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

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* 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.

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.

<center>NOMENCLATURE</center>

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° and less than 30°, 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 nonexistent, 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:

$$(W)_{1-p}(X, Y)_{1+p}Z_2O_6$$
$$W = Ca^{+2}, Na^{+1}$$
$$X = Mg^{+2}, Fe^{+2}, Mn^{+2}, Ni^{+2}$$
$$Y = Al^{+3}, Fe^{+3}, Cr^{+3}, Ti^{+4}$$
$$Z = Si^{+4}, Al^{+3}$$
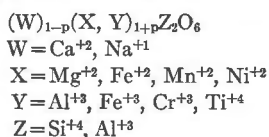
Four such units would be required by the monoclinic cell and eight by the orthorhombic. In the above formula p would be zero or close to it for the diopside-hedenbergite or acmite-jadeite series and would be 1, or close to it, for the orthorhombic pyroxenes and pigeonites.

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^{-2} 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					
W	X, Y	Z	O	W	X, Y	Z	O
(1) $+2$	$+2$	$+8$	-12	Ca^{+2}	Mg^{+2}	$2Si^{+4}$	O
(2) $+1$	$+3$	$+8$	-12	Na^{+1}	Fe^{+3}	$2Si^{+4}$	O
(3) $+2$	$+4$	$+6$	-12	Ca^{+2}	Ti^{+4}	$2Al^{+3}$	O
(4) $+2$	$+3$	$+7$	-12	Ca^{+2}	Al^{+3}	Al^{+3}, Si^{+4}	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^{+3} ion is much larger than the Si^{+4} 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 $NaCrSi_2O_6$; (2) Remaining Na ions are combined with Fe^{+3} to form $NaFeSi_2O_6$; (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 Fe^{+2} and 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 H_2O is omitted since its constituents probably do not enter the pyroxene structure. In the few cases where H_2O 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 Isodynamic 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 diabases, 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 Y 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 birefrigence since an optic axis emerges from them at approximately 20° 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

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* 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° to 60° is more accurate than most authors state. The accuracy after index corrections is certainly better than $\pm 0.5°$ and probably better than $\pm 0.3°$ 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°, 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° and 46°, an accuracy of at least $\pm 1°$ 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 ($\pm 20°$) 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°–45° and the one or perhaps two other angles will require tilts of 45°–55°. 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° and 55° should be marked as having lower accuracy than those below 45°. 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 $\|\{100\}$ can be observed
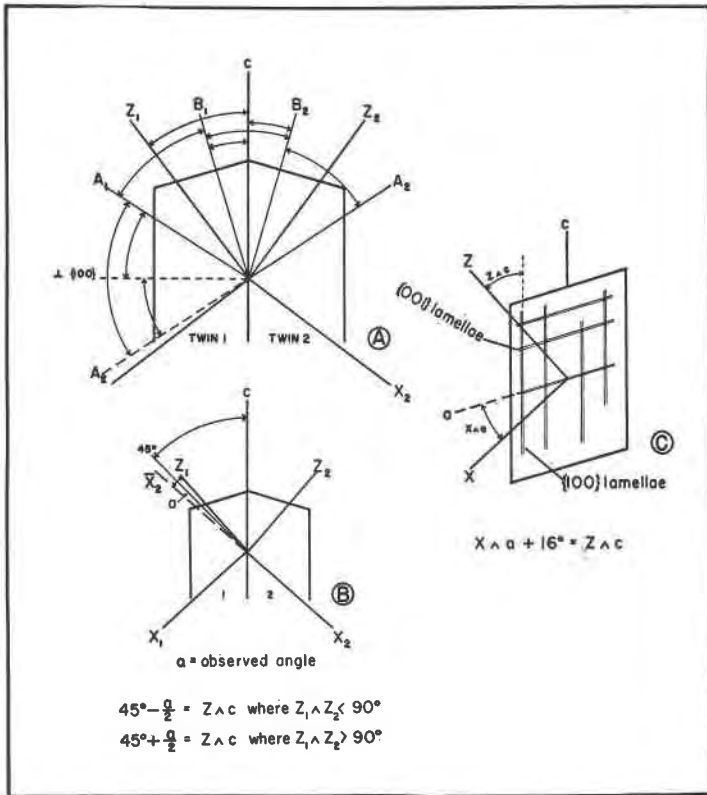
FIG. 1. Measurement of $Z\wedge c$.

or calculated with accuracy estimated to be better than 1° and probably good to $\pm0.5°$. $Z\wedge c$ and $2V$ are thus determined simultaneously.

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

In untwinned clinopyroxenes exhibiting very fine, sharp exsolution lamellae of orthopyroxene parallel to either $\{100\}$ or $\{001\}$, the angle $Z\wedge c$ or $X\wedge a$ 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 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 ± 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-

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* 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

• New Analyses

○ Analyses from Literature; New Optical Properties

• Analyses and Properties from Literature
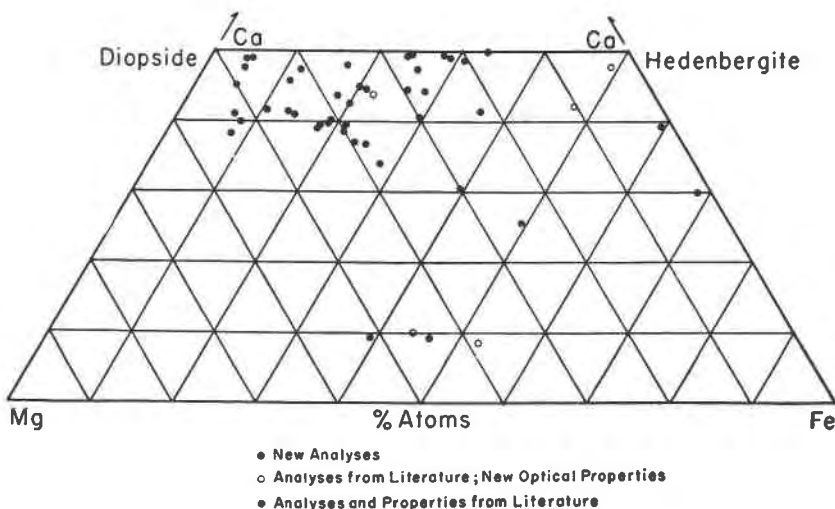
FIG. 2

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: Al_2O_3 3%; Fe_2O_3* 1.5%; Na_2O 0.4%; TiO_2 0.4%; MnO 0.3% but higher in more ferriferous samples; Cr_2O_3† 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 Fe^{+3} ions are included in the total Fe of the curves, the effect of Fe^{+3} on optical properties is not exactly the same as Fe^{+2}, so it has to be dealt with in the same way as other minor constituents.

† Cr_2O_3 content is taken care of by an extra set of dashed curves for Mg-rich augites in Plates I, II and III.

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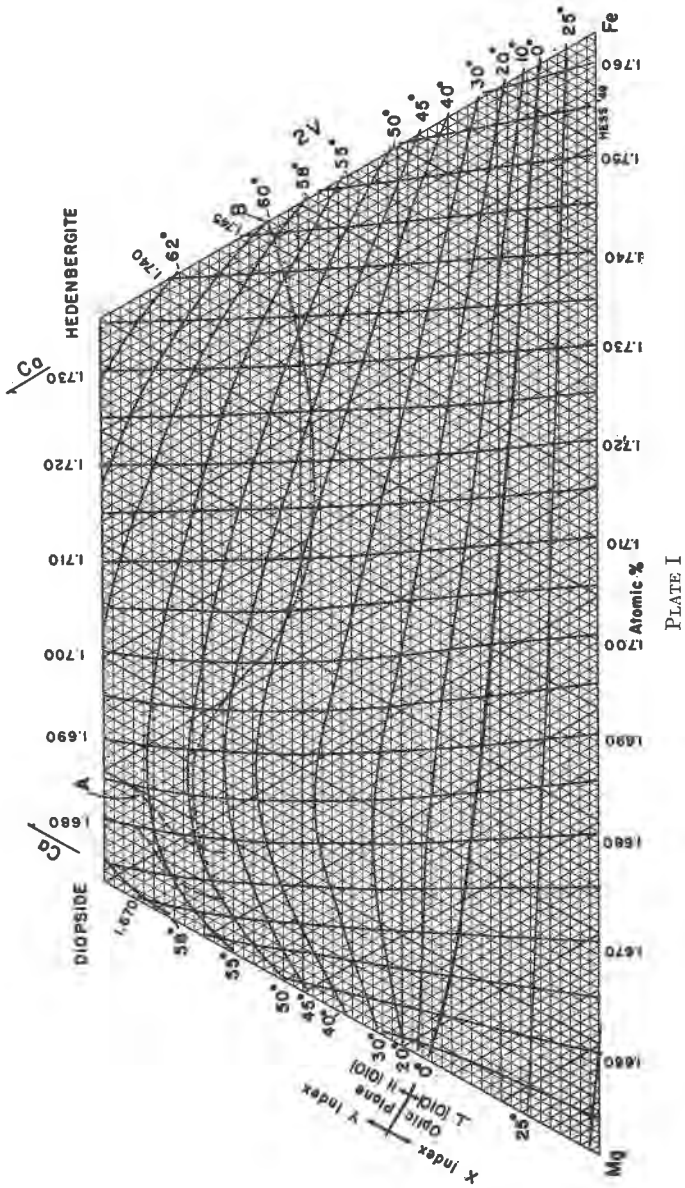
of the optical properties to group together in such a manner that they fit the curves. In a succeeeding part of this series of papers the specific effects on optical properties of each of the above mentioned minor oxides will be evaluated.

