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A MICROSCOPIC STUDY
OF
BASALT FLOWS

A dissertation submitted to the

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requirements for the degree of

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by

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INTRODUCTION

The present study is the outgrowth of an earlier problem, concerning the classification of the basalts of Oregon, which was carried on during the year 1930-1931 at the University of Oregon for a Master of Arts thesis. A portion of that thesis was devoted to the evidence for intratelluric differentiation of the magma, or magmas, which gave rise to the thick series of flows in the Columbia River Basalt formation, and an attempt was made to establish the fluctuating character of the magma from the eruptive sequence of a complete series of the superimposed Miocene flows exposed at Tygh Valley, northcentral Oregon.

Specimens from the Tygh Valley sequence, as well as many miscellaneous basalts of the Columbia River Basalt formation, proved to have essentially the same fine-grained megascopic appearance. However, a microscopical examination showed marked differences in their texture and mineralogical composition. Thin sections indicated that the dominant texture of these basalts was hyalopilitic, although many more nearly crystalline phases were noted. General observations on a large number of the thin sections indicated that the more nearly crystalline phases of the basalt were accompanied by a much greater amount of augite and magnetite. It was impossible to determine from the data at hand whether these variations were peculiarities of an entire flow or represented changes brought about by post-extrusion differentiation, more complete crystallization with depth, or other processes active upon the flows.

It was concluded that no microscopic basis for classification of the basaltic rocks could be established until individual flows had been systematically sampled and studied to determine the effects of variation in chemical composition, thickness, and volatile constituents upon the texture of the flow.

In the summer of 1951, samples were collected from several basaltic flows which would best illustrate the major textural types of the Columbia River basalts (hyalopilitic, porphyritic-hyalocrystalline, and holocrystalline). A 150 foot porphyritic-hyalocrystalline flow from Table Rock, southwestern Oregon, and a 16 foot hyalopilitic flow from Grand Coulee, Washington, were selected to represent these two types. Although neither flow is definitely correlated with the flows of the Columbia River Basalt formation of northcentral Oregon, they have the normal characteristics of those extrusions. Furthermore, they give a contrast in thickness not found between a porphyritic-hyalocrystalline flow from Blalock Canyon, west of Arlington, Oregon, and a hyalopilitic flow from the base of the Tygh Valley series which were also sampled. No holocrystalline Columbia River basalt flow was found which would show both the effects of intermediate thickness of outpour and a high percentage of volatile constituents upon its crystallization. Therefore a 31 foot flow of the Madras Formation, from near Bend, Oregon, was selected to complete the series.

Oriented specimens were collected at one foot intervals from the 16 and the 31 foot flows and at three foot intervals from the 150 foot flow. Two thin sections were made of each specimen, one parallel and the other normal to the flow surface, in order to check possible variations in mineral percentages resulting from an orientation of crystals within the flow.

Minerals were determined by their optical properties as shown in thin sections and were checked, wherever possible, by their indices of refraction from crushed fragments. The index fluids used were accurate to the third decimal place. In the microscopic determination of the plagioclases, many different zones were employed but every effort was made to locate acute bisectrix sections for their more positive albite-anorthite delimitations. In some cases, sections were found which showed both zonal growth and albite twinning and accurate determinations were made without difficulty. The composition of small microlites of plagioclase was found, in most instances, from extinction angles measured to their direction of maximum elongation.

To obtain a better understanding of the textural variations and of the percentage variation of individual minerals observed throughout the flows, an accurate linear count was made of each thin section. The larger minerals were measured directly upon the vernier of the mechanical stage and smaller ones were measured with a micrometer ocular or a special 0.01 mm. grid. In making these linear analyses, a medium power objective and a Leitz number 3 ocular were used in all instances except where it was necessary to separate the very find constituents of a glassy base. In the latter case, a higher powered objective or a Leitz oil immersion lens was employed. A grid was established on the thin section with a mechanical stage, following essentially the Rosiwal method for mechanical analyses, and the field was crossed by lines of count at distances of 1.0 mm. In glassy basalts, the average total linear distance measured was 90.7 mm., while in the coarse grained sections it averaged 162.3 mm. The accuracy of these counts was checked in thin sections of two hyalopilitic basalts by covering a total linear distance of 300 mm. In both instances, the divergence from the smaller counts was less than ± 4% in any one mineral.

The linear counts were plotted and curves were constructed to show the percentage variation of each mineral with depth in the flow. These variation curves represent the mean percentage of each mineral present in sections cut both normal and parallel to the flow surface.

It is the purpose of the thesis to present the results of the microscopic study and an interpretation of the phenomena observed in the examination of the thin sections. The thesis is divided into four main divisions. Part I deals with the study of the 150 foot porphyritic-hyalocrystalline flow, Part II with the hyalopilitic 16 foot flow, Part III with the 31 foot holocrystalline flow, and Part IV with the general conclusions.

Acknowledgments

The writer wishes to express his appreciation to Dr. George B. Barbour who generously contributed the three chemical analyses and gave valuable criticism and assistance in the work; to Prof. O. C. Von Schlichten under whose direction the thesis was completed; to Dr. E. T. Hodge, at whose instigation the original research on basalts was started; to Doctors N. L. Bowen and J. F. Shairer for their critical review of the manuscript; to Dr. A. L. Howland for helpful discussion on particular phases of the work; and to the members of the staff of the Geology Departments of both the University of Cincinnati and Northwestern University for suggestions.

PART I

PORPHYRITIC-HYALOCRYSTALLINE BASALT

TABLE ROCK, OREGON

PORPHYRITIC-HYALOCRYSTALLINE FLOW FROM TABLE ROCK

Location and Age

The flow selected to represent the porphyritic-hyalocrystalline type of extrusion forms the capping material of Table Rock which is located in the Rogue River Valley, close to the western border of the Cascade Range, 9 miles north of Medford, Oregon. It is approximately 150 feet in thickness and is essentially horizontal.

The age of the flow has never been accurately established although Powers[1], who has made the most recent mention of it, states that it is of Recent age. Diller in his reconnaissance work gives a more detailed description of the flow with some estimate of its relative age.

> "Northeast of Gold Hill just across the river (Rogue) from the railroad, is Table Rock, named from the flat black capping of basalt, which is part of a flow of lava that long before historic time spread over this region from some volcano in the Cascade Range. The lava poured over comparatively soft beds of shale, sandstone, and conglomerate of Cretaceous and Tertiary age, afterwards erosion cut through the lava in places, and attacked the softer rocks beneath." [2]

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[1] Powers, H. A., History and petrography of the Siskyou Batholith, University of Oregon Thesis (unpublished), 1926.

[2] Diller, J. S., Guidebook of Western United States, Part D, The Shasta route and coast line: U. S. Geol. Survey Bull. 614, p. 50, 1915

General Megascopic Appearance

The rock of the flow varies in color from a light, grayish, basal portion to a very dark, vitreous, gray-black upper phase which is much thicker. The color change takes place gradually in a comparatively narrow zone about fifteen feet in thickness above the light-colored base and is accompanied by a distinct change in the type of jointing. The upper part of the flow is characterized by very finely spaced vertical joints. A major system of jointing, however, follows through the entire thickness of the flow.

Megascopically the rock has a distinctly porphyritic appearance, tabular plagioclase crystals with a maximum size of 6.0 mm. constituting the larger percentage of the phenocrysts. Occasional grains of olivine and augite may be seen throughout the flow while irregular masses of iron ore are visible only at the base. The porphyritic elements average approximately one-third of the rock mass and are imbedded in a microcrystalline groundmass. A sub-parallel alignment of the tabular plagioclase phenocrysts with the flow surface gives a megascopic trachytic fabric to the rock throughout its entire thickness.

The rock is very dense and is fresh, except along joint cracks near the surface where it has been weathered into small, irregular fragments. There is a notable absence of vesicular openings in the lower part of the flow and relatively few vesicles, irregularly shaped and spaced, are present in the upper 20 feet except at the very top where the rock has a roughly cellular appearance.

In general character the flow is comparable to the "smooth-top" or Pahoehoe type of extrusion but differs markedly in its relatively small percentage of vesicular openings.

General Microscopic Appearance

Texture of the flow:

According to size, three types of crystals may be distinguished; (1) the larger phenocrysts,- plagioclase, olivine, and associated magnetite, (2) the smaller (microscopic) phenocrysts,- plagioclase, augite, and small amounts of magnetite, and (3) the groundmass consisting of an association of plagioclase, enstatite, and larger amounts of magnetite, all of which are embedded in a glassy residuum of varying proportions throughout the flow.

Granularity:

The grain size of any single crystalline constituent remains remarkably constant throughout the flow. The following tabulation (Table I) gives the average greatest dimensions of the mineral constituents and provides the initial basis for differentiation between the different mineral associations.

Table I

Average greatest grain size of the mineral constituents of the Table Rock Flow

GROUP	AVERAGE GREATEST SIZE
Large Phenocrysts	largest crystals
Plagioclase	4.0 mm. x 1.9 mm.
Olivine	2.0 mm. x 1.2 mm.
Magnetite	0.25 mm. octahedra
Smaller Phenocrysts	crystals of intermediate size
Plagioclase	2.0 mm. x 0.7 mm.
Augite	1.0 mm. x 0.4 mm.
Magnetite	0.18 mm. octahedra
Groundmass	smallest crystals
Plagioclase	0.3 mm. x .05 mm.
Enstatite	0.2 mm. x .08 mm.
Magnetite	grains, globulites, skeletal growths and aggregates of small size
Apatite	small grains to 0.6 mm.
Ilmenite	pseudomorphs after olivine

Crystallinity:

The crystallinity of the flow is best shown by the glass curve (curve A, fig. 1) which gives the percentage variation of the non-crystalline residuum with depth. The percentage of glass decreases almost steadily from the upper surface to the base. The crystallinity of the flow varies, therefore, from the different degrees of hyalocrystallinity at the upper surface to a nearly holocrystalline phase at the base.

Fabric:

The larger phenocrysts (photo B, Pl. I) are badly fractured and resorbed, with the original euhedralism of form largely destroyed by reaction with the extrusive melt. In addition, the olivine crystals have been subjected to considerable corrosion and replacement and are represented in many parts of the flow only as pseudomorphs.

The smaller phenocrysts are, in general, euhedral and do not show resorption and alteration phenomena.

A sub-parallel microscopic arrangement of the larger tabular phenocrysts of plagioclase (photo L, Pl. I) imparts to the rock a trachytic appearance which is strengthened by a secondary arrangement of smaller phenocrysts around the larger plagioclase and olivine crystals. The smaller phenocrysts, lath-shaped plagioclases and well-formed augite crystals, as well as the much smaller microscopic constituents of the groundmass, reflect the effects of movement of the flow although their trachytic arrangement is not as pronounced as that of the larger phenocrysts.

The fluidal arrangement (photo I, Pl. I) of the small skeletal plagioclase laths of the groundmass in the upper levels of the flow is replaced by a "felted" fabric (photo D, Pl. I) with the increasing crystallinity of the flow. This "felted" appearance of the groundmass at the base does not destroy the original fluidal arrangement of small laths but merely tends to obscure it.

Since the shape, size, and arrangement of the crystalline constituents are the same throughout the flow, the only variation is in texture, which ranges from fine grained, seriate-porphyritic intersertal at the base to fine grained seriate-porphyritic hyalopilitic at the top. Any departure from this condition is local and of minor importance.

Mineralogical Characteristics

The larger phenocrysts

The larger phenocrysts, olivine and plagioclase, which make up the most basic constituents of the flow occur primarily as individual crystals. However, mutually intergrown groups of the two minerals (photo A, Pl. II) have been noted and individual crystals of each commonly include parts of the other and indicate their contemporaneous separation. Magnetite associated with these larger phenocrysts is of earlier formation than either and is found in both minerals.

The original euhedralism of the plagioclase and olivine crystals has been partially destroyed, particularly in the central portion of the flow where only "husks" (photo H, Pl. II) of the original plagioclase crystals remain and most of the olivine crystals have been resorbed and subsequently replaced by chloritic material. The same condition prevails at the extreme basal portion of the flow (photo J, Pl. II) where the olivines have been completely replaced by a mixture of chloritic material and ilmenite.

Plagioclase:

The larger plagioclase phenocrysts are characterized by both oscillatory and progressive types of zonation. The gradual sweeping extinction from center to the periphery of the progressively zoned crystals shows a gradual change in the albite-anorthite ratio from An_{68} at the center to An_{62} at the periphery. Occasional zoned crystals of this type have been noted with centers ranging as high as An_{80}. The oscillatorily zoned crystals show finely divided successive zones surrounding a core of progressive zones. These oscillating zones vary in a regular series within a composition range of An_{68} to An_{62}, in such a manner that any composition within this Ab-An range may make up the periphery. Both types of zoned crystals occur in approximately equal numbers at any one position within the flow. The larger size of the oscillatorily zoned crystals gives, however, a somewhat greater area for those crystals since the progressively zoned plagioclases and the cores of the oscillatorily zoned ones approximate each other in size. Both types of these resorbed crystals are surrounded by a narrow zone ranging in composition from An_{50} at the contact with the crystal to An_{40} at the contact with the groundmass. This exterior zone is significant in that it has the same composition as the groundmass plagioclase at the exterior border.

Curve A, Figure I, shows the percentage variation of the larger plagioclases with depth. Two areas of maximum concentration are indicated at depths of 30 and 138 feet. Here the crystals preserve to a maximum degree their original euhedralism. The areas of least concentration correspond to those parts of the flow where a maximum of resorption was observed.

The large plagioclases show a degree of orientation in the flow that is not apparent in any other crystalline constituent. Not only is there an alignment of the crystals with their largest dimensions parallel to the lines of flow, but there is likewise an orientation of the (010) faces, parallel to which the crystals are flattened, parallel to the surface of the flow. Thin sections cut parallel to the surface measure, on the average, 6 % more total area of plagioclase than do those cut normal to the flow surface of the same specimen (photos J, K, L, Pl. I). This relationship is complicated and more or less destroyed where the crystals

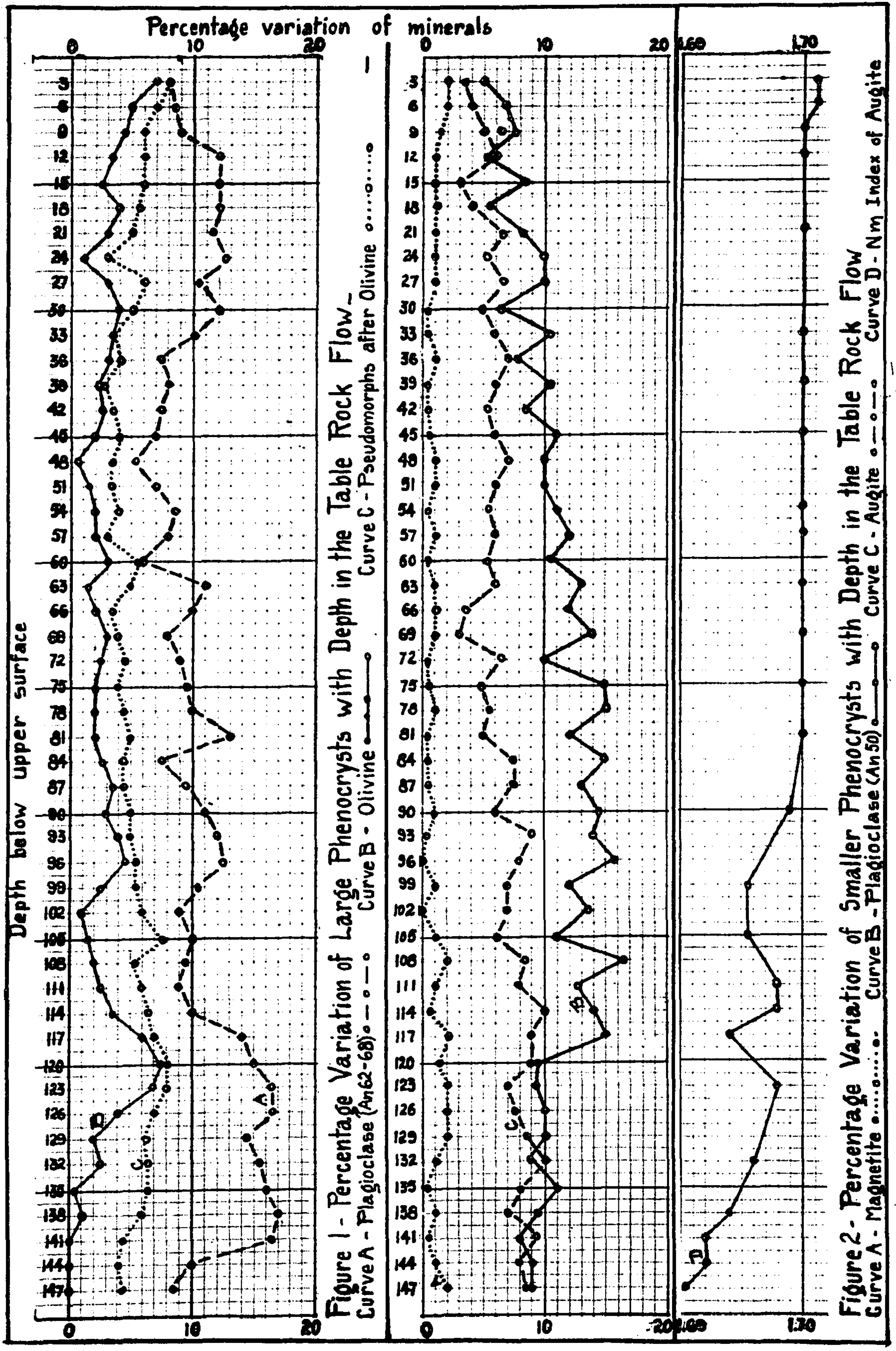

Figure 1 - Percentage Variation of Large Phenocrysts with Depth in the Table Rock Flow_

Curve A - Plagioclase (An62-68) o — o — o Curve B - Olivine ●——● Curve C - Pseudomorphs after Olivine o....o....o

Figure 2 - Percentage Variation of Smaller Phenocrysts with Depth in the Table Rock Flow

Curve A - Magnetite ●....●....● Curve B - Plagioclase (An50) o——o——o Curve C - Augite o—o—o Curve D - Nm Index of Augite are more highly resorbed. The (010) faces seem to have been less resistant to the attack of the melt and at the center of the flow the orientation has been almost entirely destroyed. At the base, where a great amount of resorption has also been noted, the orientation has been preserved with enough detail to make accurate measurements possible and to indicate that there had been a higher degree of orientation at the base than within the central portion of the flow. For tabulation of Rosiwal counts see Appendix, Table A.

Olivine:

Curve B, Figure 1, shows the percentage variation of olivine with depth. Like plagioclase, olivine has two areas of maximum concentration, the larger one at a depth from 120 feet to the base, and the other at the upper surface. Glomeroporphyritic groups of olivine (photo D, Pl. II) occur only near the upper surface and probably give an average percentage somewhat higher than that normally found in other parts of the flow, where the olivines occur only as individual crystals.

Curve C, Figure 1, shows the percentage of olivine plus its pseudomorphs which are of two kinds, ilmenite after olivine and chlorite after olivine.

Olivine, where unaltered, commonly has a very thin, distinct reaction rim of pyroxene of indeterminable composition surrounding its periphery (photo G, Pl. II). The olivine below a depth of 120 feet almost invariably shows such rims. What relation these reaction rims bear to the concentration of olivine is not clearly understood. However, augite crystals are commonly found completely formed around highly resorbed fragments of olivine (photos E, F, Pl. III) and it is thought that the rims were developed by a reaction with the melt and protected the crystals to some degree from further assimilation.

The indices of olivine remain remarkably constant throughout the flow, Ng=1.715, Nm=1.70, Np=1.682 (all readings ± .003), and indicate approximately 20% of the fayalite mole (after Winchell[1]).

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[1] Winchell, A. N., Elements of optical mineralogy, Pt. II, p. 168, New York, 1927.

Magnetite:

Magnetite is of three generations; (1) large octahedra associated with the larger phenocrysts of olivine and basic plagioclase (photo K, Pl. II), (2) smaller octahedra associated with the smaller phenocrysts of plagioclase and augite (photo C, Pl. III), and (3) very small octahedra and interstitial masses of groundmass crystallization (photos A, D, Pl. I). Curve A, Figure 2, shows the percentage variation with depth of total magnetite except that which is definitely of the groundmass stage of crystallization. Since the combined percentages of the first two generations of magnetite never exceed three per cent in any part of the flow, no attempt was made to separate the two distinct groups.

The smaller phenocrysts

The smaller phenocrysts consist of plagioclase, augite, and small quantities of magnetite. The typical occurrence of this association is in cumulophyric groups (photo A, Pl. III) of which the ratio of mutually intergrown plagioclase and augite is approximately 3:2. Both plagioclase and augite occur also as distinct individuals scattered throughout the flow.

Plagioclase:

The smaller, lath-shaped, euhedral phenocrysts of plagioclase are fresher in appearance than the larger, tabular plagioclases, and lack the high degree of resorption and fracturing which characterize those crystals. In addition to their smaller size and other physical characteristics, they are more acid in composition and maintain a constant albite_1-anorthite_1 ratio throughout the flow. Although these porphyritic elements lack the well-developed zonal growth which marks the more basic plagioclases, they commonly show a thin peripheral series of progressive zones which approach the composition of the plagioclases of the groundmass (An_{40}). This peripheral area is rarely well marked but indicates by its extinction its more acid character. Its composition was definitely determined on only a few individual crystals.

Curve B, Figure 2, indicates the percentage variation of these plagioclase crystals with depth. It may be noticed by comparing this curve with the curves of Figure 1 that the greatest concentration of these plagioclases occurs at the central portion of the flow where there has been a maximum of resorption or assimilation of the larger plagioclase phenocrysts.

The smaller plagioclase crystals have no orientation comparable to that of the larger tabular phenocrysts. They also lack the well-developed trachytic arrangement of those crystals but they show the effects of movement of the lava mass by an alignment about the larger crystals.

Augite:

The augites associated with the more acid plagioclase phenocrysts are well formed unaltered euhedral crystals, having a distinct peripheral zone of enxtatite (photo H, Pl. III) which is marked by fine inclusions of iron oxide. No definite line separates augite from its rim of enstatite.

Curve C, Figure 2, gives the percentage variation of augite with depth. A gradual increase from the upper surface to the base is indicated.

Curve D, Figure 2, shows the variation in the measured Nm index of augite from 1.705 at the upper surface to 1.69 at the base. The gradual decrease is accompanied by a corresponding decrease in the angle of extinction Z C from 43° to 38°. The composition of augite as interpreted from these optical properties varies from diopside 35%- clino-enstatite 20% - hedenbergite 45% at the upper surface to a slightly more diopsidic composition at the base.

Magnetite:

The magnetite, which is found in very small amounts as inclusions in augite, has been tabulated with that accompanying the larger phenocrysts (curve A, fig. 2).

The Groundmass

The groundmass is composed of plagioclase ($An_{60}An_{40}$), enstatite and magnetite embedded in a glassy residuum. This mineral association is distinctly more acid than the other two groups of phenocrysts.

Plagioclase:

The groundmass plagioclases occur in lath-like skeletal crystals. Their composition remains the same throughout the flow as do their general physical character-

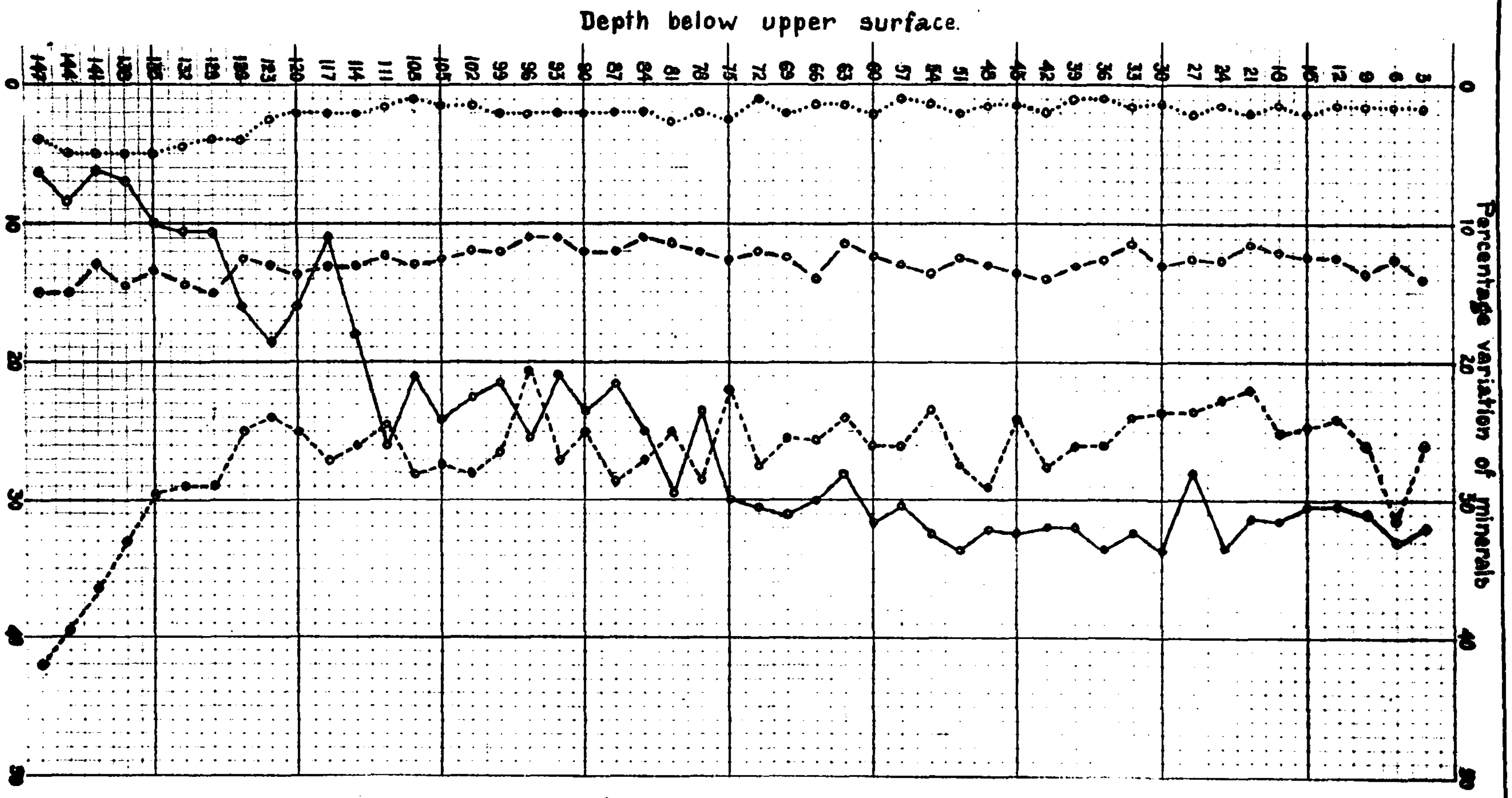

Figure 3 - Percentage Variation of Groundmass Constituents of the Table Rock Flow with depth

Curve A - Glass -

Curve B - Plagioclase

Curve C - Enstatite

Curve D - Magnetite

istics, but their amounts (curve B, fig. 3) vary inversely with the amount of glass (curve A, fig. 3). At the base of the flow where a minimum of glass occurs the larger quantity of plagioclase gives a "felted" appearance to the groundmass. An examination of the curves shows that both plagioclase and glass vary with the percentage of phenocrysts. Many of the irregularities in these curves may be due to a concentration of large phenocrysts in certain portions of the flow.

