	
Al <sub>2</sub> O <sub>3</sub> .40	Al 8			1	2	2½	Z 914			
Fe <sub>2</sub> O <sub>3</sub> .40	Fe <sup>+++</sup> 5	3			2	2½	WXY 916½	2.00	2V aver. 56½° 54½, 56½, 56½, 57½, 57½°	Dispersion, Opt. Ax. {B weak}r > v {A weak}
FeO 2.35	Fe 33									
MgO 17.19	Mn 2½									
CaO 24.90	Mg 426									
Na <sub>2</sub> O .06	Ca 444									
K <sub>2</sub> O .05	Na 2	2								
H <sub>2</sub> O+ .03	K 1	1								
H <sub>2</sub> O- .03	Ti ½			½						
TiO <sub>2</sub> .04	O 2744½									
MnO .16										
100.12										

Analyst: Lee C. Peck  
Density: 19°/4° 3.281  
Color hand specimen: Very pale green

Ca<sub>41.5</sub>Mg<sub>66.5</sub>Fe<sub>4</sub>  
% Al in Z=0.6

Remarks:

## ANALYSIS 36

Specimen No. CN 20.4. Diopside. Skarn rock from Clifton Mine, magnetite deposit, Stark Quadrangle, St. Lawrence Co., N. Y. 3.5 miles SE Degrasse hamlet. Collected by B. F. Leonard

Atomic Ratios		Fe <sup>+++</sup>		2Al	Al		Z	Cations to Six O	Indices of Refraction n <sub>X</sub> 1.6740 n <sub>Y</sub> 1.6805 n <sub>Z</sub> 1.7029	Pleochroism Colorless
		Na	Na	Ti	Fe <sup>+++</sup>	Al	Al			
		Na	Na				W			
SiO <sub>2</sub> 53.79	Si 896							1.996	Birefringence, x10 <sup>4</sup> aver. 289 286½, 288, 288, 290, 292	
Al <sub>2</sub> O <sub>3</sub> 1.41	Al 28			1		13	Z 910			
Fe <sub>2</sub> O <sub>3</sub> .33	Fe <sup>+++</sup> 4	4					WXY 915½	2.008	2V aver. 56½°	Dispersion, Opt. Ax. {B weak}r > v {A weak}
FeO 2.60	Fe 36									
MgO 16.64	Mn 3									
CaO 24.66	Mg 413									
Na <sub>2</sub> O .14	Ca 440									
K <sub>2</sub> O .04	Na 4½	4								
H <sub>2</sub> O+ .10	K ½									
H <sub>2</sub> O- .04	Ti ½									
TiO <sub>2</sub> .04	O 2735½									
MnO .22										
Cr <sub>2</sub> O <sub>3</sub> .00										
NiO .00										
100.01										

Analyst: Lee C. Peck  
Color hand specimen: white

Ca<sub>49</sub>Mg<sub>66</sub>Fe<sub>3</sub>  
% Al in Z=1.5

Remarks: Rare {001} twin lamellae.

ANALYSIS 37

Specimen No. CN 69.1. Salite. Skarn rock. Clifton Mine magnetite deposit collected by B. F. Leonard. Published by permission U. S. Geological Survey.

Atomic Ratios		Cations to Six O						Indices of Refraction	Pleochroism
		Fe <sup>'''</sup>	Al	Ti	2Al	Al	Al		
		Na	Na					Y	
		Na	Na					W	
SiO <sub>2</sub>	50.19	Si	836					Z	1.08
Al <sub>2</sub> O <sub>3</sub>	2.73	Al	52		6	23½	11½	Z	
Fe <sub>2</sub> O <sub>3</sub>	2.98							876½	2.04
FeO	7.54							11½	
MgO	12.38	Fe <sup>'''</sup>	38	14½		23½		WXY	2.04
CaO	23.58	Fe	104						
Na <sub>2</sub> O	.45	Mn	6						2.04
K <sub>2</sub> O	.00	Mg	307						
H <sub>2</sub> O+	.00	Ca	420						2.04
H <sub>2</sub> O-	.02	Na	14½	14½					
TiO <sub>2</sub>	.20	K	—						2.04
MnO	.40	Ti	3		3				
	100.47	O	2657						

Analyst: Norman Davidson (U. S. G. S.)  
 Density 22°/4° 3.373  
 Color hand specimen: medium green

Ca<sub>4.1</sub>Mg<sub>3.8</sub>Fe<sub>1.7</sub>  
 % Al in Z=4.6

Indices of Refraction  
 nX 1.6915  
 nY 1.6980  
 nZ 1.7185

Pleochroism  
 X pale bluish green  
 Y brownish green  
 Z yellow green  
 Colorless in thin section