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 $Ca_{38}Mg_{40}Fe_{22}$ 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 ferriferous 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 $2V = 0°$ and the X index for the area below $2V = 0$. The reasons for shifting from Y to X index upon crossing $2V = 0°$ are: (1) The X and Y curves come together at $2V = 0°$ 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 Cr^{+3} with high Mg which seems to occur in practically every case and in a regular manner. Cr_2O_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 $4°$. The average departure with respect to sign was $-1.25°$ and without regard to sign $1.5°$. Ninety-four per cent of the observed values depart from the curves by $3°$ or less, 80% by $2°$ or less, and 60% by $1°$ or less. The distribution of points over those areas where natural clinopyroxenes occur is good except in the ferro-augite 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 $3°$. Thus if the bulk composition of the host plus lamellae is desired, about $3°$ 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 $2V = 0°$ and Y index below $2V = 0°$. 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

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

PLATE II

% Ca, Mg, & Fe Atoms
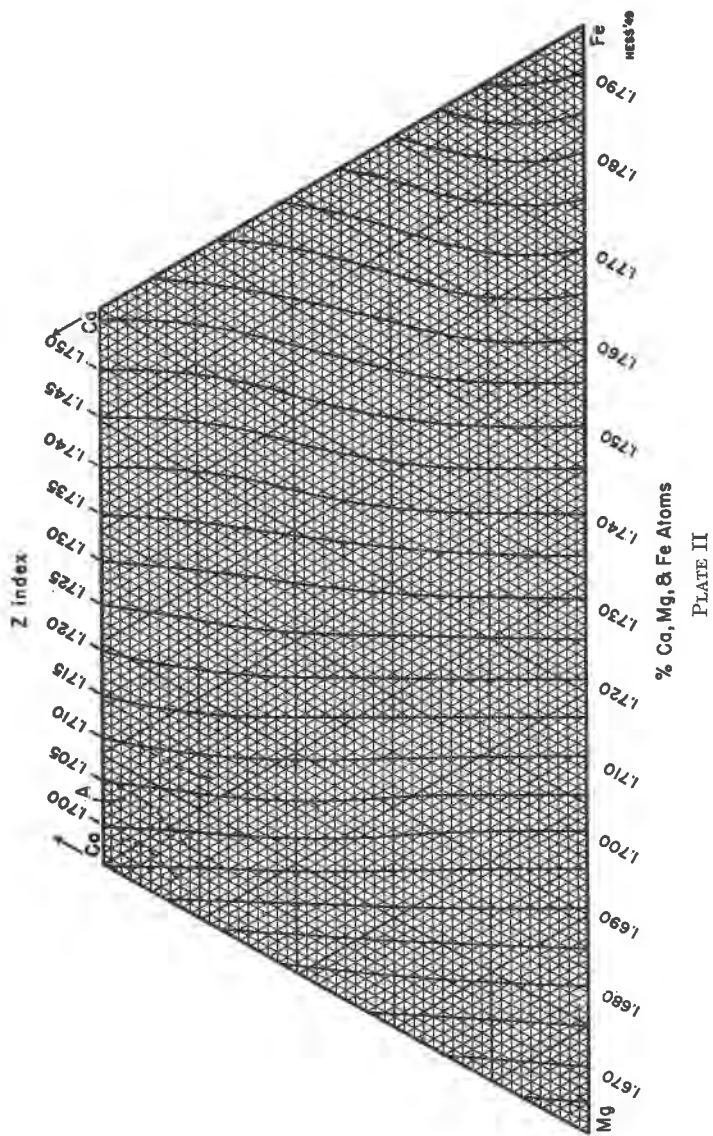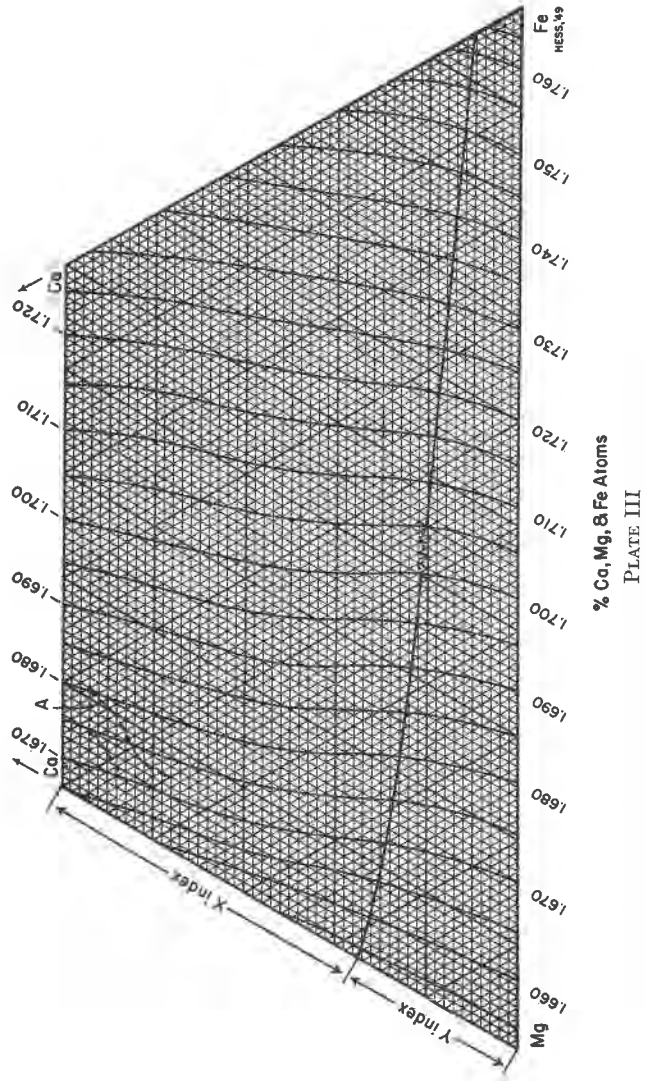
PLATE III

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 substi-
tuting for Si in the *Z* group. After determining the composition of the
clinopyroxene on Plate I, a comparison of observed vs. normal bire-
fringence as given on Plate IV will indicate deviations in Al concentra-
tion from the assumed amount. Exsolution of hypersthene lamellae from
augites will generally increase the birefringence of the host material by
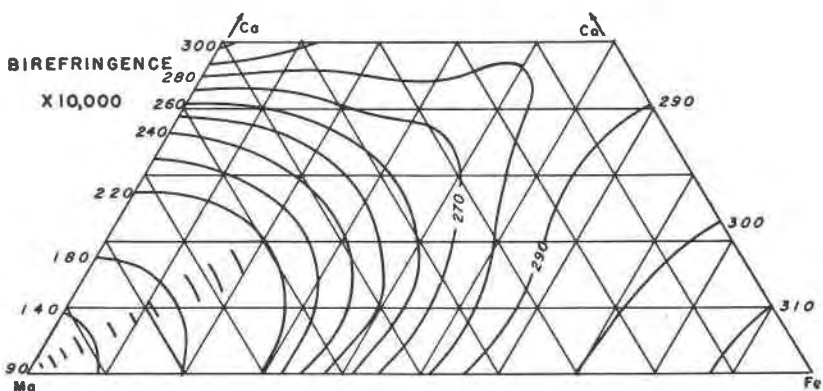
PLATE IV

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 condi-
tions of crystallization.

In succeeding parts of this study the following subjects will be con-
sidered: 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.
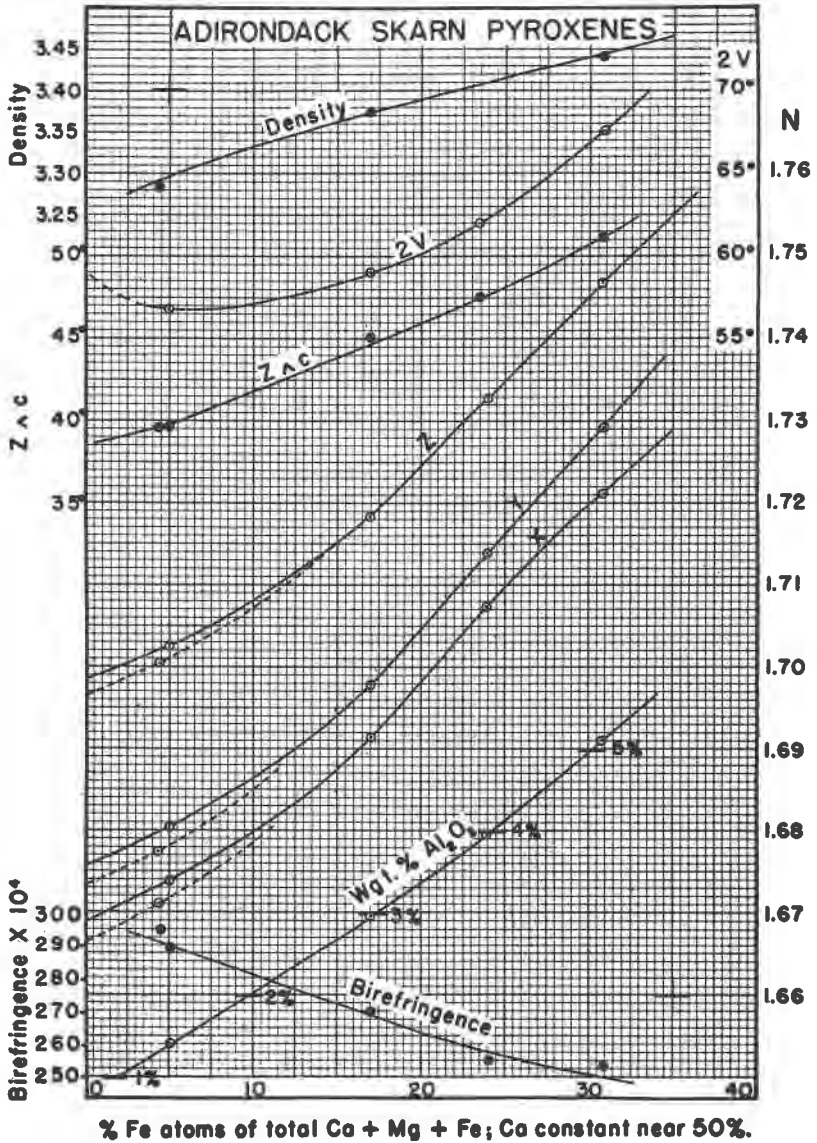
PLATE V
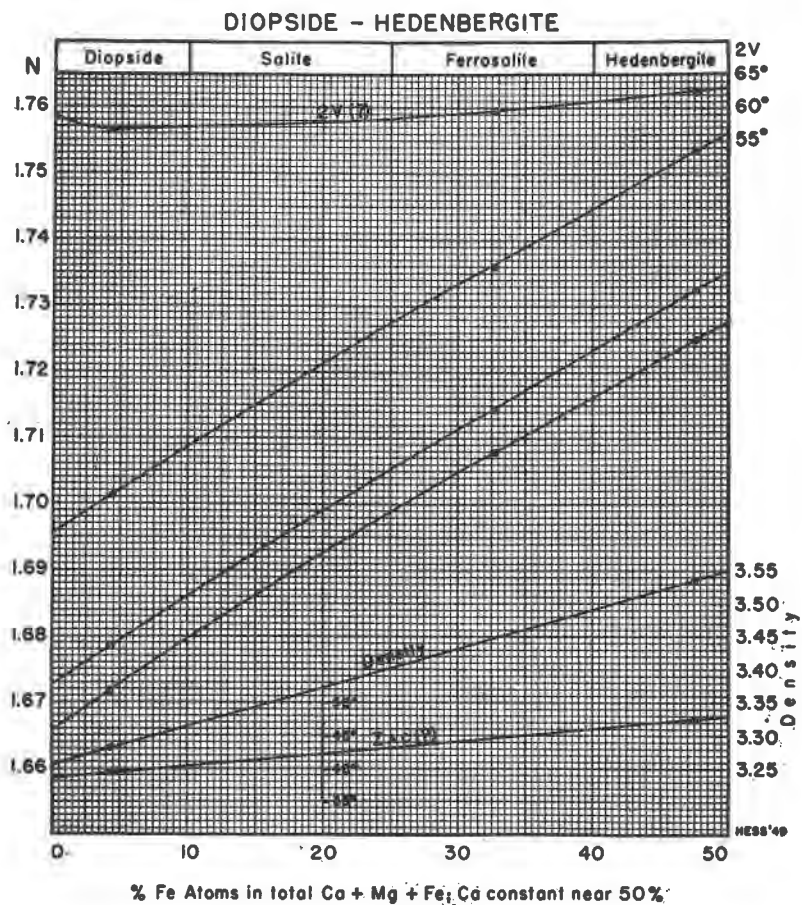
PLATE VI
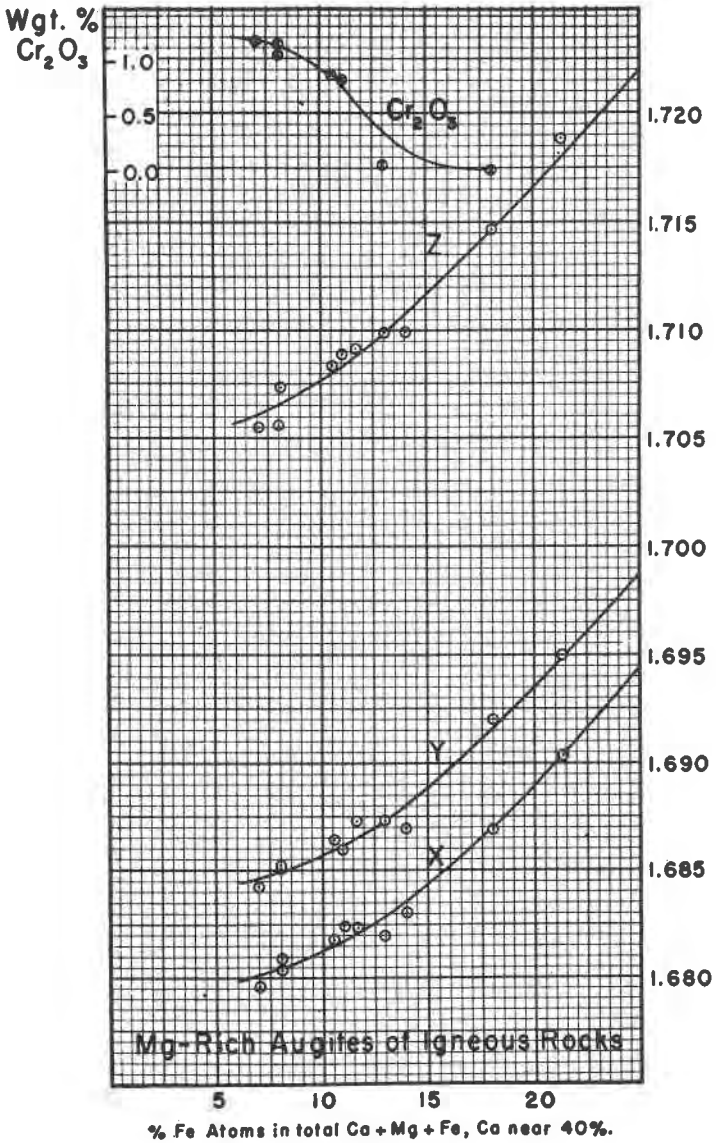
PLATE VII
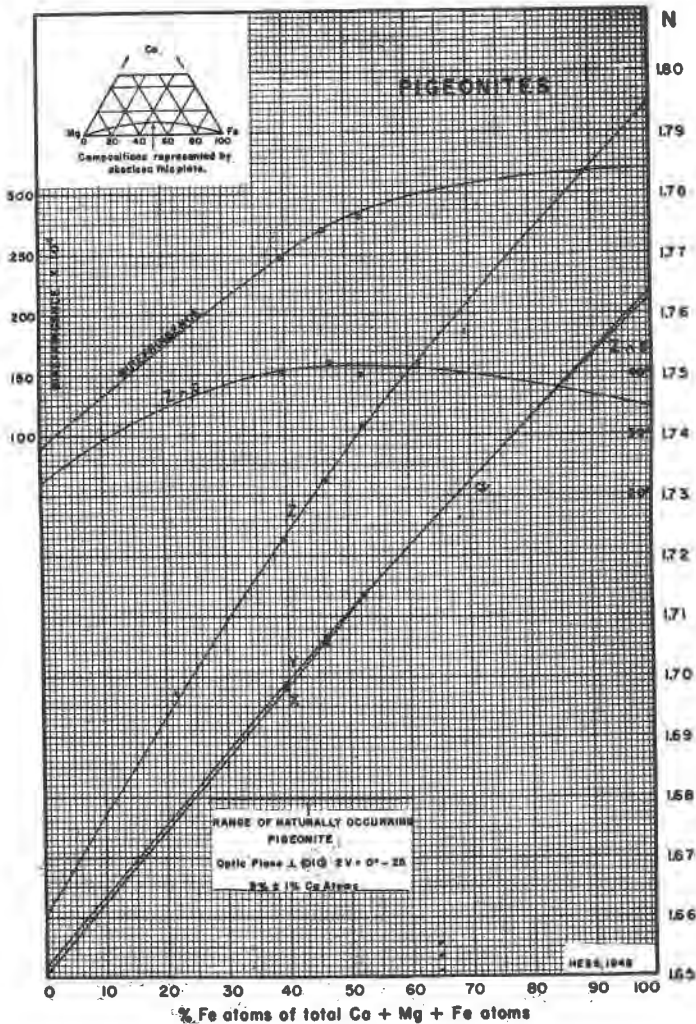
PLATE VIII

