ART. XVII.—*The Crystallization of a Basaltic Magma from the Standpoint of Physical Chemistry*; by CLARENCE N. FENNER.

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INTRODUCTION.

WITHIN the last few years petrographers have recognized the important aid which might be rendered to the interpretation of the structure and history of igneous and metamorphic rocks by an application of the principles of physical chemistry. The discoveries which have been made regarding the laws governing the crystallization of solutions, the application of the phase-rule of Gibbs and of the law of mass-action, and the new conception of the phenomena of solid solutions, are believed to be capable of rendering very great assistance in interpreting the meaning of the structures with which petrographers have become familiar.

Although the applicability of these principles is generally conceded, very little has yet been done in applying them to specific cases.

In making a study of certain peculiar phases of the basalt which forms the Watchung Mountains in New Jersey, it came to be recognized that the rather unusual conditions which had attended its solidification had produced results which illustrated certain laws of the crystallization of solutions more perfectly than could be hoped for from the most elaborately devised laboratory experiments.

In a previous article* the author has shown that the Watchung sheets were surface flows poured out over areas in which Triassic shales and sandstones were accumulating under conditions of continental sedimentation in structural valleys.† At most points the basalts present the dense, holocrystalline texture normal to this type of rock, but in certain areas the flows appear to have spread over the sites of shallow lakes, and

* Features Indicative of Physiographic Conditions Prevailing at the Time of the Trap Extrusions in New Jersey. *Journ. of Geol.*, vol. xv, No. 4, May-June, 1908.

† See also J. V. Lewis, Annual Report N. J. State Geol. Survey for 1906.

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many modifications of structure resulted. The chief effect, as regards the features which will be considered in this paper, was that the fused magma was rapidly chilled and rendered viscous. In places the stiffening liquid accumulated in masses of rounded or boulder-like forms similar to the "pahoe-hoe" of Hawaiian flows. The progress of crystallization was checked at various stages and the boulder-forms were encrusted with basaltic glass, in which examination with the microscope shows few phenocrysts, while the more slowly cooling interiors of the boulders assumed the normal texture. Between the two types transitions occur, by which one may trace the passage of the microlites of the vitrophys into the well-developed crystals of normal basalt.

The glass-encrusted boulders are especially well developed in an area lying between Paterson and Montclair Heights. Quarries have been opened at several points, as it has been found that this variety of trap is easily blasted and crushed for road-material. It has therefore been possible to obtain material for petrographic study unacted upon by weathering.

SCOPE OF THE ARTICLE.

Two principal features of the Watchung basalt will be considered, and in accordance with this the article is divided into two parts. Part I will deal with the order of crystallization of the constituent minerals, and it will be shown that, contrary to certain prevalent ideas regarding the order of succession of the minerals of a basaltic rock, the three constituents, plagioclase, diopside, and magnetite, began to appear almost simultaneously from the magma and continued to crystallize side by side until complete solidification was attained. In order to show that this result is demanded by the laws of crystallizing solutions, a very brief outline of these laws will be given as a preliminary to the petrographic study.

In Part II resorption-phenomena will be considered in connection with the resorption of olivine, a minor feature as regards the constitution of the rock, but very significant in its interpretation.

The law of mass-action will be considered in this connection, and the author will endeavor to show that the usual explanation of resorption is inadequate to explain certain phases of the phenomenon, but that a very satisfactory explanation may be derived from an application of van't Hoff's law.

PART I.

Process of Crystallization as demanded by the Laws governing Eutectiferous Solutions.

In order that the crystallization of a magma may proceed strictly along the lines indicated by eutectic laws, it is essential that

there shall be little or no reaction going on within the magmatic solution from the time that the initial crystals appear until the process of solidification is complete. In such cases the progress of solidification is very regular. Each compound present in the fusion has its temperature of solidification depressed according to the number of mols (gram-molecules) of other substances present and begins to appear at the appropriate point in the process of cooling. That mineral will first appear which, under the conditions stated regarding fusing-point, still has the highest temperature of fusion.