Enstatite:

Enstatite occurs as well-formed prismatic euhedral crystals (photo I, Pl. III) and, unlike plagioclase, it maintains an almost constant percentage through the flow (curve C, fig. 3). It shows only a slight variance in its indices values with Ng 1.671 and Np 1.661. It is easily distinguishable in the groundmass by its lack of color, low birefringence, parallel extinction, and by the presence of a large number of minute opaque inclusions.

Magnetite:

Magnetite (curve D, fig. 3), like plagioclase, varies inversely with the percentage of glass. It occurs in greatest abundance as irregular interstitial masses at the more nearly holocrystalline base (photo D, Pl. I). In the glassy upper portions of the flow, it is present in minor amounts as small cubes and octahedra (photos J, K, Pl. III).

Glass:

The non-crystalline, glassy, residuum varies in color from a deep-brown at the upper surface where it constitutes about 32% to an almost colorless isotropic substance at the base where less than 10 per cent of it is present. This change in color is accompanied by a decrease in the index of refraction from 1.54 to 1.52. It seems probable that the loss of color, lower index of refraction of the glass, and the larger percentage of magnetite at the base of the flow indicate an almost complete separation of iron oxide from the residuum of crystallization in the lower portions of the flow.

The deep brown glass is marked by an absence of globulites, trichytes and other incipient crystallization phenomena which characterize the lighter, almost colorless glass. The clear, homogeneous appearance of the darker material is destroyed only at the extreme upper surface of the flow where the glass is discolored by trichites of a very dark, opaque substnace, probably magnetite.

There were many irregularities in the crystallization of the glassy base. Small, localized, almost entirely crystalline areas have been noted throughout the flow. These areas are commonly found in the angles left by the crystallization of cumulophyric groups or in large resorption channels (photo E, Pl. II) in the larger plagioclase phenocrysts (photo J, Pl. III). In these areas magnetite occurs not as interstitial masses but as definite octahedra. This condition is the reverse of that noted in the more nearly holocrystalline groundmass where magnetite occupies the interstices of crystallization. Apatite is commonly found in the smaller, localized areas of crystallinity within the glass. Elsewhere in the flow, apatite is associated only with ilmenite which definitely replaces olivine.

Summary

The distinction between different associations of crystals made upon the basis of size is supported by marked differences in chemical composition and in the appearance and textural relationships of the individual crystals of each group. Each association is typified by a plagioclase which maintains identical physical and chemical characteristics throughout the flow. A detailed study of the different associations indicates that they represent three distinct generations or stages of crystallization. The three generations shall be referred to as the initial stage, the intermediate stage, and the final or groundmass stage of crystallization.

Secondary or Alteration Effects

Throughout the flow olivine has been subjected to a large amount of replacement with two distinct types of material forming pseudomorphs. At the base of the flow, olivine has been completely replaced by a chloritic material and an opaque substance which occur together in the pseudomorphs and discolor the adjacent groundmass material for short distances (photo J, Pl. II). Polished sections of these pseudomorphs show irregular growths and finely divided grains of opaque material in a chloritic base. The irregularity of the small opaque grains makes their determination difficult but several larger masses show distinct anisotropism in reflected polarized light, indicating that the opaque oxide is ilmenite.

The pseudomorphs after olivine in the central part of the flow consist, primarily, of chloritic material with no opaque inclusions and are associated with isotropic fillings of minute joint cracks which extend through the groundmass and cross all crystalline constituents of the flow.

Occasional ilmenite pseudomorphs after olivine occur in the central part of the flow. These pseudomorphs (photo I, Pl. II) are marked by thin halo-like rims of plagioclase of groundmass composition and have only slight amounts of chloritic material associated with them. Unlike the pseudomorphs that mark the basal phase of the flow, the chlorite here crosses the opaque material as joint fillings thus indicating their later formation.

The pseudomorphs after olivine at the upper surface of the flow consist of both ilmenite and chlorite replacements. Both occur as distinct pseudomorphs and, when associated as replacements in glomeroporphyritic groups, the ilmenite in many cases is surrounded by chlorite showing that the chlorite pseudomorphs were of later formation.

The pseudomorphic ilmenite is invariably associated with apatite although the proportional amounts of each vary considerably. Occasional prismatic crystals of apatite occur in the groundmass and are surrounded by a fluidal arrangement of groundmass plagioclase. Their relationship to the plagioclase indicates their earlier formation and is comparable to that of the euhedral prismatic crystals of enstatite (compare photos D, E, Pl. IV with photo I, Pl. III). Apatite and ilmenite are also found as joint fillings in the larger plagioclase phenocrysts (photo A, Pl. IV) and as replacements along joint cracks in augite of the smaller phenocrysts (photo B, P_1. IV). Thus they must have been formed later than the phenocrysts.

Chlorite which surrounds the ilmenite-apatite pseudomorphs after olivine at the base maintains a much later relationship to the crystalline constituents of the flow. It is associated with joint fillings of deep-red isotropic material which cross all crystalline phases of the flow. This material is often associated with irregular interstitial masses in which two sub-types may be distinguished; (1) an orange isotropic material associated with small amounts of magnetite (photo I, Pl. IV) and (2) a light green material associated with a larger amount of magnetite (photo K, Pl. IV) and having spherulitic extinction (photo L, Pl. IV). Both main types of this material show similar index of refraction values ranging from n=1.52 to n=1.54. They are commonly found within the same large masses which have two modes of occurrence; (1) localization within the interstitial tachylytic residuum, and (2) cavity fillings in plagioclase crystals which are connected with the deep red joint veinlets. All types show identical physical properties with chlorophaeite described by Peacock and Fuller,[1] which has an approximate chemical composition of $(Fe, Al)_2O_3 \cdot 2(Mg, Fe, Ca)O \cdot 4SiO_2 10H_2O$, corresponding roughly to highly hydrated augite.

The chloritic pseudomorphs in the upper parts of the flow are present only where veinlets of chlorophaeite cross an olivine crystal. At the base, there was no such localization of the replacement action but the crystals evidently were attacked all along their peripheries.

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[1] Peacock, M. A., and Fuller, R. E., Chlorophaeite, sideromelane and palagonite from the Columbia River Plateau: Amer. Min., vol. 13, p. 364, 1928.

Chemical Analyses

The relation between the distribution of minerals and the chemical composition of the flow was studied by means of three chemical analyses. Analyses 1, 2, and 3, listed in Table II were made from specimens collected respectively from depths of 147 feet (the nearly holocrystalline base), 75 feet, and 3 feet. Table II shows the norms which were computed from the analyses by the C. I. P. W. method. In addition, three other analyses are given for the purpose of comparison.

Table II

Analyses and norms of the Table Rock Flow and related rocks

Column	Bottom 1	Center 2	Top 3	4	5	6
SiO_2	57.00	56.60	56.90	49.30	59.3	57.47
Al_2O_3	16.89	16.93	16.79	14.1	16.6	14.95
Fe_2O_3	4.31	2.03	2.86	3.4	3.1	2.05
FeO	3.64	5.76	4.89	9.9	3.5	7.18
MgO	2.24	2.61	2.42	6.4	3.4	2.74
CaO	5.70	5.60	5.50	9.7	6.3	6.63
Na_2O	4.71	4.60	4.37	2.9	3.6	3.45
K_2O	2.13	2.27	2.06	1.0	1.9	2.15
H_2O	0.80	1.20	1.60	nil	1.3	0.55
H_2O-	0.60	0.60	0.80	nil	nil	0.45
CO_2	nil	nil	nil	nil	nil	nil
TiO_2	1.25	1.27	1.30	2.6	0.7	1.60
P_2O_5	0.30	0.34	0.43	0.5	0.2	0.32
MnO	0.27	0.25	0.20	0.2	0.1	0.12
	99.84	100.06	100.12			99.66

Norms			
Q	3.13	4.51	8.56
or	11.26	13.09	12.10
ab	38.27	40.13	38.35
an	17.15	18.16	19.72
di	12.03	7.32	4.66
en	10.69		
hyp		12.74	12.19
il	1.92	1.96	2.19
he	0.06		
mt	4.99	1.62	1.50
ap	0.25	0.50	0.82
	99.75	99.58	100.09

References for numbered columns

1. Table Rock, Ore., at depth of 147 feet. W. H. Herdsman, analyst.
2. Table Rock, Ore., at depth of 75 feet. W. H. Herdsman, analyst.
3. Table Rock, Ore., at depth of 3 feet. W. H. Herdsman, analyst.
4. Average plateau basalt (Daly, R. A., 1925)
5. Mean of 20 analyses of hypersthene and augite andesite (Osann-Rosenbusch, 1923).
6. Black labradorite andesite. McNeil Creek, Jackson County, Oregon. J. G. Fairchild, analyst. (Callaghan).

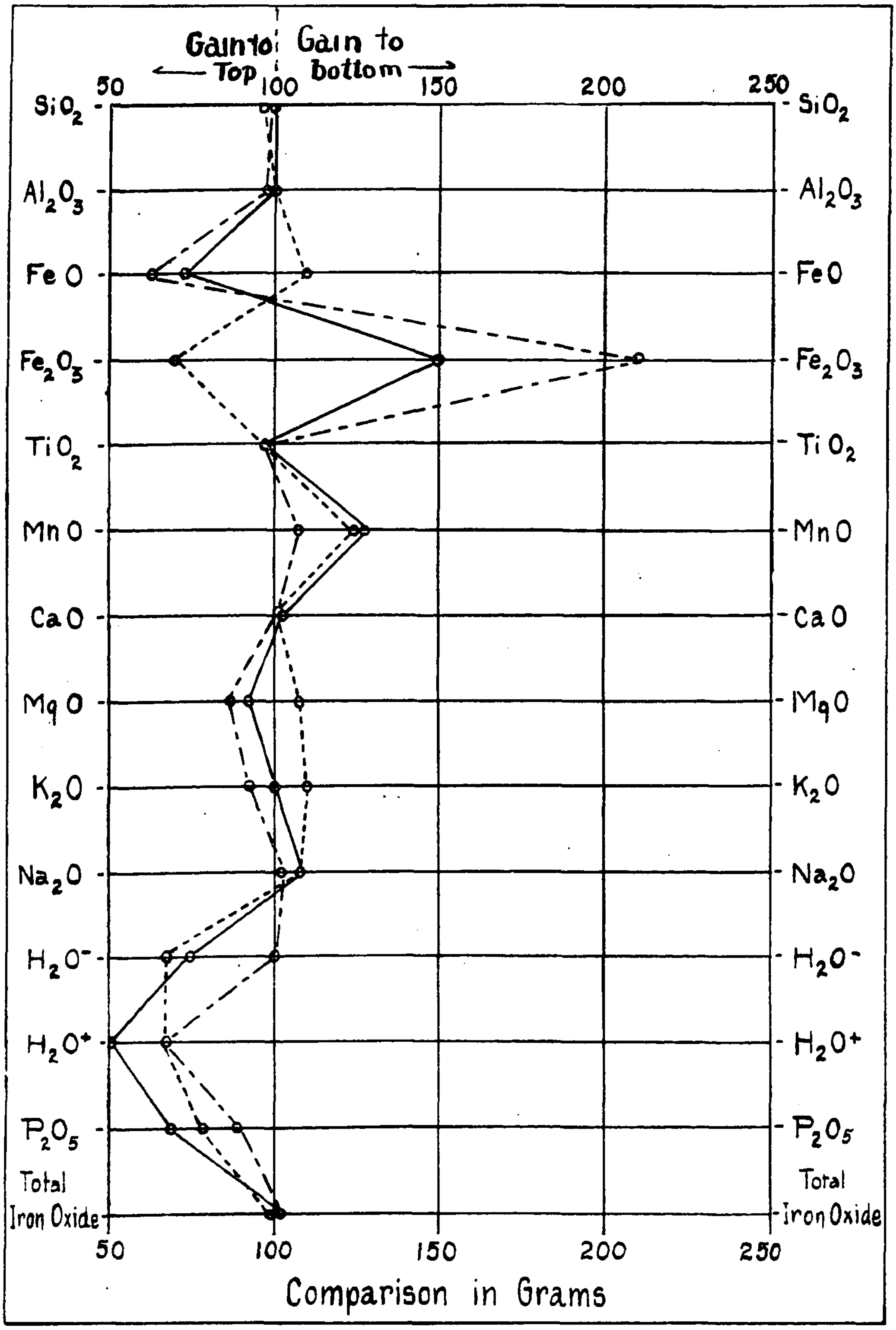

Figure 4 - Gains and losses in the analyzed constituents of the base, center and upper surface of the Table Rock Flow.

Curve A - Top to bottom o———o———o

Curve B - Center to bottom o– – –o– – –o

Curve C - Top to Center o- - - -o- - - -o

Gains and losses in the analyzed constituents of the flow are shown graphically in Figure 4. The points were constructed after the method of Leith and Mead.[1]

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[1] Leith, C. K., and Mead, W. J., Metamorphic geology, p. 288, New York, 1915.

Each individual constituent of the analysis from the base of the flow was divided by the same constituents of the analyses from the central and upper parts of the flow. The resulting quotient was multiplied by 100 for computing parts per 100 grams. In like manner, the gains and losses between the analysis of the upper surface and that of the central portion is recorded. Since there is only a slight variation in the percentage of SiO_2 and Al_2O_3 in the three analyses, their percentage may be assumed to be constant and the gains and losses of the other constituents may be interpreted with reference to them. Gains toward the bottom of the flow are figured to the right of the 100 gram line and gains toward the top to the left of it. Curve A presents the gains and losses in grains per 100 of the analysis from the base of the flow over the analysis from the upper surface. Curve B shows the same relation between the basal analysis and the analysis of the central part. In like manner, Curve C gives the relation of the oxides of the central part of the flow to those of the upper surface.

Using Fe_2O_3 as an example, it may be seen by an examination of these curves that 100 grams of rock from the base supplies as much Fe_2O_3 as 210 grams of rock from the central part, or 150 grams from the upper surface. The loss of Fe_2O_3 between the upper surface and the central part of the flow is shown in Curve C. Seventy grams of the rock from the upper surface evidently yield as much Fe_2O_3 as 100 grams from the center of the flow.

The percentage of SiO_2, Al_2O_3, TiO_2, CaO, Na_2O, and total iron oxide (Fe_2O_3 : FeO) remains remarkably constant in view of the irregularities noted in the percentage of other constituents. TiO_2 shows a gain of only four parts in 100 from the base to the upper surface while CaO and Na_2O both show slight losses in that direction.

The most notable irregularities are in the oxides of iron. Ferrous oxide increases rapidly from the base to the center, and shows slight losses from the center to the upper surface. Ferric oxide is concentrated at the base, and shows only a slight gain between the central zone and upper surface. MgO and K_2O both show gains at the center over both margins while the small amount of MnO steadily decreases in amount from the base to the upper surface. Both H_2O (-110°) and H_2O (+110°) present notable gains toward the upper surface.

The computation of the norms from the analyses (Table II) does not give a true mineralogical picture of the rock. No free quartz was noticed in a microscopic examination of the thin sections, and the olivine noted microscopically did not appear in the norms. However, the general relations are shown with some degree of accuracy, and are supported by microscopical evidence. The difficulties presented in use of the norms of this flow have been set forth and explained by Fenner.

> "The originators of the C. I. P. W. classification, in devising the system, found it necessary to make certain simplifying assumptions in calculating the norm. It would be practically impossible to take account accurately of the great complexity of some of the natural minerals. In the calculation, all of the Fe_2O_3 present is attributed to magnetite, and an equal molecular amount of FeO is assigned to it. At a matter of fact, however, much of the Fe_2O_3 seems to be dissolved in pyroxene crystals as an independent substance, and the equivalent FeO is actually combined with SiO_2. In this way, free silica of the norm is lessened or disappears in the mode. Pyroxenes also contain titanium, alkalies, and other substance of which the actual form of combination is doubtful, so that results arrived at by following the rules for calculation of the norm should be regarded only as a useful approximation to the modal composition, and not as a basis for theoretical conclusions unless supported by the evidence of the rocks themselves."[1]

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[1] Fenner, C. N., Crystallization of basalts: Amer. Jour. Sci., vol. XVIII, p. 241, 1929.

The irregularities in the norm are also reflected in the mode which indicates that the rock is neither a true basalt nor a true andesite. The groundmass is of andesitic composition and the porphyritic elements are of a true basaltic nature. Callaghan[1] used the term laboradorite-

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[1] Callaghan, Eugene, Some features of the volcanic sequence in the Cascade Range in Oregon: Trans. Geophys. Union, 14th An. Meeting, pp. 245-246, 1933.

andesite to show the irregularity in mineralogical composition of his "black lavas". The term andesite-basalt, however, is thought to be more definite in its implication of the mineralogical and chemical composition of this flow.

The capping material of Table Rock has been referred to by both Diller[1] and Powers[2] as a basalt. This microscopic study shows that the dark color of the rock is due to a dark glass base and is not the result of a large percentage of ferromagnesian minerals as would be expected in a basalt. The chemical analyses of the rock show that it cannot be satisfactorily placed in any established grouping. An interesting comparison may be drawn between the three analyses of this rock and the mean analysis of plateau basalts (column 4, Table II) and the mean hypersthene and augite andesites (column 5). It may be readily seen that the analyses of this flow more closely approach those of the andesites than of the basalts.

The analysis of the black labradorite andesite (column 6, Table II) described by Callaghan as representative of the "black lavas" which form the base of the succession in most parts of the western Cascades, correlates very favorably with the analyses of this flow. Moreover, a very close megascopic and microscopic comparison may be drawn

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[1] Diller, Op. cit.

[2] Powers, op. cit.

between the two. The following excerpt is taken from Callaghan's description of the "black lavas".

> "The lavas that form the base of the succession in most parts of the Western Cascades are characterized by their prevailing black appearance, and by their occurrence as flows that have great lateral extent as compared to their thickness, and therefore present a distinctly bedded appearance. In many respects they closely resemble the Columbia River basalt and are generally called basalts, though chemical and microscopic study indicates that probably few of the lavas (presented in this discussion in column 8, Table III) shows that SiO_2 is high and the content of CaO and iron oxides approaches those in ordinary andesite. (It has been found necessary to distinguish between andesites and basalts on the basis of proportion of ferromagnesian to feldspathic constituents rather than kind of plagioclase because of the relatively high CaO content of the plagioclase and large proportion of SiO_2)...Under the microscope this black lava shows phenocrysts of labradorite, augite, and magnetite together with small grains of the same minerals in a brown glass base. It is the glass, and not a predominance of ferromagnesian constituents, that makes the rock black. Olivine crystals are not abundant though pseudomorphs occur in a number of flows examined."[1]

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[1] Callaghan, op cit., p. 245.

The marked mineralogical similarity and the distinct chemical analogy between the "black lavas" and the Table Rock flow are striking and warrant more detailed investigation concerning the exact age of the flow. It seems logical to make correlations between flows on a chemical and microscopic basis. If so, this flow by its close affinity to the black lavas, which underlie the Columbia River basalt series, is much older than either the Recent age determination by Powers or the Late Tertiary age of Diller.

Interpretation of Microscopic and Chemical Data

The initial crystallization stage

Time of separation:

The presence of phenocrysts is an accepted indication of pre-extrusion crystallization and the best evidence concerning the nature of that intratelluric environment is based upon the zoning of the plagioclase phenocrysts. Therefore, the association of intratelluric phenocrysts of plagioclase, olivine, and magnetite is important in the flow history only as their presence affected the separation of post-extrusion generations of crystallization. A knowledge of the sequence of events from the initial intratelluric crystallization to the final solidification of the flow is therefore necessary for an interpretation of the microscopic and chemical character of the rock.

Zoning of the plagioclases undoubtedly must have taken place during a period before extrusion because (1) zoning is indicative of a slowly changing set of environmental conditions, and (2) fractures, which are definitely associated with post-extrusion phenomena, cross the zones of the crystals. However, the interpretation of the exact nature of the intratelluric environment as shown by the zoning of the plagioclases is complicated by the presence of different types of zoning in the flow, each of which has heretofore been explained as indicative of an entirely different set of conditions.

Two main recognized types of zoning are progressive, and oscillatory. Fenner[1] gives a good resume of the microscopic characteristics of both types. Progressive zoning occurs under conditions of unidirectional change in the melt and is characterized by the absence of boundaries to successive zones as shown by a sweeping extinction from core to periphery when viewed with crossed nicols as the stage is rotated. In oscillatory zoned crystals there are repeated alternations from more calcic to more sodic bands with a trend toward a sodic composition. Fenner explains oscillatory zoning with three alternative hypotheses. First, they represent the effects of successive accessions of the original magma into a reservoir in which differentiation had changed the original composition in a certain direction or, second, settling of formed crystals into more calcic portions of the magma with subsequent movement into more sodic layers, or, third, a change in form and composition of the liquid by escape of volatiles during an eruption of the overlying magma.

Both types of zoning are found in the Table Rock flow, and, in addition, a subdivision of each type has been

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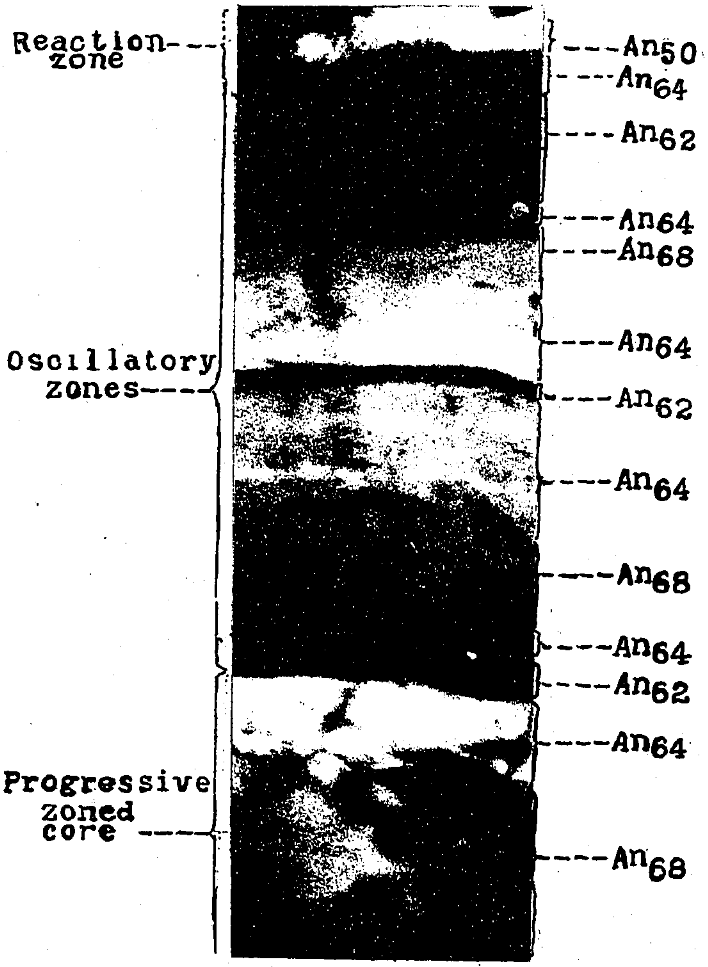
[1] Fenner, C. N., The Katmai province: Jour. Geol., vol. 34, pp. 700-703, 1926.

noted. Certain crystals show a series of bands which surround a progressively zoned core and which become successively more sodic toward the circumference of the crystal. This type obviously represents a subdivision of normal progressive zoning in which the normal progress of deposition was halted for short periods without affecting the trend of crystallization of the melt.

The most common type of plagioclase zoning present in the flow is a variety of oscillatory zonation in which there are gradual fluctuations between An_{68} and An_{62}. These alternations, each a gradual progression to the most sodic layer (An_{62}) followed by a gradual reversal back to the most calcic (An_{68}) layer, cannot be explained by either of Fenner's interpretations. It is not uncommon to find as many as four complete reversals. Table III shows characteristic oscillations of a typical zoned crystal viewed with crossed nicols. The reversal is marked by a grey band which corresponds to the composition (An_{68}) of the central portion of the progressively zoned core, and by a dark band which marks the most sodic (An_{62}) composition. The gradations always become more calcic both inward and outward from this dark zone.

Table III

Oscillations in a Typical Zoned Crystal



All four of these types of zoned crystals may be found in the same slide. Hence, all of the crystals must have been formed in the same environment and at any given instant during the crystallization of the magma plagioclase varying between An_{68} and An_{62} was being deposited. Obviously this condition cannot be explained by the accepted laws of physical chemistry which state that at any given temperature a solid with a certain definite ratio of albite to anorthite will be precipitated from a solution containing those ingredients and that with a decrease in temperature, other conditions remaining constant, successively albitic precipitations will occur. Other factors must temper these laws. This work suggests that there may have been a continuous reaction relation between crystal and melt which was interrupted in an orderly fashion by gravitative movement of the formed crystal.

Since the analyses of the flow show conclusively that the extrusion is not a typical basalt, and since the phenocrysts are of a very basic basaltic association, the rock must represent a mixing of formed crystals of a basaltic magma with a more acidic fluid. Mixing of two magmas has been described in several cases, recently by Holmes and Harwood.[1] Fenner in his work on the Katmai province indicates that mixing of magmas is a large factor in the formation of volcanic rocks.

> "Likewise, if a volcanic eruption furnishes us a sample of rock in which intratelluric phenocrysts have developed, but which has been subject to other differentiative influences (not only volatilization but assimilation, mixing of magmas, and possibly unknown processes) we are not justified in saying that

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[1] Holmes, A., and Harwood, H. F., The tholeiite dikes of the north of England: Min. Mag., vol. 22, pp. 1-52, 1929.