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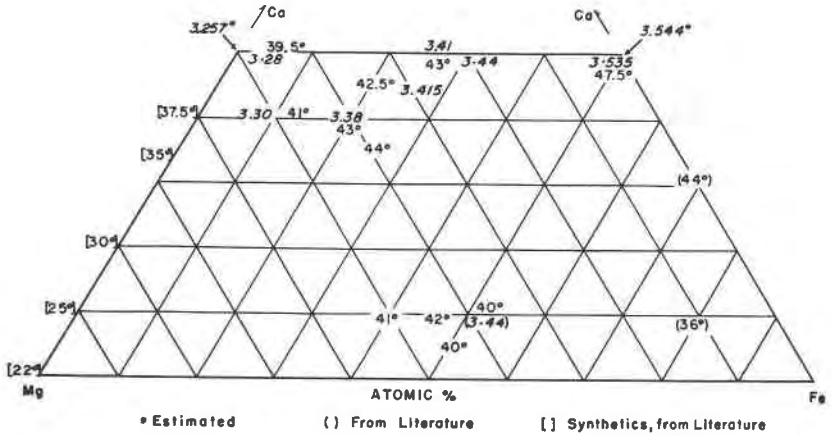
PLATE IX. Density variation.

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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

Oxide	wt %		At. Ratios	Fe''/Na	Al/Na	Cr/Na	2Al/Ti	Al/Fe''	Al/Cr	Al/Al	Z / Y / W	Cations to Six O
SiO₂	54.38	Si	905½				1	24			Z 930½	2.02
Al₂O₃	1.29	Al	25	-	-	-	-					
Fe₂O₃	2.19											
FeO	.94	Fe'''	27½	3		3½		24½				
MgO	16.96	Cr	3½									
CaO	23.71	Fe	13									
Na₂O	.14	Mn	1½									
K₂O	.08	Ni	—									
H₂O+	.14	Mg	420½								WXY 893	1.95
H₂O−	.08	Ca	423									
TiO₂	.04	Na	4½	1		3½						
Cr₂O₃	.28	K	2	2								
MnO	.09	Ti	½				½					
NiO	.00	O	2757									
P₂O₅	.10											
100.42												

$Ca_{47.3}Mg_{47.8}Fe_{4.7}$
% Al in Z = 2.7

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

Indices of Refraction
nX 1.6715
nY 1.6782
nZ 1.7007

Pleochroism Colorless in section

Birefringence, x10⁴ aver. 292
287, 290, 293, 297, 298

2V aver. 57¾°
57°, 57½°, 58¼°, 58¼°

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

Z∧c aver. 39°

Exsolution Lamellae, rare ∥ {001}

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

Oxide	wt %		At. Ratios	Fe''/Na	Al/Na	Cr/Na	2Al/Ti	Al/Fe''	Al/Cr	Al/Al	Z / Y / W	Cations to Six O
SiO₂	54.07	Si	900				6	8	2	12	Z 928	2.01
Al₂O₃	2.08	Al	40	-	-	-	-	-	-	12		
Fe₂O₃	.56							8				
FeO	2.53	Fe'''	8									
MgO	17.39	Cr	14			12			2			
CaO	22.12	Fe	35									
Na₂O	.41	Mn	1									
K₂O	.00	Ni	1									
H₂O+	.04	Mg	431								WXY 911	1.98
H₂O−	.06	Ca	394									
TiO₂	.21	Na	12			12						
Cr₂O₃	.98	K	—									
MnO	.09	Ti	3				3					
NiO	.04	O	2767									
100.58												

$Ca_{45}Mg_{50}Fe_5$
% Al in Z = 3.0

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

Indices of Refraction
nX 1.6742
nY 1.6800
nZ 1.7019

Pleochroism Colorless in section

Birefringence, x10⁴ aver. 277
254, 272, 272, 276, 278, 280, 288, 291
highly variable

2V aver. 55½°
54¼, 55, 55¼, 56½°

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

Z∧c aver. 40¼°
39½, 39¾, 40, 40, 40½, 41°

Exsolution Lamellae, rare, if any.

Remarks:

ANALYSIS 3

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

		Atomic Ratios		Fe'''	Al	Cr	2Al Na	Al Na	Al	Al	Z	Cations to Six O
				Na	Na	Na	Ti	Fe'''	Cr	Al	Y	
											W	
SiO$_2$	51.98	Si	865½								Z 911½	1.99
Al$_2$O$_3$	3.67	Al	72				4	8	9	25		
Fe$_2$O$_3$	.62									26		
FeO	3.62	Fe'''	8					8				
MgO	18.28	Cr	16			7			9			
CaO	20.13	Fe	50									
Na$_2$O	.17	Mn	2									
K$_2$O	.08	Ni	—								WXY 923	2.02
H$_2$O+	.11	Mg	453									
H$_2$O−	.03	Ca	359									
TiO$_2$	.15	Na	5		5							
Cr$_2$O$_3$	1.21	K	2		2							
MnO	.14	Ti	2				2					
NiO	.03	O	2747									
	100.2$_2$											

Indices of Refraction
nX 1.6797
nY 1.6844
nZ 1.7058

Pleochroism
Colorless in section

Birefringence, x10^4 aver. 261
255, 258, 261, 263, 269

2V aver. 50°

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

Z∧c aver. 40¾°

Exsolution Lamellae, ||{100}

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

Ca$_{41}$Mg$_{52}$Fe$_7$
% Al in Z=5.0

Remarks:

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		Fe'''	Al	Cr	2Al Na	Al Na	Al	Al	Z	Cations to Six O
				Na	Na	Na	Ti	Fe'''	Cr	Al	Y	
											W	
SiO$_2$	51.43	Si	856								Z 900	1.99
Al$_2$O$_3$	3.00	Al	58				7	17	5	15		
Fe$_2$O$_3$	1.37									15		
FeO	4.23											
MgO	19.44	Fe'''	17					17				
CaO	17.86	Cr	14			9			5			
Na$_2$O	.28	Fe	59									
K$_2$O	.02	Mn	2								WXY 905	2.00
H$_2$O+	.70	Ni	—									
H$_2$O−	.10	Mg	482									
TiO$_2$	.27	Ca	319									
Cr$_2$O$_3$	1.09	Na	9		9							
MnO	.14	K	—									
NiO	—	Ti	3½				3½					
	99.93	O	2719									

Indices of Refraction
nX 1.6810
nY 1.6853
nZ 1.7057

Pleochroism
Colorless in section

Birefringence, x10^4 aver. 247
230, 238, 238, 242, 248, 248, 250, 252, 259
268, (280?).