The first mineral may be regarded as that which is present in greatest excess over the eutectic ratio. Within a certain range of temperature it alone will be thrown out of solution. At a certain point, however, it will be joined by a second mineral, and these two in turn by a third. The composition of the solution approaches the eutectic ratio by the elimination of those constituents which are in excess. A sudden chill at any stage of the process causes a great increase of viscosity, which acts as a very effectual check to further crystallization. The result is the production of the greatly undercooled liquid of immense viscosity which is termed a glass. The composition of the glass depends upon the stage of progress toward the attainment of the eutectic ratio which has been reached. If no such interruption occurs, at the eutectic point the group of minerals forming the eutectic will crystallize out in the proper ratio. No further depression of the temperature of solidification can occur, and the loss of heat will be merely that due to the latent heat of fusion given up by each mineral in passing from the liquid to the crystalline phase. An application of the phase-rule of Gibbs confirms this conclusion, for at the eutectic point the number of phases exceeds the number of components by one, and no change of temperature or composition of the system can occur.

It is doubtful whether the solidification of a magma is ever quite such a simple process as is expressed in the form described, but though complications may ensue, the underlying principles of eutectics hold and should constitute a guide of great value in interpreting rock structures and history. In the solidification of the Watchung magma the reactions which would tend to obscure the process were of such nature that their results do not offer great obstacles. The only one of moment is that by which olivine was crystallized out and later was resorbed by the magma and did not again appear. This phenomenon will require explanation, but it is due to other physico-chemical laws, and the reaction was so nearly complete before the three final constituents, diopside, plagioclase, and magnetite, began to appear, that its effects may be disregarded for the present.

Petrographic Description of the Watchung Basalt.

In those portions of the Watchung flow in which chilling was most rapid the surfaces of the pahoehoe-like bosses were crusted with much glassy material. Apparently, however, judging from the study of a great number of slides, crystallization was under way and phenocrysts had begun to appear in the mass of flowing lava before the sudden chill occurred which stiffened it into a glass. The resultant glass shows a typical vitrophyric texture. The well-developed phenocrysts are surrounded by isotropic glass or by a groundmass in which glassy material is more or less mixed with the feathery forms of microclites. Under the generally accepted hypothesis, in a typical diabase consisting of magnetite, plagioclase, and diopside, the magnetite would be first to form, and its elimination from the magma would be complete before the plagioclase began to appear. These two are held to be followed by the third constituent, diopside, which occupies the space left by the other two. On the other hand, the manner in which the minerals should crystallize out, as demanded by the principles of eutectiferous solutions, is quite different, and in every case the sections examined conform to the latter requirements. No matter to what degree glass may be present in the slide, plagioclase and diopside appear side by side. It is evident that almost from the beginning of crystallization these two constituents were being eliminated simultaneously. At times it appears that the diopside is in somewhat preponderant amount, and at other times the plagioclase.

With regard to the magnetite the evidence is more obscure. The proportion of magnetite in the magma is not large and it seems to appear first as a dark dust. The exact point at which elimination from the fusion began is not clear, but it is certain that growth of magnetite grains continued while diopside and plagioclase were still forming.

Slide No. 105 shows a typical development of glass and phenocrysts. (See fig. 1.)

Probably three-fourths of the section is isotropic glass, uniformly pale green or light olive-green in the thin section. Scattered throughout are numerous phenocrysts of plagioclase and diopside. The plagioclase is in typical lath-like crystals reaching an ordinary maximum of $0.2-0.3^{\text{mm}}$ long by $.05^{\text{mm}}$ wide. The diopside is developed in more nearly equidimensional forms of a characteristically stouter appearance. An exceptionally large crystal measured 0.6 by 0.2^{mm} . The outline is sometimes octagonal, but in general irregular. In many cases the plagioclase and diopside are closely associated, small clusters of mutually intergrown individuals lying in groups surrounded by glass. It is noticeable in such cases

that while the plagioclase laths are indented by the diopside crystals, the characteristic elongated form of the plagioclase is maintained.

These phenocrysts of diopside and plagioclase are bordered by dark plumose growths, or hair-like tufts, fading out at the

FIG. 1.

FIG. 1. Typical structure of the vitrophyric phase resulting from quick chill. (Slide No. 105.) Elongated crystals plagioclase, stouter forms diopside, matrix light-green glass, perfectly isotropic. Actual diameter of field 1.5mm.

periphery into the surrounding glass. Under the high-power objective they are resolved into innumerable microcrystalline growths, straight or curved, sometimes branching in lattice-like forms, thrown out from the boundaries of the phenocrysts. With the high magnification they exhibit the development sketched in fig. 2.