> a trend of the residual liquid toward a granitic or other composition is the result of crystallization alone."[1]

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[1] Fenner, C. N., The Katmai magmatic province: Jour. Geol., vol. 34, p. 755, 1926.

There are no phenomena present in the Table Rock flow to indicate a method by which the crystals were mixed with their present melt.

Post-extrusion effects of the intratelluric phenocrysts

Resorption of plagioclase:

A lack of equilibrium between crystals and melt is indicated by a large amount of resorption of the phenocrysts, most of which is localized along fracture lines found only in the basic phenocrysts. Since the fracture lines cross all the zones and in some instances completely separate crystals, fracturing must have taken place at the time of extrusion of the mass before the separation of the second generation phenocrysts.

The resorption of the plagioclases by the melt is most marked in general in the central, more basic portions of the crystals which were reached by fracture conduits. In some instances, the activity was strong enough to stope out cavities, more or less completely honeycombing the cores, as shown in Plate A (an enlargement of photo C, Pl. II).

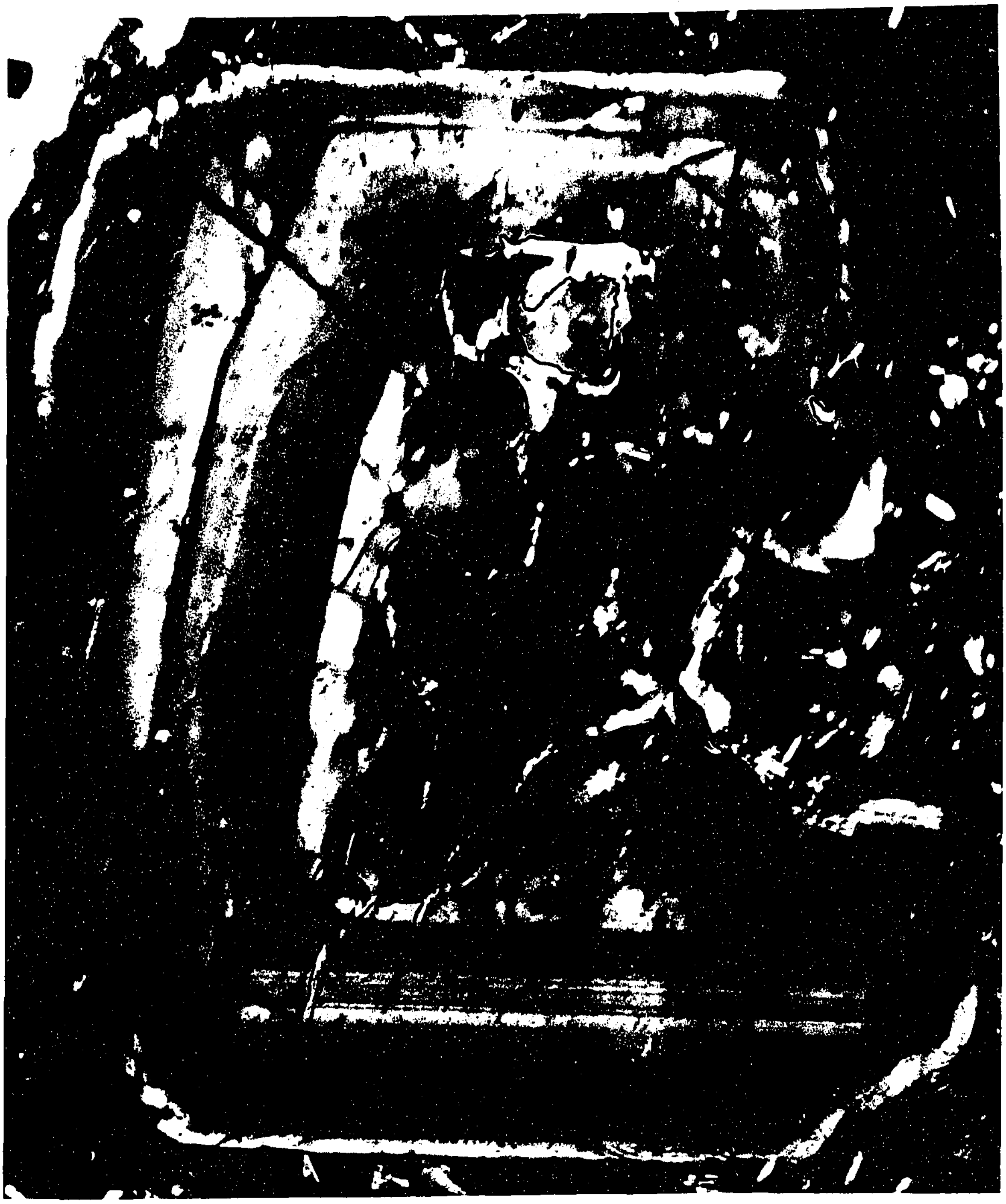

PLATE A

Highly resorbed plagioclase phenocryst with a progressively zoned core surrounded by oscillatory zones. A reaction zone completely surrounds the periphery of the fractured crystal and forms a lining to the resorption cavity. Note augite granules at contact of peripheral reaction zone and crystal.
X 250

It appears that the major portion of the fluid entered along fracture planes which cross the crystal diagonally from the corners and its activity was localized at the center in the large resorptive cavity now filled with partially crystallized glass. The crystal was also broken completely across and the irregular tongues of resorption channels may be seen on the basic margin. There is no visible connection between the central cavities and the corrosion channels on the periphery of the crystal. Further proof of the relation of fracture to resorption is offered in photograph E, Plate II, which shows a thin line of partially crystalline glass localized along a definite fracture plane.

At the upper surface of the flow, the resorption activity was confined to formation of cavities in the crystals. At the center of the flow the activity was strong enough to completely separate crystals into small fragments, after which the reaction progressed outward from the core leaving only the more acidic zones as shells or husks of the original crystals (photo H, Pl. II).

Reaction zones:

Throughout the flow the effect of a reaction between the peripheral zones and the melt is shown by a thin exterior zone which completely surrounds the resorbed and fractured surfaces of the crystal. The zone has its greatest width where it comes in contact with the most basic part of the fractured crystal (Plate A). Fine augite grains commonly mark the contact between the crystal and the zone surrounding it, suggesting that the basic plagioclase furnished some of the CaO for augite. This zone was formed after fracturing of the crystals as is indicated by the presence of very faint traces of the zones along the borders of the fracture and complete linings to the resorption cavities (photo E, Pl. II).

Approximately forty crystals were examined for the determination of the correct composition of the exterior zones. In all crystals where the orientation could be definitely established, the zone proved to have a composition of An_{50} at the contact with the crystal and a somewhat more acid composition, approximately An_{40}, at its contact with the groundmass. The break in composition is very gradual and is shown by progressively smaller extinction angles. Linings of resorption cavities, however, proved to have a composition of An_{50} without zonation.

The exterior zone at the contact has none of the characteristics of normal additive zonation but appears to be the result of a change in composition of the crystal due to the penetration of the fluid. The contact between the outside zone and the crystal is not sharp. Corners of crystals commonly are entirely replaced by the exterior zone (photo B, Pl. II) while long flat surfaces are outlined by thin zones only.

Photograph F, Plate II, shows a lining of a resorption cavity which is similar in appearance to the exterior zone of the crystals. The melt which entered the cavity evidently attacked the crystal along jagged, tongue-like prongs between which the lining has its greatest thickness. Two orientations are found in the projections of the glass into the crystal; (1) parallel to the long dimension of the cavity and (2) parallel to its short dimension and at right angles to the long dimentsion. This suggests that the glass followed lines of weakness in the crystal. If the zone had been deposited by the melt after the formation of the crystal, it would have filled these irregular projections. The contact between crystal and zone would then have been irregular and that between the zone and the glass would have been smooth. On the contrary, however, it is the contact between crystal and zone that is smooth while that between glass and zone is irregular. Evidently therefore the zone must have been formed contemporaneously with the formation of the cavity by reaction between the crystal and the melt.

The irregular internal contact of the lining with the glass filling the cavities indicates that the replacement of calcic plagioclase by more sodic plagioclase was a result of the reaction which kept pace with the attack of the crystal by the melt. The extent of the reaction depended upon the amount of the melt which could enter the cavity.

Many crystals show the effect of the attack in a large number of small centers which give a "honeycombed" appearance to the crystals. When viewed with crossed nicols (photo B, Pl. II), the crystals invariably have a very mottled appearance with extinction moving outward from the numerous glassy centers. This effect is best developed in progressively zoned crystals.

The lining of the cavities is definitely not due to mere filling but is a result of a reaction between crystal and groundmass fluid which replaced calcic plagioclase with less calcic plagioclase. It represents the effects of an abrupt change in the chemical environment of the initially crystallized plagioclase and a subsequent reaction between these basic crystals and the more acid melt in an effort to reach a state of equilibrium. It is designated here as a reaction zone.

The reaction zones are best developed in closed cavities where there was a penetration of the fluid having little interchange with the main mass of the extrusive. The association of small augite crystals and magnetite cubes in the glass filling of the cavity with the plagioclase lining of it is identical to the mineral association of the smaller phenocrysts.

Bowen[1] has described the replacement of plagioclase

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[1] Bowen, N. L., The problem of anorthosites: Jour. Geol., vol. XXV, pp. 221-222, 1917.

by microcline in anorthosites, a phenomenon which resulted in the formation of rims which are comparable to these reaction zones. The writer has noted no other reference in the literature concerning like phenomena.

Relation of resorption and gravitative settling to mineral distribution

Plagioclase:

Curve A, figure 1, shows two major areas of concentration at depths of 30 and 138 feet. The chilled upper surface gives the approximate average percentage of plagioclase included in the flow at time of extrusion, and the areas of concentration must, therefore, have resulted from a gravitative settling of the crystals toward the base of the flow. Crystal settling kept pace with the solidification of the flow in such a manner that the highest percentages of plagioclase were localized in a zone between 114 and 140 foot depths. The true nature of the curve is somewhat obscured by the large amount of assimilation of the plagioclases in the center of the flow where many "husks" or shells of crystals and highly resorbed fragments give evidence of a higher degree of initial resorption. If the resorbed fragments of plagioclase are considered as whole crystals, their curve would show an almost uniform increase from the area of concentration at the 30 foot depth to the one at a depth of 138 feet.

Olivine:

Olivine is the only other mineral included within the flow which gives evidence of post-extrusion differentiation by the character of its percentage variation curves. The general trend of its curve (curve B, fig. 1) is not dissimilar to that of the plagioclase.

Olivine occurs both as glomeroporphyritic groups and as individual crystals. The former (photo D, Pl. II) are found only in the glassy upper margin of the flow and consist of relatively unaltered crystals evidently trapped by the more sudden chilling of the melt at the upper surface. A relative scarcity of individual crystals in this chilled upper part of the flow, the localization of the heavier groups, and a general lack of resorption indicate that upon extrusion of the flow olivine was aggregated in groups. Lower in the flow, however, where the crystal groups were not protected from alteration or resorption by sudden chilling, a reaction with the melt separated them into individual crystals and assimilated large amounts of olivine.

Crystal settling, as indicated by the number of pseudomorphs and highly resorbed fragments of olivine was an active factor but its effects were obscured by a very large amount of assimilation in the lower, more fluid, parts of the flow. The olivine crystals in the area of concentration at a depth of 120 feet are surrounded by thin reaction rims of an indeterminable pyroxene (photo G, Pl. II) which evidently protected them from assimilation. There are many examples of euhedral augite crystals surrounding highly resorbed fragments of olivine (photos E, F, Pl. II) and it is thought that the thin reaction rims may also be augite.

The direct relation between the assimilation of olivine and the formation of rims of augite is therefore comparable to the similar relationship in the formation of the reaction zones on the plagioclase crystals.

Relation of rate of cooling to the distribution of the larger phenocrysts

At the upper surface the high percentage of olivine and relatively low one of plagioclase denote a comparatively sudden decrease in temperature with rapid increase in viscosity which prevented their differential settling. Lower in the flow, however, in an area between 12 and 30 feet, there is a marked concentration of plagioclase and a rapid decrease in the percentage of olivine indicating that after the initial chilling of the upper surface the decrease in temperature, through radiation of heat, was gradual enough to permit differential settling of the intratelluric phenocrysts in proportion to their density. The increasing amount of resorption, coincident with the differential movement of the crystals, indicates a degree of fluidity which would permit a freedom of interchange of material between minerals and the reacting melt that was not possible within the highly viscous upper margin. Therefore, the rate of heat loss as reflected in the fluidity of the flow must have been increasingly less pronounced with depth.

The percentage variation of figures 1, 2, and 3 indicate that heast loss was most rapid from the upper surface of the flow. It progressed at a slightly greater rate of speed than did the process of crystal settling and overtook that process before it had reached completion. The lower limit of the concentration by settling of the intratelluric crystals at the 140 foot level delimits the depth to which radiation from the upper surface of the flow was effective. In the central zone a slow loss of heat and a relatively high fluidity is shown by the more complete resorption of the intratelluric crystals which masks the true effects of gravitative movement.

It is concluded, therefore, that differential settling and the assimilation of the intratelluric crystal phases were dependent upon an initial high degree of fluidity of the extrusive melt. The processes were inhibited, primiarly, from reaching completion by the rapid loss of heat from the upper surface. The initial high fluidity of the flow must indicate a high temperature of the mass at the time of extrusion since there is a general lack of evidence to indicate that the mineralizers present within the flow could have maintained high fluidity at low temperature.

The Intermediate Crystallization Stage

Crystallization:

All microscopic phenomena indicate that the second generation of crystallization was formed at a stage when the flow was still mobile but viscosity was high enough to check crystal sorting by gravitative processes. Although the plagioclases have a definite alignment with their long axes parallel to the movement within the flow, they do not show the subsequent rearrangement which marks the more tabular crystals of the intratelluric plagioclase. Augite has no marked areas of concentration and since it occurs intergrown with plagioclase, it shows no evidence of gravitative movement.

The evidence gained from microscopic phenomena is substantiated by a general quantitative relation between the second and the first generation minerals throughout the flow (compare figs. 1 and 2). There is a maximum concentration of second generation minerals in those parts of the flow where a maximum of reaction between the intratelluric minerals and the melt occurred. At the center of the flow, where a maximum of resorption was noted on intratelluric plagioclase, where is the highest percentage of second generation plagioclase. At the upper surface where there was only a small amount of reaction, a smaller percentage of second generation crystals is found. Augite reaches its maximum percentage near the base of the flow where a high degree of assimilation of the olivine crystals was observed.

The definite quantitative relation between the intermediate stage of crystallization and resorption of the intratelluric crystals is reflected in the mineralogic changes brought about in the melt. The separation of an association of minerals, plagioclase An_{50}, augite, and magnetite, from the melt in restricted resorption cavities (discussed under the formation of reaction zones) is identical to that which makes up the second generation phenocrysts. The formation of augite granules at the contact of the reaction zone and the periphery of large plagioclase phenocrysts denotes a change in the character of the pyroxene molecule in localized positions.

The separation of augite rather than the normal groundmass pyroxene, enstatite, involved the addition of CaO and Al_2O_3 to the melt. It is believed that the assimilation of the basic plagioclases supplied these oxides and that their loss from the plagioclase is reflected in the formation of the reaction zones (An_{50}). A reaction between olivine and the melt resulted in the formation of augite reaction rims around olivine. In this reaction the CaO and Al_2O_3 necessary for the formation of augite must have been taken directly from the melt.

Time of separation of the intermediate stage:

At the time of extrusion fluidity must have been high as is indicated by the freedom of molecular interchange in the reaction of crystals and melt and by gravitative settling. When the second generation crystals were formed, fluidity was still relatively high as is shown by the euhedralism and comparatively large size of these crystals. Yet some loss of fluidity prior to their separation is evidenced by lack of differential settling of the smaller phenocrysts. Constant composition and size of the second generation plagioclases indicate their separation throughout the flow under similar conditions.

Zoning of the second generation crystals also points to relatively high fluidity during their formation. The plagioclases have thin peripheral zones which become progressively more sodic and which at the outside have a composition identical to that of groundmass plagioclase (An_{40}). Individual augite crystals commonly show a peripheral zone of enstatite around slightly rounded margins (photo H, Pl. III). This zone is marked by parallel extinction and contains the minute opaque inclusions characteristic of groundmass enstatite.

Since the zones on the plagioclase crystals are very thin and no resorption is apparent, a comparison cannot be drawn between the origins of the reaction rims on the larger and of those of the smaller phenocrysts. However, the slightly rounded outlines of a few individual augite crystals indicates that the enveloping zone of enstatite possibly resulted from a reaction between crystal and melt and perhaps this reaction took place in a manner similar to the one which occurred between phenocrysts and melt at a higher temperature.

The general approach in composition of the second generation to that of the groundmass marks the close of the intermediate stage of crystallization. Individual in cumulophyric groups do not exhibit zoning except where they come in contact with the groundmass. Although the interstitial glass crystallized with the normal groundmass association, apparently it was not present in sufficient quantity to effect reaction. Furthermore, there is no proportional relationship between groundmass glass (figs. 2 and 3) and the smaller phenocrysts. These facts indicate that the second generation crystals were completely formed before the groundmass crystals separated.

The time for separation of the second generation was considerably shorter at the upper surface where rapid chilling occurred than it was lower within the flow. It is believed that the progressive decrease in the Nm value of augite (fig. 2, curve D) and a corresponding increase in the extinction angles with depth, which seems to follow the general cooling curve of the flow, reflect the greater length of time permitted for the development of augite lower in the flow.

The higher index of refraction of augite and its greater extinction angles suggest that it contains a higher percentage of iron oxide at the upper surface. Following the normal order of crystallization of the second generation, magnetite occurs as inclusions in both augite and plagioclase. At the upper surface, however, the small amount of magnetite associated with cumulophyric groups and the almost entire absence of magnetite inclusions within augite crystals indicates that more iron oxide must have been included in the augite here than elsewhere. Throughout the central part of the flow where separation covered a longer time, magnetite occurs in noticeable quantities both as inclusions in augite and as individual crystals (photo D, Pl. III). At the base augite is present in greatest quantity, is relatively free of magnetite, and exhibits its lowest index of refraction. Here the decrease in temperature was relatively slow and magnetite separated comparatively early in reference to augite.

It is evident that plagioclase, augite, and magnetite separated contemporaneously from the melt within a definite temperature range. Plagioclase crystallized with the same albite$_1$-anorthite$_1$ ratio regardless of the rate of temperature decrease. Iron oxide separated as magnetite but was incorporated with and increased the indices value of augite where crystallization proceeded very rapidly. The relation between the indices of augite and the crystallinity of a flow has been noted also by Lund in a study of a thick basalt flow. His results substantiate, in some respects, the general applicability of the above conclusions.

> "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 (on crystallization of the flow). They both indicate a general decrease in tenor of iron from the margins toward the middle of the flow, except for the chilled borders."[1]

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[1] Lund, R. J., Differentiation in the Cape Spencer flow: Amer. Min., vol. 15, p. 562, 1930.

The Final Crystallization Stage - The Groundmass

The groundmass, averaging 60 to 65 per cent of the rock, is the most significant part of the flow from both a chemical and physical viewpoint since it gives much evidence which has a bearing on the order of crystallization of the minerals, the factors controlling their crystallization, and the general trends of that crystallization.

Order of Crystallization:

The order of crystallization within the groundmass is best indicated by the percentage variation curves of its individual minerals with depth. Attention should be directed to the fact that fluctuations in the total percentage of groundmass constituents may, in part at least, result from local concentrations of the porphyritic elements. For instance, toward the base of the flow, a higher percentage of intratelluric plagioclase lowers the total percentage of the groundmass constituents.

The percentage of enstatite (curve C, fig. 3) is practically constant throughout the flow regardless of the amount of glass present. Its constant percentage and euhedral form denote an early crystallization and an almost complete separation of the mineral from the melt.

Plagioclase (curve B, fig. 3) occurring in skeletal crystals, varies almost inversely with the percentage of glass. At the more nearly holocrystalline basal portion, there is a very high percentage of plagioclase and a low percentage of glass. From a depth of 110 feet to the upper surface there is a gradual decrease of plagioclase and a corresponding increase in the percentage of glass. Plagioclase with its incomplete form and wide variance in percentage throughout the flow must be of late separation from the melt.

Magnetite (curve D, fig. 3) also varies inversely with the percentage of glass, and it crystallizes through a wider range than any other mineral of the groundmass. The greater proportion of the magnetite appears as a separate from the last residuum of glass and occupies the interstices of the plagioclase at the base of the flow (photo D, Pl. I). In any one part of the flow, there is less than one per cent of the earlier magnetite which occurs as definite octahedra and as inclusions in enstatite crystals.

Factors controlling groundmass crystallization:

Rate of cooling and mineralizers:

The primary control of the crystallinity of the melt under surface conditions of temperature and pressure would have been the rate of cooling of the mass. Fenner[1] has shown that sudden chilling promotes a great increase in viscosity, checks crystallization processes, and produces glass. Mineralizers in the flow, however, tend to promote a higher degree of fluidity, increase the crystallinity and decrease the effects of heat radiation.

Under normal circumstances where radiation is equally effective from both margins of the mass, the rate of cooling is as the square of the distance from the margins of

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[1] Fenner, C. N., The crystallization of a basaltic magma from the standpoint of physical chemistry: Amer. Jour. Sci., vol. 29, p. 219, 1910.

the sheet, and the average area of augite, in cross-section, is proportional to the square of the distance from the margins.[1] That these ideal conditions may be altered by the presence of mineralizing solutions is well shown by Emmons.[2]

Since the groundmass constituents of the Table Rock flow maintain identical physical and chemical properties throughout the flow, their progressive increase in percentage toward the base must be indicative of a progressively slower rate of cooling. The localization of the most holocrystalline part of the flow near the base indicates either (1) a much slower rate of cooling at the base, or (2) a concentration of mineralizers at that position, or (3) a combination of those factors.

The abrupt decrease in the percentage of both the olivine and larger plagioclase phenocrysts below a depth of 140 feet indicates that an initial increase in viscosity (brought about by loss of heat from the base) checked their movement. The higher degree of crystallinity of the groundmass in this area, however, shows that a greater length of time was allowed here for the separation of each mineral than

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[1] Lane, A. C., The grain of rocks: Jour. Geol., vol. 5, pp. 22-23, 1897.

[2] Emmons, R. C., Diabase differentiation: Amer. Jour. Sci., vol. 13, pp. 73-82, 1927.

higher in the flow. This must have been due primarily to a slower rate of cooling combined with a progressively greater concentration of mineralizers which kept the fluidity of the residuum high and thereby also slowed up the rate of cooling. The concentration of mineralizers with depth must have been in itself the result of the more complete separation of the crystalline constituents with depth. Thus the two factors controlling the rate of cooling, the loss of heat and the amount of mineralizers, are interdependent and probably operated after the manner suggested by Washington.[1]

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[1] Washington, H. S., The formation of Aa and Pahoehoe: Amer. Jour. Sci., 5th ser., vol. 6, pp. 409-423, 1923.

> "In the first place, the separation of the crystals, in which gases are not appreciably soluble, increases the gas concentration (and the pressure)within the remaining liquid, thus maintaining a high degree of fluidity and consequent possibility of internal molecular movement, so that crystallization is facilitated."[1]

Washington also lists two other possible factors which have a tendency to increase the fluidity; (1) the latent heat of crystallization and (2) an increase of femic material in the residuum. The effects of latent heat cannot be distinguished microscopically from other factors, and since there is an increase in plagioclase rather than augite in the residuum, the increase of femic material can be of no importance in this flow.

Since vesicular openings are found only at the very upper margin it is assumed that volatile constituents in a free state were lacking at the time of extrusion. If they were present they escaped before they could be trapped in viscous portions of the flow. Since it is only in solution with the melt that mineralizers increase its fluidity, it is concluded that upon extrusion of the mass and immediately preceding any crystallization the mineralizers were in small enough quantities to be kept in solution. However, with the crystallization of the second generation phenocrysts, all the mineralizers could not be contained in solution by pressure and certain small quantities were released.

With the separation of the groundmass stage a larger quantity of volatile constituents was concentrated in the residual glass. At the upper surface they were trapped by chilling while lower in the flow their escape from solution was probably hindered by the pressure of the overlying more viscous mass. Finally, with cooling and contraction of the mass, joints were developed which presented an easy means of escape.

The exact dating and evidence for these two distinct stages of release of mineralizers will be discussed in relation to the separation of magnetite and the two stages of hydrothermal alteration of olivine.

The Early Stage of Hydrothermal Activity; The Ilmenite-Apatite Stage

At the vesicular upper surface occasional ilmenite-apatite pseudomorphs may be traced directly to adjacent vesicles. Lower in the flow, however, where the rate of cooling was slower and the relative fluidity therefore higher, the released solutions escaped upwards and were trapped by the angular irregularities of cumulophyric groups, or by indentations in highly resorbed first generation plagioclase crystals (photo J, Pl. III) where they were redissolved and promoted crystallization. In the groundmass, apatite (photo K, PL. II), the characteristic mineral of this stage, is commonly associated with isolated patches of greater crystallinity. It is also characteristic of these various isolated areas of greater crystallinity that magnetite is of early separation (as definite octahedra).

The exact dating of this release of mineralizers may be done microscopically. The replacement of olivine by ilmenite and apatite indicates alteration later than the formation of the first generation. The association of apatite and ilmenite as fracture fillings in intratelluric plagioclase (photo A, Pl. IV) and in second generation augite (photo B, Pl. IV) denoted release later than the second generation minerals. Apatite, however, also occurs as distinct prisms in the groundmass (photo D, Pl. IV) where it occupies a position similar to that of enstatite, the first mineral to crystallize from the groundmass. It is evident from a study of this later occurrence of apatite that the earlier stage of hydrothermal activity was completed before the entire separation of the groundmass constituents and after the crystallization of the intermediate stage. Since it occurred before the separation of the groundmass, the activity must have been accomplished by the action of solutions set free by the crystallization of the second generation crystals. However, the pseudomorphs of ilmenite after olivine are surrounded by a halo of plagioclase free of enstatite which indicates its crystallization from a melt from which enstatite had crystallized. This may limit the period of complete formation of the pseudomorphs to a period of time between the separation of the second generation crystals and the plagioclase of the groundmass generation.

