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DIFFERENTIATION IN THE CAPE SPENCER FLOW*

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INTRODUCTION

For years the problem of differentiation in igneous rocks has been the cause for prolonged and intense discussion on the part of geologists from all parts of the world, and at present the matter is still far from settled. The relatively recent theory postulated by Bowen¹ that the great variety of igneous rocks is derived from a parental basaltic magma by a differentiation which is brought about by fractional crystallization and the relative movement of crystals and liquid has gained wide recognition. Fenner² has led an attack against the theory on the grounds that the enrichment in iron of the residual liquid during the fractional crystallization of the pyroxene series will not allow for the derivation of the more acidic rocks from the more basic by Bowen's method of differentiation, termed fractionation, alone. The aim of this paper is to present the facts obtained from a detailed microscopic study of a thick Triassic flow from Nova Scotia in their bearing on the prob-

* A thesis submitted to the Graduate School of the University of Wisconsin in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

¹ N. L. Bowen, *The Evolution of the Igneous Rocks*, Princeton University Press, 1928.

² C. N. Fenner, *The Crystallization of Basalts*, *Am. Jour. Sci.*, vol. 18, 1929, pp. 225-253.

lem of differentiation within the flow and of differentiation in general.

Powers and Lane made a careful study of this same flow some fourteen years ago from which they concluded that gravitative differentiation had been operative during its crystallization.³ Several years later Professor Lane very kindly sent to Madison a representative drill core from hole A which penetrated this flow, and it has been through a detailed study of this core that conclusions on this specific problem are herein drawn.

If fractionation as advanced by Bowen has been active through fractional crystallization and the relative movement of crystals and liquid during the cooling of the flow, then it is only natural to expect a more or less progressive change in the composition and properties of the constituent minerals throughout the flow, providing these minerals form a continuous reaction series. In other words, such fractionation should be reflected by a definite trend in the course of crystallization of the plagioclase feldspars and the pyroxenes, the dominant constituent minerals, throughout the flow.

Rosival counts of thin sections taken at intervals averaging twenty-five feet were made to determine variations in the mineralogical composition in the flow, and in the main these results substantiated those obtained by Powers and Lane. A noticeable enrichment of pyroxene was found just below the middle and an even more striking enrichment of feldspar was found above the middle part of the flow.

A determination of the refractive indices of the pyroxenes at eight different points in the flow was made by the use of the double variation method as described by Emmons.⁴ The results, while seeming to portray in the main a progressive trend in the composition and properties of the pyroxenes, were sometimes erratic, probably due to the presence of pigeonite, within a single crystal of which the optical properties may vary quite considerably. The indices tend to decrease from the margin toward the center of the flow, except for the chilled border, suggesting a decrease in the tenor of iron in the pyroxenes toward the center.

³ S. Powers and A. C. Lane, Magmatic Differentiation in Effusive Rocks, *Trans. A. I. M. E.*, vol. 54, pp. 442-457, 1916.

⁴ R. C. Emmons, *American Mineralogist*, vol. 13, 1928, p. 540; *idem*, vol. 14, 1929, pp. 414-426, and pp. 441-461.

The plagioclase feldspars were determined at nine different points within the flow by means of the measurement of extinction angles in sections normal to a bisectrix. These determinations showed in general a trend from more calcic plagioclase at the margins to more sodic plagioclase near the middle of the flow.

Five chemical analyses within the flow given by Powers and Lane⁵ were studied as regards both the variations in the FeO:MgO ratio and the variations in the ratio of the total iron calculated to FeO:MgO. The former of these showed a progressive decrease from each of the margins to a point well above the center of the flow, while the latter followed essentially a similar course in the bottom half of the flow, but departed most radically from it in the upper portion.

When all these results are correlated a marked trend seems to be apparent in the properties and composition of the plagioclase feldspars and the pyroxene series through the flow, together with a progressive change in the FeO:MgO ratio, which strongly suggests, if it does not actually prove, that fractionation brought about by fractional crystallization together with the relative movement of crystals and liquid has been operative during the cooling of the Cape Spencer flow, and that a progressive enrichment in iron of the residual liquid does not necessarily follow in the fractionation of such a mass of basaltic magma.

The kindness of Professor Lane in sending a large set of core samples to Madison, thus making possible this investigation, is hereby acknowledged. Thanks are also extended to Professors Winchell and Emmons of the Department of Geology of the University of Wisconsin for their invaluable help and criticism during the course of the study, and to the University of Wisconsin for granting to the author a fellowship during the year that the investigation was in progress.

REVIEW OF THE LITERATURE PERTAINING TO THE PROBLEM

The Cape Spencer flow is the thickest and lowest of a series of five Triassic lava flows found on Cape d'Or, Nova Scotia, a conspicuous headland extending into Minas Channel from the north. The literature which has been written on the geology of this general region is quite extensive. Powers⁶ has given an excellent pic-

⁵ *Op. cit.*, pp. 452-453.

⁶ S. Powers, The Acadian Triassic, *Jour. Geol.*, vol. 24, 1916, pp. 1-26, 105-122, and 254-268.

ture of the geology of the Acadian Triassic which has been used almost exclusively to obtain a general idea of conditions there. The Bay of Fundy is fringed on the south, and locally on the north, by a series of sedimentary rocks and lava flows showing a gentle monoclinical structure with a prevailing northwesterly dip, interrupted by broad, low folds, and cut by many normal faults which are usually of small displacement. From paleontological and paleobotanical evidences these Acadian rocks have been proved to correspond in age with the Newark group of eastern United States, which in turn has been correlated with the middle and upper divisions of the Alpine Trias. The Acadian Triassic is divided into three formations, being, from oldest to youngest, the Annapolis formation, comprising about 2,000 feet of red beds, largely calcareous, with some small interbedded basaltic flows near the top; the North Mountain basalt, a succession of lava flows totalling from 800–1,000 feet in thickness; and the Scots Bay formation, a calcareous white sandstone which has been stripped by erosion from all localities except the Wolfville-Scots Bay region, where the maximum amount preserved in small synclines is only 12 feet.

The North Mountain basalt, of which the Cape Spencer flow comprises the basal member at Cape d'Or, is quite extensively exposed along the south shore of the Bay of Fundy and in only a few scattered localities on the north shore. It stands out in conspicuous relief due to its marked resistance to erosion as compared with the associated sedimentary beds above and below. In each locality where the basalt is found there are several flows, indicating successive extrusions within such a short time of each other that no sedimentary material was deposited between them. These individual flows are clearly recognized by a thin amygdaloidal base and a relatively thick amygdaloidal top, the amygdules being filled with either quartz, calcite, or a zeolite. The basalt itself is a dark-gray or dark-greenish fine-grained rock composed of plagioclase feldspar and pyroxene with accessory amounts of magnetite, olivine, and glass. The feldspar ranges from sodic bytownite to calcic andesine. The texture of the rock is typically ophitic, so it should more properly be termed a diabase. Chlorite, magnetite, limonite, hematite, and serpentine are present as alteration products.