FIG. 2.

FIG. 2. Microlitic growth of plagioclase and diopside, greatly magnified.

The phenocrysts were probably formed during rather slow cooling in the flowing mass of lava, and the bordering microlitic growths represent the continuation of the crystallization during the initial stages of chilling, before increasing viscosity put a stop to the process. Their brown color seems best explained by the separation of magnetite dust at the same time that diopside and plagioclase were crystallized out. If this is true, the eutectic ratio had been reached, and if normal crystallization had been followed the continuation of the process would have taken the form of simultaneous growth of crystals of diopside, plagioclase, and magnetite. This was prevented by the increasing viscosity of the liquid, with which crystallization could not keep pace.

The almost simultaneous appearance of diopside and plagioclase at the initiation of crystallization, attended or followed after only a short interval by magnetite, would appear to demonstrate that the composition of the magma as erupted did not differ greatly from that required to form a eutectic of the three.

The only other feature of interest in the slide is the presence of a number of olivine crystals, which have been strongly attacked and resorbed by the magma. This phenomenon will be taken up later.

Slide No. 1 is almost a duplicate of No. 105 and exhibits the same set of phenomena, except that there is no evidence of olivine grains, and that the glassy groundmass shows with high magnification abundant brown dust. Diopside phenocrysts are a very minor constituent but plagioclase is abundant.

In No. 57 the chilling was apparently a little less sudden, for the phenocrysts have a tendency to blend with the plumose microlitic borders and a smaller proportion of the slide is occupied by strictly undifferentiated glass.

Slides 30, 85, and 90 are other examples showing essentially the same relations of phenocrysts, microlites, and undifferentiated glass. In No. 132 (fig. 3), the microlites are seen to be spreading over a greater portion of the field, and in No. 2 a further stage is shown.

This latter slide was taken from the same hand specimen as No. 1, but whereas the portion of the rock from which No. 1 was taken presented a decidedly vitreous appearance, that from which No. 2 was prepared was a little farther removed from the chilled crust and was of a felsitic character. Microscopic examination confirms the deduction which would naturally be drawn. In No. 1 the phenocrysts are merely bordered by plumose microlites and a large part of the section is undifferentiated glass. In No. 2 the microlites have spread over the entire field not occupied by the phenocrysts and no glass can

be perceived. Instead there is a beautiful development of tufts and sheaves of feathery microlites occupying the entire groundmass. The phenocrysts, as before, show groups of diopside and plagioclase in mutual intergrowth. The general dark brown color of the groundmass appears to be due to dust

FIG. 3.

FIG. 4.

FIG. 3. Microlitic additions to phenocrysts of diopside and plagioclase. (Slide No. 132.) Diameter of field 1.5mm.

FIG. 4. Intermediate texture between microlitic and holocrystalline. (Slide No. 58.) Diameter of field 1.5mm.

and grains of magnetite developed along the lines of growth of the feathery microlites and outlining their form.

In slides No. 96 and No. 58 (fig. 4) a step in advance is shown toward the holocrystalline texture of a normal basalt resulting from moderately slow cooling. The sharply defined outline of the phenocrysts has been lost and their borders fray out into the finely crystalline groundmass. The groundmass itself is coarser than in the earlier described sections and the subhedral crystals are comparable in size to the phenocrysts. Some of the magnetite is in distinct grains, but much of it is still in the form of a dark dust lying between the lighter minerals.

Nos. 98, 99, and 18 (Photograph, fig. 5) show successively coarser phases of crystallization, and Nos. 23, 24, and 25 show the normally developed texture of these basalts. Nos. 47 and 64 represent the maximum of coarseness of crystallization attained.

In the normally crystallized basalt the essential constituents are plagioclase, pyroxene (diopside), and magnetite, the first two in crystalline forms, the last in dust, granules, or trellis-like groups. (See fig. 6.)

The plagioclase is in lath-shaped crystals, euhedral to subhedral, generally showing two or three stripes of albite-twinning lamellæ. Pericline twinning is rarely present. Its average

dimensions are $\cdot 15$ by $\cdot 03^{\text{mm}}$, but occasionally crystals of larger size up to 1^{mm} in length, and more nearly equidimensional, are scattered through the mass. It comprises, roughly speaking, two-fifths of the whole.