Birefringence, x10<sup>4</sup> aver. 270  
 269½, 270, 270. Z-Y=210

2V aver. 59°

Dispersion, Opt. Ax. {B weak }<sub>r>v</sub>

Z∧c aver. 45(?)°

Exsolution Lamellae, none

Remarks:

ANALYSIS 38

Specimen No. CN 28.14. Salite. Skarn rock, Clifton mine magnetite deposit. Collected by B. F. Leonard

Atomic Ratios		Cations to Six O						Indices of Refraction	Pleochroism
		Fe <sup>'''</sup>	Al	Ti	2Al	Al	Al		
		Na	Na					Y	
		Na	Na					W	
SiO <sub>2</sub>	48.40	Si	805½					Z	1.993
Al <sub>2</sub> O <sub>3</sub>	3.95	Al	78		7	33	19	Z	
Fe <sub>2</sub> O <sub>3</sub>	3.90							864½	2.010
FeO	10.52								
MgO	8.92	Fe <sup>'''</sup>	48	15		33		WXY	2.010
CaO	23.20	Fe	146						
Na <sub>2</sub> O	.46	Mn	5½						2.010
K <sub>2</sub> O	.02	Mg	221						
H <sub>2</sub> O+	.16	Ca	414						2.010
H <sub>2</sub> O-	.04	Na	15	15					
TiO <sub>2</sub>	.27	K	—						2.010
MnO	.39	Ti	3½		3½				
	100.23	O	2601						

Analyst: Lee C. Peck  
 Color hand specimen: dark green

Ca<sub>4.9</sub>Mg<sub>2.5</sub>Fe<sub>2.4</sub>  
 % Al in Z=6.9

Indices of Refraction  
 nX 1.7073  
 nY 1.7140  
 nZ 1.7328

Pleochroism  
 X=Y dark blue green  
 Z yellowish blue green  
 ⊥bc yellow brown

Birefringence, x10<sup>4</sup> aver. 255  
 250, 251, 256, 262½

2V aver. 62°

Dispersion, Opt. Ax. {B moderate }<sub>r>v</sub>  
 {A strong }

Z∧c aver. 47½(?)°

Exsolution Lamellae, none

Remarks:

## ANALYSIS 39

Specimen No. OF 1.15. Ferrosalite. Skarn rock, Outaft mine, magnetite deposit, Stark Quadrangle, St. Lawrence Co. N. Y. 4 miles NNW of Cranberry Lake village. Collected by B. F. Leonard

		Atomic Ratios		Fe <sup>'''</sup>	Al	Ti	2Al	Al	Al	Z	Cations to Six O	Indices of Refraction n <sub>X</sub> 1.7210 n <sub>Y</sub> 1.7290 n <sub>Z</sub> 1.7463	Pleochroism X dark blue green Y blue green Z yellow green ⊥ bc brownish yellow
		Na	Na	Na	Na	Na	Na	Na	Na	W			
SiO <sub>2</sub>	45.80	Si	763							Z	1.997	Birefringence, x10 <sup>4</sup> aver. 253 249½, 254, 255	
Al <sub>2</sub> O <sub>3</sub>	5.11	Al	100			8	63	14½		Z			
Fe <sub>2</sub> O <sub>3</sub>	5.87											2V aver. 67½°	
FeO	12.44							14½					
MgO	6.86	Fe <sup>'''</sup>	74	11			63					2.011	Dispersion, Opt. Ax. {B moderate } r > v {A strong } r > v
CaO	22.54	Fe	173							WXY	856		
Na <sub>2</sub> O	.35	Mn	6									ZΛc aver. 51(?)°	Exsolution Lamellae, none
K <sub>2</sub> O	.02	Mg	171½										
H <sub>2</sub> O+	.17	Ca	402									Remarks:	
H <sub>2</sub> O-	.09	Na	11	11									
TiO <sub>2</sub>	.31	K	—										
MnO	.41	Ti	4			4							
	99.97	O	—										

Analyst: Lee C. Peck  
Density: 25°/4° 3.44  
Color hand specimen: dark green

Ca<sub>48.6</sub>Mg<sub>22.4</sub>Fe<sub>20.8</sub>  
% Al in Z=10

## ANALYSIS 40

Specimen No. CM. Augite. Cerro Mercado, Durango, Mexico. U. S. Museum no. 92159. Obtained from E. P. Henderson. U. S. Nat. Mus. Analysis from Foshag (1928)