2V aver. 48¾°

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

Z∧c aver. 40½°
39½, 39¾, 40¾, 41, 41°

Exsolution Lamellae, ||{100}

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

Ca$_{37}$Mg$_{56}$Fe$_7$
% A in Z=4.9

Remarks:

ANALYSIS 5

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

Oxide	%	Atomic Ratios		Fe''' (Na)	Al (Na)	Cr (Na)	Ti (2Al)	Fe'' (Al)	Cr (Al)	Al (Al)	Z / Y / W	Cations to Six O
SiO_2	52.55	Si	875								Z 917	2.00
Al_2O_3	2.98	Al	58	—	—	—	6	14	6	16		
Fe_2O_3	1.17									16		
FeO	3.98	Fe'''	14					14				
MgO	18.21	Cr	16			10			6			
CaO	19.23	Fe	55									
Na_2O	.32	Mn	2									
K_2O	.00	Ni	1								WXY 912½	2.00
H_2O+	.14	Mg	451½									
H_2O-	.08	Ca	344			10						
TiO_2	.24	Na	10									
Cr_2O_3	1.18	K	—				3					
MnO	.12	Ti	3									
NiO	.05	O	2746½									
	100.25											

Indices of Refraction
nX 1.6805
nY 1.6852
nZ 1.7075

Pleochroism
Colorless in section

Birefringence, x10⁴ aver. 270
249, 254, 258, 272, 272, 276, 282, 295 (variable).

2V aver. 49°
49, 49, 49¼°

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

Z∧c aver. 40½°
39, 39¾, 40, 40¼, 40¾, 40¾, 41, 41½, 42¼°

Exsolution Lamellae, ∥{100} well developed

Remarks:

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

$Ca_{40}Mg_{52}Fe_8$
% 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.

Oxide	%	Atomic Ratios		Fe''' (Na)	Al (Na)	Cr (Na)	Ti (2Al)	Fe'' (Al)	Cr (Al)	Al (Al)	Z / Y / W	Cations to Six O
SiO_2	52.92	Si	881								Z 919	2.01
Al_2O_3	2.80	Al	54	—	—	—	12	5	6	15		
Fe_2O_3	.85									16		
FeO	5.57	Fe'''	10	5				5				
MgO	16.40	Cr	12			6			6			
CaO	19.97	Fe	78									
Na_2O	.35	Mn	2								WXY 899	1.97
K_2O	.01	Ni	1									
H_2O+	.10	Mg	407									
H_2O-	.07	Ca	356									
TiO_2	.50	Na	11	5		6						
Cr_2O_3	.88	K	—				6					
MnO	.15	Ti	6									
NiO	.10	O	2737									
	100.67											

Indices of Refraction
nX 1.6818
nY 1.6865
nZ 1.7085

Pleochroism
Colorless in section

Birefringence, x10⁴ aver. 267
253, 262, 267, 273, 274, 274

2V aver. 49°
42¾, 47½, 48, 48¼, 53, 53°

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

Z∧c aver. 40¾°
39¾, 40¾, 41°

Exsolution Lamellae, ∥{100}

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

$Ca_{41.5}Mg_{48}Fe_{10.5}$
% Al in Z=4.2

Remarks:

ANALYSIS 7

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

Oxide	wt %	Atomic Ratios		Fe''' / Na	Al / Na	Cr / Na	Ti (2Al)	Fe'' (Al)	Cr (Al)	Al (Al)	Z / Y / W	Cations to Six O
SiO$_2$	50.90	Si	847								Z	
Al$_2$O$_3$	3.83						24	4	–	23	898	2.00
Fe$_2$O$_3$	1.29	Al	74	–	–	–	–	–	–	23		
FeO	5.49											
MgO	16.07	Fe'''	16	12				4				
CaO	18.92	Cr	11			11						
Na$_2$O	.69	Fe	76									
K$_2$O	.06	Mn	3								WXY	
H$_2$O+	.71	Ni	—								901	2.00
H$_2$O−	.20	Mg	399									
TiO$_2$	.94	Ca	338									
Cr$_2$O$_3$	.84	Na	22	11		11						
MnO	.19	K	1	1								
NiO (.034)	.03	Ti	12				12					
	100.16	O	2697									

Indices of Refraction
nX 1.6825
nY 1.6860
nZ 1.7090

Pleochroism
Colorless in section

Birefringence, x10^4 aver. 265
262, 265, 269

2V aver. 48°
45½, 48¾, 52¼°

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

Z∧c aver. 40¾°

Exsolution Lamellae, ||{100}

Analyst: Lee C. Peck
Color hand specimen: brown
Ca$_{40.7}$Mg$_{48.2}$Fe$_{11}$
% Al in Z=5.7
Remarks:

ANALYSIS 8

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

Oxide	wt %	Atomic Ratios		Fe''' / Na	Al / Na	Ti (2Al)	Fe'' (Al)	Al (Al)	Z / Y / W	Cations to Six O
SiO$_2$	52.61	Si	876						Z	
Al$_2$O$_3$	2.72					11	8	17	912	2.01
Fe$_2$O$_3$	1.36	Al	53	–	–	–	–	17		
FeO	5.85									
MgO	15.97	Fe'''	17	9			8			
CaO	20.50	Fe	81							
Na$_2$O	.28	Mn	2½						WXY	
K$_2$O	.02	Mg	396						894	1.98
H$_2$O+	.19	Ca	366							
H$_2$O−	.04	Na	9	9						
TiO$_2$	.44	K	—							
MnO	.18	Ti	5½			5½				
	100.16	O	2718							

Indices of Refraction
nX 1.6823
nY 1.6874
nZ 1.7093

Pleochroism
Colorless in section

Birefringence, x10^4 aver. 270
266, 268, 269, 270, 274, 279

2V aver. 51½°
48¾, 50¾, 51½, 51¾, 52½, 52½, 53°

Dispersion, Opt. Ax. $\{$B weak / A very weak$\}$ r>v

Z∧c aver. 41°
39, 39½, 40, 40¾, 41, 41⅛, 41¼, 41½, 41¾, 41¼, 42¾

Exsolution Lamellae, ||{100}. 2V lamellae orthopyroxene=66°±2°=Mg$_{75}$Fe$_{25}$

Analyst: R. B. Ellestad
Color hand specimen: greenish brown
Ca$_{42.3}$Mg$_{46}$Fe$_{11.7}$
% Al in Z=3.9
Remarks: Twinned on {100}

ANALYSIS 9

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

		Atomic Ratios		Fe″	Al	Cr	Ti	Fe‴	Cr	Al	Z Y W	Cations to Six O
							2Al	Al	Al	Al		
				Na	Na	Na						
SiO₂	52.47	Si	873½					12	9		12½	Z 907	2.01
Al₂O₃	2.28	Al	46	–	–	–	–				12½		
Fe₂O₃	1.49										12½		
FeO	6.61	Fe‴	18	9					9				
MgO	15.71	Cr	1			1							
CaO	20.28	Fe	92									WXY 894	1.99
Na₂O	.31	Mn	3										
K₂O	.02	Ni	½										
H₂O+	.20	Mg	390										
H₂O−	.04	Ca	361										
TiO₂	.46	Na	10	9			1						
Cr₂O₃	.08	K	—					6					
MnO	.20	Ti	6										
NiO	.04	O	2708										
	100.19												

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

$Ca_{41.5}Mg_{45.5}Fe_{13}$
% Al in Z=3.7

Indices of Refraction
nX 1.6820
nY 1.6875
nZ 1.7101

Pleochroism
Colorless in in section

Birefringence x10⁴ aver. 281
272½, 281, 283, 287½ (margin one grain 254)

2V aver. 51¾°
50¼, 51¾, 52, 52¾°

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

Z∧c aver. 42½°

Exsolution 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		Fe″	Al	Ti	Fe‴	Al	Z Y W	Cations to Six O
							2Al	Al	Al		
				Na	Na					
SiO₂	51.83	Si	863				12	8	20	Z 903	2.007
Al₂O₃	3.07	Al	60	–	–	–			20		
Fe₂O₃	1.38							8			
FeO	7.21	Fe‴	17	9							
MgO	16.00	Fe	100								
CaO	19.21	Mn	2½							WXY 894	1.987
Na₂O	.27	Mg	397								
K₂O	.02	Ca	342½								
H₂O+	.47	Na	9	9							
H₂O−	.11	K	—								
TiO₂	.49	Ti	6				6				
MnO	.17	O	2700								
	100.23										

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

$Ca_{41}Mg_{45}Fe_{14}$
% Al in Z=4.4

Indices of Refraction
nX 1.6832
nY 1.6870
nZ 1.7100

Pleochroism
Colorless in thin section

Birefringence, x10⁴ aver. 268
266, 268, 269

2V aver. 52°. Average of 16 values

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

Z∧c aver. 42.1°. Average of 16 values

Exsolution 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		Fe''	Al	Cr	2Al / Ti	Al / Fe'''	Al / Cr	Al / Al	Z / Y / W	Cations to Six O		Indices of Refraction	Pleochroism
				Na	Na	Na							nX 1.6870	Not perceptibly
SiO$_2$	51.86	Si	863								Z 898	2.02		nY 1.6921	pleochroic in
Al$_2$O$_3$	2.33	Al	44				14	12		9				nZ 1.7149	thin section
Fe$_2$O$_3$	1.60	Fe'''	20	8	—	—		12	—	9					
FeO	9.45	Cr	—											*Birefringence,* x10^4 aver. 279	
MgO	14.50	Fe	131											275, 278, 283	
CaO	18.92	Mn	3½								WXY 876½	1.97			
Na$_2$O	.23	Ni	—											2V aver. 50¾°. Average of 22 values.	
K$_2$O	.00	Mg	360												
H$_2$O+	.37	Ca	338											*Dispersion,* Opt. Ax. {B moderate / A weak} $r>v$	
H$_2$O−	.09	Na	8	8											
TiO$_2$	.55	K	—											Z ∧ c aver. 42°. Average of 22 values.	
Cr$_2$O$_3$	.01	Ti	7				7								
MnO	.24	O	2674½											*Exsolution Lamellae,* ‖ {001} and ‖ {100}	
NiO	.02														
100.17															

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

Ca$_{39.5}$Mg$_{42.5}$Fe$_{18}$
% Al in Z=3.9

Remarks: Twinned on {100}.