FIG. 5.

FIG. 5. Photograph of normally crystallized basalt. (Slide No. 18.) Diameter of field $2\frac{1}{4}^{\text{mm}}$.

FIG. 6.

FIG. 6. Ophitic texture of normally crystallized basalt. (Slide No. 47.) Plagioclase laths, diopside granules, and crystals and dust of magnetite in mutual intergrowth. The magnetite is mostly included in the diopside, but partly also in the plagioclase. Diameter of field $1\cdot 5^{\text{mm}}$.

Extinction angles measured on symmetrically extinguishing albite twins give maxima of 33–34 degrees. This indicates a medium labradorite of about the composition Ab 40 An 60.

The pyroxene is in stouter forms of an irregularly angular outline. The grains show a tendency to coalesce in groups of

individuals of different extinction. Single units show dimensions of 0.2 by 0.15^{mm} with occasional larger grains up to 0.5^{mm} in size. The crystals are almost colorless, with a faint tinge of brown or green. In many slides twinning is a common characteristic. Twinning and composition plane the orthopinacoid (100). Polysynthetic basal twinning is absent. Optical character biaxial and positive. No difference in dispersion between red and violet can be perceived. Prismatic cleavage often poor in the small grains but well developed in the larger. Birefringence 0.020–0.022.

Extinction measured from the ortho-pinacoidal twinning plane to the axis of minimum elasticity, *Z*, gave angles of 45 degrees. The mineral is evidently not pure diopside, but whether it varies toward hedenbergite or toward augite would be difficult to determine without chemical analysis. It is referred to as diopside. The quantity is somewhat in excess of the plagioclase.

The magnetite is seldom in euhedral crystals, more often in fine dust or in trellis-like or fir-tree groups. During the crystallization of the plagioclase and diopside the magnetite appears to have been mechanically pushed aside until the last stages of crystallization were reached, and then included within the final crystals of the lighter constituents, to which it gives a dark brown color. Even in the final stages the plagioclases seem to have had the power to free themselves of the magnetite dust fairly effectually, and most of it is included within diopside grains. A small portion is enclosed within irregular patches of light-green chloritic material, which may represent resorbed olivines subsequently chloritized.

In addition to these essential constituents there are a number of well-defined areas of what was originally olivine, but which show strong resorption and later alteration to serpentine and chlorite.

The magnetite in these rocks is probably titaniferous, as it gives rise on decomposition to milky-white leucoxene.

In examining those slides which have the texture normal to basalts the plagioclases appear to have the crystals developed in more nearly euhedral forms than the diopside, and it might be argued that this is confirmatory of the generally accepted view that the growth of the plagioclases was finished before that of the diopside began, and that the latter mineral molded itself around the plagioclase. It is only necessary, however, to devote a little study to the question to determine that this is emphatically not the case. In those vitrophyric rocks first described (e. g. No. 105 and No. 57) in which plagioclase and diopside undoubtedly developed while swimming freely in a

liquid, the plagioclase is bounded by plane faces, while the diopside has irregular outlines, and it appears that this difference in development is due to the mode of growth, the cause of which is not germane to the subject. When, in the more glassy types, the plagioclase and diopside form groups of intergrown crystals, as they often do, the characteristic form is shown in fig. 7, a notable feature of which is the manner in which the plagioclase laths wedge out toward the central portion of the diopside grains.

FIG. 7.

FIG. 7. Intergrowth of diopside and plagioclase. (Slides Nos. 2 and 57.)

These features are apparent in all phases of development of the basalt from glassy to holocrystalline, and alone would be

FIG. 8.

FIG. 8. Modification of forms of plagioclase and diopside resulting from simultaneous crystallization. A few magnetite grains (black) and some chlorite (gray) are also present (Slide No. 64).

almost conclusive evidence of simultaneous growth of the two minerals.

In the holocrystalline phases the plagioclase gives, at first, an impression of being much more euhedral than the diopside, but it is almost impossible to find a crystal in which the symmetry is not destroyed by encroachment of diopside, and the extremely irregular growth of plagioclase sketched in fig. 6 (Slide No. 47) and fig. 8 (Slide No. 64) is entirely normal and characteristic.