		Atomic Ratios		Fe <sup>'''</sup>	Al	Ti	2Al	Al	Al	Z	Cations to Six O	Indices of Refraction n <sub>X</sub> 1.700 n <sub>Y</sub> 1.711 n <sub>Z</sub> 1.728	Pleochroism X=Z green, slightly bluish Y green, slightly yellowish ⊥ bc light brown
		Na	Na	Na	Na	Na	Na	Na	Na	W			
SiO <sub>2</sub>	50.97	Si	848							Z	1.97	Birefringence, x10 <sup>4</sup> aver. 276 257, 268, 278, 282, 293	
Al <sub>2</sub> O <sub>3</sub>	.95	Al	18½			5	15½*			Z			
Fe <sub>2</sub> O <sub>3</sub>	7.08											2V aver. 77°	
FeO	6.96												
MgO	11.55	Fe <sup>'''</sup>	88½	61			15½					2.06	Dispersion, Opt. Ax. {B weak } r > v {A strong } v > r
CaO	20.96	Fe	97							WXY	907½		
Na <sub>2</sub> O	1.86	Mn	—									ZΛc aver. 51°, variable	Exsolution Lamellae
K <sub>2</sub> O	.05	Mg	286½										
H <sub>2</sub> O+	.19	Ca	374									Remarks: * 2 Fe <sup>++</sup> included here in the Z group to balance charge.	
H <sub>2</sub> O-	—	Na	60	60									
TiO <sub>2</sub>	.20	K	1										
MnO	—	Ti	2½	1		2½							
	100.77	O	2649½										

Analyst: F. A. Gonyer  
Color hand specimen: green

Ca<sub>41</sub>Mg<sub>21</sub>Fe<sub>22</sub>  
% Al in Z=2.3

ANALYSIS 41\*

Specimen No. TR-1-P. Pigeonite. Coarse diabase pegmatite, Goose Creek, Va. (Triassic).  
See TR-1-A augite analysis from same sample.

	Atomic Ratios							Cations to Six O	Indices of Refraction nX 1.6980 nY 1.6988 nZ 1.7228	Pleochroism Colorless	
		Fe''	Al	2Al	Al	Al	Z				
		Na	Na	Ti	Fe'''	Al	Al				Y
		Na	Na				W				
SiO <sub>2</sub> 51.53	Si 858							Z 880	2.019	Birefringence, x10 <sup>4</sup> aver. 248 Z-X=240	
Al <sub>2</sub> O <sub>3</sub> 1.64	Al 32			13		9					Z 861½
Fe <sub>2</sub> O <sub>3</sub> .18	Fe''' 2	2	1			9		WXY		Dispersion, Opt. Ax. moderate r > v † Z∧c aver. 40-41°	
FeO 23.35	Fe 325										O 2621½
MgO 17.27	Mn 7							O 6½		Remarks: * Analysis corrected for augite impurity and recalculated to 100%. Original sample ⅔ pigeonite and ⅓ augite. † Anomalous dispersion colors greenish blue concave side of isogyre and purple convex side.	
CaO 4.47	Mg 428		1								O 6½
Na <sub>2</sub> O .10	Ca 80							O 6½			
K <sub>2</sub> O .00	Na 3										O 6½
H <sub>2</sub> O+ .32	K —							O 6½			
H <sub>2</sub> O- .14	Ti —										O 6½
TiO <sub>2</sub> .51	O 2621½							O 6½			
MnO .49											O 6½
100.00*								O 6½			

Ca<sub>2.8</sub>Mg<sub>0.3</sub>Fe<sub>0.7</sub>  
% Al in Z=2.5

ANALYSIS 42\*

Specimen No. LAM 12 P. Pigeonite. Diabase sill (Triassic) south of Lambertville, N. J.  
Sample came from approximately 750 feet above base and 1000 feet below roof.

	Atomic Ratios							Cations to Six O	Indices of Refraction nX 1.7055 nY 1.7066 nZ 1.7325	Pleochroism X faint pink Y faint pink Z faint green		
		Fe''	Al	Cr	2Al	Al	Z					
		Na	Na	Na	Ti	Fe'''	Al				Al	Y
		Na	Na	Na							W	
SiO <sub>2</sub> 51.24	Si 853							Z 869½	2.023	Birefringence, x10 <sup>4</sup> aver. 270 Z-Y=259		
Al <sub>2</sub> O <sub>3</sub> 1.07	Al 21				12		4½				Z 839½	1.986
Fe <sub>2</sub> O <sub>3</sub> .05	Fe''' 1	1					4½	WXY		Dispersion, Opt. Ax. moderate r > v		
FeO 26.85	Cr —										O 2578½	
MgO 14.85	Fe 374							O 2578½		Ezsolution Lamellae		
CaO 4.31	Mn 8										O 2578½	
Na <sub>2</sub> O .02	Ni —							O 2578½				
K <sub>2</sub> O .02	Mg 368										O 2578½	
H <sub>2</sub> O+ .36	Ca 77							O 2578½				
H <sub>2</sub> O- .18	Na 1										O 2578½	
TiO <sub>2</sub> .50	K —							O 2578½				
Cr <sub>2</sub> O <sub>3</sub> .00	Na 1										O 2578½	
MnO .55	K —							O 2578½				
NiO —	Ti 6										O 2578½	
100.00*	O 2578½							O 2578½				