The work of Powers and Lane,⁷ already mentioned, consisted of a detailed study of a series of six drill cores which penetrated

the North Mountain basalt to a greater or lesser degree at Cape d'Or. Five separate flows were noted, varying in thickness from 11 to 556 feet, the lowest one of which was termed the Cape Spencer flow. It was completely penetrated only by drill hole A, where it was found to be 556 feet thick, with the upper 20 feet being amygdaloidal. A series of volumetric and chemical analyses, and determinations of specific gravity and size of grain were made on core A through the Cape Spencer flow. The results showed a concentration of the leucocratic, felsic constituents at the top of the flow, and the melanocratic, mafic constituents at the base. The quickly chilled top and bottom of the flow, when free from alteration, showed the original composition of the magma. The size of grain of the rock, while difficult to determine with a great degree of accuracy due to several factors indicated, was shown to vary with the depth, being greatest just below the center. The specific gravity determinations showed a marked increase just below the center of the flow with a gradual decrease above and a more sudden decrease below this point. It must be remembered, however, that alteration was not taken into account, so that the determinations should not be interpreted as trends in the specific gravity of the fresh rock. At the top zeolitization and other forms of alteration gave a lighter rock, while at the bottom chloritization and other forms of alteration gave lower figures.

A comparison of the specific gravity determinations with the results for volume composition and size of grain showed a marked agreement between the maximum concentration of the augite, the maximum size of grain, and the maximum specific gravity—all slightly below the center of the flow.

The combined chemical results showed an increase downward in the percentage of ferrous iron, magnesia, lime, and perhaps potash, a decrease in soda, with silica remaining about constant.

They concluded, then, that the results of their investigation of the differentiation within the flow agreed with the experimental results of Bowen and Anderson on artificial solutions; namely, that heavier minerals tend to sink during the cooling while very light minerals may rise.

Bowen's⁸ theory of fractionation to account for the evolution of the various types of igneous rocks from a parental basaltic

⁷ *Op. cit.*

⁸ *Op. cit.*

magma should be explained in more detail. From a very careful, intensive laboratory study of crystallization in silicate systems it was found that a relation of liquid to crystals, characterized by reaction between them, is very common during the normal course of crystallization. The striking difference between crystallization in which reaction is involved and crystallization in purely eutectic systems is plainly indicated, the fundamental difference being that in eutectic systems crystals bear a simple subtraction relation to the liquid, and once subtracted they play no further part in the equilibrium. In the systems exhibiting reaction between crystals and liquid there is a continual reaction between liquid and crystals until the last liquid is exhausted. Any solid solution series exhibits this reaction principle in that there is a continuous reaction between the crystals already formed and the liquid, the change in composition of the crystals being a perfectly continuous one taking place by infinitesimal increments. Such a solid solution series is therefore termed a continuous reaction series.

In a binary system in which a compound is formed which has an incongruent melting point, crystals of the first compound react with the liquid to produce the second during the normal course of crystallization. Such a pair of compounds is termed a reaction pair.

A reaction relation of this latter type may exist between three or more compounds, and the compounds, when arranged in proper order, then constitute a discontinuous reaction series. The distinction between the two types of reaction series lies in the fact that every gradation of composition is exhibited in the continuous series, whereas the change of composition in discontinuous series is by definite steps. Bowen points out that the plagioclase feldspars constitute a continuous reaction series and that pyroxene, amphibole, and mica form a discontinuous series.

The continuous reaction series of the plagioclase feldspars is probably the best understood series of rock minerals, and inasmuch as the series is of such particular importance in igneous rocks, it is fortunate that the series is so well known. In the crystallization of this series there is a continual enrichment of the liquid in alkaline feldspar, with the separation of the potash variety of alkaline feldspar as a separate phase when it has exceeded its solubility in the plagioclase mixture. Bowen further shows how, through the action of the reaction principle, the ferromagnesian minerals pass

from the olivines through the pyroxenes, amphiboles, and biotites; and converge with the continuous reaction series of plagioclases when potash feldspar begins to separate. Liquid which has not been used up in the reaction thus far may then crystallize to form principally potash feldspar and quartz.

The other fundamental requisite to Bowen's theory of fractionation is the relative movement of crystals and liquid. This effectively shuts off the earlier formed crystals from the liquid and prevents them from reacting with it. Thus, since the earlier formed minerals in the plagioclase series, for instance, are more calcic than the liquid from which they crystallize, the course of crystallization will proceed to a point much more alkalic if these earlier crystals are removed and not allowed to react with the liquid. This relative movement of crystals and liquid may be brought about by gravity or by deformative forces, the former being stressed during the comparatively early stages of crystallization while the latter reaches its height of effectiveness only in the middle and late stages of crystallization.

Zoning of minerals, whereby inner zones are effectively prevented from reaction with the liquid, is also of importance in producing fractionation.

VARIATION IN PERCENTAGE MINERAL CONTENT

A series of twenty-seven Rosiwal counts was made from thin sections at intervals averaging twenty-five feet through the flow to determine the variation in percentage mineral content. The fresh rock is composed almost entirely of feldspar, pyroxene, magnetite, and glass; so these were the only constituents considered in the Rosiwal counts. The magnetite and glass were grouped together, inasmuch as the glass is usually intimately associated with very fine-grained magnetite. The medium power objective was used exclusively with the 7.5 micrometer ocular. The thin sections were crossed an average of 9.6 times each, the average linear distance for each section covered in the counts being 7,561 small divisions of the ocular or 120.976 mm. The lines were run parallel to each other for convenience. The sections of a very fine-grained rock, of course, were crossed a lesser number of times than the sections of a coarser grained rock. A check was run on section A-18 from the 161 foot depth at right angles to the first measurement to determine the variation in percentage mineral content intro-

duced either by the personal element or by difference in direction of the lines through the section. The results of this check are given below, and show that agreement was obtained to within roughly two to three percent for each of the constituents.

CONSTITUENT	FIRST DETER- MINATION	SECOND DETER- MINATION	DIFFER- ENCE
Pyroxene	47.1	45.1	2.0
Feldspar	38.2	41.8	3.6
Magnetite and Glass	14.7	13.1	1.6

Linear distance covered in mm. 103.76 112.048

The results are shown in tabular form in Table I and graphically on Plate I. They show a marked agreement with those obtained

TABLE 1.

Section No.	Total Depth	Depth below top of flow	% Feldspar	% Pyroxene	% Magnetite and Glass
A-13	250	36	43.4	32.6	24.0
A-14	275	61	36.1	36.8	27.1
A-15	300	86	33.65	36.7	29.65
A-15a	300	86	37.6	39.6	22.8
A-16	325	111	38.8	43.4	17.8
A-17	350	136	55.1	31.9	13.0
A-18	375	161	40.05	46.05	13.9
A-18a	375	161	50.3	42.8	6.9
A-18b	375	161	51.8	44.9	3.3
A-18c	375	161	52.0	44.0	4.0
A-19a	402	188	53.8	40.5	5.7
A-19	412	198	59.3	32.4	8.3
A-20	462	248	50.3	47.4	2.3
A-21	475	261	45.9	51.8	2.3
A-22	500	286	48.4	47.4	4.2
A-22a	502	288	52.2	43.1	4.7
A-24	505	291	54.0	42.6	3.4
A-23	528	314	47.1	48.0	4.9
A-24a	550	336	49.5	48.0	2.5
A-25	575	361	44.4	49.5	6.1
A-26	600	386	44.0	51.4	4.6
A-27	625	411	51.0	47.6	1.4
A-28	650	436	43.7	46.8	9.5
A-29	675	461	47.4	48.6	4.0
A-30	700	486	52.0	45.0	3.0
A-31	725	511	47.5	44.1	8.4
A-32	750	536	50.9	42.9	6.2