The magnetite is often in such fine grains that no conclusions can be drawn regarding its period of growth, but in No. 23 it is found in better developed crystals, which show unmistakably a simultaneous deposition with plagioclase and diopside. Fig. 9 shows the general relations.

FIG. 9. Inter-growth of magnetite, diopside, and plagioclase (eutectic structure—Slide No. 23).

PART II.

The Crystallization of a Magma as affected by the Law of Mass-Action.

It was pointed out on a preceding page that in order that the crystallization of a magma should follow strictly the laws of eutectiferous solutions the compounds present in the fusion-solution should have no inter-reaction during crystallization, but that simply the freezing-point of each should be depressed by the presence of the others and each should begin to crystallize at the appropriate temperature as thus modified. In the Watchung magma it appears that this ideal course was nearly realized as regards the final products of crystallization, and in many other cases this is probably true, especially where the range of temperature from the beginning of crystallization until the final consolidation of the eutectic is not large and where great variations of pressure do not occur. Reference was made, however, to resorbed olivines which appear in certain slides, and resorption-phenomena are of common occurrence in the study of igneous rocks. Their chief features are explainable by the law of mass-action.

It is well understood that when substances capable of reaction are brought together in a solution the reaction does not ordinarily proceed to completion, but that in principle every reaction is reversible and the degree to which a reaction will proceed under given conditions of temperature and pressure is dependent primarily upon the concentrations or active masses of the substances participating.

In solutions of molten silicates it is recognized that we have very little knowledge of the extent to which reactions proceed to attain equilibrium; but we know that the state of equi-

brium, i. e., the proportions in which various mineral compounds exist in the solution, depends upon the concentrations of the various oxides present.

If we imagine that in a solution of this nature in which equilibrium has been attained, crystallization begins, it is seen that a disturbing factor is introduced: for the removal by crystallization of one or more compounds is constantly changing the relative proportions of the substances left in the mother-liquor. It is evident that certain substances which may have been present in small amount in the original magma may reach a high degree of concentration in the residual dregs of mother-liquor. The conditions of equilibrium are completely shifted. New compounds are formed, while those compounds which were present in preponderant amount in the original magmatic solution may be entirely broken up and destroyed. As a result the crystals first deposited become unstable in contact with the mother-liquor and are either taken up by the solution or react with it to form zones of new minerals. This consequence of the principle of mass-action is well understood. Pirsson has thus explained reaction-rims of enstatite and biotite surrounding olivine crystals and separating them from alkali feldspar in the shonkinite of the Little Belt Mountains, Montana.*

While it is possible to account for certain phases of the phenomena of resorption in this manner, there are others which cannot be brought into line with this explanation. Magmas consolidating at depth frequently exhibit a different association of minerals from magmas of the same composition consolidating on the surface; and a magma in which intra-telluric crystallization has begun may, when erupted at the surface, attack the minerals first deposited and take them more or less completely into solution, and in the final consolidation these minerals may not re-appear. In the Watchung magma olivine crystals of the intra-telluric period were attacked and in most cases almost completely resorbed before any notable development of the three final products of surface crystallization appeared. In this case it is obvious that the phenomenon cannot be explained by reference to a concentration of material in a residual mother-liquor. To account for such occurrences the author would offer another explanation, based upon the displacements of equilibrium which take place within a solution under conditions of simultaneous diminution of pressure and temperature.

Displacements of equilibrium within a solution effected by changes of temperature and pressure—van't Hoff's law.—The extension of the law of mass-action to include changes of tem-

* L. V. Pirsson: 20th Ann. Rept. U. S. Geol. Sur., 1898-99, p. 482.

perature was developed by van't Hoff. The principle is of great importance, but it does not appear to have received the attention it merits in the study of petrological problems.

The basic principle of van't Hoff's law is that change of temperature displaces the equilibrium within a solution. If, then, crystallization of a magma can be brought about, in one case at a higher and in another case at a lower temperature, the chemical state of the solution as regards compounds existing within it will be different in the two cases. Change of pressure between the depths of the earth and the surface is an effective agent in changing the temperature at which crystallization begins. Pressure alone, as has been pointed out by several writers,* is not capable of causing great variations in the melting-points of minerals; but it is quite conceivable, and in fact probable, that within a complex solution the variation of the temperature of crystallization caused by relief of pressure is often attended by displacements of equilibrium, such that reactions proceed further in one direction or another and the relative proportions of the various compounds present is altered. These displacements of equilibrium find corresponding expression in the point at which crystallization is initiated and in the minerals deposited. The change thus begun tends to progress continuously in the same direction and may result at the final consolidation in an association of crystallized products quite different from what would be found under conditions of greater pressure.†

* A. Harker: *The Natural History of Igneous Rocks*, New York, 1909, pp. 163 and 194.