ANALYSIS 12

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

		Atomic Ratios		Fe''	Al	2Al / Ti	Al / Fe'''	Al / Al	Z / Y / W	Cations to Six O		Indices of Refraction	Pleochroism
				Na	Na							nX 1.6905	Pale smoky green
SiO$_2$	51.39	Si	855½						Z 888	2.00		nY 1.6951	with a purplish tint
Al$_2$O$_3$	2.45	Al	48			10	7	15½				nZ 1.7190	in most directions but
Fe$_2$O$_3$	1.26	Fe'''	16	—	—	—	—	15½					⊥ bc yellowish brown
FeO	11.63	Fe	162	9			7						
MgO	14.21	Mn	4½						WXY 888	2.00		*Birefringence,* x10^4 aver. 285	
CaO	18.12	Mg	352									283, 284, 285, 285, 286	
Na$_2$O	.27	Ca	323										
K$_2$O	.02	Na	9	9								2V aver. 47½°	
H$_2$O+	.03	K	—									41, 43¾, 45, 45, 45½, 46½, 46½, 46¾, 47, 48,	
H$_2$O−	.07	Ti	5			5						48½, 48¾, 48¾, 48⅞, 49¼, 49¾, 50¼, 51, 51½,	
TiO$_2$	.41	O	2663									53°	
MnO	.32												
100.18												*Dispersion,* Opt. Ax. {B strong / A moderate} $r>v$	

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

Ca$_{38.7}$Mg$_{41}$Fe$_{21.3}$
% Al in Z=3.7

Z ∧ c aver. 44° (average 25 observations)

Exsolution Lamellae, ‖ {100} and {001}

Remarks: Twinned on {100}

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	Fe''' / Na	Al / Na	$2Al / Ti$	Al / Fe'''	Al / Al	Z / Y / W	Cations to Six O
SiO_2	51.01	Si	849			10	8½	17	Z 884½	2.001
Al_2O_3	2.69	Al	52½					17		
Fe_2O_3	1.86	Fe'''	23½	15			8½			
FeO	10.07	Fe	140							
MgO	12.41	Mn	7						WXY 882½	1.997
CaC	20.59	Mg	308							
Na_2O	.47	Ca	367							
K_2O	.02	Na	15	15						
H_2O+	.19	K	—							
H_2O-	.06	Ti	5			5				
TiO_2	.40	O	2651½							
MnO	.48									
	100.25									

Indices of Refraction
nX 1.6924
nY 1.6973
nZ 1.7193

Pleochroism
X faint green
Y pink
Z faint green
‖c axis faint green
⊥ bc pink

Birefringence, x10⁴ aver. 270
268, 270, 271, 273

2V aver. 50½°
48½, 48½, 49¼, 51½, 52, 52½

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

Z∧c aver. 42½°

Exsolution Lamellae, ‖{100}

Remarks: Rare twinning on {100}

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

$Ca_{43.5}Mg_{36.5}Fe_{20}$
% Al in Z=4.2

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	Fe''' / Na	Al / Na	$2Al / Ti$	Al / Fe'''	Al / Al	Z / Y / W	Cations to Six O
SiO_2	50.54	Si	841½			6	4	22	Z 873½	2.011
Al_2O_3	2.74	Al	54					22		
Fe_2O_3	2.42	Fe'''	30	26			4			
FeO	12.80	Fe	178							
MgO	9.65	Mn	2						WXY 859½	1.979
CaO	20.16	Mg	239							
Na_2O	.75	Ca	359½							
K_2O	.07	Na	24	24						
H_2O+	.17	K	2	2						
H_2O-	.04	Ti	3			3				
TiO_2	.25	O	2606½							
MnO	.15									
	99.74									

Indices of Refraction
nX 1.6985
nY 1.7055
nZ 1.7270

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

Birefringence, x10⁴ aver. 280
277, 282, 284. Y−X=215

2V aver. 57½°
55½, 56, 57¾, 58, 59°

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

Z∧c aver. 43°?

Exsolution Lamellae, a few ‖{001}

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

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

$Ca_{44.5}Mg_{29.5}Fe_{26}$
% Al in Z=3.7

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		Fe'''	Al	Ti	Fe''	Al	Z / Y / W	Cations to Six O
				Na	Na	2Al	Al	Al		
SiO_2	51.53	Si	858				5	$12\frac{1}{2}$	6	Z $881\frac{1}{2}$	
Al_2O_3	1.50	Al	$29\frac{1}{2}$	--	--	--			6		
Fe_2O_5	2.72							$12\frac{1}{2}$			
FeO	13.13	Fe'''	34	$21\frac{1}{2}$						WXY $859\frac{1}{2}$	1.982
MgO	8.92	Fe	183								
CaO	20.17	Mn	12								
Na_2O	.67	Mg	221								
K_2O	.00	Ca	360								
H_2O+	.36	Na	$21\frac{1}{2}$	$21\frac{1}{2}$							
H_2O-	.06	K	—								
TiO_2	.19	Ti	$2\frac{1}{2}$				$2\frac{1}{2}$				
MnO	.82	O	2602								
	100.07										

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

$Ca_{44.5}Mg_{27.25}Fe_{28.25}$
% Al in Z = 2.7

Indices of Refraction
nX 1.6995
nY 1.7063
nZ 1.7280

Pleochroism
X, Y and Z pale bluish green, $\perp bc$ pink

Birefringence, x10⁴ aver. 284
278, 278, 285, 288, 290

2V aver. $48\frac{1}{2}°$
$47\frac{1}{2}$, $47\frac{3}{4}$, $48\frac{1}{2}$, $48\frac{3}{4}$, $49\frac{3}{4}$, $50\frac{1}{4}°$

Dispersion, Opt. Ax. $\begin{cases} B\ weak^* \\ A\ moderate \end{cases} r>v$

$Z \wedge c$ aver. $42\frac{1}{2}°$ variable

Exsolution Lamellae, many || {100} and {001}
Lamellae are ferrohypersthene $Mg_{22}Fe_{78}$ estimated from $2V=77°$ 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.

ANALYSIS 16

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

		Atomic Ratios		Fe'''	Al	Ti	Fe''	Al	Z / Y / W	Cations to Six O
				Na	Na	2Al	Al	Al		
SiO_2	50.71	Si	844				2	$9\frac{1}{2}$		Z $855\frac{1}{2}$	2.018
Al_2O_3	1.06	Al	21	--	--	--			$9\frac{1}{2}$		
Fe_2O_3	.53										
FeO	18.57	Fe'''	6	6							
MgO	5.70	Fe	$258\frac{1}{2}$								
CaO	22.86	Mn	$2\frac{1}{2}$							WXY $832\frac{1}{2}$	1.964
Na_2O	.16	Mg	$141\frac{1}{2}$								
K_2O	.02	Ca	$407\frac{1}{2}$								
H_2O+	.08	Na	6	6							
H_2O-	.04	K	—								
TiO_2	.07	Ti	1				1				
MnO	.18	O	$2543\frac{1}{2}$								
	99.98										

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

$Ca_{50}Mg_{17}Fe_{33}$
% Al in Z = 1.4

Indices of Refraction
nX 1.7080
nY 1.7140
nZ 1.7360

Pleochroism
Faint green not appreciably pleochroic

Birefringence, x10⁴ aver. 280
275, 277, 277, 283, 287
X−Y=69

2V aver. $59\frac{3}{4}°$
59, $59\frac{1}{2}$, $59\frac{1}{4}$, $60\frac{1}{4}°$

Dispersion, Opt. Ax. $\begin{cases} B\ weak \\ A\ moderate \end{cases} r>v$

$Z \wedge c$ aver. 43?°

Exsolution Lamellae, none

Remarks:

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		Fe''' / Na	Al / Na	Ti	2Al	Al	Fe'''	Al	Z / Y / W	Cations to Six O
SiO_2	50.33	Si	838				7	2		18	Z 865	2.022
Al_2O_3	2.32	Al	45½						2	18½		
Fe_2O_3	1.88	Fe'''	23½	21½								
FeO	18.23	Fe	254									
MgO	6.92	Mn	12								WXY 836½	1.956
CaO	18.39	Mg	175½									
Na_2O	.61	Ca	328									
K_2O	.07	Na	20	20								
H_2O+	.16	K	1½		1½							
H_2O-	.09	Ti	3½			3½						
TiO_2	.28	O	2567									
MnO	.83											
	100.11											

Indices of Refraction	Pleochroism
nX 1.7080	X, Y, Z pale bluish
nY 1.7145	green
nZ 1.7350	$\perp$ bc plane, pink

Birefringence, x10⁴ aver. 270
259, 261, 275, 277; X−Y=65.

2V aver. 57°
56¼, 56½, 56¾, 57½, 58½°

Dispersion, Opt. Ax. $\begin{Bmatrix} \text{B none} \\ \text{A weak} \end{Bmatrix}$ r>v

Z∧c aver. 47½°

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

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

$Ca_{41.5}Mg_{22}Fe_{36.5}$
% 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		Fe''' / Na	Al / Na	Ti	2Al	Al	Fe'''	Al	Z / Y / W	Cations to Six O
SiO_2	48.34	Si	805				2	4			Z 811	2.00
Al_2O_3	.30	Al	6						4			
Fe_2O_3	1.50											
FeO	22.94	$*Fe'''$	19	5								
MgO	1.06	Fe	319									
CaO	21.30	Mn	53								WXY 803	1.98
Na_2O	.14	Mg	26									
K_2O	.03	Ca	380									
H_2O+	.46	Na	5	5								
H_2O-	—	K	—									
TiO_2	.08	Ti	1									
MnO	3.70	O	2430									
	99.85											

Indices of Refraction	Pleochroism
nX 1.7225	Colorless in section
nY 1.7300	or faint brown
nZ 1.7505	nonpleochroic

Birefringence x10⁴ aver. 280
268, 270, 272, 273, 274, 280, 295, 287, 289, 300

2V aver. 62½°
Range 61°–67°

Dispersion, Opt. Ax. $\begin{Bmatrix} \text{B none} \\ \text{A strong} \end{Bmatrix}$ r>v

Z∧c aver. 47½°
Range 46°–49°

Exsolution Lamellae, rare ||{001}

Remarks: Pair and multiple twins with {100} composition plane. Good {100} and {010} partings.
  * Insufficient Al^{+3} to balance electrical charge Fe^{+3} by substitution Al^{+3} for Si^{+4}

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

$Ca_{47.7}Mg_{3.2}Fe_{49.1}$
% Al in Z=0.8

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		Fe'''	Al	Ti	Fe''	Al	Z	Cations to Six O
						2Al	Al	Al		
				Na	Na				Y	
									W	
SiO₂	48.28	Si	804							
Al₂O₃	1.45					7		9½	$\left.\begin{array}{c}Z\\820½\end{array}\right\}$	2.02
Fe₂O₃	3.96	Al	28	--	--		--			
FeO	27.02					2		9½		
MgO	.32	Fe'''	50	50						
CaO	16.18	Fe	376							
Na₂O	1.51	Mn	10½							
K₂O	.14	Mg	8						$\left.\begin{array}{c}WXY\\800\end{array}\right.$	1.97
H₂O+	.15	Ca	188½							
H₂O−	.15	Na	49	47	2					
TiO₂	.28	K	3	3						
MnO	.76	Ti	3½			3½				
		O	2441							
	100.20									

Indices of Refraction
nX 1.7355
nY 1.7450
nZ 1.7650

Pleochroism
X blue green
Y yellow green
Z yellow green
c axis blue green
⊥ bc brownish yellow green

Birefringence, x10⁴ aver. 295
283, 295, 297, 297, 299

2V aver. 70¼°

Dispersion, Opt. Ax. $\left\{\begin{array}{l}\text{B strong } v\\\text{A strong } r\end{array}\right\}\begin{array}{l}>r\\>v\end{array}$

Z∧c aver. 56½(?)°

Exsolution Lamellae, ‖{001} coarse

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

$Ca_{39.5}Mg_1Fe_{59.5}$
% Al in Z=2.0

Remarks:

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		Fe'''	Al	Ti	Fe''	Al	Z	Cations to Six O
						2Al	Al	Al		
				Na	Na				Y	
									W	
SiO₂	52.11	Si	867½							
Al₂O₃	1.86					2	5½	14½	$\left.\begin{array}{c}Z\\889½\end{array}\right\}$	2.01
Fe₂O₃	4.59	Al	36½	--	--					
FeO	7.93							14½		
MgO	11.32	Fe'''	57½	52			5½			
CaO	20.16	Fe	110½							
Na₂O	1.61	Mn	3							
K₂O	.06	Mg	281						$\left.\begin{array}{c}WXY\\879½\end{array}\right.$	1.99
H₂O+	.12	Ca	360							
H₂O−	.05	Na	52	52						
TiO₂	.06	K	—							
MnO	.23	Ti	1			1				
		O	2650							
	100.10									

Indices of Refraction
nX 1.6977
nY 1.7055
nZ 1.7240

Pleochroism
X blue green
Y brownish green
Z pale green
⊥ bc nearly colorless

Birefringence, x10⁴ aver. 263
263, 263, 264

2V aver. 66° variable
61°, 69°, 73°, 75±°

Dispersion, Opt. Ax. $\left\{\begin{array}{l}\text{B weak}\\\text{A moderate}\end{array}\right\}\begin{array}{l}r>v\\v>r\end{array}$

Z∧c aver. 50° variable

Exsolution Lamellae, probably ‖{100}

Analyst: Lee C. Peck
Color hand specimen: green

$Ca_{44.5}Mg_{34.5}Fe_{21}$
% Al in Z=2.5

Remarks:

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			Fe'''	Al	2Al	Al	Al	Z	Cations to Six O	Indices of Refraction	Pleochroism
							Ti	Fe''	Al	Y			
			Na	Na						W			

SiO₂	49.96	Si	832				17	7½	29½	Z 886½	2.014	

Indices of Refraction
nX 1.6892
nY 1.6950
nZ 7.7164

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

SiO₂ 49.96
Al₂O₃ 4.30
Fe₂O₃ 1.96
FeO 8.87
MgO 12.00
CaO 20.43
Na₂O .52
K₂O .00
H₂O+ .64
H₂O− .10
TiO₂ .67
MnO .22
————
99.67

Si 832
Al 84
Fe''' 24½
Fe 123½
Mn 3
Mg 297½
Ca 364
Na 17
K —
Ti 8½
O 2640

	2Al	Al	Al	Z	W,X,Y	Cations
	17	7½	29½	Z 886½		2.014
			30		WXY 878	1.995
	8½	7½				
Na 17						

Birefringence, x10⁴ 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(?)°

Exsolution Lamellae, ‖{100}

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

Ca₄₃.₇₅Mg₃₅.₇₅Fe₁₉
% 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

SiO₂ 50.13
Al₂O₃ 4.71
Fe₂O₃ 2.67
FeO 9.66
MgO 10.98
CaO 19.54
Na₂O .81
K₂O .14
H₂O+ .91
H₂O− .05
TiO₂ .58
MnO .23
————
100.41

Si 834½
Al 92
Fe''' 17
Fe 134½
Mn 3
Mg 272
Ca 348½
Na 27
K 3
Ti 7
O 2619½

	Fe'''	Al	2Al	Al	Al	Z	Cations to Six O
			14		32½	Z 881	2.018
		13			32½		
17						WXY 857½	1.964
Na 14	13						
K 3			7				

Indices of Refraction
nX 1.6925
nY 1.6980
nZ 1.7195

Pleochroism
X yellow green
Z blue green

Birefringence, x10⁴ 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. 45¾(?)°

Exsolution Lamellae, coarse ‖{100}

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

Ca₄₅Mg₃₅Fe₂₀
% 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		Fe'''	Al	2Al Ti	Al Fe''	Al Al	Z Y W	Cations to Six O
				Na	Na					
SiO_2	48.81	Si	812						Z	
Al_2O_3	4.37					18	$9\frac{1}{2}$	$28\frac{1}{2}$	868	2.00
Fe_2O_3	2.12	Al	$85\frac{1}{2}$	– –	– –					
FeO	12.70							29		
MgO	8.79	Fe'''	$26\frac{1}{2}$	17			$9\frac{1}{2}$			
CaO	21.70	Fe	181							
Na_2O	.53	Mn	3						WXY	
K_2O	.00	Mg	218						$870\frac{1}{2}$	2.00
H_2O+	.10	Ca	387							
H_2O-	.03	Na	17	17						
TiO_2	.70	K	—							
MnO	.23	Ti	9			9				
		O	$2607\frac{1}{2}$							
	100.08									

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

$Ca_{47.5}Mg_{26.75}Fe_{25.75}$
% Al in Z=6.1

Indices of Refraction
nX 1.6990 — X pale gray green
nY 1.7048 — Y pale brownish green
nZ 1.7260 — Z pale gray green
$\perp bc$ pink

Birefringence, x10⁴ aver. 270
268, 269, 270, 274

2V aver. 56°
$55\frac{1}{2}, 55\frac{1}{2}, 55\frac{3}{4}, 56\frac{1}{2}, 56\frac{1}{2}$, margins 1° higher than cores

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

$Z \wedge c$ aver. 45?°

Exsolution Lamellae, none

Remarks: not twinned.

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		Fe'''	Al	2Al Ti	Al Fe''	Al Al	Z Y W	Cations to Six O
				Na	Na					
SiO_2	45.80	Si	$762\frac{1}{2}$						Z	
Al_2O_3	7.06					36	17	$42\frac{1}{2}$	858	1.997
Fe_2O_3	3.14	Al	$138\frac{1}{2}$	– –	– –					
FeO	10.29							43		
MgO	8.42	Fe'''	39	22			17			
CaO	21.58	Fe	143							
Na_2O	.68	Mn	3						WXY	
K_2O	.01	Mg	209						862	2.006
H_2O+	.30	Ca	385							
H_2O-	.10	Na	22	22						
TiO_2	1.42	K	—							
MnO	.20	Ti	18			18				
		O	2578							
	99.00*									

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

$Ca_{49.5}Mg_{26.75}Fe_{23.75}$
% Al in Z=11.2

Indices of Refraction
nX 1.7087 — Z=X olive green
nY 1.7140 — Y brownish green
nZ 1.7339 — $\perp bc$ pink
Colors very faint in thin section

Birefringence, x10⁴ aver. 247
245, 245, 248, 251

2V aver. 56°
55, $55\frac{1}{4}, 55\frac{1}{2}$, 56, $56\frac{1}{4}$, 57°

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

$Z \wedge c$ aver. 44(?)°

Exsolution Lamellae, none

Remarks: not twinned.

* Low summation, probably some carbonate alteration decreasing SiO_2. CO_2 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		Fe''' / Na	Al / Na	Ti (2Al)	Fe'' (Al)	Al (Al)	Z / Y / W	Cations to Six O
SiO_2	45.30	Si	754			32	10	55	Z 851	1.98
Al_2O_3	7.74	Al	152	– –	– –			55		
Fe_2O_3	3.36	Fe'''	42	32			10	55		
FeO	12.27	Fe	171							
MgO	7.04	Mn	2						WXY 876	2.04
CaO	21.74	Mg	175							
Na_2O	.88	Ca	383							
K_2O	.16	Na	28	28						
H_2O+	.39	K	4	4						
H_2O-	.06	Ti	16			16				
TiO_2	1.30	O	2578							
MnO	.15									
	100.39									

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
$\perp bc$ pinkish brown

Birefringence, x10^4 aver. 245
237, 239, 247, 247, 250, 252

2V aver. 57¼°
56¾, 57¼, 57¼, 57¾°

Dispersion, Opt. Ax. $\begin{Bmatrix} \text{B strong} \\ \text{A weak} \end{Bmatrix} r > v$

$Z \wedge c$ aver 46½(?)°

Exsolution Lamellae, fine $\|\{100\}$ a few $\|\{001\}$

Remarks: Some sphene inclusions, probably exsolution products.

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

$Ca_{49.5}Mg_{22.5}Fe_{28}$
% 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		Fe''' / Na	Al / Na	Ti (2Al)	Fe'' (Al)	Al (Al)	Z / Y / W	Cations to Six O
SiO_2	46.85	Si	780			37	21½	20	Z 858½	2.007
Al_2O_3	5.03	Al	98½	– –	– –			20		
Fe_2O_3	2.91	Fe'''	36½	15			21½			
FeO	13.63	Fe	190							
MgO	7.03	Mn	3						WXY 848	1.982
CaO	21.90	Mg	174½							
Na_2O	.46	Ca	390½							
K_2O	.00	Na	15	15						
H_2O+	.24	K	–							
H_2O-	.05	Ti	18½			18½				
TiO_2	1.47	O	2567							
MnO	.20									
	99.77									

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
$\perp bc$ pink
Weakly colored in thin section

Birefringence, x10^4 aver. 255
250, 256, 257

2V aver. 54¼°
53¾, 54¼, 54¼, 54¼

Dispersion, Opt. Ax. $\begin{Bmatrix} \text{B strong} \\ \text{A moderate} \end{Bmatrix} r > v$

$Z \wedge c$ aver. 44(?)°

Exsolution Lamellae, none

Remarks: Much exsolved sphene as minute blebs or rods (checked by x-ray). Not twinned. Host material minus sphene = $Ca_{48}Mg_{22.5}Fe_{29.5}.$ 7.3% Al in Z.

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

$Ca_{49}Mg_{22}Fe_{29}$
% 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		Fe''	Al	Ti	Fe''	Al	2Al	Al	Al	Z	Cations to Six O
			Na	Na								
SiO₂	47.58	Si 797									Z	
Al₂O₃	1.16					9	13½				} 819½	2.002
Fe₂O₃	2.60	Al 22½	— —	—	—	—						
FeO	24.21											
MgO	3.34	Fe''' 32½	19				13½					
CaO	18.80	Fe 337										
Na₂O	.47	Mn 8½									WXY	
K₂O	.21	Mg 83									} 819½	2.002
H₂O+ }	.34	Ca 335										
H₂O− }		Na 15	15									
TiO₂	.37	K 4	4									
MnO	.59	Ti 4½			4½							
		O 2456½										
	99.67											

Indices of Refraction
nX 1.7258
nY 1.7327
nZ 1.7550

Pleochroism
X, Y, Z yellow green
⊥ bc yellow
Weakly pleochroic

Birefringence, x10⁴ aver. 292
286, 287, 290, 291, 294, 295

2V aver. 58½°
56¾, 58¼, 59½, 59½°

Dispersion, Opt. Ax. { B moderate | v > r
                          A strong | r > v

Z∧c aver. 48(?)°

Exsolution Lamellae, none

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

Ca₄₂Mg₁₀.₅Fe₄₇.₅
% Al in Z = 2.7

Remarks:

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		Fe'''	Al	Cr	Ti	Fe''	Cr	Al	2Al	Al	Al	Al	Z	Cations to Six O
			Na	Na	Na										
SiO₂	50.79	Si 845												Z	
Al₂O₃	3.48					26	5	3	17					} 896	2.00
Fe₂O₃	1.37	Al 68 {	— —	—	—	—	− −		− −						
FeO	9.41								17						
MgO	14.64	Fe''' 17	12				5								
CaO	18.55	Cr 3						3							
Na₂O	.36	Fe 131													
K₂O	.03	Mn 3½												WXY	
H₂O+	.03	Ni —												} 800½	1.99
H₂O−	.04	Mg 363													
TiO₂	1.03	Ca 331													
Cr₂O₃	.25	Na 12	12												
MnO	.24	K —													
NiO	.03	Ti 13				13									
		O 2682½													
	100.25														

Indices of Refraction
nX 1.6930
nY 1.6968
nZ 1.7215

Pleochroism
Pale purplish
brown not
appreciably
pleochroic

Birefringence, x10⁴ aver. 285
282, 285½, 287

2V aver. 43½°
42½, 42½, 43½, 44¾, 45°

Dispersion, Opt. Ax. { B strong | r > v
                          A weak |

Z∧c aver. 43½°

Exsolution Lamellae, none

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

Ca₃₉Mg₄₃Fe₁₈
% Al in Z = 5.7

Remarks:

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	Fe''' / Na	Al / Na	Cr / Na	Ti	Fe'''	Cr	Al	Z / Y / W	Cations to Six O
						2Al	Al	Al	Al		
SiO$_2$	50.76	Si	845				25	8		11½	Z 889½	2.00
Al$_2$O$_3$	2.83	Al	56	—	—	—	—	—	—	11½		
Fe$_2$O$_3$	1.35											
FeO	10.23	Fe'''	16	8			8					
MgO	14.22	Cr	2			2						
CaO	19.08	Fe	142									
Na$_2$O	.32	Mn	3½								WXY 889½	2.00
K$_2$O	.00	Ni	—									
H$_2$O+	.02	Mg	352½									
H$_2$O−	.01	Ca	—									
TiO$_2$	.99	Na	—	8		2						
Cr$_2$O$_3$	.19	K	—									
MnO	.25	Ti	—				12½					
NiO	.02	O	2669									
	100.27											

Indices of Refraction
nX 1.6941
nY 1.6984
nZ 1.7218

Pleochroism
Faint purplish brown not perceptibly pleochroic in thin sections.

Birefringence, x10⁴ aver. 277
272, 275½, 277, 281, 282

2V aver. 46¾°
46¼, 47¼°

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

Z∧c aver. 44°

Exsolution Lamellae, none

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

Ca$_{39.7}$Mg$_{41.4}$Fe$_{18.9}$
% 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	Fe''' / Na	Al / Na	Cr / Na	Ti	Fe'''	Cr	Al	Z / Y / W	Cations to Six O
						2Al	Al	Al	Al		
SiO$_2$	50.85	Si	846				26	6		10	888	2.00
Al$_2$O$_3$	2.70	Al	52	—	—	—	—	—	—	10		
Fe$_2$O$_3$	1.11											
FeO	10.36	Fe'''	14	8			6					
MgO	14.09	Cr	2			2						
CaO	19.20	Fe	144									
Na$_2$O	.30	Mn	3½								WXY 888½	2.00
K$_2$O	.00	Ni	—									
H$_2$O+	.01	Mg	349									
H$_2$O−	.09	Ca	343									
TiO$_2$	1.05	Na	10	8		2						
Cr$_2$O$_3$	.13	K	—									
MnO	.25	Ti	13				13					
NiO	.02	O	2666½									
	100.16											

Indices of Refraction
nX 1.6937
nY 1.6982
nZ 1.7221

Pleochroism
Z, X faint purplish brown color
Y pink

Birefringence, x10⁴ aver. 284
279, 283½, 284, 285, 287½

Z−Y=239, 241, 241

2V aver. 47°
46¼, 46½, 46½, 47, 47½, 48¼°

Dispersion, Opt. Ax. {B moderate / A weak} 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$_{40}$Mg$_{41.1}$Fe$_{18.9}$
% Al in Z=4.7

Remarks:

ANALYSIS 31

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

		Atomic Ratios		Fe'''	Al	Cr	2Al	Al	Al	Al	Z	Cations to Six O
				Na	Na	Na	Ti	Fe''	Cr	Al	Y	
											W	
SiO₂	50.85	Si	846½								Z	
Al₂O₃	2.38						26	3		9½	885	2.00
Fe₂O₃	.96	Al	48	–	–	–	–	–		9½		
FeO	11.92											
MgO	13.50	Fe'''	12	9				3				
CaO	18.80	Cr	—									
Na₂O	.28	Fe	165									
K₂O	.00	Mn	4								WXY	
H₂O+	.04	Ni	—								883½	2.00
H₂O−	.04	Mg	335									
TiO₂	1.03	Ca	336									
Cr₂O₃	.03	Na	9	9								
MnO	.29	K	—									
NiO	.01	Ti	13				13					
P₂O₅	.00	O	2653½									
	100.13											

Indices of Refraction
nX 1.6954
nY 1.7005
nZ 1.7250

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

Birefringence, x10⁴ aver. 296
289, 293, 297, 297½, 300, 300

2V aver. 49°
44, 47, 47½, 48¼, 48½, 48¼, 51½, 53, 53¼°

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

Z∧c aver. 44(?)°

Exsolution Lamellae, rare ‖ {001}

Remarks:

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

Ca₃₉.₅Mg₃₉.₂Fe₂₁
% Al in Z=4.3

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		Fe'''	Al	2Al	Al	Al	Z	Cations to Six O
				Na	Na	Ti	Fe''	Al	Y	
									W	
SiO₂	50.74	Si	845						Z	
Al₂O₃	3.21					12		25	882	2.001
Fe₂O₃	.70	Al	63 {	– –		– –	–	25		
FeO	13.07				1					
MgO	13.45	Fe'''	9	9						
CaO	17.40	Fe	182							
Na₂O	.30	Mn	4½						WXY	
K₂O	.06	Mg	333½						881	1.999
H₂O+	.28	Ca	310							
H₂O−	.01	Na	9	8	1					
TiO₂	.46	K	1	1						
MnO	.32	Ti	6			6				
	100.00*	O	2645							

Indices of Refraction
nX 1.6950
nY 1.6990   Range
nZ 1.7220   ± .002

Pleochroism
Barely pleochroic
X=Y=Z   purplish brown
⊥ bc light brown

Birefringence, x10⁴ aver. 270
267, 270, 271, 273

2V aver. 43½°
41⅛, 42½, 43, 43½, 43½, 43¾, 44¼, 45¾°
Rims about 6° higher than cores

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

Z∧c aver. 43½(?)°

Exsolution Lamellae, numerous ‖ {001}

Remarks: Twinned on {100}.

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

Ca₃₇Mg₃₉.₇Fe₂₃.₃
% Al in Z=4.2

* 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

Oxide	wt%	Atomic Ratios		Fe''' / Na	Al / Na	2Al / Ti	Al / Fe''	Al	Z / Y / W	Cations to Six O
SiO₂	50.53	Si	841						Z	
Al₂O₃	2.49					22		13½	876½	1.999
Fe₂O₃	.59	Al	49					13½		
FeO	14.25					½				
MgO	13.08	Fe'''	7½	7½						
CaO	17.38	Fe	198							
Na₂O	.23	Mn	5½						WXY	
K₂O	.03	Mg	324½						878	2.002
H₂O+	.25	Ca	310							
H₂O−	.09	Na	8	7½	½					
TiO₂	.87	K	—							
MnO	.38	Ti	11			11				
	100.17	O	2631							

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

Ca₃₆.₇Mg₃₈.₄Fe₂₄.₉
% Al in Z=4.1

Indices of Refraction
nX 1.6972
nY 1.7005
nZ 1.7240

Pleochroism
Light purplish brown
Pleochroism not evident in thin section

Birefringence, x10⁴ aver. 285

2V aver. 40°

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

Z∧c aver. 44°

Exsolution Lamellae, none

Remarks: Twinned on {100}

ANALYSIS 34*

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

Oxide	wt%	Atomic Ratios		Fe''' / Na	Al / Na	2Al / Ti	Al / Fe''	Al	Z / Y / W	Cations to Six O
SiO₂	50.72	Si	843						Z	
Al₂O₃	2.28					21	1½	10	875½	2.01
Fe₂O₃	.84	Al	44					10½		
FeO	16.32	Fe'''	10½	9			1½			
MgO	12.63	Fe	227							
CaO	15.46	Mn	4½						WXY	
Na₂O	.28	Mg	313						860½	1.98
K₂O	.00	Ca	275½							
H₂O+	.22	Na	9	9						
H₂O−	.08	K	—							
TiO₂	.84	Ti	10½			10½				
MnO	.33	O	2613							
	100.00*									

Analyst: Lee C. Peck
Color hand specimen: brown

Ca₃₃Mg₃₈Fe₂₉
% Al in Z=3.7

Indices of Refraction
nX 1.6950
nY 1.7010
nZ 1.7240

Pleochroism
Faint purplish brown not appreciably pleochroic

Birefringence, x10⁴ aver. 265
258, 261, 261, 263, 264, 265, 268, 269, 270, 271

2V aver. 44°

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

Z∧c aver. 43½°

Exsolution Lamellae, none

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''' / Na	Al / Na	2Al Ti	Al Fe'''	Al Al	Z Y W	Cations to Six O	
SiO₂	54.51	Si	908½						Z 914	2.00	
Al₂O₃	.40	Al	8	– –	– –	1	2	2½			
Fe₂O₃	.40							2½			
FeO	2.35										
MgO	17.19	Fe'''	5	3			2				
CaO	24.90	Fe	33								
Na₂O	.06	Mn	2½						WXY 916½	2.00	
K₂O	.05	Mg	426								
H₂O+	.03	Ca	444								
H₂O−	.03	Na	2	2							
TiO₂	.04	K	1	1							
MnO	.16	Ti	½			½					
		O	2744½								
	100.12										

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

$Ca_{48.8}Mg_{46.8}Fe_{4.4}$
% Al in Z=0.6

Indices of Refraction
nX 1.6718
nY 1.6785
nZ 1.7013

Pleochroism
Colorless

Birefringence, x10⁴ aver. 295
289, 295, 299

2V aver. 56½°
54½, 56¾, 56¾, 57¼, 57¾°

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

$Z \wedge c$ aver. 39½°

Exsolution Lamellae, none

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''' / Na	Al / Na	2Al Ti	Al Fe'''	Al Al	Z Y W	Cations to Six O	
SiO₂	53.79	Si	896						Z 910	1.996	
Al₂O₃	1.41	Al	28	– –	– –	1		13			
Fe₂O₃	.33				1			13			
FeO	2.60										
MgO	16.64	Fe'''	4	4							
CaO	24.66	Fe	36								
Na₂O	.14	Mn	3						WXY 915½	2.008	
K₂O	.04	Mg	413								
H₂O+	.10	Ca	440								
H₂O−	.04	Na	4½	4	½						
TiO₂	.04	K	½		½						
MnO	.22	Ti	½			½					
Cr₂O₃	.00	O	2735½								
NiO	.00										
	100.01										

Analyst: Lee C. Peck
Color hand specimen: white

$Ca_{49}Mg_{46}Fe_5$
% Al in Z=1.5

Indices of Refraction
nX 1.6740
nY 1.6805
nZ 1.7029

Pleochroism
Colorless

Birefringence, x10⁴ aver. 289
286½, 288, 288, 290, 292

2V aver. 56¾°

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

$Z \wedge c$ aver. 39½°

Exsolution Lamellae, very rare {100}

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.