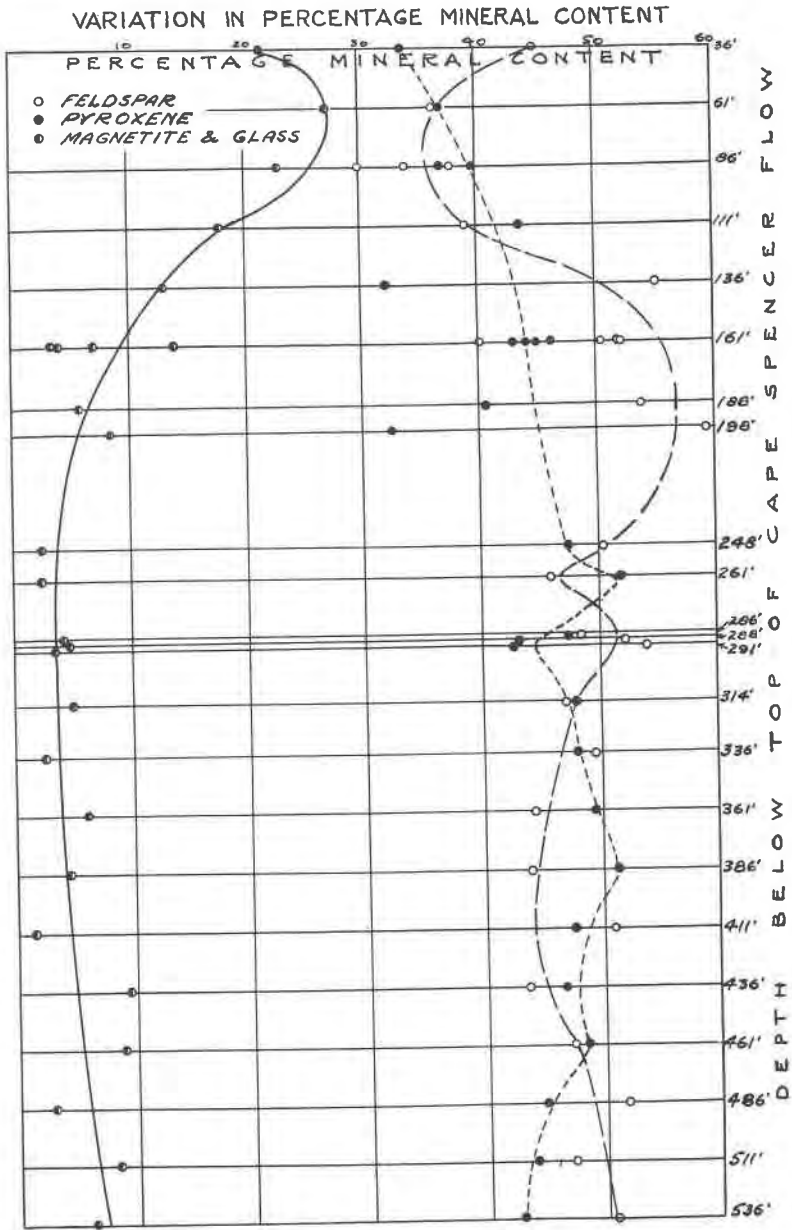


PLATE I

by Powers and Lane⁹ except for a minor variation in the middle of the flow. A very marked enrichment in feldspar is apparent just above the middle with a somewhat less apparent concentration of pyroxene below the middle of the flow. The magnetite and glass rise in a very noticeable amount toward the top, and in a much lesser amount near the base of the flow. The two sudden breaks in the curves for the pyroxene and feldspar at the middle were thought at first to represent relatively insignificant departures from the normal curves; but when the same irregularities appeared in other independent determinations, which will be discussed later, it was thought best to break the curves at this point to bring out this fact. The break shows a slight enrichment of pyroxene just above the center and a more noticeable enrichment of feldspar just below the middle. The interpretation of these facts will be left for a later page.

VARIATION IN THE PYROXENE SERIES

A series of thirteen determinations taken at eight different points within the flow was made to note the variation in indices of the pyroxenes at these points. The double variation method as described by Emmons¹⁰ was used to make these determinations.

This method involves the immersion of grains of the mineral to be examined in an oil of suitable index range. The slide is then mounted on a perfected water cell which fits into a modified universal stage, a suitable grain chosen which will not move upon rotation of the stage, and orientation of the grain made by which either X, Y, or Z in the grain is made to correspond in direction with the axis of the microscope. Then, by varying both the temperature of the water in the cell and the wave length of the light being used, points at which the index of the mineral is equal to the index of the liquid are determined by the Becke line method. The index of the liquid at each particular temperature and wave length is then determined by means of an Abbé refractometer, corrections made, and the points platted to form curves for each index.

Due to the fact that the refractometer only reads indices up to 1.70 a modification of this procedure had to be made for the measurement of the higher indices encountered in the work. A greatly enlarged chart was made from the critical data for liquids 1 and

⁹ *Op. cit.*, p. 447.

¹⁰ *Op. cit.*

2 as given by Emmons,¹¹ and by means of interpolation, curves were drawn at intervals of 5° temperature, while the horizontal interval of 100 millimicrons was divided into tenth lines to facilitate accurate reading of wave length. Checks between readings from the chart and from the corrected refractometer, whenever available, agreed within 0.001 of each other.

Difficulty in getting a long continuous set of points for indices N_o and N_p was nearly always encountered due to the fact that the cold extreme practically never allowed a reading far toward the red for N_o , while the hot extreme very seldom allowed readings far toward the blue for N_p .

In practically all cases no optic angle was observable. In about fifty per cent of the cases this was due to the fact that when the grain was oriented the optic plane was in a horizontal position, and rotations of ninety degrees of the stage are very seldom possible. In the rest of the cases the inability to obtain the angle was due to an inability to rotate quite far enough from the vertical (usually obtuse) bisectrix to locate an axis. The optic angles, therefore, were computed from the indices by means of an enlargement of Wright's graph given by Emmons.¹²

Rotation readings to obtain the index for the direction which was vertical when the grain was oriented, together with calculations of the indices from the observed readings, were made by following the procedure as indicated by Emmons.¹³

In locating exact "change points"—those points at which the index of the mineral is equal to the index of the liquid—by means of the Becke line method it was found necessary to confine the attention to one specific area or edge of the grain in all the readings. This was necessitated by the observation in some grains of good Becke lines moving out upon raising the objective in one part of the grain while good lines moved in in other parts of the same grain. Because of this fact rotation readings may not have attained the accuracy expected, for in rotating the grain it was absolutely necessary to work on a different part or edge of the grain, be it ever so slight a difference. The indices were found to vary, then, within a single grain.

As a result of a cursory examination of the pyroxene in thin

¹¹ R. C. Emmons, *Am. Mineral.* vol. 14, 1929, p. 417.

¹² R. C. Emmons, *Am. Mineral.* vol. 14, 1929, p. 459.

¹³ *Ibid.*, pp. 454-461.