† The effects of temperature and pressure upon reactions within a system of the nature of a magmatic solution are expressed by two fundamental equations. The first is van't Hoff's formula

$$\log K' - \log K = \frac{q}{R} \left(\frac{1}{T'} - \frac{1}{T} \right)$$

in which K' and K are the constants of mass-action at the (absolute) temperatures T' and T , q is the heat of the reaction per unit considered, and R is the gas-constant ($= 2$ cal.)

From this equation it follows that with decrease of temperature (T greater than T') a reaction which evolves heat (q positive) is driven forward or in that direction in which heat is given out. (It will be noted that this is in accord with Le Chatelier's theorem.)

If, for example, two substances, A and B , unite to form AB with evolution of heat, the formation of the compound AB will increase as the temperature is lowered, and the greater the value of q the greater will be the amount of the compound formed.

The effect of pressure in inducing crystallization at a higher temperature is expressed by the formula

$$\frac{\Delta p}{\Delta T} = \frac{w}{T(v_1 - v_2)}$$

in which Δp is the pressure required to cause crystallization to begin at the temperature increased ΔT degrees above the normal crystallizing point, w is the latent heat of fusion, T is the absolute temperature, and v_1 and v_2 are the specific volumes of the substance in the liquid and solid forms respectively.

Resorption of Olivine in the Watchung Basalt.

In hand specimens, both of the vitreous and the aphanitic varieties of the Watchung basalt, small, dark-green spherulitic bodies can often be seen. They appear in many of the thin sections and are found to be built up of concentric shells of lighter and darker material of chloritic or serpentinous nature. A typical example is shown in slide No. 105 (fig. 10).

The diameter of the spherulite is about 0.2 mm , but larger ones are not uncommon. The central portion is composed of

FIG. 10. Chloritic nodule in vitrophyr (Slide No. 105).

comparatively large blades of radial chlorite, decidedly birefringent. The outer shells are very feebly polarizing and appear to be made up of minute scales of chlorite mingled with isotropic glass. Beyond the border of the spherulite the normal vitrophyric structure is found, consisting of small crystals and grains of feldspar and diopside and brown microlitic tufts, set in the paste of glass. In this case resorption and alteration have progressed so far that there is almost nothing suggestive of the manner in which the spherulite originated, but in other cases the evidence is plain. Outlines of some original mineral are left, to whose resorption by the magma the spherulites are attributable. None of the mineral itself remains,

FIG. 11.

FIG. 12.

FIG. 11. Partially resorbed olivine, subsequently altered. (Slide No. 105.)

FIG. 12. Separation of oxide of iron along cracks in olivine crystals which have been replaced by secondary products.

the crystal outlines being filled with chlorite, calcite and other alteration products. These retain certain features, however, which point strongly to olivine.

All stages of resorption appear in different parts of this slide. An example is sketched in fig. 11. Without the analyzer the corroded forms shown in heavy lines in the sketch (now replaced by calcite) are all that appear, but with crossed nicols the crystal form, almost complete, is brought out in serpentine. Immediately adjacent are remnants of several other crystals which the crossed nicols similarly outline.

In fig. 12 the typical manner in which oxide of iron has separated along cleavage cracks of the original mineral is shown, although nothing but alteration products survive. The resemblance to olivine is obvious.

From such examples one may pass by gradual transition to the results of almost complete resorption, in which the rounded and blurred outlines convey only a vague suggestion of the original form of the crystal, and upon whose areas, spreading out into the glass, microlites are encroaching. The color in such cases is practically the same as that of the surrounding glass, but crossed nicols show the presence of aggregates of minute chlorite scales.

The stages of the process and the relations which the olivines bear to the plagioclase and diopside are sketched in fig. 13. Similar phenomena are shown in slide No. 83, in No. 30, and in No. 48. In No. 57 the several steps can be followed very perfectly.

FIG. 13.