The presence of large masses of either magnetite or ilmenite in the groundmass evidently exerted an attraction for the plagioclase in the liquid since many octahedra of magnetite of intratelluric origin are also surrounded by a halo of plagioclase (photo K, Pl. I). Frequently these magnetite crystals are highly resorbed and in many cases they have been replaced by apatite (photo C, Pl. IV). In all cases, where halos are present, there is abundant evidence, either in the adjacent groundmass or in the crystal itself, to indicate that the halo was formed in an area where the concentration of mineralizers was relatively high before the separation of the groundmass plagioclase. In pseudomorphs of ilmenite after glomeroporphyritic groups of olivine, the plagioclase halo surrounds only the ilmenite and not the remaining highly resorbed fragments of olivine. At the base of the flow the "halo" of plagioclase around the ilmenite centers of the pseudomorphs is replaced by chloritic masses of the later hydrothermal stage. This continual replacement of olivine by both types of hydrothermal material indicates the slower, more constant and progressive release of gases throughout the complete crystallization history at the base and marks the overlap of the two stages of hydrothermal activity.

There is good evidence of transportation of ilmenite by the mineralizers of the early stage. Small amounts of this mineral are found associated with apatite prisms (photos E, A, Pl. IV) and the general relation of the ilmenite to apatite indicates the earlier separation of ilmenite from the solutions. There is also a slight increase of ilmenite pseudomorphs after olivine toward the upper surface of the flow. This replacement could not have been effected by the transference of material from the base since the upper parts had become viscous enough to prohibit active movement on the part of solutions before crystallization started at the base. Evidently the alteration activity upon the olivine crystals was accomplished by solutions highly charged with ilmenite leached from localized areas and transported for only short distances.

The high percentage of titanium dioxide throught the flow cannot be accounted for as a molecular constituent of olivine crystals since olivine shows no unusual properties. It is thought that the TiO_2 is included with FeO in the glassy residuum and was transported, in large part, by the solutions of the early stage of hydrothermal activity and was precipitated as limenite upon reaction with the olivine crystals.

The Separation of Magnetite

Two occurrences of magnetite have been discussed (P. 19). Since the early stage of magnetite is always associated with hydrothermal minerals, the small cubes may have resulted from the oxidizing effects of the solutions released by the second generation of crystallization. This suggests that the greater portion of iron oxide was concentrated in the late residuum of crystallization as ferrous oxide which, in the presence of an increasingly greater concentration of mineralizers was finally oxidized to magnetite.

The assumption that there was a concentration of ferrous iron in the glass is supported by the chemical analyses which show a general increase in FeO from the base toward the upper surface with a slight concentration at the center. Since the percentage of ferromagnesian crystalline constituents is constant throughout the flow, the FeO must be concentrated in the non-crystalline tachylytic residuum. The decrease in the index of the glas from 1.54 at the upper surface to 1.52 at the base may reflect the decrease in the percentage of FeO as shown chemically. However, George[1] has shown graphically that the presence of iron oxide (presumably Fe_2O_3) raises the index of the glass and his observations may be checked by the fact that the highest index was observed on the glass within the upper 9 foot zone where trichites and frond-like masses of ferric oxide are present. It is believed that the lower index at the base resulted from a higher concentration of mineralizers (in large part H_2O as shown by the analyses). This contention is supported by the results of Tyrell and Peacock[2] showing the decrease in the index value of sideromelane with the addition of water.

The conclusion that iron oxide must have been concentrated as FeO in the glass and then oxidized to magne-

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[1] George, W. O., Physical properties of natural glasses: Jour. Geol., vol. 32, p. 366, 1924.

[2] Tyrell, G. W., and Peacock, M. A., The petrology of Iceland: Trans. Soc. of Edinburgh, vol. LV., pt. I (no. 3), p. 70, 1926.

tite is supported in part by Washington[1] who indicates that ferrous iron dominates over the ferric iron in glassy forms of all effusives, while ferric dominates over ferrous in the holocrystalline forms. He contends that the ferrous iron is kept from oxidation by the general reducing effect of the gases. Butler and Burbank,[2] however, find that oxidation is effected in part at least by the action of gases (dominantly H_2O and CO_2) given off by the lava iteslf. They believe nevertheless that since the greatest amount of oxidation is at the upper surface of the flow, it is effected by gases set free in the early stages of flow history. Obviously the Lake Superior flows with which they were particularly concerned must have contained a much higher content of gaseous constituents than did the Table Rock flow. This difference is shown not only in the chemical analyses where a higher percentage of potential volatiles has been recorded in the Lake Superior flows but also by the enrichment of total Fe at the upper surface of these flows. Butler and Burbank conclude that at sufficiently high temperatures the oxidizing solutions carried iron in solution which was precipitated

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[1] Washington, H. S., Rhyolites of Lipari: Amer. Jour. Sci., vol. 50, pp. 458-461, 1920.

[2] Butler, B. S., and Burbank, W. S., The copper deposits of Michigan: U. S. Geol. Surv. Prof. Pap. 144, p. 45, 1929.

with temperature decrease at the upper margin. The only concentration of total Fe with the Table Rock flow is a very slight one at the central portion. It is definitely associated with late hydrothermal chloritic material as deposits along fractures. Therefore, it must have been carried by later mineralizers set free by the crystallization at the base after the overlying portions of the flow had cooled and fractured enough to allow those solutions easy means of escape.

The Later Stage of Hydrothermal Activity: The Chlorite-Chlorophaeite Stage

The solutions which were active in oxidizing the iron oxide at the base of the flow were also active in transportin the chlorophaeite which is found as joint fillings and may be traced directly to large residual interstitial areas lower in the flow. The solutions attacked olivine along fractures and formed pseudomorphs of chlorite. It has been possible to show the exact relationship of the early and late alteration of olivine by the fact that chlorophaeite may be traced directly across ilmenite pseudomorphs of the early stage. The solutions also had a pronounced resorptive effect upon plagioclase phenocrysts and the effect was commonly localized in cavities filled with chlorophaeite at the center of basic crystals (photos H, J, Pl. IV). These cavities may be distinguished from the cavities formed earlier by the reaction with the melt, first, by the regular shape of the cavities, and, second, by the absence of typical tachylytic glass either in the cavity itself of in the fracture conduits leading to it.

There are many localized patches of all three of the described types of chlorophaeite in the groundmass. They maintain the same relation to the crystalline constituents at the base that residual tachylyte does higher in the flow, and in places phases of the chlorophaeite may be traced into normal tachylyte. It is therefore concluded that the chlorophaeite represents the very end product of crystallization.

The Trend of Crystallization

Microscopic evidence indicates that crystallization progressed in a regular manner from the upper surface to the base of the flow. At the upper surface crystallization was completely finished and the rock solidified while different phases were still separating lower in the flow. The progressive crystallization resulted primarily from slower cooling towards the base which permitted a more complete separation of minerals and a consequent concentration of mineralizers which in turn kept up the fluidity.

There is a greater percentage of groundmass plagioclase at the base and the crystals are here more nearly euhedral, "felted" masses rather than incompletely formed skeletal crystals. Moreover, a somewhat fluidal arrangement of plagioclase and enstatite is found only in the upper part of the flow. These facts give evidence that the upper part of the flow was still mobile when separation of the groundmass constituents occurred there, but lower down crystallization continued to take place after flow movement had ceased.

The most important indication of the progressive crystallization is in the overlap of the two stages of hydrothermal activity at the base of the flow and the filling of joint cracks higher in the flow with the end products of crystallization. It is the most conclusive evidence that chlorophaeite developed only in the very last stages of flow history.

Since chlorophaeite is much more basic than the flow as a whole, it is concluded that there was a progressive enrichment of the residuum in basic constituents rather than in more siliceous material as advocated by the proponents of crystallization-differentiation. In this respect, the Table Rock flow is more in accord with the views of Fenner[1] expressed in an article concerned primarily with residual liquids of crystallizing magmas.

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[1] Fenner, C. N., The residual liquids of crystallizing magmas: Min. Mag., vol. 22, p. 550, 1931.

> "In the basalts that I have studied there seems to be nothing in the present relations of the constituents that indicates the processes suggested by Dr. Bowen and his collaborators to explain the formation of iron-rich residues. So far as may be deduced from the sections the course of crystallization brought about the precipitation of plagioclase, pyroxene, and magnetite almost from the beginning and an uncomplicated continuance of these minerals to the end with magnetite in large amount in the final residue."

The Relation of Crystallization to Chemical Variation

At the time of extrusion, the flow must have had a constant chemical composition throughout since there is no evidence of an unequal mixing of fluid and included intratelluric crystals. Any variation in composition in the flow would be the result of post-extrusive processes active upon the flow. The only two processes noted in this flow which were capable of effecting a chemical variation were the differential settling of the intratelluric crystals and their reaction with the melt, and the upward transfer of material by volatiles at a much later stage. The former process affected successively lower parts of the flow and the latter brought about an increase in certain basic constituents in the upper part. The general relations may be somewhat obscured by the action of both processes on the same constituent, i.e., differential settling of olivine crystals and subsequent hydrothermal activity upon them.

The most obvious concentration resulting from differential settling is the gradual increase of CaO and Na_2O toward the base. Intratelluric plagioclases are the only differentiated crystals which could have supplied the excess of these molecular constituents at the base. This chemical variation checks favorably with the plotted percentage of plagioclase when the inverse relation between the resorption of intratelluric plagioclase and the crystallization of the smaller phenocrysts is considered.

MnO is the only other oxide which shows a steady increase with depth, and therefore must have originally been in combination with olivine. However, the upper surface shows a higher concentration of unaltered olivine crystals than do the other levels from which the other two analyses were taken. MnO must have been set free by the early assimilation of olivine and may have crystallized with augite which gradually increases toward the base and reflects the large amount of assimilation of olivine there.

Al_2O_3 and K_2O are present in slightly greater amounts at the base than at the upper surface of the flow but have a maximum concentration at the center. This condition can be explained by an original concentration of larger plagioclase crystals through gravitative settling after which assimilation released the oxides which were then transported upward by hydrothermal solutions and concentrated at the center of the flow. K_2O offers more difficulties to this interpretation than does Al_2O_3 which was necessary for the composition of chlorophaeite, the late hydrothermal mineraloid. K_2O, however, is not indicated by the composition of the hydrothermal constituents. Moreover, it should be present only in minor amounts in the basic plagioclases since Alling[1] has shown that the percentage of K_2O included in plagioclase feldspar varies inversely with the percentage of lime. It is possible that K_2O is concentrated in the second generation plagioclase with whose percentage variation curve, K_2O nearly coincides. There is no direct microscopic evidence of the presence of K_2O in the flow.

TiO_2, P_2O_5, H_2O (-), and H_2O (+) show an increase toward the upper surface. All of these oxides are definitely connected with hydrothermal activity; TiO_2 and P_2O_5 with the early stage, and H_2O (+) and possibly H_2O (-) with the later stage. It is concluded that their variations result from their upward transportation either as volatiles or through the agency of volaties.

The general increase of MgO and FeO toward the upper margin with maximum concentrations at the center of the flow is not reflected in the distribution of ferromagnesian minerals, augite, olivine, or enstatite. Evidently the excess of oxides is contained in chlorophaeite which occurs throughout the upper portions but has its maximum

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[1] Alling, H. L., Indices of refraction of feldspars: Jour. Geol., vol. 37, p. 473, 1929.

concentration at the central zone.

It is also apparent from a study of the FeO:MgO and total Fe as FeO:MgO ratios in Table IV that the excess of FeO over that of MgO was carried by these late hydrothermal solutions.

Table IV

FeO:MgO Ratio of the Table Rock Flow

	Bottom	Center	Top
FeO	3.64	5.76	4.89
MgO	2.24	2.61	2.42
Ratio FeO:MgO	1.62	2.17	2.02
Total Fe as FeO	7.53	7.59	7.47
Ratio total Fe:MgO	3.37	2.91	3.09
Fe_2O_3	4.31	2.03	2.86
Ratio Fe_2O_3:FeO	1.18	.35	.58

The sharp increase in the FeO:MgO ratio at the center of the flow shows that the late solutions carried more FeO than MgO. The decrease in the total Fe as FeO:MgO ratio at the center indicates an impoverishment of Fe_2O_3 supported by both the chemical composition of the flow and the absence of microscopic indications of magnetite at the center of the flow. The larger amount of Fe_2O_3 at the upper surface rather than at the center is probably the result of surface oxidation in the initial stages of flow history. Since the total Fe as FeO remains remarkably constant and the percentages of FeO and Fe_2O_3 vary in direct proportion to that total and inversely with each other, it is believed that the larger percentage of Fe_2O_3 at the base resulted from more complete oxidation of FeO in the residuum.

It is concluded, therefore, that FeO was the principal oxide of iron present upon extrusion of the mass and that it was in combination with the ferromagnesian minerals and in combination in the glass. Fe_2O_3 was an accessory constituent of the ferromagnesian minerals but occurred mainly as magnetite of different generations of crystallization.

The constancy of silica throughout the flow is very important since it indicates that there was no pronounced concentration of silica in the residuum of crystallization which could be transferred by the movement of volatiles. In fact, the positions of maximum concentration of late hydrothermal material corresponds to the position of least concentration of silica. There is a very slight SiO_2 increase of 0.5 parts per 100 from upper surface to base and a slight decrease of 1 part per 100 at the center over both margins. This enrichment at the base may be due to concentration of initial crystals. However, the variations are so slight that they may be due to errors in the analyses.

General Summary and Conclusions

The microscopic and chemical analyses of the flow permit certain definite conclusions concerning both the character of the mass at time of extrusion and the factors influencing its crystallization.

The extrusive mass, consisting of a mixture of basic crystals, and a more acidic melt, was extruded at a high temperature with a high degree of fluidity and a low gas content. These initial conditions of extrusion permitted a differential settling of the intratelluric crystals and fostered the assimilation of a large amount of the basic material by the melt.

The formation of a thick, highly viscous, upper chilled zone retarded the rate of radiation lower in the flow by destroying any conditions of convection that might have existed between the fluid mass and the atmosphere. With slower cooling a progressive increase in concentration of mineralizers occurred and a higher degree of fluidity was maintained in the center of the flow for a considerably longer period of time than at the margins, and more complete resorption and segregation of the intratelluric minerals was possible. The smaller phenocrysts represent the crystallization of excess basic material derived from the assimilation of intratelluric crystals. Their large size and sub-trachytic arrangement indicate conditions of relatively high fluidity which permitted a freedom of growth not exhibited by later minerals. However, the lack of differential movement of individual crystals denotes much lower fluidity than at the time of extrusion.

Resorption of the larger phenocrysts and reciprocal crystallization of the second generation became progressively more complete with depth as the effects of radiation became gradually less pronounced. With an increase in the crystalline constituents of the melt and a successively longer duration of a temperature range, a concentration of mineralizers was effected which still further retarded viscosity and promoted the crystallization of groundmass enstatite. With increasing crystallization, solutions were released, moved toward the upper zones, and escaped through cooling fractures. This upward movement of hydrothermal solutions effected the replacement of olivine by ilmenite and apatite, and in some instances the mineralizers were redissolved and promoted crystallization in localized areas within the residuum.

The progressive crystallization of the melt is shown in the fluidal arrangement of only the second generation crystals at the base and of both the second generation and the groundmass crystals at the upper surface, which indicates that crystallization of the intermediate stage at the base began at approximately the same time that the plagioclases of the groundmass were crystallizing in the upper parts of the flow. The slower rate of cooling at the base effected almost complete separation of the groundmass plagioclase and thereby increased the relative quantity of mineralizers held in solution there. After separation of this plagioclase the mineralizers were released from solution in sufficient quantities to oxidize the ferrous iron included in the residuum. At the time of the crystallization of the plagioclase at the base, the upper parts of the flow had become completely solidified. The mineralizers which brought about the chloritic replacements of olivine and carried small amounts of magnetite were allowed to escape to the surface through narrow tension cracks in which they deposited relatively large amounts of chlorophaeite.

Crystallization of the melt at a high temperature permitted the separation of the intermediate stage and used up the excess of basic material derived from the assimilation of intratelluric crystals. No further offsetting or fractionation of the liquid took place and with the crystallization of the groundmass, the interstitial residuum was enriched in FeO and MgO and volatiles.

The direct relation between the appearance of magnetite and the release of volatiles from solution is significant in interpreting the different stages of crystallization of magnetite in the flow.

PART II

HYALOPILITIC BASALT

GRAND COULEE, WASHINGTON

HYALOPILITIC BASALT

YAKIMA OR COLUMBIA RIVER BASALT FORMATION

A 16 foot flow was selected for the study of a thin hyalopilitic basalt flow. It is the topmost of a series which make up the eastern cliff face of Grand Coulee at Dry Falls State Park, Washington, and belongs to a series of Miocene flows which were originally included in Russell's "Columbia lava".[1] Smith,[2] in order to differentiate between the distinct periods of intrusion represented in Washington, referred to these Miocene phases of the Columbia lava as the Yakima Basalt. Calkins[3] used this later term as a formational name for the series in Grand Coulee and traced the formation southward from the Okanogan Highlands to Idaho and Oregon. Bretz[4] in a more recent publication refers to the basalt in the general region of Grand Coulee as the Columbia

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[1] Russell, I. C., Reconnaissance in Central Washington: U. S. Geol. Surv., Bull. 108, p. 90, 1893.

[2] Smith, G. O., Geology and water resources of a portion of Yakima County, Wash., U. S. Geol. Surv. Wat. Sup. Pap. 55, p. 15, 1901.

[3] Calkins, F. C., Geology and water resources of a portion of East Central Washington, U. S. Geol. Surv. Wat. Sup. Pap. 118, p. 30, 1905.

[4] Bretz, J. H., The Dalles type of river channel: Jour. Geol., vol. 32, pp. 139-149, 1924.

Basalt Formation and traces it down the Columbia River from Wenatchee in southcentral Washington to Cook, Washington, a distance of 300 miles. Hodge[1] uses the term Columbia River Basalt to distinguish the Miocene basalts from both older and younger formations of the Columbia lavas in Oregon. Although the nomenclature is somewhat confused, it is apparent that the basalts of Grand Coulee have been correlated with the extensive Miocene flows in Oregon, Washington, and Idaho.

General Megascopic Appearance

The rock has a similar megascopic appearance throughout. It is very dense, and aphanitic, and has a silvery-black color in all portions.

The upper three feet are slightly vesicular, individual shot-like vesicles averaging approximately 3 mm. in diameter. Occasional chlorophaeite filled vesicles are commonly found in the central portions of the flow. At the base there are many thin, irregular patches and small dot-like areas of chlorophaeite which impart a yellowish gray color to local areas of the rock.

The only megascopic crystals are a few small grains of equidimensional olivine at the base and a few slightly

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[1] Hodge, E. T., Geological map of north central Oregon, Univ. of Oregon Publication, vol. 1, no. 5, p.4, 1932.

larger, lath-like plagioclase crystals which are scattered throughout the mass.

General Microscopic Appearance

Textural Variation

Microscopically, the rock contains a small quantity of phenocrysts of zoned plagioclase and altered olivine, embedded in a matrix of plagioclase, augite, magnetite and glass. The percentage of glass decreases irregularly from 49% at the upper surface to 4% at the base (curve A, fig. 5). The most holocrystalline phase of the flow, the base, is characterized by a higher percentage of augite and magnetite (curves B, C, fig. 5) and by slightly larger individual crystals than are found at the glassy upper surface. Plagioclase (curve D, fig. 5) maintains an almost constant percentage throughout the flow varying from 30% at the upper surface to 40% at the base while augite varies from 9% at the upper surface to 40% at the base. Magnetite has a concentration in interstitial grains and skeletal crystals which together total 10% at the base while only 1% is visible at the upper surface.

Small quantities of zoned plagioclase crystals and of badly altered olivines make up the porphyritic elements of this extrusive. Olivine (curve E, fig. 5) gradually decreases from 8% at the upper surface to less than 1% at the base.

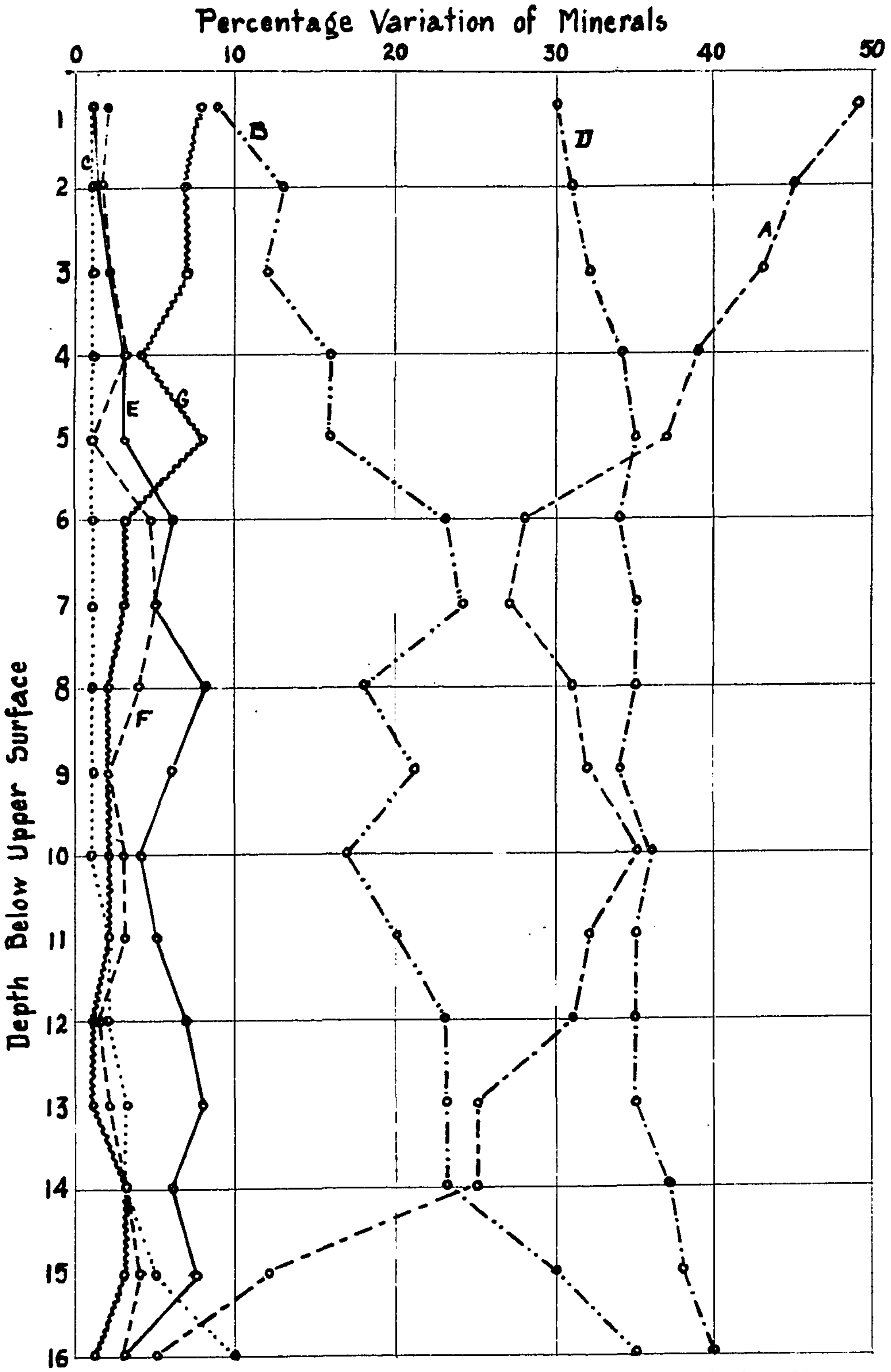

Figure 5 - Percentage Variation of Minerals with Depth in in the Hyalopilitic Flow -

The general curve is broken by a slight concentration of 3% at a point 2 feet above the lower margin. Plagioclase phenocrysts have a very irregular distribution but show a slight concentration at the center (curve F, fig. 5).

Table B (appendix) gives a tabulation of the variation in percentage of each mineral in both those sections cut parallel and those cut normal to the flow surface.

Table V gives the average grain size of the different constituent minerals at the upper surface and at the base of the flow.

Table V

Average Grain Size of the Minerals of the Grand Coulee Flow

Phenocrysts	Upper Surface	Base
Plagioclase	0.8 to 1.0 mm.	0.8 to 1.0 mm.
Olivine	irregular small euhedral crystals to 0.3 mm.	0.3 to 0.8 mm.
Groundmass		
Plagioclase	0.1 to 0.3 mm.	0.3 to 0.8 mm.
Pyroxene	0.05 mm. to 0.1 mm. granules	0.2 mm. granules and aggregates to 0.5 mm.
Magnetite	trichites, globulites	granular aggregates, skeletal crystals

Although the grain size of the groundmass constituents increases slightly with depth, they are all so small that they may be classed as equigranular. The porphyritic elements are distinctive because of their larger size and more equidimensional crystals. The microscopic texture of the rock, therefore, varies from a fine grained, porphyritic, hyalopilitic character at the upper surface to a fine-grained porphyritic, intersertal phase at the nearly holocrystalline base. The textural changes may be followed in the photographs of Plate V.

The Phenocrysts

Plagioclase occurs as badly fractured, highly resorbed phenocrysts which are commonly progressively or oscillatorily zoned and range in composition from An_{65} at the center to An_{60} at the periphery. The highly resorbed character of the plagioclase crystals and their replacement by augite along fracture lines presents evidence of their reaction with the melt after extrusion of the mass (photo D, Pl. VI). Reaction zones are also apparent and are similar to those described as a characteristic feature of the plagioclase phenocrysts of the andesite-basalt of the Table Rock Flow but are developed on a much smaller scale. In general, the highest degree of resorptive activity is found on those areas where the least amount of plagioclase phenocrysts has been plotted. Although the phenocrysts are oriented parallel to the flow surface, there is no evidence of a differential movement of the crystals within the flow.

Olivine shows the same general characteristics of an early crystallization that characterizes the zoned plagioclases. It contains the amount of Fe normal to chrysolite. The indices, Np=1.71, Nm=1.70, Np= 1.68, indicate approximately 20% of the Fayalite mole (after Winchell)[1]. Olivine, like plagioclase, shows little evidence of differential movement in the flow. Its percentage variation with depth is the result of varying degrees of its alteration and assimilation by the melt.

A definite relation between the percentage of olivine and that of augite is shown both in the plotted percentages of these minerals and in their microscopic relations. At the upper surface of the flow, resorption and assimilation of large olivine crystals has left many small anhedral grains. The groundmass adjacent to these grains is charged with numerous very small granules of augite while the groundmass surrounding olivines which have suffered little assimilation does not show as high a percentage of the augite. This general relation may be traced throughout the flow with the largest amount of augite separating at the base where only a low percentage of olivine is present. The fact that the slightly altered olivines at the base are

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[1] Winchell, A. N., Elements of optical mineralogy, part II, p. 168, New York, 1927.

commonly intergrown with the more basic, zoned plagioclase phenocrysts (photo A, Pl. VI) indicates their contemporaneous separation from the intratelluric melt.