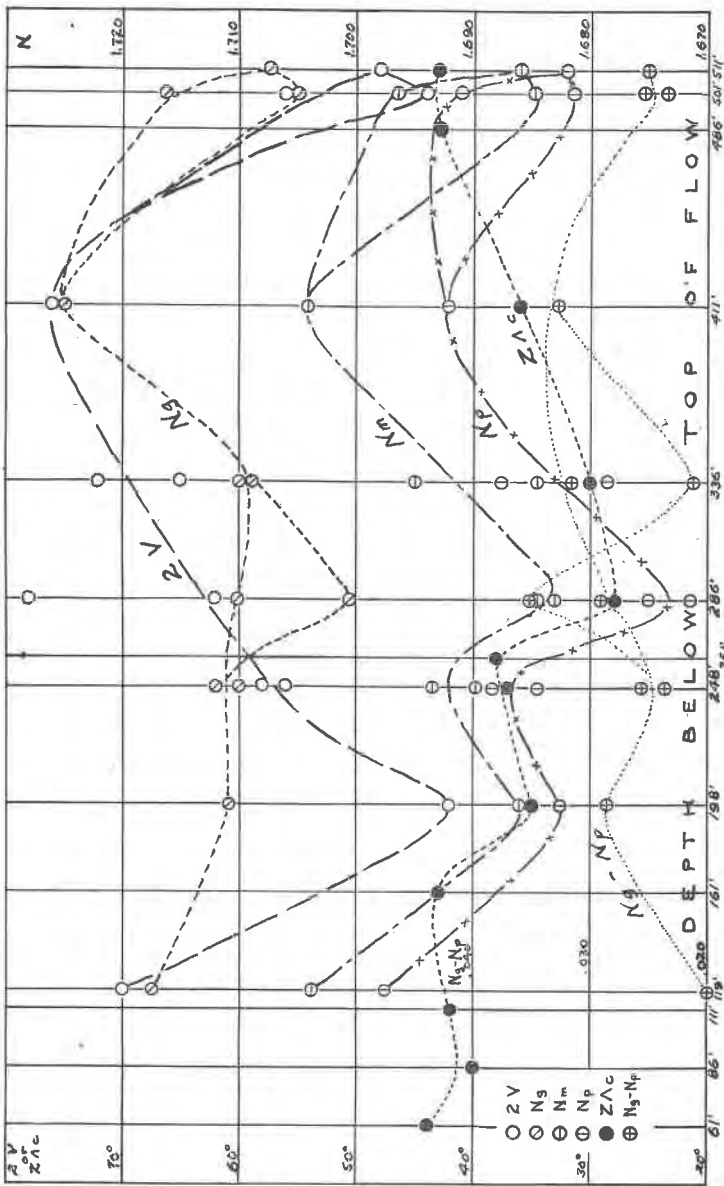
sections on the universal stage it was found that the optic angle ($2V$) within a single crystal varied as much as from $(+)$ 29° up through 90° to $(-)$ 83° , or a total of 68° . There was no zoning or any other indication apparent to explain such a fact. The crystal went to good normal extinction, but when the vertical plane was searched for an optic axis it went to extinction in different parts, with no apparent pattern whatsoever, through this wide angular range. Several readings of 0° for $2V$ were observed which is a characteristic of pigeonite, a member of the pyroxene series. Also, it is known that the optic angle is conspicuously variable in pigeonite,¹⁴ not only in different crystals, but even within a single crystal. Daly and Barth¹⁵ in a recent article have substantiated this fact. Due to the observed facts, then, that the indices may vary within a single grain (through how large a range, unfortunately, is not known) and that the optic angle may vary as much as 68° within a single crystal, and inasmuch as this particular type of pyroxene (pigeonite) is not conspicuously identifiable optically by any other method than by its optic angle and indices, it is at once obvious that the results obtained in this particular phase of the thesis should be accepted only with reservations. It is unfortunate that at this time it is impossible to state the extent of such reservations.

A series of determinations of the extinction angles for the pyroxenes was made at twelve different points within the flow by means of locating crystals in thin section cut normal to Y , and measuring the angle between Z and c .

All these results pertaining to the pyroxenes are shown graphically on Plate II. The graph shows a tendency for the indices to take a rather sudden rise in going upward from the base, then to fall off more gradually toward the center, and to rise, in turn, toward the upper margin of the flow. An abrupt break is apparent between the 248 foot and 286 foot depths. The optic angle follows, in general, the same course, without showing the break to which reference was just made. The extinction angles again show the same trend, without the rise in going upward from the base. The birefringence ($N_o - N_p$) portrays a tendency to rise from the two margins inward.

¹⁴ N. H. and A. N. Winchell, *Elements of Optical Mineralogy*, Part II, 1927, p. 181.

¹⁵ R. A. Daly and T. F. W. Barth, *Dolerites Associated with the Karroo System*, S. Africa, *Geol. Magaz.*, March, 1930, p. 103.



VARIATION IN PYROXENE SERIES THROUGH FLOW
 PLATE II

Plates VI and VII (following bibliography) show two of the double variation graphs obtained in the study. It was from these and ten other similar graphs that most of the data on Plate II were obtained. Plate VI was taken as typifying the pyroxene curves, in which the dispersion for N_m is $F-C=0.0163$. Plate VII shows a striking example of optic axis dispersion due to the rather radical departure of the dispersion for N_m from that for N_o and N_p .

Unfortunately it is impossible to trace this course of properties into terms of chemical composition and thence into a course of crystallization on any graphs found which deal with the pyroxene series. Probably this is due to the entrance of molecules into the mineral which are not shown on the graphs examined.

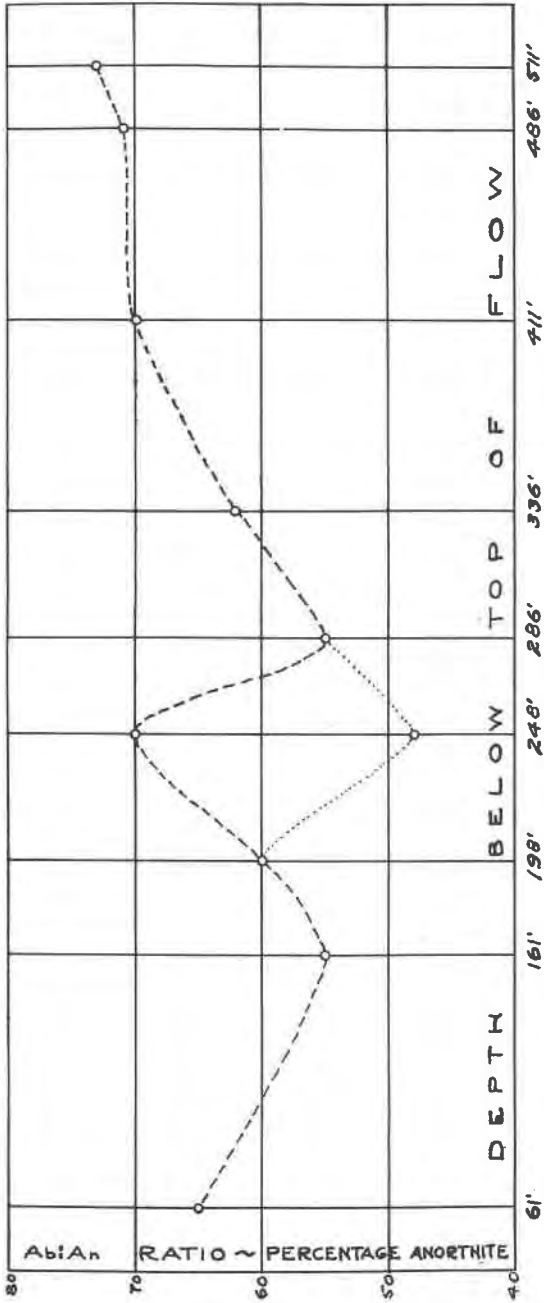
An interpretation of these results will be given in a later section.