FIG. 13. Breaking-up and resorption of olivine. Several stages, found in various portions of the slide, are brought together. (Slide No. 105.) Diameter of field 1.5mm.

In No. 54 the outline of an original olivine crystal is preserved, but most of the area within the boundary of the original crystal is occupied by a mixture of brown glass and irregular grains of a dark brown color. This form of attack upon the olivine, by which the crystal has been broken up into many fragments, appears to have been common, and the brown grains show up in many of the slides, at times associated

with chloritic areas retaining a suggestion of a crystal unit, and again scattered through the glass.

FIG. 14.

FIG. 14. Inclusions in glass, resulting from the breaking-up of olivine crystals. (Slide No. 17.) Diameter of field 1.5mm.

These effects are shown in slide No. 17, sketched in fig. 14. The greenish glass is filled in places with brownish inclusions, arranged in crescentic or cusp-like figures. The inclusions appear to be in part surviving fragments of olivine, and in part magnetite dust set free in the reaction. The figures

FIG. 15.

FIG. 15. Effects of resorption of olivine accentuated by secondary alteration. (Slide No. 54.) Diameter of field 1.5mm.

assumed would appear to be due to the manner in which the resorbed material was diffusing in the surrounding magma when increasing viscosity terminated the process. Diopside and plagioclase are present in minor amount.

A slight degree of subsequent zeolitic alteration of glasses containing partially resorbed olivines serves to accentuate the features described. This is seen in slide No. 54 (fig. 15) and in many other cases. Even in advanced stages of secondary alteration traces of these features persist.

In all cases the olivine shows unmistakably that corrosion had attacked it and that it was in process of resorption by the magma, from which plagioclase, diopside, and magnetite were beginning to crystallize. At some point in the history of the magma the olivine which was first deposited became unstable and would undoubtedly have gone completely into solution if sufficient time had been allowed. It is noticeable that in the later crystallization olivine did not again appear as one of the products. It must follow, therefore, that the olivine molecule which was absorbed underwent some change within the solution by which it entered into new combinations.

Considered from the standpoint of the principles previously developed, the most probable explanation of the resorption of the olivine appears to be the following: Before extrusion the magma had cooled sufficiently so that crystallization had begun. Inasmuch as most rock-forming minerals occupy less volume in the solid than in the fused condition, the great pressure to which the magma was subjected aided crystallization, so that it was initiated at a somewhat higher temperature than would be the case under less load. The effect upon the crystallization of a given mineral would vary inversely as the heat of solution and directly as the difference in volume between the two states. Pressure may also have had an appreciable effect upon the direction of reaction within the fusion-solution.

Olivine was the chief mineral deposited under these conditions but there are indications that a little plagioclase had also begun to crystallize out. (In slide No. 47 a large plagioclase crystal shows some indication of zonal structure, most probably developed during this period.)

When extrusion of the magma occurred it was attended by great changes in all the physical conditions.

Diminution of load would be a factor of prime importance in causing the minerals which had crystallized out to be resorbed. The loss by volatilization of aqueous and other vapors also affected the combinations existing within the solution. It can hardly be supposed that the vapors evolved existed in the solution entirely in the combinations in which they were given off. Undoubtedly a portion of the vaporized material was combined with the nonvolatile portion and its removal from the system necessitated more or less readjustments of equilibrium throughout.

Under these circumstances it is not surprising that most of the olivine which had been deposited was taken up by the magma. Still if the olivine molecule continued its existence in the re-fused mixture it would be redeposited when the appropriate temperature was reached under the new conditions, but it appears that the lower temperature to which the initiation

of crystallization was carried, together with the other disturbing factors, resulted in an entirely new chemical arrangement. The olivine molecules which were resorbed thereby lost their entity, being distributed among other compounds in a manner which cannot be completely followed, and olivine as such did not reappear among the products of crystallization.

The fact that remnants of the olivine persist is due to lack of time given for resorption before increasing viscosity put an end to the process. Under somewhat different conditions, easily conceived, the less complete resorption of a mineral would be attended by the formation of reaction rims, or replacement by an aggregate of other minerals; or its slow solution in a magma in which crystallization was far advanced would constantly change the composition of the mother-liquor, with consequent displacements of equilibria. In the case studied the resorption or solution was nearly complete before the second period of crystallization began, and the effect as regards complexity of results was almost a minimum.

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Columbia University,
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