The Groundmass

The plagioclase crystals of the groundmass have a constant Ab_{45}-An_{55} ratio throughout the flow. They also maintain a similarity of size and form with the exception of small amounts of skeletal crystals at the upper surface which indicate incomplete separation as well as incomplete growth. The arrangement of the laths in the flow ranges from a fluctional sub-trachytic one at the upper surface to a typical diabasic one at the base. This arrangement denotes crystallization from a moving mass at the upper surface and a stationary one at the base, and indicates a considerable period of time separating the two crystallizations of the same mineral. The sub-trachytic adjustment of crystals to flow at the upper surface is also reflected in an average of 6% more total area of plagioclases in sections cut parallel than in those cut normal to the surface. An increase in size and in the euhedralism of the groundmass plagioclase also reflects its slightly greater separation with depth.

The percentage of augite varies with depth more than does the plagioclase and shows a wider range in size of the individual granules. Equidimensional granules at the upper surface range from a very small size to a maximum diameter of 0.1 mm. At the lower margin they reach a diameter of 0.2 mm. and commonly aggregate in masses which average 0.5 mm. This variation may be noted in the photographs of Plate V.

In so far as the optical characteristics of augite can be determined by microscopic methods, they do not vary appreciably with depth. The average indices value, Ng=1.723, Nm=1.704 shows a variation ranging as high as .01. The indices indicate, according to Winchell,[1] a pyroxene, variety augite, with the composition diopside 40, hedenbergite 45, clinoenstatite 15. Other than locating the pyroxene in its general position, little confidence can be placed in the accuracy of these determinations. The fineness of the grain size makes positive identification of the orientation of crushed fragments extremely difficult. Their general chemical composition is partly substantiated by the maximum extinction angle measured on larger granules at the base where $Z \wedge C = 40\text{-}45^\circ$.

Magnetite occurs in slight amounts in the glassy portions of the flow as irregular streamers and frond-like masses. It has a maximum concentration of 10% at the base where it appears as large interstitial bodies and skeletal

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[1] Winchell, op. cit., p. 186

crystals filling the interstices between the augite granules. Photograph L, Plate V, gives the general interstitial character of the magnetite and Photograph I, Plate VI, illustrates its typical skeletal growths. Some evidence of the replacement of both augite and plagioclase by magnetite is shown in both the above photographs.

The percentage of glass decreases from the upper surface to the base in an irregular manner. Between the 6 foot and 10 foot levels its increase is slight and below the 10 foot level its percentage decreases very rapidly. The glass in the hyalopilitic upper portions of the flow has a deep brown color and is so densely charged with material in an incipient stage of crystallization that it is nearly opaque. Its index is very high, averaging 1.593 (±0.016). There is no microscopic evidence to indicate the cause of this variation in the index of the glass unless it results from sub-microscopic molecular agganrements. At the base of the flow the glass has a much lower and more constant index of refraction, 1.554 (± .005), which is reflected by its lighter color and nearly homogeneous appearance. Here the interstitial residuum is highly charged with indeterminable radiating crystallites (of augite?) (photo E, Pl. VI) which are well enough separated to enable the more accurate determination of the index of the glass than is possible at the upper surface. The decrease in the index of the glass and the change in color, from a deep brown, nearly opaque residuum at the upper surface to a light brown at the base reflects the degree of separation of magnetite and augite from the melt.

The percentages of both augite and magnetite vary inversely with the percentage of glass. Plagioclase, however, shows but a slight increase toward the base. The smaller quantity at the upper surface results from the incomplete crystallization of larger numbers of skeletal crystals, generally found in localized areas in which there is an almost entire absence of augite (photo J, Pl. VI). Such areas of incomplete crystallization are also found to a depth of 15 feet in the flow where they are surrounded by crystalline patches (photo B, Pl. VI). The presence of these areas indicates both the speed of crystallization and the irregular progress of crystallization throughout the flow.

Hydrothermal Activity

Chlorophaeite occurs in larger quantities in this extrusion than in the Table Rock flow. It is represented by all three described types, red, orange, and green, and is characterized by similar index range (1.52-1.54). It corresponds, therefore, both in physical and chemical properties, to the chlorophaeite of the thicker flow and its interstitial relation to the groundmass crystals indicates that it owes its origin to the effect of the mineralizers upon the mesostasis of crystallization (photo K, Pl. V, and photos K and L, Pl. VI).

Crystallization of the Flow

The occasional intergrowths of olivine and basic plagioclase indicate a contemporaneous separation of the two minerals. This separation occurred in an intratelluric reservoir of basaltic magma under a set of conditions which permitted the progressive and oscillatory types of zoning of the plagioclases.

The high percentage of augite in the groundmass of the flow and the relatively high ratio of albite to anorthite of the plagioclase in the groundmass (Ab_{45}-An_{55}) suggest the extravasation of both liquid and crystalline phases of a fractionated basaltic magma.

The phenocrysts were perhaps fractured upon release of pressure at the time of extrusion. Under the surface conditions, with a lowering of temperature and pressure, a reaction was fostered between crystals and melt. That this reaction was centered along the planes of weakness is well shown by the replacement of plagioclase by augite along irregular fracture planes, and by the separation of larger olivine crystals into small granules through their resorption and assimilation along the microscopic fractures. The initial effects of the reaction between fluid and olivine may be seen in photograph G, Pl. VI. The alteration and resorption of a basic plagioclase is shown in photograph H, Plate V, where a glass filled resorption cavity is located along a fracture line at the central part of a progressively zoned crystal which has been replaced locally by augite. Augite granules definitely connect with fracture plane conduits as shown in photographs D, H, Plate VI.

Thin reaction zones border the periphery of the plagioclase phenocrysts. The thinness and general indistinctness of these zones make determination of their Ab-An ratio impossible but their presence signifies at least a definite reaction of the fluid even with the less calcic periphery of the crystals.

It is significant that apparently there was less reaction between the intratelluric plagioclase and the melt than there was between olivine and melt. In this flow, plagioclases remain pratcially constant in percentage and, although they are highly resorbed in certain areas, they have not been affected to the same high degree as the olivine crystals which decrease in quantity toward the base. The decrease in percentage of olivine with depth is the reverse of what would otherwise be expected from settling of a mineral with a higher specific gravity than the melt. In the andesite-basalt flow the reverse was the case with plagioclase being more completely assimilated in the early stages while olivine was attacked mainly by late hydrothermal solutions.

The type of selective reaction between phenocryst and melt of the two flows may result from the difference in composition of the two melts since the phenocrysts have approximately the same composition in both. The more basic melt of the Grand Coulee flow concentrated its activity upon the olivine crystals, while the acid melt of the Table Rock flow was more active upon the plagioclase crystals.

The large percentages of augite commonly present in localized areas with small granules of highly resorbed olivine crystals (see page 79) indicates that the assimilation of olivine enriched the melt in the molecular constituents necessary for the formation of augite. Furthermore, throughout the flow there is a definite relation between the amount of augite and assimilation of the olivines. The general increase in the percentage of augite with depth (curve B, fig. 5) must be partially the result of an enrichment of the melt in basic constituents derived from the assimilation of olivine and, in great part, the result of more favorable crystallization conditions.

The presence of skeletal crystals of groundmass plagioclase and the relatively high percentage of intratelluric olivine crystals at the top of the flow as well as the general lack of resorption of the plagioclases there, indicate that assimilation of the phenocrysts and crystallization of the melt proceeded together and were stopped at the upper surface by the sudden decrease in temperature through loss of heat while the flow was still mobile but in a highly viscous state. Chilling halted crystallization of the plagioclase and permitted only a slight assimilation of the olivine.

The general increase in the percentage of groundmass crystals toward the base indicates a gradual decrease in the rate of the loss of heat with depth together with an increased fluidity probably brought about by a progressively greater concentration of mineralizers. The general increase of mineralizers toward the base of the flow is indicated by the curve of chlorophaeite (curve E, fig. 5) which parallels approximately the percentage variation curve of augite (curve B, Fig. 5). It is concluded that the mineralizers, gradually being concentrated in the residuum by continual crystallization, were not released until after the separation of augite, the final mineral to separate. Their release was brought about possibly by the great increase in pressure within the small remaining portion of the glass or by the fracturing of the upper surface upon contraction of the mass. Microscopically, the localization of the mineralizers as reflected by the presence of chlorophaeite in irregular interstitial masses, particularly at the base of the flow, appears to be the result of its confinement in the residuum by the crystallization of augite. In many cases, it surrounds the plagioclase of the groundmass (photo K, Pl. V) and definitely shows that the hydrothermal solutions must have been released later than the crystallization of plagioclase.

The released volatiles may have had the additional effect of oxidizing the ferrous iron in the interstitial glass to magnetite. There is also some indication of the transportation of iron oxide by volatiles in the replacement of augite and olivine along microscopic fractures by small irregular masses of magnetite. The general interstitial relation of the higher percentage of magnetite at the base indicates that transportation was of less importance than the oxidation of a ferrous iron-rich interstitial residuum of crystallization. The presence of skeletal crystals, in perfect chains and arborescent growths (photo I, Pl. VI) signifies crystallization from a stationary mass, any movement of which would have destroyed these fragile crystallites.

The diabasic, non-trachytic, arrangement of the plagioclase laths, the localization of chlorophaeite in interstitial areas, the complete separation of magnetite, and the slightly larger size of the groundmass constituents at the base, as well as more complete crystallinity, denote separation from a stationary melt in which crystallization was facilitated by a relatively slow temperature decrease and by a greater fluidity than that at the upper margin.

General Summary and Conclusions

The effusive mass, consisting of fluid and a small quantity of intratelluric crystals, was extruded at an initial high temperature and with a high degree of fluidity. Any gases which may have been set free by release of pressure at the time of extrusion and did not remain in solution in the melt escaped early in the flow history and did not leave any indication of their former presence. The initially high fluidity, therefore, must have been the result of the high temperature.

Crystallization progressed from the upper margin of the flow inward toward the base and was controlled by the rate of heat loss from the upper surface. It is concluded that the comparatively slow decrease in the rate of cooling with depth permitted a longer time for reaction between the melt and intratelluric crystals, and a more complete separation of the groundmass constituents. The more complete separation of crystals with depth in turn increased the concentration of the mineralizers in the melt to the extent that they could maintain a high degree of fluidity and, therefore, counteract the effect of cooling. The slower rate of cooling and the higher fluidity at the base promoted the development of slightly larger minerals, as well as a more complete crystallization of the mass.

There is no evidence of fractional crystallization toward a more acidic residuum. All phenomena point directly to an enrichment of the residuum of crystallization in augite, magnetite, and mineralizers which were progressively released by crystallization.

It is believed that the period of time between the crystallization of the upper surface and that of the base was a relatively short one and that the upper surface had not become sufficiently cool to contract before the concentration of mineralizers by crystallization lower in the flow. Otherwise a means of escape would have been offered to the mineralizers and they would not be found concentrated as the interstitial areas of chlorophaeite throughout the groundmass but would be located along definite fractures as was the case in the thicker andesite-basalt flow.

PART III

HOLOCRYSTALLINE BASALT

BEND, OREGON

HOLOCRYSTALLINE BASALT

LATE PLIOCENE OR PLEISTOCENE BASALT OF THE MADRAS FORMATION

Location and Correlation

This formation, named by Hodge[1] after its most typical exposure near Madras, Oregon, consists of basalt flows with interbedded tuffaceous material. It forms a very strong physiographic member of the north central Oregon volcanic series, lies close to the eastern border of the Cascade Mountains and is overlain by the Cascade series of andesites. Hodge has traced the formation from the Dalles to Bend, Oregon, and Powers[2] has correlated the surface rock at Bend with the Warner Basalt formation of the Modoc Lava Bed quadrangle in northern California.

Megascopically the Madras basalt is very similar to the described Warner basalts. Both are characterized by a very fresh appearance, light-grey color, equigranular, and finely vesicular texture, and by their holocrystallinity. Characteristic also are the fresh light green to yellow and

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[1] Hodge, E. T., Geological map of North Central Oregon, Univ. of Oregon Publ., Supplement to Geology Series, vol. 1, p. 5, 1932.

[2] Powers, H. A., The geology of the Modoc Lava Bed Quadrangle: Amer. Min., vol. 17, p. 266, 1932.

iridescent olivine crystals imbedded in a groundmass of plagioclase and grayish green pyroxene, and the clear opal which fills some of the larger vesicles. Where the true field relations are not known the distinctive appearance of the Madras Formation provides a very satisfactory means of separating it from the underlying Miocene Columbia River basalts which are denser, finer grained, and commonly of much darker color.

In Oregon, the Madras formation is essentially horizontal, and in northern California, according to Powers, the Warner Basalt is comparatively undisturbed. The lack of deformation in both formations, the thinness of their individual flows, their similar megascopic appearance, and remarkably close microscopic correlation, indicate that these basalts are closely related in age, if not of the same age and formation. Together they make up a large part of the superficial covering east of the Cascade Mountains. From the Dalles, Oregon, where it is present only as a narrow tongue of basalt, the Madras Formation rapidly widens to the south and probably reaches its greatest width along the southern boundary of Oregon or in northern California where Russell[1] has found the Warner basalt to be very widespread.

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[1] Russell, R. J., Basin Range structure and stratigraphy of the Warner Range, Northeastern California, Univ. of Calif. Publ., Bull. 17, p. 416, 1928.

It was thought that a microscopic study of a flow from the Madras Formation might give some evidence for future correlation of the younger flows east of the Cascade Mountains, in addition to serving its purpose of showing variations in the course of the crystallization of a holocrystalline, relatively fresh and unaltered basalt. Therefore, a typical flow, located two miles below Bend, Oregon, on the Deschutes River was selected. The flow is 31 feet thick and was sampled at one foot intervals. Thin sections of each specimen were made parallel with and normal to the flow surface.

General Megascopic Description

A light grayish black color is characteristic of the rock throughout the flow with the exception of the margins where a vitreous texture and a slightly darker color is apparent. This slightly darker color is restricted to a thickness of approximately three feet and is marked by the coaresly vesicular base and upper surfaces of the flow.

The vesicles at the upper surface are tube-like in shape. Irregular groups of joined vesicles with a maximum diameter of 2.5 cm. may be traced for distances of 6 to 8 inches. These tube-like chains are not inclined from the vertical and give no evidence of having been formed while the flow was moving. The vesicles at the base are not joined.

They have a roughly circular cross-section and are about the same length as those at the upper margin. The rock between the margins of the flow is also vesicular but the vesicles are very small, averaging only 1 mm. in diameter. They are very irregular in shape and are so evenly distributed that they give the rock a distinctly porous appearance. This appearance is disturbed by two irregular, highly vesicular lenses, which vary from 1 inch to 1 foot in thickness, at depths of 6 and 19 feet. The vesicles of these lenses are similar in size and shape to the vesicles at the margins of the flow. Excluding the coaresly vesicular margins there is also a slight increase in porosity of the rock from 7% at the base to 16% within the holocrystalline phase of the flow. This change in porosity is the result of the increase in quantity of small vesicles rather than an increase in their size.

A megascopic mineralogical feature characteristic of the Madras Formation is the presence of opal as fillings in the vesicular cavities of flows. The larger vesicles at the upper surface of this flow are encrusted or partially filled with a colorless, transparent opal which is also found in small amounts as cavity fillings in both vesicular lenses referred to above. The colorless opal of the larger cavities is replaced by a yellowish-brown to yellowish-green earthy opal in the small pore-like vesicles. The earthy opal breaks down into a limonitic material which stains the fracture planes and vesicles, and gives in localized areas a fine-grained, "mottled" appearance to the rock. The vesicles at the base of the flow contain no opal and are only coated with a thin film of hematitic material.

The rock is a typical diabase. Small lath-like feldspars and interstitial dark colored pyroxene make up the groundmass in which are imbedded numerous fresh, light green olivine crystals and an occasional phenocryst of plagioclase. A distinct feature of the texture of the rock is the presence of megascopic glomeroporphyritic groups of equigranular olivine grains in an area at a depth of 25 feet. These groups although not closely spaced commonly reach a maximum length of 1.0 cm. and comprise a much larger percentage of the rock than olivine does elsewhere in the flow.

General Microscopic Appearance

Minerals

Two distinct generations of crystallization and a later group of minerals which replace both earlier stages are distinguished by their size, microscopic characteristics, and their textural relations. The percentage variation curves showing the distribution of different minerals with depth are included in Figure 6.

The first generation is made up of an association

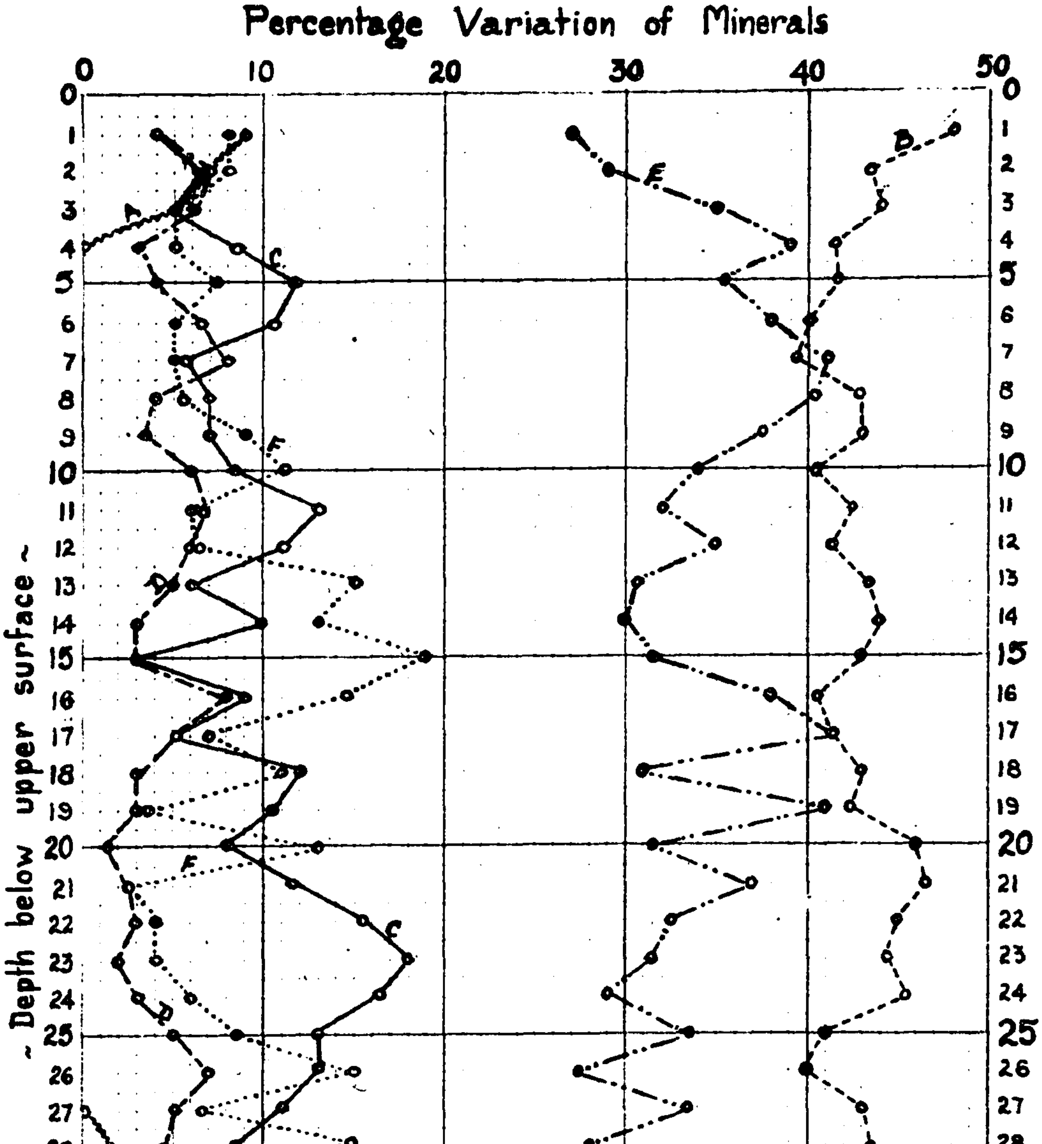

Figure 6 - Percentage Variation of Mineral with Depth in Holocrystalline Basalt Flow.

Curve A - Glass
Curve B - Groundmass plagioclase
Curve C - Olivine
Curve D - Plagioclase phenocrysts
Curve E - Augite
Curve F - Magnetite

of olivine and plagioclase crystals which are commonly intergrown. They are distinctly porphyritic and are badly altered and resorbed. The plagioclase crystals are progressively zoned from a core having an $Ab_{15}-An_{85}$ ratio to the periphery with an $Ab_{25}-An_{75}$ ratio. Oscillatory zoning is uncommon although it has been noted in occasional highly resorbed shells. The indices of olivine, Ng=1.72, Nm=1.705, Np=1.68, remain constant throughout the flow and indicate approximately 22% of fayalite.

The second generation makes up the groundmass of the flow and consists of an association of augite and plagioclase. The plagioclase crystals have a constant $Ab_{32}-An_{68}$ ratio throughout the flow and occur as lath-like subhedral crystals which have a diabasic arrangement and show no effects of flow movement. Augite fills the interstices left by the crystallization of the groundmass plagioclase and by the earlier formed more basic phenocrysts, olivine and plagioclase. In the central portion of the flow it forms a poikilitic fabric in localized areas completely surrounding the earlier formed crystalline facies. The indices of augite have no marked variance from Ng=1.719, Nm=1.698 ($\pm$.004) throughout the flow. The indices, together with the extinction $Z \wedge C$ averaging 43°, denote an approximate composition of diopside 40, hedenbergite 35, clinoenstatite 25.

Glassy, isotropic material, is found only at the extreme margins. It gradually decreases from 8% at either surface to 0% at a distance of approximately 4 feet from each margin. The glass is so highly charged with opaque material and augite, in granules and radiating fibers, that its index of refraction cannot be accurately determined.

Magnetite occurs in all parts of the flow as a very late replacement of olivine and augite. It has no definite crystalline form but is found as irregular stringers and granular aggregates. In the glass margins of the flow, it appears as globulites and very fine dust-like particles so densely packed that they give an opaque appearance to the normally colorless glass.

Associated with magnetite and appearing as replacements of plagioclase, are small elongated prisms of a low birifringent mineral with parallel extinction. This mineral has many of the characteristics of apatite but its small size and incomplete development make exact determination impossible. It maintains a small percentage, less than 1%, throughout the flow and therefore is not shown in Figure 6.

Opal is found both in coaresely vesicular lenses, at the upper surface, and in the irregular interstitial areas throughout the flow. At the upper surface and in the vesicular lenses the opal is a colorless cryptocrystalline mass with an index N=1.441. The pore-like vesicles are filled with a bright yellow opal, N=1.453 (+.003) associated with included octahedra of magnetite which, however, commonly occurs as granular aggregates, lining cavity walls. The percentage of opal is highly variable, ranging from as high as 5% in some thin sections to a total absence in many others. Much of the interstitial opal was probably lost in the process of grinding the sections, and since it definitely has a very late origin and is not an essential constituent of the flow, the various percentages were not plotted.

Table C (appendix) gives the percentage variation with depth of minerals in sections cut both parallel and normal to the flow surface. Curves of Figure 6 represent the mean readings of this table.

Textural Relations

Crystallinity:

Curve A, Figure 6, shows that with the exception of the four foot margins of the flow, where varying quantities of glass were recorded, the flow is completely crystalline.

Granularity:

The grain size of the different stages of crystallization are shown in Table VI.

Table VI

Average Grain Size of Minerals of the Bend Flow

Phenocrysts:	Base	Center	Top
Plagioclase (An$_{75}$-An$_{85}$)	Highly resorbed euhedral crystals 1.8 x 0.8 mm.		
Olivine	2.4 x 2.9 mm.		
Groundmass:			
Plagioclase (An$_{62}$)	Skeletal crystals 1.0 x 0.2 mm.	Subhedral laths	laths and skeletal crystals 1.0x0.2 mm.
Augite	0.1 mm. granules	Interstitial granules and ophitic masses 5.0 mm.	0.1 to 0.3 mm. granules
Hydrothermal			
Magnetite	fine dust -like particles globulites	Irregular aggregates replacing olivine and augite	globulites dust-like particles
Opal	no opal	Interstitial cavity fillings; average size 1.0 mm.	
Apatite (?)	Very small fibrous masses		

The granularity of the rock varies primarily with the increase in the size of augite toward the center of the flow. The rock is fine grained, slightly porphyritic, and phanerocrystalline with the exception of the glassy margins.

Fabric:

The fabric is the result primarily of the diabasic arrangement of the groundmass plagioclase laths and of the degree and character of the crystallization of augite (curves B and E, fig. 6).

Augite at the margins of the flow appears as fine granules interstitial to plagioclase crystals. This arrangement gives a typical intersertal texture to the rock. There is a gradual increase in the size of the augite granules for a distance of approximately 4 feet from the upper margin and 3 feet from the base, where there is a complete absence of the mesostasis of glass. At these points the rock has a characteristic intergranular texture. As the center is approached from either intergraunular area, there is a marked increase in the size of the augite which develops a sub-ophitic texture with plagioclase. At the central part of the flow, augite forms in large poikilitic masses (plate B) with remarkable optical continuity, often twinned, and completely enclosing areas of groundmass plagioclase.

The texture of this rock, which may be termed an olivine basalt may be described therefore as fine-grained, diabasic, inequigranular, hypocrystalline and intersertal at the margins. It ranges through holocrystalline facies from intergranular to sub-ophitic and finally to true ophitic texture at the central portion of the flow. The photographs of Plate VI show the general change from each margin inward to the center of the flow.

The Crystallization of the Flow

Phenocrysts

The zonation of the plagioclase phenocrysts indicates their intratelluric origin and since olivine is occasionally found as small inclusions within the larger basic plagioclase crystals, it must have crystallized slightly before, or contemporaneously with, plagioclase.

The phenocrysts were fractured upon extrusion and both plagioclase and olivine were being resorbed at the margins before the crystallization of the groundmass started. Resorption was most active along the fracture planes and progressed more rapidly where the fluid had access to the central, more basic parts of plagioclase crystals. Photographs A and B, Plate VIII show the extent to which resorption of plagioclase had progressed before crystallization of the groundmass. Well formed, distinct reaction zones are found surrounding the periphery of the crystals (photo B, Pl. VIII). These reaction zones show characteristics identical to those described in Part I of this thesis and give positive evidence of a lack of chemical equilibrium between crystals and melt after extrusion.