Ca<sub>2.2</sub>Mg<sub>0.4</sub>Fe<sub>0.3</sub>  
% Al in Z=1.9

## ANALYSIS 43

Specimen No. MC. Pigeonite. Moore County N.C. meteorite. For description see Hess and Henderson (1949) *Am. Mineral.*, **34**, 499

	Atomic* Ratios	Cations to Six O						Indices of Refraction <i>n</i> X 1.7085 <i>n</i> Y 1.7095 <i>n</i> Z 1.7360	Pleochroism Faint brown nonpleochroic
		Fe <sup>3+</sup>	Al	2Al	Fe <sup>2+</sup>	Al	Z		
		Na	Na				Y		
SiO <sub>2</sub> 49.37	Si 822						Z	Birefringence, $\times 10^4$ aver. 275 2V aver. 21° Dispersion, Opt. Ax. moderate $r > v$ Z $\wedge$ c aver. 40° Resolution Lamellae. Coarse augite lamellae $\parallel$ {001} Remarks: * 14Fe <sup>2+</sup> , 13Fe <sup>2+</sup> and 6Ti <sup>4+</sup> subtracted from these ratios to take care of magnetite-ilmenite inclusions. † Composition of host less augite lamellae Ca <sub>2</sub> Mg <sub>0.7</sub> Fe <sub>0.7</sub>	
Al <sub>2</sub> O <sub>3</sub> 1.55	Al 30			4	9	8	843		
Fe <sub>2</sub> O <sub>3</sub> 1.83									
FeO 26.44									
MgO 15.54	Fe <sup>2+</sup> 9				9				
CaO 4.60	Fe 355								
Na <sub>2</sub> O —	Mn 5								
K <sub>2</sub> O —	Mg 385						WXY		
H <sub>2</sub> O+ —	Ca 82						847		
H <sub>2</sub> O- —	Na —								
TiO <sub>2</sub> .62	K —								
MnO .37	Ti 2			2					
100.32	O —						2.005		
Analyst: E. P. Henderson Color hand specimen: light brown		Ca <sub>10</sub> Mg <sub>9</sub> Fe <sub>11</sub> † % Al in Z=2.5							

## ANALYSIS 44

Specimen No. Mull. Pigeonite. "Uniaxial augite" described by Hallimond (1914) from glassy lava 1 mile south-south-west of Pennygael, Mull. Rock analysis Summ. Prog. of Geol. Surv. Great. Brit. 1912-1913, p. 69

	Atomic Ratios	Cations to Six O						Indices of Refraction <i>n</i> X 1.7137 <i>n</i> Y 1.7137 <i>n</i> Z 1.7417	Pleochroism X, Y pale greenish brown Z pale yellowish or reddish brown
		Fe <sup>3+</sup>	Al	2Al	Fe <sup>2+</sup>	Al	Z		
		Na	Na				Y		
SiO <sub>2</sub> 49.72	Si 828						Z	Birefringence, $\times 10^4$ aver. 280 278, 279, 279, 280, 286 2V aver. 0°-12° in place $\perp$ {010}. Dispersion, Opt. Ax. moderate $r > v$ Z $\wedge$ c aver. 39°-40° Resolution Lamellae, none Remarks: * 3 Fe <sup>2+</sup> substituted for Al to balance charge. † 5½ Fe <sup>2+</sup> should go in Z group to balance charge. This analysis made in 1914 is suspected of being slightly high in Si and low in Al. It is nevertheless a very good analysis.	
Al <sub>2</sub> O <sub>3</sub> .90	Al 18			21*			849		
Fe <sub>2</sub> O <sub>3</sub> 1.72									
FeO 27.77									
MgO 12.69	Fe <sup>2+</sup> 22	8			11†				
CaO 3.80	Fe 386½								
Na <sub>2</sub> O .23	Mn 14						WXY		
K <sub>2</sub> O .12	Mg 314½						823½		
H <sub>2</sub> O+ 1.27	Ca 68								
H <sub>2</sub> O- .08	Na 6	6							
TiO <sub>2</sub> .85	K 2	2							
MnO .98	Ti 10½			10½					
NiO .00	O 2524								
Li <sub>2</sub> O tr									
100.13							1.96		
Analyst: E. G. Radley Density: 3.44 (S. G. 17°C. 3.44 Hallimond) Color hand specimen: yellow brown		Ca <sub>10</sub> Mg <sub>9</sub> Fe <sub>10.5</sub> % Al in Z=2.6							