VARIATION IN THE PLAGIOCLASE SERIES

Determinations of the feldspars were made at nine different points within the flow by means of the measurement of extinction angles in sections normal to a bisectrix. In one or two cases in which centered bisectrix figures could not be found the feldspar was determined by measuring the maximum extinction angles in the zone perpendicular to (010) between X and (010). The accuracy of the bisectrix determinations is very high, the maximum error probably being within two or three percent for the amount of anorthite present in the mineral.

The results are shown graphically on Plate III. It is shown that in going up from the base of the flow there is a progressive lowering in the amount of the anorthite molecule and hence an increase in the albite molecule until the 286 foot depth is reached. At the 248 foot depth several determinations agreed with the $Ab_{30}An_{70}$ ratio while one grain normal to a bisectrix showed the composition $Ab_{52}An_{48}$. At the 198 foot depth the composition has changed to $Ab_{40}An_{60}$, at the 161 foot depth to $Ab_{45}An_{55}$, while from there up to the 61 foot depth the composition changes until it becomes $Ab_{35}An_{65}$.

If the lower point at the 248 foot depth could be taken instead of the upper, the curve would be quite normal in aspect. As it is, however, the break corresponds in position to that already found for the variation in composition curves and the curves for the variation in the pyroxenes. The range in the feldspar present is not very great, being from sodic bytownite at the 511 foot depth



VARIATION IN PLAGIOCLASE SERIES THROUGH FLOW

PLATE III

to calcic andesine for the low point at the 248 foot depth. Practically all of the feldspars, except for these limiting points, fall within the class termed labradorite.

VARIATION IN THE FeO:MgO RATIO

Five chemical analyses given by Powers and Lane¹⁶ were studied as regards both the variation in the FeO:MgO ratio and the variation in the total Fe as FeO:MgO. The chemical analyses, together with the figures for the various ratios studied, are given in Table 2.

TABLE 2.

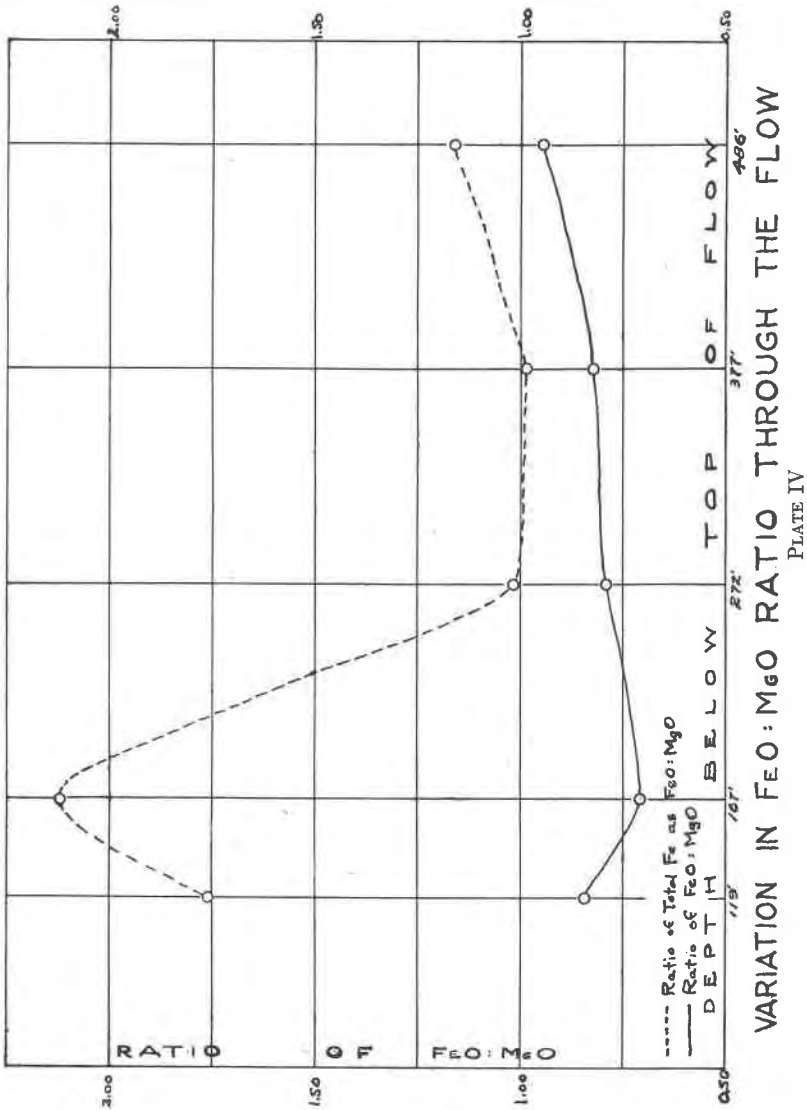
Depth below top of flow	119 ft.	167 ft.	272 ft.	377 ft.	486 ft.
SiO ₂	52.5	53.00	51.92	51.76	51.56
Al ₂ O ₃	14.30	14.71	13.25	13.49	13.57
Fe ₂ O ₃	6.15	7.30	2.28	1.71	2.00
FeO	5.14	3.32	7.16	7.42	7.80
MgO	6.08	4.67	9.05	9.05	8.26
CaO	9.08	9.40	11.22	11.62	10.80
Na ₂ O	2.56	4.11	2.42	2.38	2.58
K ₂ O	0.66	0.71	0.64	0.67	0.69
H ₂ O	1.64	1.00	0.65	0.60	0.90
TiO ₂	1.24	1.30	0.78	0.79	1.14
P ₂ O ₅	0.14	—	—	—	—
CuO	0.002	—	—	—	—
MnO	0.18	0.13	0.14	0.12	0.12
BaO	trace	trace	trace	—	—
Total	99.67	99.65	99.51	99.61	99.42
Ratio FeO:MgO	.846	.711	.791	.820	.944
Ratio of total Fe as FeO:MgO	1.76	2.12	1.02	.990	1.16
Ratio Fe ₂ O ₃ : FeO	1.20	2.20	.318	.230	.256

The analysis from the 119 foot depth was taken from the core of drill hole C, located a little less than $\frac{1}{4}$ mile to the north of drill hole A. All others are from the core of drill hole A.

Plate IV shows the variation in these ratios graphically. The variation in the straight ratio of FeO:MgO shows a progressive

¹⁶ *Op. cit.*, pp. 452-453.

decrease in going upward from the bottom of the flow until the 167 foot depth is reached. From here to the topmost analysis, that at the 119 foot depth, the ratio shows a marked rise.