Olivine was also highly resorbed by the melt after extrusion, the greatest amount of resorption being localized in the central portion of the flow. Large corrosion channels extended into the crystals along irregular intersecting fracture planes (photo E, Pl. VIII), destroyed their original euhedralism, and divided the olivine crystals into small, highly resorbed anhedral grains.

Distribution of phenocrysts:

Olivine varies in a very irregular manner from approximately 5% at both margins to a concentration of 18% at a depth of 23 feet. The presence of olivine at the area of concentration may be noted both megascopically and microscopically and gives good evidence of its post-extrusion settling since there is no microscopic evidence to indicate that it was unequally mixed with the melt at the time of extrusion.

Plagioclase of intratelluric formation (curve D, fig. 6) maintains an almost constant percentage throughout the flow. It has, however, suffered more resorption than olivine and the true relation is not shown by the percentage alone but rather in the total number of highly resorbed fragments of crystals in various parts of the flow. The marked increase in the total number of fragments toward the upper surface indicates an initial upward movement of the plagioclase crystals if each fragment may be assumed to represent an original crystal.

The high degree of assimilation of intratelluric plagioclases has destroyed much of the orientation established by those crystals in the moving lava. Very little difference in percentage was noted in the study of sections cut normal and those cut parallel to the flow surface, except from the glassy margins where a greater total area was recorded in sections cut parallel to the surface.

An initially high degree of fluidity of the extrusive mass is deduced from the differential movement of the intratelluric crystals, and to some extent from their high degree of resorption. A high degree of fluidity could have been maintained either by a high temperature of extrusion or ,more probably, by a high content of mineralizers which is evident from the high porosity and vesicularity of the flow.

Groundmass

Plagioclase (An_{62}) and augite are the essential constituents of the groundmass. Magnetite also occurs as a groundmass mineral and makes up a large percentage of the rock but since it definitely replaces both olivine and augite and shows evidence of transportation it will be discussed under the heading of "Hydrothermal Activity".

The progress of crystallization is best interpreted from a study of the percentage variation curves. Plagioclase (curve B, fig. 6) maintains a constant percentage throughout the flow with a slight increase at the upper surface. The shape of curve B denotes almost complete crystallization even at the marginal surfaces where 8% of the glassy residuum is present. Separation of plagioclase at the margins was initiated before augite began to crystallize and had progressed almost to completion before the two minerals were crystallizing simultaneously. In the later stages, augite continued to crystallize and included, where conditions were favorable, many of the incompletely formed plagioclases in large poikilitic masses. In the diagram (curve E, fig. 6) augite has a highly irregular curve and has a complicated relation to both olivine and magnetite, for which an explanation will be given shortly.

A sudden chilling of the margins of the flow is indicated by the small percentage and small size of the augite crystals, as well as by the presence of glass. Although plagioclase maintains practically the same percentage at the margins, its slightly smaller grain size and greater number of skeletal crystals also give proof of its crystallization from a more viscous melt than that at the center of the flow.

Effect of assimilation of olivine:

The highly irregular nature of the augite variation curve throughout the holocrystalline part of the flow is found to be the result of two factors. First, augite bears a direct relation to the amount of resorption of the olivine crystals. More augite is present in areas where the olivine crystals have been highly resorbed. Second, the replacement of augite by magnetite occurred in localized areas and brought about abrupt local variations which obscure the true nature of the curve.

The relation between the augite and the resorption of olivine is also true at the margins although smaller quantities of both minerals are found there. Olivine crystals at those positions have suffered less resorption and show a higher degree of euhedralism than do those in the central parts of the flow. The sudden increase in viscosity at the margins halted their assimilation by the melt and, as a consequence, less of the olivine molecule was allowed to diffuse into the fluid. The lack of the basic material at the margins should have permitted a greater separation of plagioclase since lower in the flow some of the CaO would have entered into chemical combination with basic material, derived from olivine, to form augite.

This relation of plagioclase is well shown in its variation curve but augite crystallized later and its true relation is obscured by the presence of varying amounts of glass. Yet, even considering the glass as pure augite mesostasis, its additional quantity added to crystalline augite would bring the total percentage only to an amount approaching the average percentage of augite in the central portions where olivine is more abundant. Since a large portion of the glass is charged with finely divided iron oxide, there is a deficiency of augite at the flow margins.

The effect of the assimilation of the basic plagioclase cannot be shown to have appreciably affected crystallization.

Effect of mineralizers:

The greater resorption of intratelluric crystals at the center of the flow indicates a higher degree of fluidity there than elsewhere. The increasing size of augite from small granules at the margins to large poikilitic twinned areas at the center (photos F and G, Pl. VII) also denotes an increasing freedom of crystallization. It is unlikely that the temperature of crystallization of augite at the center of the flow was any different from that at the margins since the composition of augite is essentially the same. Although it is possible that the latent heat of crystallization of the groundmass constituents at the center of the flow helped to maintain a more constant fluidity, or that the early crystallization of plagioclase increased the remaining liquid in femic material and thereby increased the fluidity, it is believed that these effects upon crystallization were subordinate, at least, to the effects of mineralizers.

The diabasic arrangement of the plagioclase laths and the vertical attitude of the large vesicle-chains at the margins indicate crystallization from a stationary mass. The vertical vesicles and the interstitial character of the pore-like vesicles indicate that both were formed by mineralizers set free from solution by separation of crystals.

The rims of the larger vesicles are irregular and indented by plagioclase laths (photo I, Pl. VIII) which in some instances seem to have been pushed aside by the growth of the vesicles. The glass material surrounding the vesicles at the margins is more highly charged with skeletal crystals of magnetite and granular augite than that in adjacent areas. The solutions included in the cavities, therefore, must have oxidized the iron oxide and may have also promoted a more complete separation of augite around the peripheries of the vesicles. These phenomena indicate that the vesicles were formed after the crystallization of plagioclase and before the general period of separation of the augite crystals. The relative quantity of mineralizers in solution in the melt was increased to such an extent by the separation of the groundmass plagioclase that large quantities were set free. The volatiles may have been trapped by the higher viscosity of the mass at the margins and formed these vesicular areas.

The cavities of the irregular lenses of high vesicularity at depths of 6 and 19 feet show microscopic relations similar to those of the vesicular margins. They suggest, therefore, the limits to which mineralizers released by the crystallization of plagioclases lower in the flow could permeate through the melt before being trapped by the increased viscosity of the overlying portions. The lenses present a definite evidence for a progressive crystallization inward from the margins of the flow surfaces. The rate of cooling from the lower margin of the flow was similar to that from the upper surface since there are comparable textural gradations from both margins toward the center. Cooling was slower, however, from the base as high fluidity directly above the lower margin after its consolidation is indicated by narrower textural zones and by a concentration of differentiated olivine crystals at a depth of 23 feet. Volatiles released by the crystallization of plagioclase at the basal and upper chilled margins of the flow were trapped in place by the sudden increase in viscosity. Gases released in the zone overlying the base were allowed to filter upward through the fluid interior to the 19 foot level where their upward movement was halted by increased viscosity which had there become pronounced through heat loss from the upper surface.

Butler and Burbank[1] have given a somewhat different interpretation to the vesicular banding in the smooth top flows of Michigan.

> "The distribution of vesicles in layers and the elongation of the vesicles in the plane of the lode have commonly been ascribed to flow movement in the lavas. It seems likely that the banding in the Michigan flows may be explained as follows: A period in which rising gas bubbles collected under a solidified surface was followed by a period of relatively rapid consolidation when few bubbles collected, and so on till a depth was attained where the gas was not present in sufficient quantity to form vesicles. The amygdules are fewer and the banding less distinct near the base of an amygdaloid. A similar grouping of vesicles is present in slags solidified in pots where there is no movement of the liquid.
>
> "All relations suggest that these flows were very fluid and relatively full of gas when they poured out....In the highly liquid lava, the rising gas bubbles were able to combine into much larger ones that, on reacing the bottom of the crust at any given stage of its formation, coalesced commonly into the extensive flat layers already described."[1]

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[1] Butler, B. S., and Burbank, W. S., The copper deposits of Michigan: U. S. Geol. Surv. Prof. Pap. 144, pp. 28-29, 1929.

Both the interpretation of the vesicular layers in the Michigan flows and those in the Bend flow involve a progressive release of gaseous constituents. However, since the large vesicles of the Bend flow were definitely formed after the crystallization of plagioclase, they do not represent an accumulation of gases set free at the time of

PLATE B

Typical poikilitic crystal of augite at center of flow which shows the relation of the small marginal vesicles to the main mass and to the replacement of interstitial augite by magnetite. Note highly resorbed plagioclase fragment at center of crystal and general smaller size of skeletal plagioclase crystals within the crystal than of those at the periphery.
X 200

extrusion. They present evidence of a gradual release of gases from solution accumpanying the progressive plagioclase crystallization which occurred during a definite temperature range in the flow history.

The high temperature necessary for separation of the plagioclase insured a high degree of fluidity. Consequently, the plagioclases had better conditions for complete separation than augite which crystallized later, at a lower temperature. Augite was not able to totally separate from the melt at the margins where the decrease in temperature was very rapid. In the intergranular zones, the rate of cooling was slower and augite completely crystallized with a granular form. At the central ophitic zone (Plate B) the slow decrease in temperature, combined with the normally high concentration of gaseous constituents, permitted greater molecular diffusion and prolonged fluidity. Hence augite in this zone was enabled to develop into large poikilitic crystals. Since the crystallization point of augite was lower than that of plagioclase, the viscosity of the melt must have been higher during its separation. Volatiles whose escape from solution was prevented by the high viscosity of the melt during the separation of augite, were released in the late stages and were localized by crystal growth in interstitialareas at the margin of the ophitic masses (Pl. B). These small interstitial vesicles (photo J, Pl. VIII) give the porous appearance to the rock and represent the last effects of the progressive crystallization of the melt. The alteration and replacement of the ferromagnesian minerals by magnetite and the replacement of plagioclase by the radiating fibrous masses of apatite (?) may both be traced from the replaced minerals along thin fractures, joint cracks, to the smaller vesicles. The replacement and alteration must have resulted from the hydrothermal activity of the released mineralizing solutions.

Hydrothermal Activity

The major effects of hydrothermal activity are confined to the holocrystalline portions of the flow and show a direct relation to the porosity of the rock. That is, in the central portions of the flow where the porosity reached a maximum of 16% of the rock, a greater amount of hydrothermal material is found, as will be discussed under the following sub-heading.

Magnetite:

Magnetite is the most prominent hydrothermal mineral and is associated with very small quantities of apatite and variable amounts of opal. The true proportion of magnetite to other constituents of the flow is best shown in the chilled margins where 8% of very fine globulites of magnetite indicate the original percentage of iron oxide in the residuum. With this percentage as a basis for calculation it is possible, therefore, to show definite quantitative concentrations of magnetite in the holocrystalline parts of the flow where a maximum of 19% is found at a depth of 15 feet (curve F, fig. 6). A slightly lower concentration (15%) was found at both the 25 and 28 foot levels. A minimum of magnetite of slighly less than 3% was noted at depth of 21 feet.

Magnetite occurs in highly irregular, granular aggregates replacing olivine, outlining the periphery of the crystals, and extending inward along fracture planes (photo C, Pl. VIII). Smaller anhedral, highly resorbed fragments of olivine have been almost completely replaced by magnetite. Augite in localized areas of subophitic texture has been almost completely replaced by magnetite (photo H, Pl. VIII). This is particularly true in the central portion of the flow in localized areas surrounding large poikilitic bodies of augite, and lower in the flow at the contact between groundmass and large plagioclase or olivine phenocrysts (photos A, B, H, Pl. VIII).

The attack of the solutions was not general but was localized in particular areas surrounding the small interstitial vesicles. It extended outward for considerable distances from the vesicles along thin fractures, and replaced the ferromagnesian minerals which were crossed by the fracture. The larger poikilitic masses were not fractured and were attacked only at the margins. The replacement effects of solutions permeating upward along narrow joint cracks were localized within the finer grain areas at the margins of the poikilitic augite crystals. This condition implies an initial fracturing upon cooling which was operative only on the finer grained portion of the groundmass and did not effect the larger, more homogeneous bodies.

The fractures of the flow cross all crystalline constituents and, therefore, must have followed crystallization and proceeded from the margins inward to the center. Solutions released from vesicles at the base of the flow could escape upward for only short distances before being trapped by the overlying crystallizing mass. Their replacement effects were localized in a very small area. On the other hand, solutions released through fracturing at the upper surface of the flow were allowed to escape and their effects were comparatively slight. Conditions were favorable, therefore, for the concentration of ascending solutions and a much greater amount of hydrothermal replacement in the central part of the flow.

Apatite:

Apatite occurs in small quantities associated with magnetite throughout the holocrystalline part of the flow, but it is not visible in the chilled border phases. It is present only as local replacements of plagioclase. A typical occurrence is shown in photograph D, Plate VIII, where apatite needles, fringing the border of a magnetite replacement after augite, extend outward, "fan-fashin", into a plagioclase crystal of the groundmass. It is evident from the lack of apatite in late residuum and from the replacement of plagioclase by apatite that there was a deficiency of calcium oxide in the hydrothermal solutions. A reaction between phosphorous oxide included in the solutions with the calcic plagioclase of the groundmass was necessary for the separation of the apatite.

Opal:

The opal which occurs in the small interstitial vesicles is associated with slight amounts of magnetite in regular octahedra (photo J, Pl. VIII) and has an ochreous appearance suggestive of discoloration by iron oxide or chloritic material. The ochreous opal is less resistant to the action of surface weathering than the transparent, colorless variety of the larger vesicles, and breaks down into a clayey, limonitic substance. The euhedralism of the magnetite octahedra shows a freedom of separation only possible in the early stages of solidification of the siliceous solutions filling the vesicles.

The lack of euhedral magnetite in the holocrystalline phases of the flow and the presence of well formed octahedra in the opal filled cavities indicate that the process of crystallization of the melt was toward an enrichment of the fluid residuum in relatively large quantities of iron oxide. Upon release, the solutions replaced the silica of the ferromagnesian minerals, olivine and augite, with ferric oxide. The leached silica was carried in solution and was deposited in vesicular cavities with small remaining amounts of iron oxide. The end-product of hydrothermal activity is the transparent colorless opal filling the larger cavities in the upper vesicular lenses and margins of the flow. The total absence of clear opal at the coarsely vesicular lower margin is direct evidence of the upward migration of the volatile constituents after their release from solution by late fracturing of the mass.

General Summary and Conclusions

The crystallization of the holocrystalline Madras flow differs markedly from the hyalocrystalline flows in its textural variations and in the gradations in grain size of the augite crystals. These variations resulted from two factors; (1) the greater concentration of mineralizers in the holocrystalline flow, and (2) the order of crystallization of its mineral constituents.

At the time of extrusion the effusive mass of the Bend flow consisted of a mixture of intratelluric crystals, olivine and plagioclase, and a melt from which the groundmass constituents, augite and plagioclase, crystallized after the lava had become completely stationary. Extrusion took place under conditions of sufficiently high temperature and fluidity of the melt to permit differential movement of the intratelluric phenocrysts.

Plagioclase was the first mineral to crystallized from the melt. Its occurrence in relatively constant proportions throughout the flow with only slight variations in size denotes not only early separation but also a separation during a definite range in the temperature and fluidity of the melt. The slightly smaller size of the laths at the margins indicates a more rapid drop of temperature and consequent increase in viscosity there. These conditions did not permit the freedom of crystallization present later at the central portions of the flow where more euhedral laths crystallized. The crystallization of plagioclase increased the concentration of volatiles in the melt and released a certain amount whose upward movement and localization at definite levels mark the progressive crystallization of the flow.

The separation of plagioclase was almost complete before augite started to crystallize. Hence, augite shows to better advantage the effects of the rate of cooling upon the texture of the rock mass. At the margins of the flow where rapid loss of heat brought about a great undercooling of the liquid, augite is found as very small granules embedded in a glassy residuum. The general decrease in the rate of cooling inward from the margins is reflected by a gradual increase in size and quantity of these granules. With slow cooling at the center, the normally high quantity of mineralizers made possible a maintenance of a high degree of fluidity and, thereby, promoted greater freedom in crystallization and permitted the formation of large poikilitic masses of augite. It is evident, therefore, that the variation in size and form of augite was dependent primarily upon the rate of cooling of the mass.

The initially high fluidity of the flow fostered an assimilation of the intratelluric crystals, but with loss of fluidity assimilation was halted. Assimilation of olivine, and, to a less apparent degree, the resorption of plagioclase changed the composition of the melt, and, thereby, influenced the crystallization of the groundmass. A notable increase in the percentage of augite is found in those portions of the flow where a greater amount of assimilation of olivine enriched the melt in constituents necessary for the formation of augite. At the chilled margins of the flow where little reaction between phenocrysts and melt is noted a higher percentage of plagioclase separated, indicating that the effects of assimilation brought about molecular combinations before the separation of groundmass plagioclase.

The general trend in crystallization was toward the enrichment of a fluid residuum in iron oxide. The crystallization of augite forced the residuum into interstitial areas from which it was set free upon the initial contraction and fracturing of the mass. The released solutions moved upward through the flow and attacked the ferromagnesian constituents, removing silica and depositing iron oxide as magnetite during the process of replacement. Very probably the silica thus obtained was deposited as opal in the vesicular openings.

PART IV

CONCLUSIONS

CONCLUSIONS

General Statement

Certain general conclusions may be drawn regarding the problem of variation within single flows and the possibility of correlating flows on the basis of their microscopical characteristics.

1. Variations in the texture of a single flow are as wide as those observed in a series of flows from which samples were collected without regard to their position in the flow.
2. The minerals of a flow may be divided into different groups, stages, or generations of crystallization on the basis of their textural relations, physical characteristics, and chemical composition as reflected by their optical properties. Each stage is characterized by a definite mineral association and typified by a plagioclase of constant chemical composition which may be present in varying amounts in different parts of the flow.

It should be possible microscopically to make close correlations between flows through a comparison of the associations in their most holocrystalline phases. Correlation should be made on the basis of the composition of the minerals present, rather than their percentage.

The most holocrystalline phases of hyalocrystalline flows are generally localized near the base. They may be recognized megascopically by their lighter color, and more commonly wider spaced joint system. The glossy black color of basaltic rocks generally indicates a predominance of much glass rather than a large percentage of ferromagnesian minerals, and is generally accompanied by a more closely spaced system of joints, both indicative of more rapid cooling.

3. Correlations made from chemical analyses are as subject to variation with depth in a flow as are microscopic correlations. In preparing specimens for chemical analyses care should be taken to use samples collected from the most crystalline portions of the flow. Variations in the mode, such as segregation of intratelluric phenocrysts or concentrations of hydrothermal constituents, cannot be deduced from chemical analyses.

The adaptability of the above conclusions was tested in the case of the five uppermost flows of the Tygh Valley, northcentral Oregon, sequence of Miocene flows. The holocrystalline portion of each flow was sampled and resampled along the strike of the outcrop at distances ranging up to two miles. In that distance there was no variation either in textural relation or in the types of minerals present.

Textural Variations

The same fundamental factors controlled the variation in the texture of all three flows and therefore permit the following generalizations.

1. The rate of cooling is the most important factor influencing the crystallinity of a flow. The percentage of the minerals of each crystallization stage shows a progressive increase with distance from the margin, or margins, from which cooling was most active. Since heat loss must become progressively slower with distance from the surface (or surfaces) of a flow, the progressive increase in crystallinity must coincide with the cooling curve of the mass.

2. The constant size of each crystalline constituent, particularly in the hyalocrystalline lavas, indicates separation under essentially the same condition of viscosity. Since viscosity in these mineralizer-poor lavas was determined

primarily by the temperature, the size of individual minerals was determined by their temperature of separation from the melt.

3. Since the size of crystals was dependent upon the viscosity of the flow, variations in size must indicate variations of fluidity. It has been shown that the larger size of crystals at the center of the holocrystalline flow resulted from a higher concentration of mineralizers in solution during late stages of crystallization. Since neither of the hyalocrystalline lavas showed marked variations in size of individual crystals and neither had as high a concentration of mineralizers as the holocrystalline flow, it is concluded that high fluidity can be maintained with decreasing temperature only in those flows containing a large quantity of volatiles in solution.

4. With separation of solid phases the relative quantity of mineralizers was increased and certain amounts were allowed to escape from solution. In the early stages when the fluidity was high enough to permit their movement through the flow, they worked their way toward the upper surface and were trapped at definite levels by the increasingly viscous mass. The released mineralizers did not increase the fluidity, or affect crystallization except where they were locally redissolved. They did, however, promote hydrothermal alteration and the formation of magnetite in

the last stages. The release of hydrothermal solutions may be divided into distinct epochs, each of which functioned in a slightly different manner.

5. The chemical composition of a melt is important since it definitely controls the order of separation of individual constituents and therefore has a pronounced effect upon the resulting fabric of the rock. An examination of these flows and of a collection of basalt and allied extrusives from various parts of the world indicates that the chemical composition of a melt is reflected in the order of crystallization. In intermediate basic flows bordering on andesites, plagioclase is invariably the last mineral to crystallize in quantity from the melt, while in more basic flows it is the first to separate. In the holocrystalline portions of the basic flows examined, the percentages of plagioclase and augite are approximately equal. In the more acidic flows, plagioclase is much in excess of the pyroxene component.

6. The crystal habit of the individual minerals of an association and their different orders of crystallization shape the fabric of the rock mass. In all flows studied, plagioclase had a definite tendency to assume a lath-like form regardless of its composition (Ab-An ratio), or of the fluidity of the melt at the time of its separation. Pyroxene, on the other hand, had a variety of habits, each of which

was dependent upon the condition of fluidity under which it crystallized.

In andesitic flows, in general, there is a tendency, with the late development of the lath-like plagioclases, toward fluidal structures and trachytic textures. In more basic flows with the early development of plagioclases intersertal to ophitic phases of diabasic texture are common and result from the late separation of augite or other pyroxene.

The Effect of the Intratelluric Crystals upon Textural Variations of a Flow

Crystals of intratelluric formation occur in varying amounts in all three flows and they are the only minerals segregated by gravitative settling. Their effect upon the texture and chemical composition of the rock is a direct function of the fluidity of the mass at the time of extrusion. Both a high percentage of mineralizers and a high temperature fostered high fluidity which permitted more complete resorption and differential movement of the phenocrysts.

In each flow there was a distinct relation between the amount of resorption of the large phenocrysts of olivine and plagioclase and the percentage of groundmass constituents. This relation is strikingly shown in the thick andesite-basalt flow where assimilation of the intratelluric phenocrysts affected the composition of the melt to such an extent that the separation of an association of crystals intermediate in composition between groundmass crystals and intratelluric phenocrysts was possible. In the more basic flows assimilation of olivine increased the separation of augite from the melt. It should be noted that the acidic melt assimilated olivine more easily than plagioclase, while the more basic melts assimilated more plagioclase than olivine.

The observed effects of intratelluric crystals seem to be of sufficient importance to warrant further investigation. A study of their relations to different types of extrusions should give considerable data concerning intratelluric crystallization as well as the formation of different types of extrusives by mixing of formed crystals and different melts. In a study of thin sections of basaltic rocks from world localities, it was found that intratelluric phenocrysts, or their resorbed traces, are an integral part of almost every extrusion. In many instances, classification of these flows has evidently been made without due regard to the divergence between the composition of phenocrysts and of the groundmass.

Chemical Variation

Chemical variations in a flow are not brought about by crystallization alone since individual crystals of an association of minerals maintain a constant composition throughout. Variations in chemical composition result from (1) gravitative adjustment of the basic phenocrysts of intratelluric origin early in the extrusive history of the flow, and (2) the release of mineralizers, late in the flow history. The latter effected the alteration of basic crystals, transported basic oxides toward the upper surface, and oxidized iron oxide to magnetite.

The Trend of Crystallization

The general trend of crystallization in all three flows was toward a progressive enrichment of the residuum in ferromagnesian constituents rather than in silica. In this respect, the phenomena of crystallization support the observations of Fenner.

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PHOTOMICROGRAPHS

PLATE I

A. Depth of 147 feet. Note lighter color of rock as compared to B and C, large plagioclase phenocrysts badly resorbed, and the interstitial character of magnetite. X 25 approx.

B. Depth of 96 feet. Dense groundmass, typical large phenocrysts of plagioclase badly fractured and resorbed, smaller phenocrysts of plagioclase, augite, and magnetite. X 40 approx.

C. Depth of 3 feet. Section showing very dense character of groundmass at upper surface. Relation of large plagioclase to the smaller phenocrysts both as to size and arrangement. X 35 approx.

D, E, F. High power of A, B, C, respectively. Felted character of groundmass plagioclase and interstitial magnetite in A. Note enstatite with inclusions of ferric oxide (?) and lack of arrangement of plagioclase laths in E. Parallel arrangement of groundmass plagioclase laths in F. The dark material in E and F is the tachylytic residuum. X 150 approx.

G, H. Subparallel arrangement of smaller phenocrysts of plagioclase at a depth of 147 and 75 feet respectively. X 40 approx.

I. Fluidal arrangement of groundmass plagioclase around badly fractured and resorbed large plagioclase phenocrysts at a depth of 78 feet. X 40 approx.

J, K, L. Contrast between areas of plagioclase in sections cut parallel and normal to the flow surface. Taken from depths of 144, 75, and 6 feet respectively. Note the badly resorbed larger phenocrysts particularly in photograph K where only resorbed fragments remain. X 25 approx.