Oxide	wt%	Atomic Ratios		Fe''/Na	Al/Na	Ti (2Al)	Fe'' (Al)	Al (Al)	Z / Y / W	Cations to Six O
SiO_2	50.19	Si	836						Z $876\frac{3}{4}$	1.98
Al_2O_3	2.73	Al	52	—	—	6	$23\frac{1}{2}$	$11\frac{1}{4}$		
Fe_2O_3	2.98							$11\frac{1}{4}$	Y	
FeO	7.54	Fe'''	38	$14\frac{1}{2}$			$23\frac{1}{2}$			
MgO	12.38	Fe	104						WXY $903\frac{1}{2}$	2.04
CaO	23.58	Mn	6							
Na_2O	.45	Mg	307							
K_2O	.00	Ca	420							
H_2O+	.00	Na	$14\frac{1}{2}$	$14\frac{1}{2}$						
H_2O-	.02	K	—							
TiO_2	.20	Ti	3			3				
MnO	.40	O	2657							
	100.47									

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, x10⁴ aver. 270
$269\frac{1}{2}$, 270, 270. Z-Y=210

2V aver. 59°

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

Z∧c aver. 45(?)°

Exsolution Lamellae, none

Remarks:

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

$Ca_{46}Mg_{33}Fe_{17}$
% Al in Z=4.6

ANALYSIS 38

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

Oxide	wt%	Atomic Ratios		Fe''/Na	Al/Na	Ti (2Al)	Fe'' (Al)	Al (Al)	Z / Y / W	Cations to Six O
SiO_2	48.40	Si	$805\frac{1}{2}$						Z $864\frac{1}{2}$	1.993
Al_2O_3	3.95	Al	78	—	—	7	33	19		
Fe_2O_3	3.90								Y	
FeO	10.52	Fe'''	48	15			33			
MgO	8.92	Fe	146							
CaO	23.20	Mn	$5\frac{1}{2}$						WXY 872	2.010
Na_2O	.46	Mg	221							
K_2O	.02	Ca	414							
H_2O+	.16	Na	15	15						
H_2O-	.04	K	—							
TiO_2	.27	Ti	$3\frac{1}{2}$			$3\frac{1}{2}$				
MnO	.39	O	2601							
	100.23									

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, x10⁴ aver. 255
250, 251, 256, $262\frac{1}{2}$

2V aver. 62°

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

Z∧c aver. $47\frac{1}{2}$(?)°

Exsolution Lamellae, none

Remarks:

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

$Ca_{49.5}Mg_{26.5}Fe_{24}$
% Al in Z=6.9

ANALYSIS 39

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

Oxide	wt%	Atomic Ratios		Fe''' / Na	Al / Na	2Al / Ti	Al / Fe''	Al / Al	Z / Y / W	Cations to Six O
SiO₂	45.80	Si	763						Z 848½	1.997
Al₂O₃	5.11					8	63	14½		
Fe₂O₃	5.87	Al	100					14½		
FeO	12.44									
MgO	6.86	Fe'''	74	11			63			
CaO	22.54	Fe	173							
Na₂O	.35	Mn	6						WXY 856	2.011
K₂O	.02	Mg	171½							
H₂O+	.17	Ca	402							
H₂O−	.09	Na	11	11						
TiO₂	.31	K	—							
MnO	.41	Ti	4			4				
	99.97	O	—							

Indices of Refraction: nX 1.7210, nY 1.7290, nZ 1.7463

Pleochroism: X dark blue green; Y blue green; Z yellow green; ⊥ bc brownish yellow

Birefringence, x10⁴ aver. 253: 249½, 254, 255

2V aver. 67½°

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

Z∧c aver. 51(?)°

Exsolution Lamellae, none

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

Ca₄₈.₆Mg₂₀.₅Fe₃₀.₉ % Al in Z=10 Remarks:

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)

Oxide	wt%	Atomic Ratios		Fe''' / Na	Al / Na	2Al / Ti	Al / Fe''	Al / Al	Z / Y / W	Cations to Six O
SiO₂	50.97	Si	848						Z 868½	1.97
Al₂O₃	.95					5	15½*			
Fe₂O₃	7.08	Al	18½							
FeO	6.96									
MgO	11.55	Fe'''	88½	61			15½			
CaO	20.96	Fe	97							
Na₂O	1.86	Mn	—						WXY 907½	2.06
K₂O	.05	Mg	286½							
H₂O+	.19	Ca	374							
H₂O−	—	Na	60	60						
TiO₂	.20	K	1	1						
MnO	—	Ti	2½			2½				
	100.77	O	2649½							

Indices of Refraction: nX 1.700, nY 1.711, nZ 1.728

Pleochroism: X=Z green, slightly bluish; Y green, slightly yellowish; ⊥ bc light brown

Birefringence, x10⁴ aver. 276: 257, 268, 278, 282, 293

2V aver. 77°

Dispersion, Opt. Ax. {B weak} r>v; {A strong} v>r

Z∧c aver. 51°, variable

Exsolution Lamellae

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

Ca₄₄Mg₃₄Fe₂₂ % Al in Z=2.3

Remarks: * 2 Fe⁺³ included here in the Z group to balance charge.

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		Fe'' (Na)	Al (Na)	Ti	Fe''	Al	2Al	Al	Al	Z / Y / W	Cations to Six O
SiO₂	51.53	Si	858						13		9	Z 880	2.019
Al₂O₃	1.64	Al	32			1		9				Y	
Fe₂O₃	.18	Fe'''	2	2									
FeO	23.35	Fe	325										
MgO	17.27	Mn	7									WXY 861½	1.976
CaO	4.47	Mg	428										
Na₂O	.10	Ca	80										
K₂O	.00	Na	3	2	1								
H₂O+	.32	K	—										
H₂O−	.14	Ti	6½					6½					
TiO₂	.51	O	2621½										
MnO	.49												
	100.00*												

Indices of Refraction
nX 1.6980
nY 1.6988
nZ 1.7228

Pleochroism: Colorless

Birefringence, x10⁴ aver. 248
Z−X=240

2V aver. 18°⊥{010}
12, 12¼, 16, 19, 19, 20½, 20½, 23°

Dispersion, Opt. Ax. moderate r>v†

Z∧c aver. 40–41°

Exsolution Lamellae, very fine and regular ‖{001}

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.

Analyst: Lee C. Peck
Color hand specimen: Light brown

Ca₉.₅Mg₅₀.₈Fe₃₉.₇
% 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		Fe'' (Na)	Al (Na)	Cr (Na)	Ti	Fe''	Cr	Al	2Al	Al	Al	Al	Z / Y / W	Cations to Six O
SiO₂	51.24	Si	853							4½	12			4½	Z 869½	2.023
Al₂O₃	1.07	Al	21							4½					Y	
Fe₂O₃	.05	Fe'''	1	1												
FeO	26.85	Cr	—													
MgO	14.85	Fe	374												WXY 839½	1.986
CaO	4.31	Mn	8													
Na₂O	.02	Ni	—													
K₂O	.02	Mg	368													
H₂O+	.36	Ca	77													
H₂O−	.18	Na	1		1											
TiO₂	.50	K	—													
Cr₂O₃	.00	Ti	6				6									
MnO	.55	O	2578½													
NiO	—															
	100.00*															

Indices of Refraction
nX 1.7055
nY 1.7066
nZ 1.7325

Pleochroism: X faint pink, Y faint pink, Z faint green

Birefringence, x10⁴ aver. 270
Z−Y=259

2V aver. 22° opt. plane ⊥ {010}
14, 15¾, 17½, 22½, 23¾, 26, 28, 29°

Dispersion, Opt. Ax. moderate r>v

Z∧c aver. 42?°

Exsolution Lamellae

Remarks:
* Sample contained 17% augite LAM 12 A also analyzed. Augite subtracted from above analysis and remainder recalculated to 100%.

Analyst: Lee C. Peck
Color hand specimen: light purplish brown

Ca₉.₃Mg₄₄.₄Fe₄₆.₃
% 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		Fe''	Al	Na	Ti	Fe''	Na	2Al	Al	Al	Z / Y / W	Cations to Six O
SiO₂	49.37	Si	822								4	9	8	Z 843	1.996
Al₂O₃	1.55													
Fe₂O₃	1.83	Al	30	–	–	–	–		9				9		
FeO	26.44													
MgO	15.54	Fe'''	9						9					
CaO	4.60	Fe	355											
Na₂O	—	Mn	5										WXY 847	2.005
K₂O	—	Mg	385										
H₂O+	—	Ca	82										
H₂O−	—	Na	– –										
TiO₂	.62	K	– –										
MnO	.37	Ti	2				2						
		O	—										
	100.32												

Analyst: E. P. Henderson
Color hand specimen: light brown

$Ca_{10}Mg_{46}Fe_{44}$†
% Al in Z = 2.5

Indices of Refraction
nX 1.7085
nY 1.7095
nZ 1.7360

Pleochroism
Faint brown
nonpleochroic

Birefringence, x10⁴ aver. 275

2V aver. 21°

Dispersion, Opt. Ax. moderate r > v

Z ∧ c aver. 40°

Exsolution Lamellae. Coarse augite lamellae ∥ {001}

Remarks:
* 14Fe⁺³, 13Fe⁺² and 6Ti⁺⁴ subtracted from these ratios to take care of magnetite-ilmenite inclusions.
† Composition of host less augite lamellae $Ca_5Mg_{47.5}Fe_{47.5}$.

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		Fe''	Al	Na	Ti	Fe''	Na	2Al	Al	Al	Z / Y / W	Cations to Six O
SiO₂	49.72	Si	828								21*			Z 849	2.02
Al₂O₃	.90													
Fe₂O₃	1.72	Al	18	–	–	–	–		– –	– –				
FeO	27.77													
MgO	12.69	Fe'''	22	8				11†						
CaO	3.80	Fe	386½										
Na₂O	.23	Mn	14										WXY 823½	1.96
K₂O	.12	Mg	314½										
H₂O+	1.27	Ca	68										
H₂O−	.08	Na	6	6									
TiO₂	.85	K	2	2									
MnO	.98	Ti	10½				10½						
NiO	.00	O	2524										
Li₂O	tr												
	100.13												

Analyst: E. G. Radley
Density: 3.44 (S. G. 17°C. 3.44 Hallimond)
Color hand specimen: yellow brown

$Ca_{9.4}Mg_{38}Fe_{52.5}$
% Al in Z = 2.6

Indices of Refraction
nX 1.7137
nY 1.7137
nZ 1.7417

Pleochroism
X, Y pale greenish brown
Z pale yellowish or reddish brown

Birefringence, x10⁴ aver. 280
278, 279, 279, 280, 286

2V aver. 0°–12° in place ⊥ {010}.

Dispersion, Opt. Ax. moderate r > v

Z ∧ c aver. 39°–40°

Exsolution Lamellae, none

Remarks:
* 3 Fe⁺³ substituted for Al to balance charge.
† 5½ Fe⁺³ 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.