The variation in the ratio of total Fe as FeO:MgO follows practically a parallel course to that just described in the bottom

half of the flow, while in the upper half a most striking increase in the ratio is found, being a maximum of 2.12 at the 167 foot depth. A study of this radical change in character of the analysis for

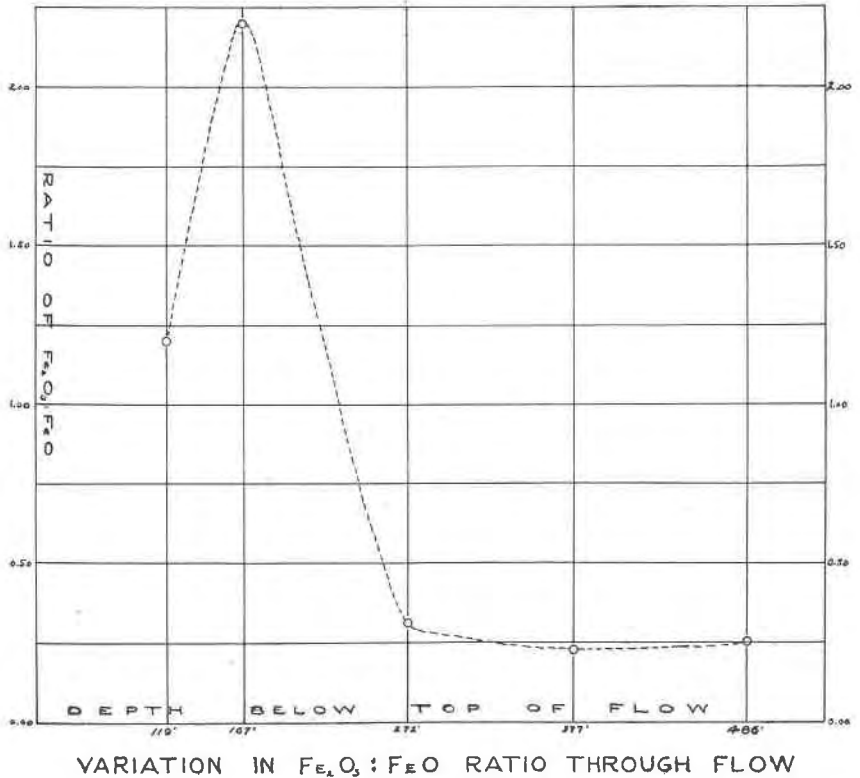


PLATE V

this depth led to an examination of the variation in the $Fe_2O_3:FeO$ ratio. This is shown on Plate V. The rise in the ratio at the 167 foot depth is even more abrupt in this case than in the latter.

An interpretation of these results appears in the next chapter.

INTERPRETATION OF THE RESULTS

A logical interpretation of the facts already presented in the preceding four sections will be attempted in this section. The results of each section will be treated separately, leaving the correla-

tion of all these interpretations for the last division, entitled
CORRELATION OF RESULTS AND CONCLUSIONS

As a result of the numerous Rosiwal counts made through the flow the conclusion is reached that there has been an enrichment of pyroxene in the lower part of the flow—from the 214 foot depth to the 461 foot depth—while there has been an even more striking enrichment of feldspars extending from about the 255 foot depth up to a depth of about 120 feet, with the maximum around the 200 foot depth. Magnetite and glass show a marked enrichment at the top of about 25 per cent, then drop off gradually to around 5 per cent at the 188 foot depth which they hold through the main part of the flow, with a much less marked enrichment near the bottom.

The upper and lower margins show approximately the composition of the magma, the lower being probably more accurate since the percentage of glass of unknown composition is lower. Here there is about 50 percent plagioclase feldspar, 43 percent pyroxene, and 7 percent magnetite plus glass. The results are further interpreted as indicating a gravitative settling of the heavier pyroxene into the bottom part of the flow, thus producing this enrichment; while the feldspar enrichment in the upper part is interpreted as indicating the crystallization of the final liquid of the magma which, through the gravitative settling of the more basic pyroxenes, has thus been enriched in the more alkalic constituents of the magma. The fact that the amount of magnetite and glass is so much higher in the upper part of the flow than in the lower indicates clearly the more rapid chilling which has taken place there.

The breaks in the curves—*i.e.*, the local enrichment of pyroxene at the 261 foot depth and the local enrichment of feldspar at the 288 and 291 foot depths—may be interpreted (1) as irregularities which have been caused either by currents of some nature which have interrupted the normal course of crystallization of the magma or by the engulfment of portions of crust, thus giving an abnormal result to the final crystallization product, and (2) as a definite break in the crystallization of the magma as a whole. According to the latter explanation really two flows would be present rather than only one, with the enrichment in feldspar at the top of the lower one indicated by the high feldspar at the 288 and 291 foot depths, and the enrichment in pyroxene at the base of the upper one represented by the high pyroxene at the 261 foot depth. How-

ever, the small enrichment in feldspar at the 288 and 291 foot depths is far out of proportion to the enrichment in pyroxene below this, while similarly the enrichment in pyroxene at the 261 foot depth is practically negligible as compared to the great enrichment in the feldspar above. A more convincing argument against this latter explanation is that texturally there is no indication of any break here whatsoever—the rock is relatively coarse-grained, no amygdaloid texture is present, and the amount of magnetite and glass is relatively low as compared to that in the rest of the flow. The former explanation is therefore strongly indicated—that the break from the normal curve in the center is merely an irregularity caused by either currents or engulfment of crustal fragments, as already explained.

The results of the study of the plagioclase series as already described indicates a course of crystallization as follows, neglecting the high anorthite figure at the 248 foot depth and the figure for the 198 foot depth. Crystallization of the magma began at the base when plagioclase of a composition slightly more calcic than $Ab_{27}An_{73}$ began to separate from a liquid which was more sodic. Crystallization continued upward, with the separation of plagioclase of constantly more sodic character until at the 486 foot depth it was of the composition $Ab_{29}An_{71}$. From this depth to the 411 foot depth the change was effected by smaller increments, the composition moving to $Ab_{30}An_{70}$. From this depth up to the 361 foot depth crystals of increasingly more sodic plagioclase kept forming from the liquid until they had attained the composition $Ab_{35}An_{65}$. At this point crystallization of the plagioclase began at the 61 foot depth also, with crystals of the same composition separating. Crystallization continued to proceed inward within the flow from each edge of the liquid, with constantly more sodic plagioclase separating, the composition of the crystals having changed at the 161 and 286 foot depths to $Ab_{45}An_{55}$. This process continued until at the 248 foot depth, or thereabouts, the last of the remaining liquid crystallized to form a rock in which the plagioclase was of the approximate composition $Ab_{52}An_{48}$.

Here, again, the break in the normal curve indicated by the plagioclase of the composition $Ab_{30}An_{70}$ at the 248 foot depth and by the plagioclase of the composition $Ab_{40}An_{60}$ at the 198 foot depth may be interpreted as indicating two separate flows. However, due to the fact that plagioclase of the approximate composition

to be expected at the 248 foot depth was found there, and inasmuch as the factors already outlined strongly suggest the improbability of there being two flows, it is concluded again that these two abnormal determinations indicate merely irregularities which may be expected due to currents of some nature bringing in liquid or crystals foreign to that normal position within the flow or to the engulfment of crustal matter which again will result in a departure from the normal order of crystallization.

The results of the study of the plagioclase series indicate, therefore, that, with these two exceptions, the crystallization in the flow proceeded more or less constantly from the top and bottom with the separation of more and more sodic plagioclase from the residual liquid until the last of the liquid crystallized slightly above the middle to form a rock containing plagioclase of the most alkalic composition. The range, however, is not great, since in the main the plagioclase variations lie within the labradorite group.