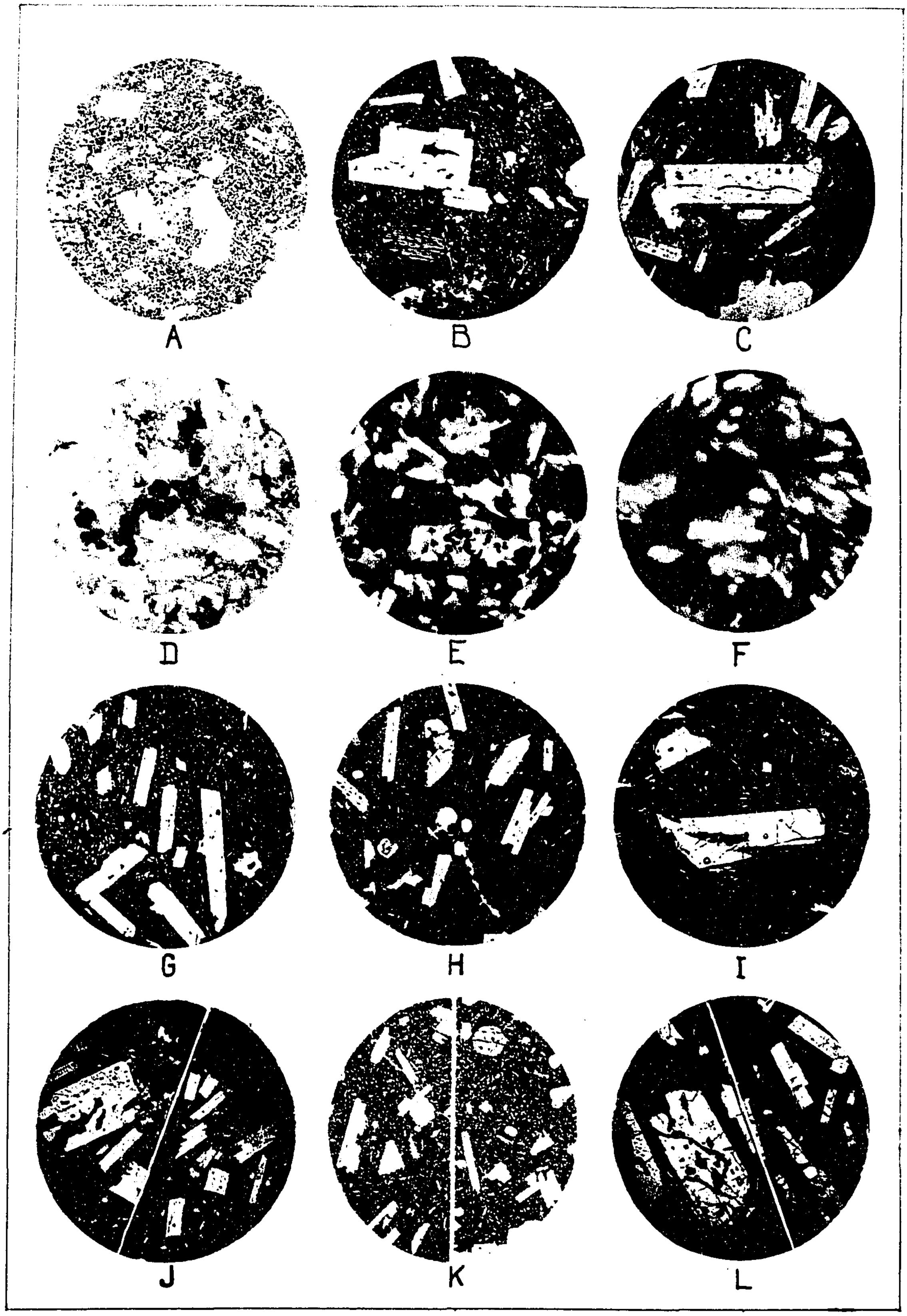

Plate I - Textural Variations in Table Rock Flow —

PLATE II

A. Mutually intergrown olivine, plagioclase, and magnetite from a depth of 15 feet. X 30.

B. Large "mottled", honeycombed, plagioclase phenocryst showing effects of resorption in localized areas within a progressively zoned crystal. A reaction zone surrounds the periphery of the crystal. Note the more complete replacement of angular corners of the crystal by the reaction zone. Depth of 3 feet. Crossed nicols. X 15

C. Large plagioclase phenocryst. Oscillatory zones around a progressively zoned core. A reaction zone completely surrounds the periphery and lines the resorption cavities at the center of the crystal. Diagonal fractures are channels whereby the fluid entered the crystal. Note greater width of reaction rim on the progressively zoned core. X 40.

D. Glomeroporphyritic group of olivine at depth of 15 feet. X 15.

E. B$_a$dly fractured plagioclase phenocryst with partially crystalline material filling the fractures. Note fluidal arrangement of groundmass plagioclase at periphery of crystal. Depth of 6 feet. X 10.

F. High power of resorption cavity shown in C. Note regular contact of reaction zone with crystal and jagged contact with glass. Irregular areas in glass are augite grains. X 200.

G. Reaction rim of pyroxene, augite (?), surrounding olivine crystal. Chlorite and magnetite replacing olivine. X 150.

H. Husks of badly resorbed plagioclase near the center of the flow. 1, 2, 3, at depths of 66, 88, and 97 feet respectively. Note well developed reaction rims on oscillatorily zoned crystals. X 125.

I. Ilmenite pseudomorph after a glomeroporphyritic group of olivine crystals at depth of 15 feet. X 20.

J. Ilmenite pseudomorph after olivine surrounded by chlorite-magnetite phase of hydrothermal material. Note small basal sections of apatite in ilmenite. Depth of 147 feet. X 30.

K. Resorbed intratelluric magnetite crystal with halo of groundmass plagioclase. Depth of 6 feet. X 60.

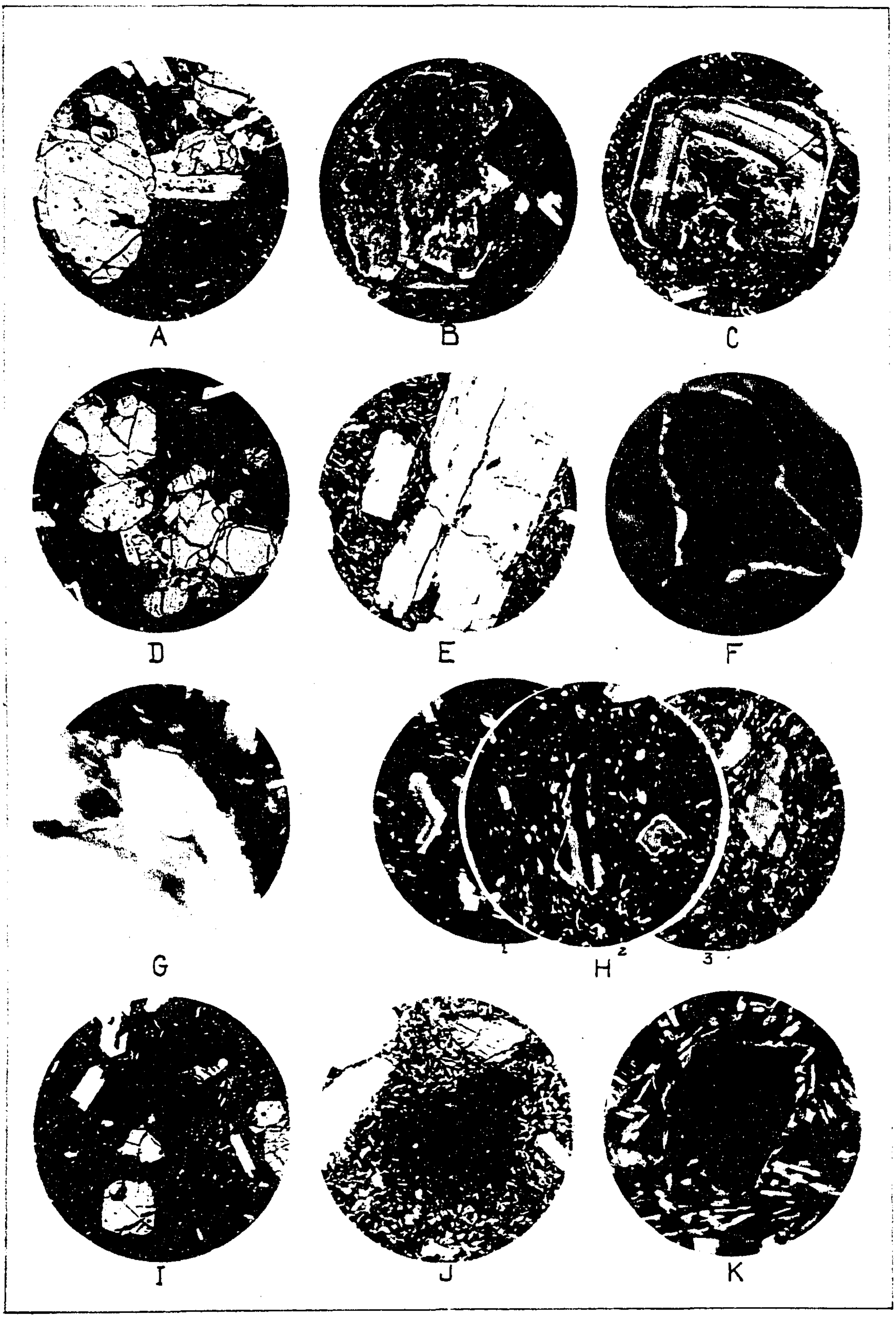

Plate II - Large Phenocrysts of the Table Rock Flow —

PLATE III

A. Typical cumulophyric group of smaller phenocrysts. Note mutual intergrowths of plagioclase and augite. Depth of 108 feet. X 20.

B. Contrast in size between large and smaller plagioclase phenocrysts. Subparallel arrangement of smaller crystals with larger one. X 20.

C. Glomeroporphyritic group of augite grains at depth of 108 feet. X 30.

D. Slightly resorbed augite with inclusions of magnetite. Depth of 39 feet. X 40.

E. Slightly resorbed augite with well defined reaction rim of enstatite. Note circular core of highly resorbed olivine. Depth of 36 feet. X 40.

F. Augite intergrown with plagioclase surrounding a resorbed core of olivine. Depth of 18 feet. X 50.

G. Augite replacing large plagioclase phenocryst at depth of 147 feet. X 70.

H. Reaction rim of enstatite (marked by inclusions of magnetite) surrounding augite. Depth of 78 feet. X 125.

I. Typical enstatite crystal of the groundmass. Depth of 6 feet. X 100.

J. More completely crystalline area in angle of resorbed plagioclase phenocryst. Note octahedra of magnetite. Depth of 78 feet. X 150.

K. Small crystalline area in groundmass. Note apatite prism and octahedra of magnetite. Depth of 108 feet. X 200.

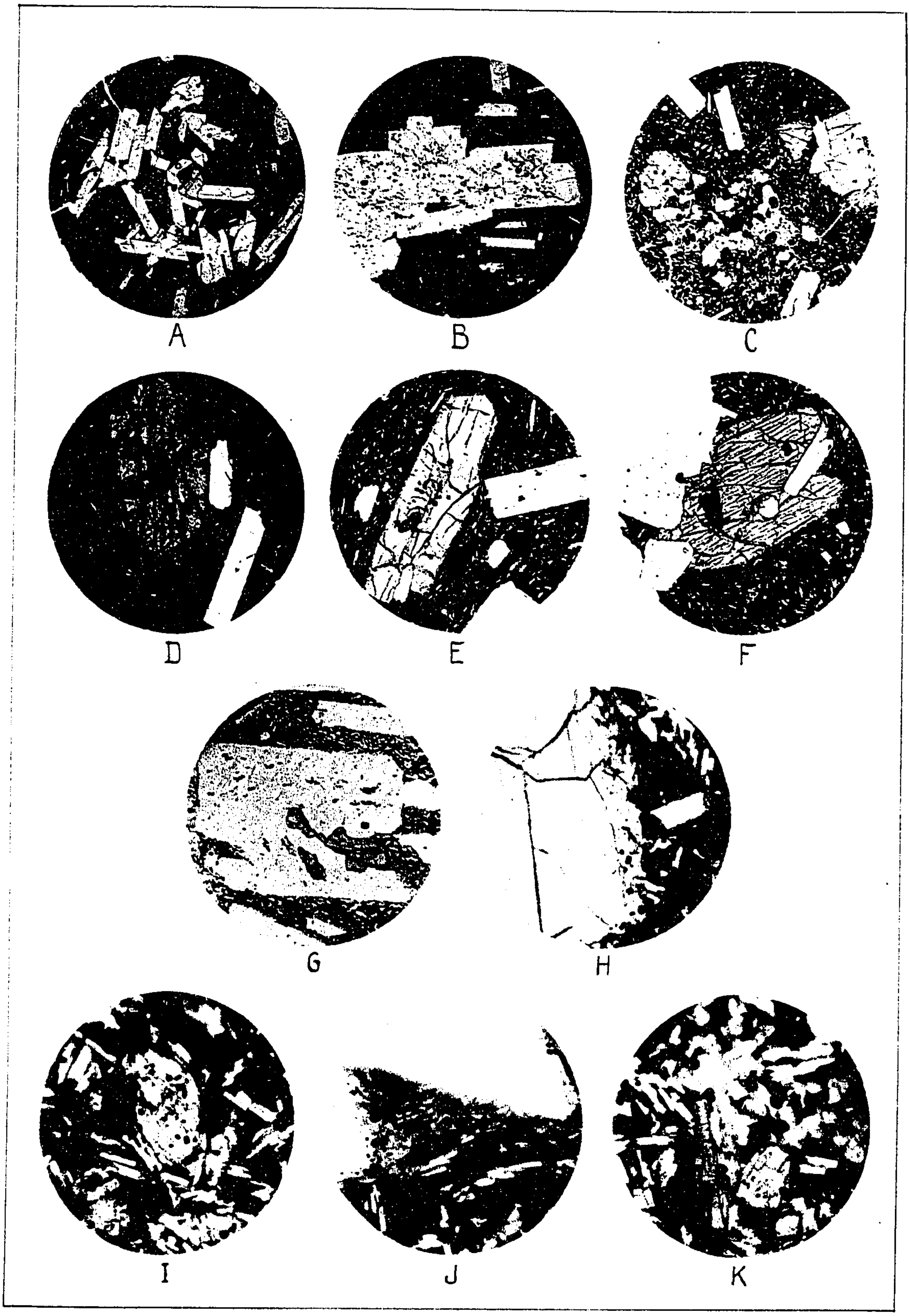

Plate III - Smaller Phenocrysts and Groundmass Constituents of the Table Rock Flow.

PLATE IV

A. Apatite prism associated with ilmenite (?) forming in a fracture plane of a large plagioclase phenocryst. Depth of 6 feet. X 150.

B. Apatite with ilmenite (?) within augite. Depth of 12 feet. X 80.

C. Ilmenite pseudomorph with apatite after olivine. Note halo of groundmass plagioclase around the ilmenite. Depth of 123 feet. X 50.

D. Apatite in the groundmass. Arrangement of plagioclase laths clearly indicate the earlier separation of apatite. Depth of 6 feet. X 90.

E. Apatite associated with augite. Note ilmenite (?) at contact and relation of groundmass plagioclase to apatite as in D. Depth of 6 feet. X 90.

F. Chlorite and magnetite replacing a group of olivine crystals along fractures. Depth of 3 feet. X 30.

G. Ilmenite- Apatite pseudomorph after olivine surrounded by later chlorite-magnetite stage of hydrothermal activity. Depth of 147 feet. X 20.

H. Orange glass filling fractures in large plagioclase phenocryst. Depth of 144 feet. X 50.

I. High power of H. Showing contraction of chlorophaeite from cavity walls and separation of a small amount of magnetite. X 150.

J. Green glass filling cavity in large plagioclase phenocryst. Depth of 81 feet. X 50.

K. High power of J. Note circular arrangement of material in cavity and larger amount of magnetite separating them in the orange glass. X 150.

L. Spherulitic extinction in a chlorophaeite nodule at depth of 45 feet. X 150.

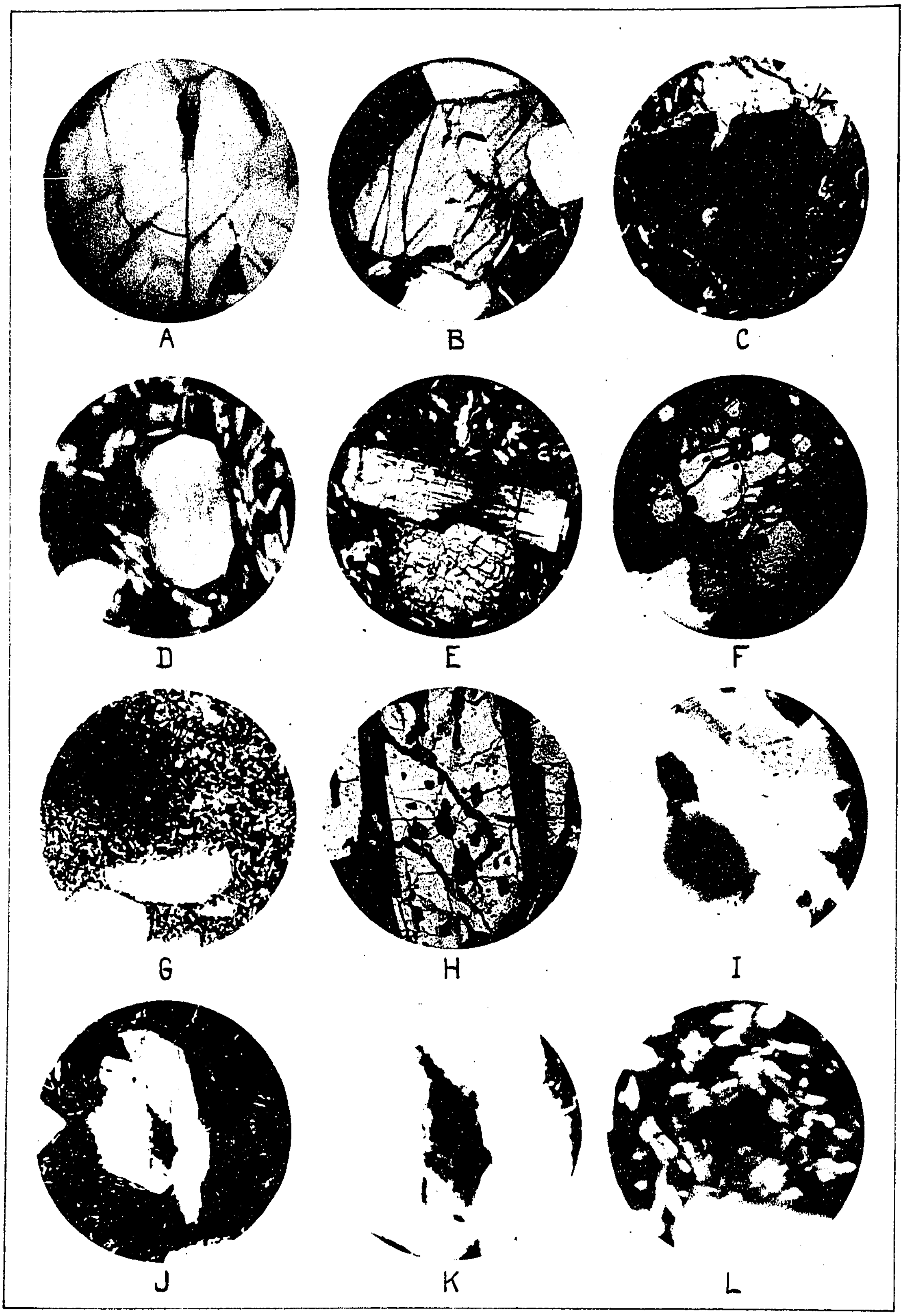

Plate · IV - Hydrothermal Constituents of the Table Rock Flow —

PLATE V.

Textural Change in the Grand Coulee Flow

A, B, C. From depths of 3, 10, and 16 feet respectively. A gives the typical hyalopilitic texture with B giving the variation to the intersertal texture, C, at the base. X 20.

D. Depth of 1 foot. Note almost complete absence of augite except in a few isolated patches where it is intergrown with plagioclase. X 30.

E. Depth of 2 feet. Hyalopilitic texture with only a small quantity of augite granules. Resorbed phenocrysts of plagioclase. X 30.

F. Depth of 5 feet. Large phenocryst of plagioclase badly fractured and resorbed. Note slightly larger amount of augite granules. X 30.

G. Depth of 7 feet. X 30.

H. Depth of 11 feet. Note larger separation of augite granules in area surrounding olivine crystal in center of photograph. X 30.

I. Depth of 13 feet. X 30.

J. Depth of 14 feet. Plagioclase phenocryst, chlorophaeite nodular areas (center and upper sections of photo). Note slightly greater quantity of augite. X 30.

K. Depth of 15 feet. Chlorophaeite areas, almost complete separation of augite and plagioclase. X 30.

L. Depth of 16 feet. Most crystalline portion of flow. Note interstitial character of magnetite. Badly resorbed plagioclase phenocryst being replaced by augite. Typical intersertal character. X 30.

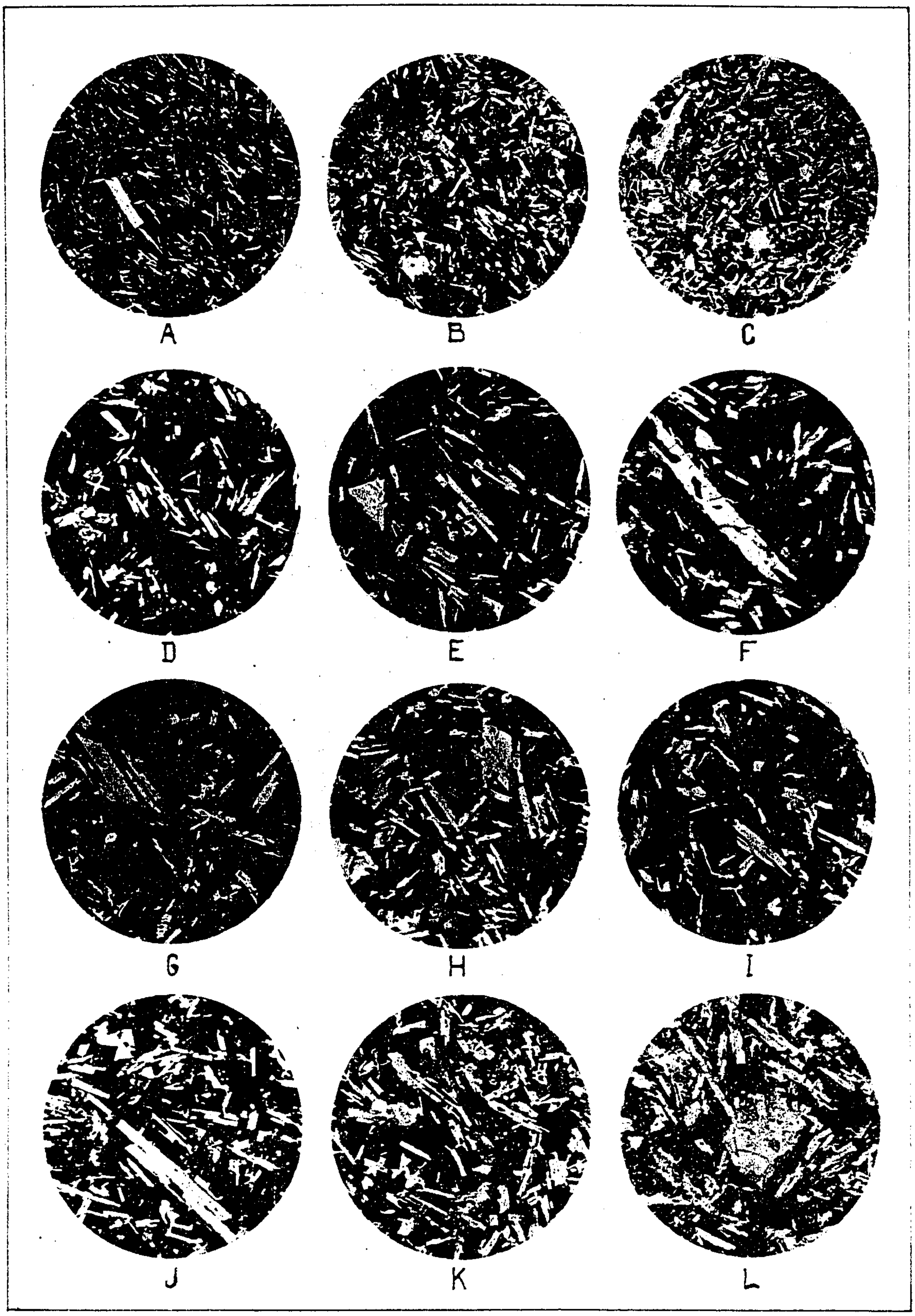

Plate V - Textural Variations in the Grand Coulee.

PLATE VI

A. Intergrown plagioclase and olivine (badly chloritized). Depth of 15 feet. X 150.

B. Olivine phenocrysts. Depth of 3 feet. X 30.

C. Group of badly resorbed plagioclase phenocrysts at depth of 6 feet. X 40.

D. Augite replacing plagioclase at a depth of 16 feet. (High power of photo L, Pl. V).

E. Radiating fibers of augite (?) in the residuum at a depth of 16 feet. X 150.

F. Augite intergrowing with plagioclase of the groundmass. Depth of 15 feet. X 125.

G, H. Relation of sections cut parallel and those cut normal to the flow surface. Depth of 12 and 18 feet respectively. Sections cut parallel (right side of each photo) average 6 % greater total area of plagioclase. X 30.

I. Skeletal arborescent growth of magnetite at depth of 15 feet. X 150.

J. Skeletal plagioclase with indistinct augite granules separating in the hyalopilitic upper portion of the flow. Depth of 1 foot. X 150.

K. Indistinct relation of hydrothermal material in center of photograph completely surrounding plagioclase and augite. Depth of 9 feet. X 30.

L. Chlorophaeite nodule, lower right hand corner of photograph. Depth of 14 feet. X 30.

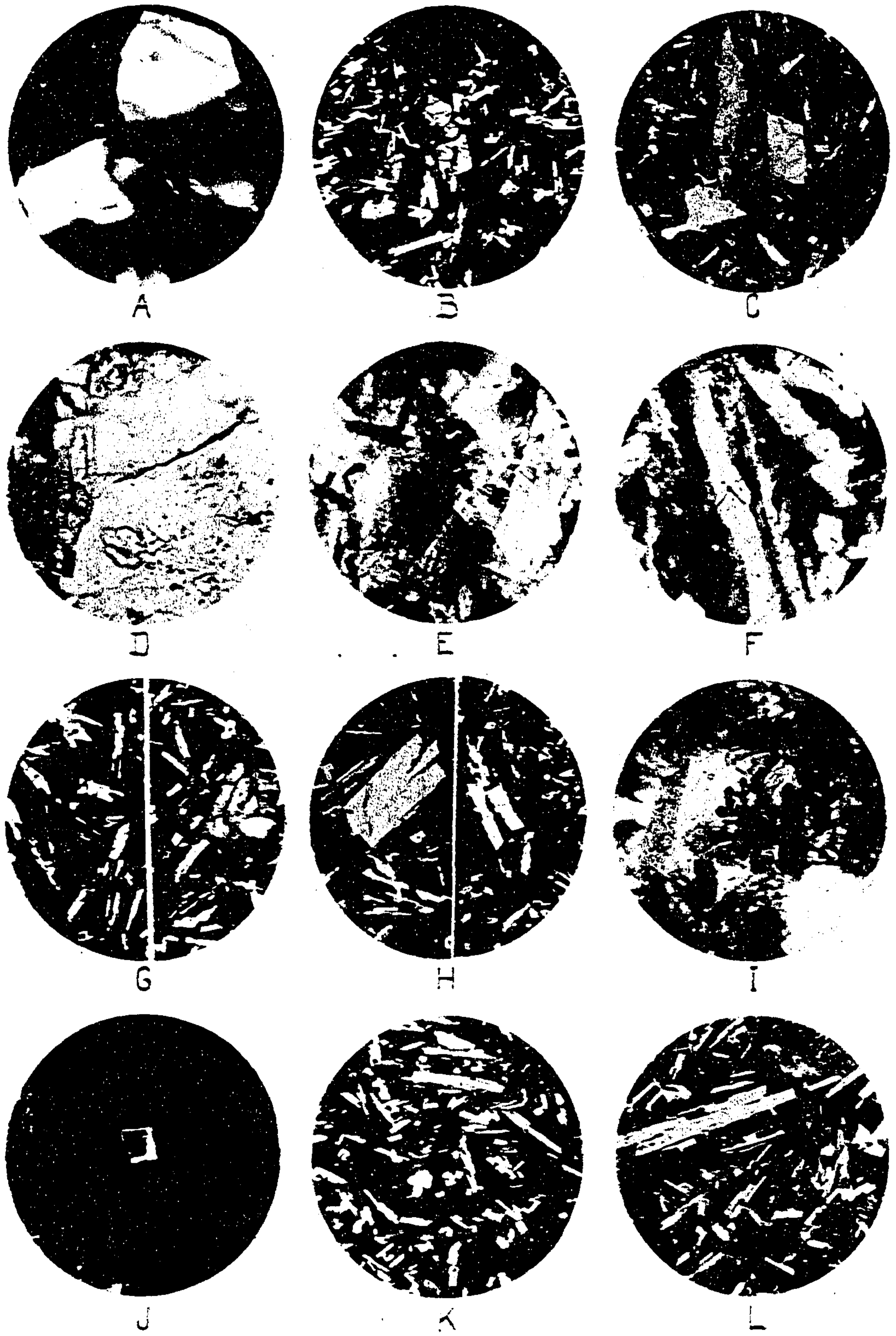

Plate VI — Minerals of the Grand Coulee Flow

PLATE VII

Textural Variations in the Bend Flow

A. Depth of 1 foot. Typical diabasic, inequigranular hyalocrystalline intersertal texture. Note deep black character of residuum. X 20.

B. Depth of 2 feet. Essentially the same as A. Note reaction rim of augite around large olivine in lower portion of photograph. X 20.

C. Depth of 4 feet. Holocrystalline, intergranular phase. X 20.

D. Depth of 11 feet. Holocrystalline, sub-ophitic phase. Note resorbed plagioclase phenocryst. X 20.

E. Depth of 18 feet. Holocrystalline ophitic textural phase at center of flow. Note shape and character of vesicles at margins of ophitic mass. X 20.

F. Depth of 28 feet. Extreme depth of holocrystalline ophitic phase. Note interstitial character of magnetite. X 20.

G. Depth of 22 feet. X 40.

H. Depth of 21 feet. Holocrystalline sub-ophitic phase below center of flow. Note replacement of olivine by magnetite along fractures and at the periphery. X 20.

I. Depth of 28 feet. Holocrystalline, intergranular phase below center. Note replacement of small plagioclase phenocryst at center of photograph. X 20.

J. Depth of 30 feet. Hyalocrystalline, intersertal textural phase at base. Augite in very fine granules. Note higher percentage of plagioclase here and also in photograph A. X 20.

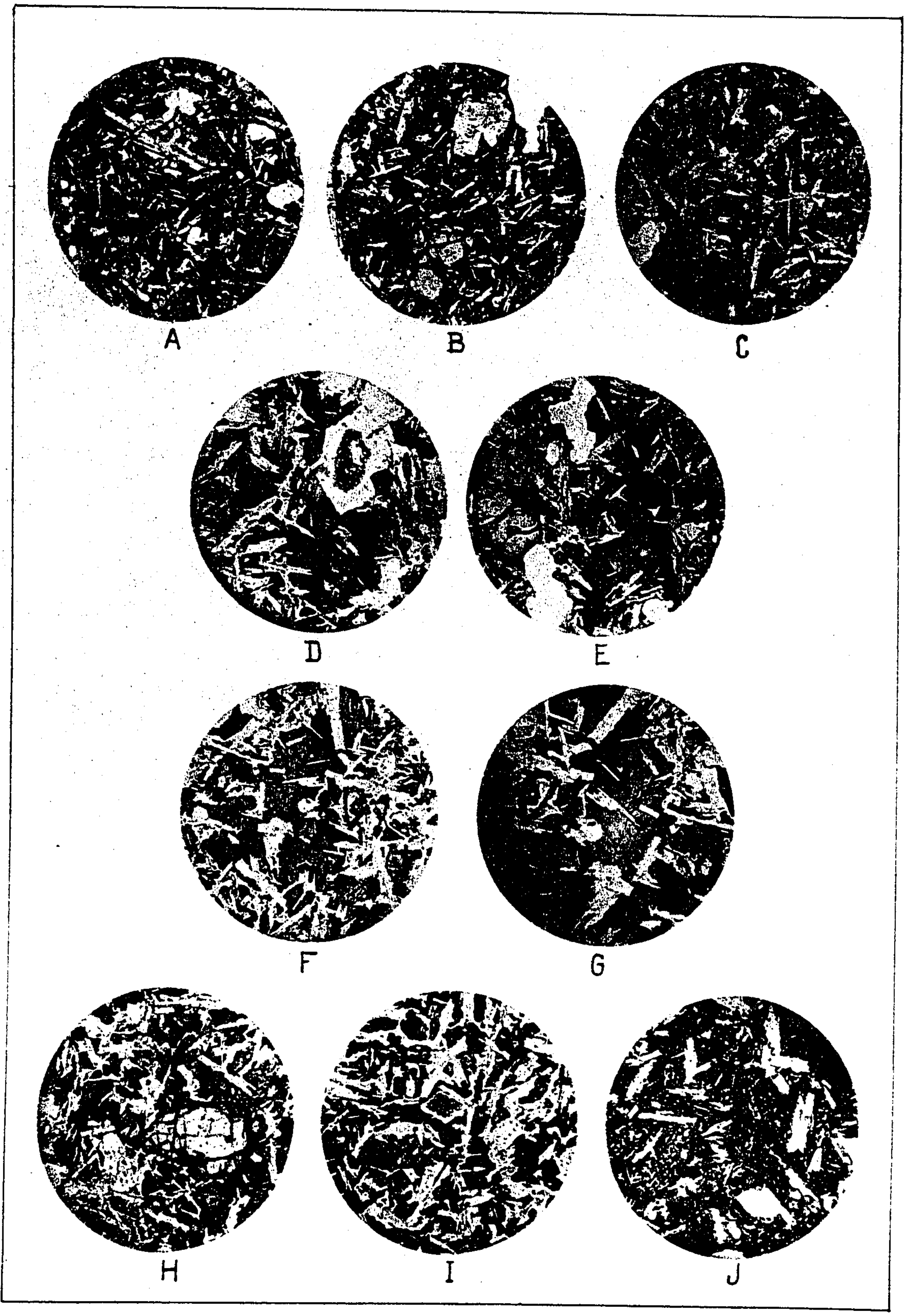

Plate VII Textural Variations in the Bend Flow—

PLATE VIII

A. Large plagioclase phenocryst. Depth of 11 feet. This crystal has the progressively zoned calcic core almost completely replaced by fine augite granules. X 80.

B. Typical large plagioclase phenocryst badly fractured and resorbed. Depth of 25 feet. Note reaction zone completely surrounding the corroded original crystal. Magnetite is found in larger quantities near the contact of these crystals and the groundmas. X 20.

C. Augite replacing the basic plagioclase phenocryst shown in B. Note reaction zone surrounding basic core. X. 60.

D. Typical occurrence of apatite (?) extending outward, fan-fashinn, into plagioclase from the contact between two crystals. Note association with magnetite. Depth of 16 feet. X 125.

E. Olivine crystal with augite occupying a corrosion channel. Note replacement of olivine by magnetite along fractures. Depth of 18 feet. X 60.

F. Augite crystallizing around an olivine crystal. Depth of 10 feet. X 30.

G. Reaction rim of augite around an olivine crystal at depth of 10 feet in the flow. X 80.

H. Replacement of olivine and augite by magnetite. Depth of 14 feet. X 20.

I. Large vesicle filled with colorless opal, indented by plagioclase laths and lined with ferric oxide. Depth of 6 feet. X 40.

J. Small interstitial vesicle filled with yellowish opal. Note separation of magnetite octahedra. Depth of 7 feet. X 100 approx.

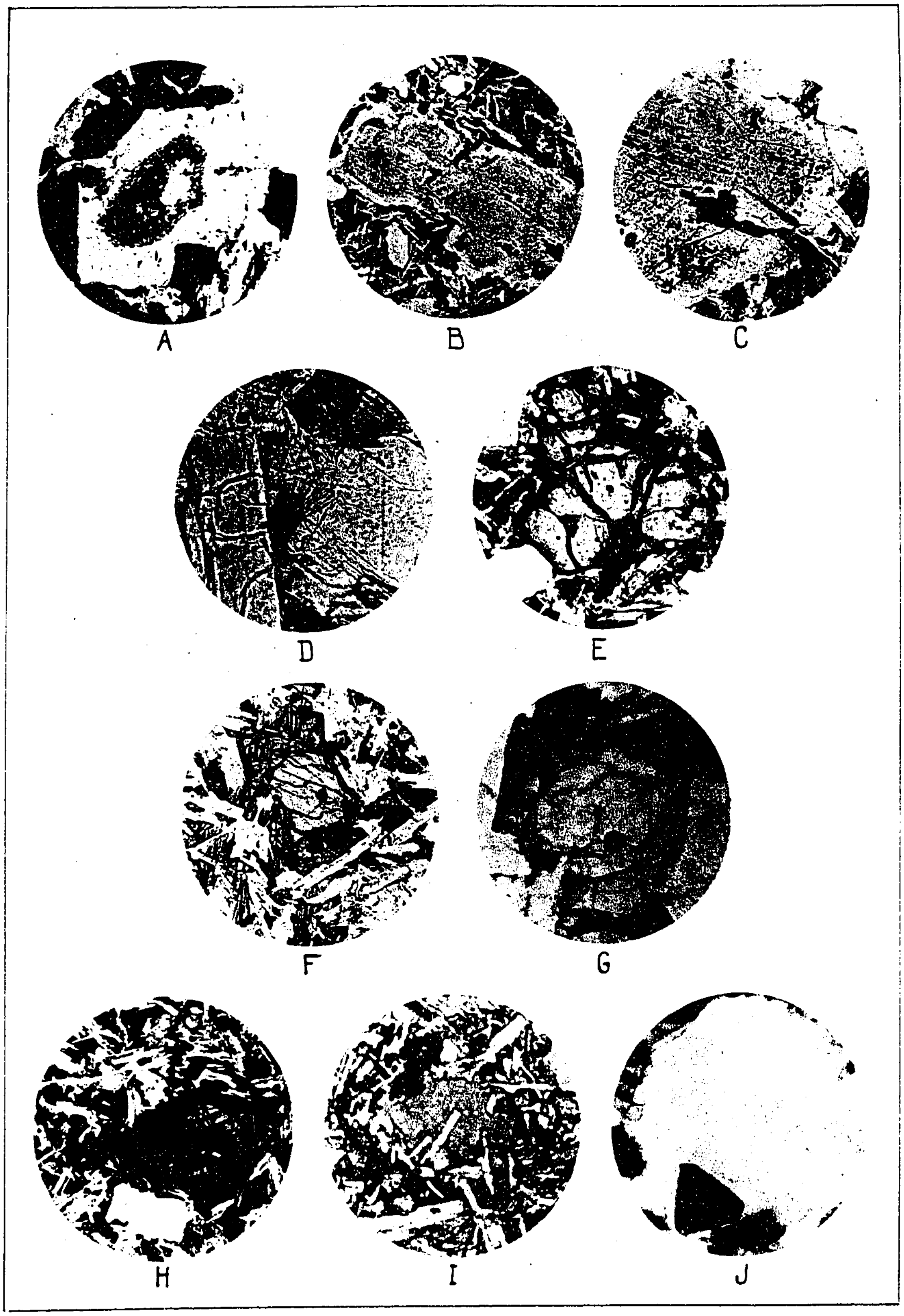

Plate VIII - Minerals of the Bend Flow

APPENDIX TABLES

TABLE A

Percentage Variation of Minerals with Depth in the Table Rock

Columns A - Sections cut parallel to flow surface
Columns B - Sections cut normal to flow surface

Depth	LARGE PHENOCRYSTS						SMALL PHENOCRYSTS				GR			
	Plag.(An)		Olivine		Magnetite		Plag.(An)		Augite		Plag.(An)		Enstatite	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
3	10	6	6	8	0	2	3	7	4	3	26	26	14	14
6	11	7	5	8	2	0	7	7	2	5	[illegible]	33	12	13
9	11	7	4	5	0	1	7	8	4	6	26	27	15	13
12	14	8	3	4	1	1	9	8	6	6	24	24	13	12
15	15	9	3	5	1	1	8	9	4	2	25	24	10	15
18	14	9	8	0	1	1	2	8	4	4	24	26	11	13
21	17	6	4	2	1	1	7	10	5	8	21	23	11	12
24	16	9	1	1	1	1	10	10	3	7	21	24	12	13
27	14	7	1	5	1	1	10	10	5	8	25	24	13	13
30	14	10	3	5	0	1	5	2	5	5	24	23	14	12
33	12	6	2	5	0	1	11	10	6	6	22	26	13	10
36	8	7	5	1	1	1	6	9	8	6	24	26	12	13
39	13	3	4	1	1	0	9	10	7	5	24	28	11	15
42	8	7	3	2	0	1	6	11	4	7	26	28	15	13
45	11	8	2	2	0	1	17	5	5	7	20	28	12	15
48	6	5	1	0	1	1	11	9	3	2	26	30	13	13
51	7	7	3	0	1	1	11	9	4	4	25	29	12	13
54	7	10	6	2	0	1	5	17	7	4	27	30	15	12
57	8	8	2	2	1	1	12	11	4	6	27	25	13	13
60	7	5	1	5	1	0	8	13	2	9	22	24	14	11
63	12	9	2	1	1	1	11	15	3	10	26	[illegible]	13	11
66	10	8	2	2	1	1	9	15	3	4	28	[illegible]	11	14
69	5	7	4	2	1	1	11	17	2	4	29	[illegible]	13	[illegible]

TABLE 4.

entage Variation of Minerals with Depth in the Table Rock Flow.

Columns A - Sections cut parallel to flow surface
Columns B - Sections cut normal to flow surface.

	SMALL PHENOCRYSTS				GROUNDMASS									
etite	Plag.(An[illegible])		Augite		Plag.(An[illegible])		Enstatite		Magnetite		Glass		Hydrothermal	
B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
2	3	7	4	3	26	36	14.	14	1	[illegible]	34	32	0	0
[illegible]	7	7	2	5	32	28	12	12	2	1	32	34	2	1
1	7	8	4	6	25	27	15	12	1	2	30	32	1	2
1	9	8	6	6	24	24	13	12	2	1	26	35	2	3
1	8	9	4	[illegible]	25	24	10	15	2	2	29	32	3	4
1	8	8	4	4	24	26	11	13	1	2	28	30	1	2
1	7	10	5	8	21	23	11	13	2	2	30	33	2	2
1	10	10	3	7	21	24	12	12	2	1	32	34	4	0
1	10	10	5	8	25	24	13	13	3	1	27	29	3	3
1	5	9	5	5	24	23	14	12	1	2	34	33	1	1
1	11	10	6	6	22	26	13	10	2	1	30	33	0	0
1	6	9	2	6	24	26	12	12	1	1	34	32	1	1
0	9	12	7	5	24	23	11	15	1	1	30	34	0	1
1	6	11	4	7	26	29	15	13	2	2	25	32	1	1
1	17	5	5	7	20	28	12	15	1	2	30	35	2	2
1	11	9	3	3	25	30	13	13	2	1	29	35	3	2
1	11	9	4	4	25	32	12	13	3	3	30	25	3	1
1	5	17	7	4	27	30	15	12	1	3	25	30	2	2
1	12	11	4	6	27	25	13	13	1	1	21	30	0	1
0	8	13	2	9	30	24	14	11	2	2	34	29	0	3
1	11	15	5	10	26	33	13	11	1	2	29	27	4	3
1	9	15	3	4	28	23	14	14	2	1	30	32	1	2
1	11	17	4	4	29	22	13	12	2	3	32	32	1	1

TABLE A (Continued)

	LARGE PHENOCRYSTS						SMALL PHENOCRYSTS							
Depth	Plag.([illegible])		Olivine		Magnetite		Plag.(An$_{50}$)		Augite		Plag.(An$_{40}$)		Enstatite	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
72	13	4	[illegible]	2	0	1	15	6	6	7	29	27	11	13
75	7	10	[illegible]	2	0	1	18	15	5	5	21	23	12	13
78	8	10	1	2	1	1	12	18	8	3	30	27	13	13
81	11	9	2	[illegible]	0	1	12	10	4	6	25	25	13	11
84	3	12	3	2	1	0	14	16	8	7	30	24	12	10
87	10	9	3	4	1	0	10	16	9	7	27	30	12	1
90	12	10	3	2	1	1	17	15	6	6	[illegible]	26	12	12
93	15	12	4	4	1	0	13	15	6	10	37	25	15	10
96	13	12	2	7	0	0	12	20	8	8	31	18	12	10
99	13	9	3	3	1	1	9	16	8	6	25	29	13	12
102	9	10	1	1	0	1	12	15	3	6	26	30	12	12
105	10	10	[illegible]	1	1	1	12	12	8	4	27	28	13	12
108	11	8	[illegible]	[illegible]	[illegible]	[illegible]	13	20	10	7	30	26	13	14
111	11	7	1	4	1	1	13	13	9	7	26	23	13	13
114	12	8	4	3	1	0	13	16	10	10	25	27	14	12
117	16	12	8	4	[illegible]	2	15	15	12	8	24	20	13	13
120	17	12	6	9	1	3	8	11	10	8	26	[illegible]	15	1
123	18	15	5	9	[illegible]	[illegible]	10	9	7	7	[illegible]	32	14	12
126	20	13	5	3	2	3	13	7	9	6	[illegible]	26	9	16
129	17	12	1	3	3	2	10	10	9	8	25	33	15	15
132	18	13	4	1	1	1	9	8	12	8	31	34	15	1
135	20	1	0	1	0	1	6	16	6	10	32	27	16	1
138	21	13	1	1	1	1	9	10	8	6	28	28	15	17
141	20	13	0	0	1	0	6	6	10	9	36	37	13	15
144	11	9	0	0	1	1	9	10	8	8	30	40	14	16
147	10	7	0	0	[illegible]	2	10	8	5	11	42	42	13	1

TABLE A (Continued)

TS		SMALL PHENOCRYSTS				GROUNDMASS									
Magnetite		Plag. (An_{50})		Augite		Plag. (An_{40})		Enstatite		Magnetite		Glass		Hydrothermal	
A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
0	1	12	8	6	7	28	27	11	13	1	1	27	34	1	3
0	1	18	12	5	5	21	23	12	13	2	3	31	39	2	2
1	1	12	18	8	3	30	27	12	13	2	2	25	20	1	4
0	1	12	13	4	6	25	25	12	11	1	3	32	27	1	5
1	0	14	16	8	7	30	24	12	10	2	2	24	26	3	1
1	0	10	16	8	7	27	30	12	13	3	1	25	20	1	1
1	1	17	12	6	6	24	26	12	12	2	2	21	26	2	3
1	0	13	15	8	10	27	25	12	10	2	2	20	22	1	1
0	0	12	20	8	8	21	18	12	10	2	2	29	22	1	1
1	1	8	16	8	6	25	28	12	13	3	2	24	29	6	0
0	1	12	15	3	6	26	30	13	12	2	1	25	20	6	4
1	1	10	12	8	4	27	28	13	12	1	2	19	27	9	3
2	2	13	20	10	7	30	26	12	14	1	1	27	15	2	5
1	1	12	13	9	7	26	23	12	13	1	2	24	26	3	4
1	0	13	15	10	10	25	27	14	12	2	2	16	20	3	3
2	2	15	15	10	8	24	30	13	13	1	3	11	11	0	2
1	2	8	11	10	8	26	22	15	12	2	3	15	17	0	1
2	2	10	9	7	7	23	23	14	12	4	1	17	20	0	2
2	2	13	7	9	6	22	26	9	16	3	6	14	18	3	3
2	2	10	10	9	8	25	33	15	15	5	3	11	10	5	4
1	1	9	8	12	8	24	34	15	14	5	4	10	11	2	6
0	1	6	16	6	10	30	27	16	11	7	3	10	10	5	7
1	1	9	10	8	6	28	38	12	17	6	4	6	8	5	5
1	0	8	8	10	9	36	37	13	15	5	5	7	6	2	7
1	1	8	10	3	8	39	40	14	16	5	5	10	7	4	4
2	2	10	8	5	12	42	42	15	15	4	4	7	8	5	4

TABLE B

Percentage Variation of Minerals with Depth in the Grand Coulee Flow

Columns A - Sections cut parallel to flow surface
Columns B - Sections cut normal to flow surface

	PHENOCRYSTS				GROUNDMASS						
Depth	Plag. (An_{60})		Olivine		Plag. (An_{50})		Augite		Magnetite		Glass
	A	B	A	B	A	B	A	B	A	B	A
1	3	1	1	1	32	28	15	17	1	1	47
2	1	1	2	2	36	31	16	17	1	1	43
3	2	3	2	2	34	30	16	16	1	1	42
4	4	2	3	1	38	30	14	18	1	1	38
5	1	1	4	0	33	32	17	21	1	1	35
6	6	4	1	3	36	32	22	23	1	1	22
7	6	4	2	2	40	30	20	26	1	1	27
8	5	3	2	2	33	32	16	20	1	1	34
9	2	2	0	4	34	34	22	20	1	1	35
10	3	3	2	2	32	34	16	20	1	1	35
11	2	4	1	3	38	33	20	19	1	3	34
12	1	1	1	1	37	33	20	26	2	2	31
13	2	2	1	1	35	35	24	22	2	4	30
14	4	2	1	5	38	34	23	23	2	4	25
15	5	3	3	3	38	38	30	30	5	5	12
16	3	3	0	0	40	40	40	40	10	10	4

TABLE B

Percentage Variation of Minerals with Depth in the Grand Coulee Flow

Columns A - Sections cut parallel to flow surface
Columns B - Sections cut normal to flow surface

	GROUNDMASS								HYDROTHERMAL	
livine	Plag. (An_{50})		Augite		Magnetite		Glass		Chlorophaeite	
B	A	B	A	B	A	B	A	B	A	B
1	32	28	15	17	1	1	47	51	1	1
2	36	31	16	17	1	1	43	47	1	1
2	34	30	16	16	1	1	42	46	3	3
1	38	30	14	18	1	1	38	42	2	6
0	38	33	17	21	1	1	35	37	4	8
3	36	32	22	23	1	1	22	31	7	7
2	40	30	20	26	1	1	27	31	4	4
2	35	32	16	20	1	1	34	30	4	12
4	34	34	22	20	1	1	35	29	6	10
4	38	34	16	20	1	1	35	35	5	5
3	36	33	20	19	1	3	34	30	4	8
1	37	33	20	26	2	2	31	29	8	8
1	35	35	24	22	2	4	30	26	6	10
5	38	34	23	23	2	4	25	25	7	7
3	38	38	30	30	5	5	12	12	8	8
0	40	40	40	40	10	10	4	4	3	3

TABLE C

Percentage Variation of Minerals with Depth in the Bend Flow

Columns A - Sections cut parallel to flow surface
Columns B - Sections cut normal to flow surface

Depth	PHENOCRYSTS				GROUNDMASS							
	Plag. (An_{75})		Olivine		Plag. (An_{62})		Augite		Magnetite		Glass	
	A	B	A	B	A	B	A	B	A	B	A	B
1	4	4	4	4	45	51	27	27	8	8	12	6
2	7	6	5	8	44	43	29	29	8	8	7	6
3	6	6	5	5	44	44	33	37	7	3	5	5
4	3	3	9	8	41	43	37	40	10	6	0	0
5	6	2	11	11	40	43	35	36	8	8	0	0
6	7	6	12	11	38	42	35	39	8	2	0	0
7	10	7	9	2	36	44	40	42	5	5	0	0
8	4	4	5	9	45	41	40	41	6	5	0	0
9	4	3	8	6	43	43	32	43	13	5	0	0
10	9	3	7	10	40	41	34	34	10	12	0	0
11	7	3	11	13	42	43	37	30	3	9	0	0
12	4	8	14	8	40	43	35	35	7	6	0	0
13	6	4	5	7	43	44	31	30	15	15	0	0
14	1	4	10	11	45	43	35	25	9	17	0	0
15	3	3	5	1	43	44	31	32	18	20	0	0
16	10	6	8	10	40	41	28	28	14	15	0	0
17	6	4	3	7	43	40	41	42	7	7	0	0

TABLE C (Continued)

Depth	PHENOCRYSTS Plag. (An75) A	B	Olivine A	B	GROUNDMASS Plag. (An62) A	B	Augite A	B	Magnetite A	B	Glass A	B
18	3	3	10	4	44	42	31	31	12	10	0	0
19	5	1	8	13	42	43	40	41	5	5	0	0
20	1	[illegible]	5	11	48	44	31	30	15	11	0	0
21	3	[illegible]	10	13	47	46	33	36	[illegible]	3	0	0
22	2	4	19	12	43	47	32	33	4	4	0	0
23	4	[illegible]	19	17	44	45	30	33	5	5	0	0
24	3	3	17	16	45	46	29	29	5	6	0	0
25	3	5	9	17	45	37	34	33	9	8	0	0
26	7	7	10	16	37	33	33	27	13	17	0	0
27	7	3	13	9	39	47	34	33	7	8	0	0
28	6	3	5	3	43	43	35	29	10	20	1	2
29	10	7	[illegible]	8	44	43	36	32	8	10	0	0
30	10	5	6	11	41	44	27	24	9	7	7	9
31	5	9	10	7	47	43	23	28	8	3	7	11