The results obtained from a study of the pyroxene series must be accepted, as was stated previously, only with reservations. This is due to the fact that the rotation readings necessary to obtain a complete set of results are of questionable accuracy because of the fact that a different part or edge of the grain had to be used after the rotation, and it was found that the indices and optic angle varied considerably within one grain or crystal. The results should be taken, therefore, as portraying tendencies which probably exist for the majority of the pyroxenes through the flow. These tendencies as already described are for the indices to fall off to lower values from the outermost parts of the flow towards the center; the base, however, showing lower indices also. The abnormality at the 248 foot depth is again apparent.

It is a well established fact that increase in the value of indices in the ferromagnesian minerals is practically proportional to the increase in tenor of iron in these minerals, and vice versa. The results would indicate, therefore, that as crystallization started from the base pyroxenes of higher iron content continued to crystallize until some point in the neighborhood of the 411 foot depth was reached. From here, for some reason or other, the tenor of iron in the pyroxenes began to drop off progressively and crystallization started near the top of the flow soon after this change took place, as already indicated by the feldspars. With continued crystallization of the rock pyroxenes of constantly lower

iron content kept crystallizing until, if the curves were projected below the abnormal readings found at the 248 foot depth, the pyroxenes of minimum iron content would crystallize out at about the depth just named. The extinction angle ($Z \wedge c$) follows in general a similar course except for its failure to show a drop near the base of the flow. This general lowering of extinction angle again suggests lower iron content toward the middle of the flow. The birefringence shows a general tendency to rise in value from the margins of the flow toward the middle which, judging from the diopside-hedenbergite system, would again suggest a lower iron content towards the middle of the flow.

The breaks in the pyroxene curves at the 248 and 286 foot depths have already been pointed out. This departure from the normal corresponds in location with those abnormalities already found in the variation in percentage composition and in the variation in the plagioclase series. The results, again, are interpreted as irregularities caused either by currents of some nature or by engulfment of crustal matter.

It is unfortunate that the results could not be traced more specifically into terms of chemical composition and thence into a definite course of crystallization for the pyroxenes. It is suspected that some of the acmite molecule is present to bring up the optic angle so high in the lower-middle and upper parts of the flow, but this is only a surmise. It may be that the pigeonite present has really produced abnormalities in the curves which just above have been interpreted as portraying the properties for the majority of the pyroxenes present in each particular part of the flow studied. The whole matter hinges on the range in indices and optic angle which can be expected in a given grain or crystal of pigeonite, and upon the proportion of pigeonite present in each particular part of the flow studied. Unfortunately time did not permit a comprehensive study of this subject—it would really constitute a problem in itself. The possibility is here suggested that the variability in optical properties of pigeonite may be due to the fact that at ordinary or low temperatures the mineral is not stable and thus breaks up into its chief constituent molecules to form scattered areas of diopside and clinoenstatite. Other molecules—possibly acmite—may have been present in the pigeonite to complicate further the final result. The fact that pigeonite is usually found in effusive rocks which have crystallized rapidly while diopside

and clinoenstatite, its chief constituents, are found in the plutonic rocks strongly suggests such a possibility. An X-ray pattern of the pure pigeonite found in this flow might yield very interesting results.

The results of the study of the variation in the FeO:MgO ratio through the flow indicate a general lowering of the ratio from the base up to the 167 foot depth, where it begins to rise and continues in this course to the 119 foot depth. Since the amount of magnetite is fairly constant through the flow up to the 119 foot depth these results seem to indicate that as the pyroxenes crystallized they did not tend to become enriched in FeO as compared to MgO. The variation in the ratio of total Fe as FeO:MgO follows essentially the same course except for the radical rise in the ratio at the 167 foot depth. The possibility of the analysis having been made from a point in the flow which had been subjected to oxidation and perhaps even to the introduction of FeO was at once suspected. This led to a comparison of the Fe_2O_3 :FeO ratio through the flow, and the even more marked rise in this ratio at this point is strong evidence that oxidation has taken place there. The sudden drop in the value for MgO and CaO suggests further that alteration of a katamorphic nature has been operative on the specimens from which the analyses at the 167 and 119 foot depths have been made. It is concluded, therefore, that inasmuch as indications suggest that these analyses were not made from strictly fresh rock they should not be included in the study of the variations in the FeO:MgO ratio through the flow. The acceptable results indicate, therefore, the crystallization of pyroxene of a lower FeO:MgO ratio from the 486 foot depth up to the 272 foot depth.

CORRELATION OF RESULTS AND CONCLUSIONS

The results obtained from the study of the variations in the mineralogical composition, in the plagioclase series, in the pyroxene series, and in the FeO:MgO ratio have been found to correlate rather nicely. The remarkable agreement in the first three of these phases of the study with regard to the abnormal condition at about the middle part of the flow, constitutes a correlation that cannot be denied. A disagreement introduced by the fact that the variations in the plagioclase series and the pyroxenes indicates the end of crystallization at about the 248 foot depth, while the variation in percentage mineral content indicates from the maxi-

mum feldspar content that crystallization ended at about the 200 foot depth, may be explained by a rising of some of the feldspars as they crystallized. Powers and Lane¹⁷ concluded that the feldspar had risen, so this result substantiates their conclusion.

The fact that agreement was obtained, in general, between the results pertaining to the variation in tenor of iron in the pyroxene series as determined by the measurement of indices and by chemical analyses of the rock constitutes another good check. They both indicate a general decrease in tenor of iron from the margins toward the middle of the flow, except for the chilled borders.

In summary and conclusion, the combined results as obtained through a comprehensive optical study of the Cape Spencer flow indicate that:

(1) A type of differentiation which Bowen has termed "fractionation" was operative during the crystallization of the flow, having been brought about by fractional crystallization of the plagioclase and probably the pyroxene series, together with the relative movement of the pyroxenes and, to a lesser degree, the plagioclase feldspars with respect to the liquid from which the crystals formed.

(2) Crystallization began at the base of the flow when plagioclase of a composition slightly more calcic than $Ab_{27}An_{73}$ began to crystallize together with the pyroxene. As crystallization proceeded upward the residual liquid became enriched in alkalic constituents with the consequent crystallization of constantly more sodic plagioclase. The pyroxene formed at the base was higher in MgO than the liquid from which it crystallized, with the consequent enrichment of the liquid in FeO. Pyroxenes of a composition increasingly higher in FeO with respect to MgO continued to crystallize until about the 411 foot depth was reached. From this point onward, for some reason or other, the pyroxenes failed to show this increase in tenor of FeO with respect to MgO, actually indicating a decrease in this ratio. When crystallization had proceeded to the 361 foot depth, when the plagioclase had attained the composition $Ab_{35}An_{65}$, crystallization also began at the 61 foot depth, with the separation of plagioclase of the same composition. As crystallization proceeded, plagioclase of increasingly alkalic composition continued to crystallize, together with pyroxene of increasingly low tenor of

¹⁷ *Op. cit.*, p. 447.

FeO with respect to MgO, until at approximately the 248 foot depth the last of the residual liquid crystallized to form plagioclase of the composition $Ab_{52}An_{48}$ together with pyroxene of the lowest FeO:MgO ratio.

(3) An abnormal condition in the middle part of the flow is due either to currents of some nature bringing in foreign matter or to the engulfment of foreign crustal matter.

(4) A progressive enrichment in tenor of iron of the residual liquid as postulated by Fenner is not indicated during the crystallization of this flow.

(5) The amount and cause of the range in variation of the optical properties of pigeonite is unknown and constitutes a very interesting problem in mineralogical research.

BIBLIOGRAPHY

- N. L. Bowen, *The Evolution of the Igneous Rocks*, Princeton University Press, 1928.
- R. A. Daly and T. F. W. Barth, Dolerites Associated with the Karroo System, S. Africa, *Geol. Magaz.*, March, 1930.
- R. C. Emmons, The Double Dispersion Method of Mineral Determination, *Amer. Mineral.*, vol. 13, 1928, pp. 504-515. The Double Variation Method of Refractive Index Determination, *Amer. Mineral.*, vol. 14, 1929, pp. 414-426. A Modified Universal Stage, *Amer. Mineral.*, Vol. 14, 1929, pp. 441-461.
- C. N. Fenner, The Crystallization of Basalts, *Am. Jour. Sci.*, vol. 18, 1929, pp. 225-253.
- S. Powers, The Acadian Triassic, *Jour. Geol.*, vol. 24, 1916, pp. 1-26; 105-122; and 254-268.
- S. Powers and A. C. Lane, Magmatic Differentiation in Effusive Rocks, *Trans. A. I. M. E.*, vol. 54, pp. 442-457, 1916.
- N. H. and A. N. Winchell, *Elements of Optical Mineralogy*, Part II, 1927.

DOUBLE VARIATION GRAPH

Pyroxene - 248'

$N_g = 1.7120$
 $N_m = 1.6935 \pm .0005$
 $N_o = 1.6883$
 $N_g - N_o = .0237$
 $2V = 45.8^\circ \pm 2^\circ$

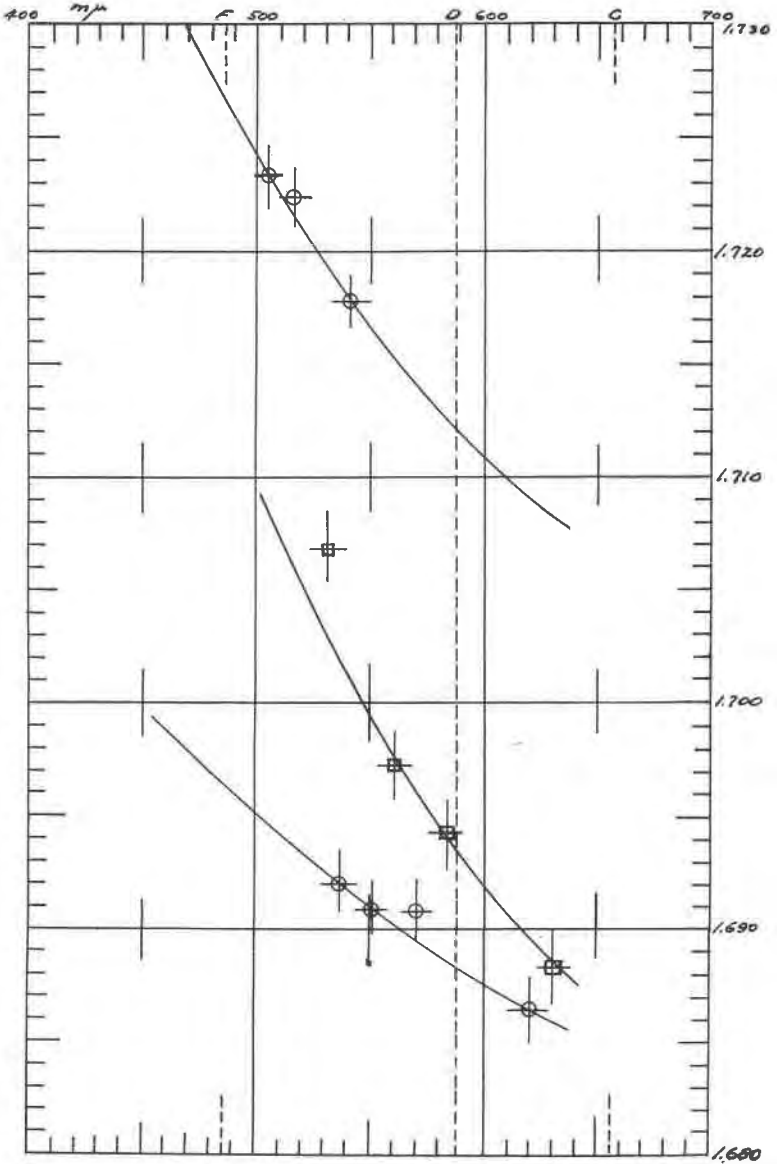


PLATE VI

DOUBLE VARIATION GRAPH

Pyroxene ~ 198'

$N_g = 1.7109$
 $N_m = 1.6880$
 $N_p = 1.6825$ } $\pm .0005$
 $N_o - N_p = .0284$
 $2V = 42^\circ \pm 2^\circ$

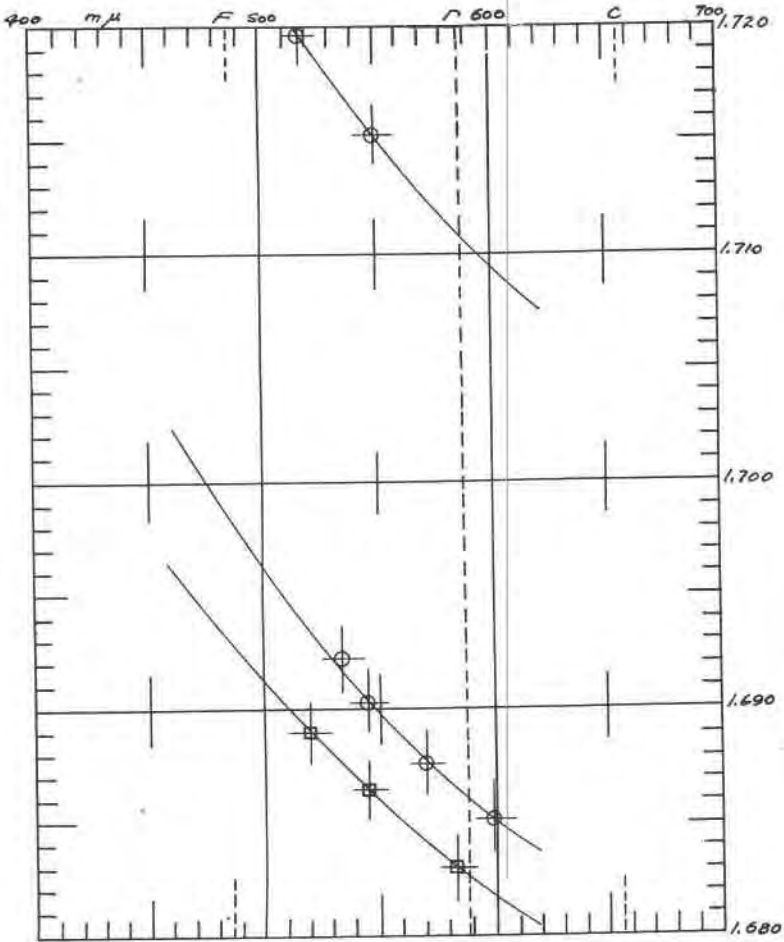


PLATE VII