

The Method and its Principle of Delineating the Composition-Variation Curve of a Zoned Plagioclase with an Example

By

Fujio HOMMA

With 10 Text-figures and 3 Tables

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I Introduction

Since 1932¹⁾ the writer has made public many composition-variation curves of zoned plagioclases found in igneous rocks but he has not described precisely how the measurements were carried out in the laboratory. The purpose of the present paper is to discuss the methods.

As the writer pointed out in his recent paper²⁾, knowledge of the chemical composition of a crystal, ascertained by studying its features from the centre to the periphery of a crystal, is necessary if the crystal's growth is to be explained; though he does not insist that its history can always be determined by this kind of study. He suggests that before discussing the origin of the crystal, it is necessary to locate the variation-curve obtained according to the classification system of the writer for the purpose of determining its position among the zonal structures of plagioclase found in igneous rocks.

A composition-variation curve can be constructed first by drawing an extinction-variation curve and then transforming it into a composition-variation curve. A preparatory step precedes this work and a classificatory treatment of the curve follows it, as will be shown later in this paper.

For the preliminary work a thin slide of the rock is examined

1) F. HOMMA, Über das Ergebnis von Messungen an zonalen Plagioklasen aus Andesiten mit Hilfe des Universaldrehtisches, Schweiz. Min. Petr. Mitt. Band XII, 1932, pp. 345—352.

2) F. HOMMA, The Classification of the Zonal Structure of Plagioclase, Memoirs of Col. Sc. Kyoto. Imp. Uni. Series B, Vol. XI, 1936, pp. 135—155.

under the petrographic microscope to ascertain the general characteristics of the rock and to find the crystals fit for measurement. These crystals must be of types which either have the zonal structures dominantly present or that are important for genetic reasons. (1) Photographs are taken of the crystal in the positions at which the zonal structures are observed most distinctly. On each photograph, a line XY is drawn from the centre to the periphery of the crystal to indicate the position where the variation curve is made. (2) The thin section, then, being mounted on the universal microscope, an extinction-variation curve is constructed along the line XY making use of the methods which will be described later. (3) The chemical composition of some wide zones in the crystal is measured by the universal stage method. (4) Making use of these results, the extinction-variation curve can be transformed to a composition-variation curve. (5) Before completing the work of constructing the curve, a reexamination of the curve is needed, because an inspection of the structure, while rotating the three axes of the universal stage, frequently betrays that zones apparently simple are composed of finer microzones or that a zone migrating continuously to neighbouring ones is an inclined boundary plane between two discontinuous zones. (6) Lastly, for the sake of facilitating the genetic explanation of the crystal, the curve is divided into many groups, which are subdivided into successive orders such as subgroup, zone, subzone and microzone, based on the changes of chemical composition, according to the writer's classification, recently proposed.

It must be remembered, however, that the variation curve is only a curve made along a rather arbitrary line drawn on a crystal, which had suffered occasionally from the magmatic resorptions during its growth. Thus curves constructed in the different sections may be somewhat different. Important divisions, which sometimes occur at points exhibiting no remarkable change in the variation curve, are determined through general observations of zonal structure.

II The Preparatory Work

In order to construct an exact composition-variation curve and to get an effective petrological result, the following preliminary work must be done: First, the thin slide of the rock must be examined under the ordinary petrological microscope to learn the general characteristics of the rock and to ascertain the petrogenetic positions of the crystals to be measured in the rock under question.

In many kinds of igneous rock, especially among those of volcanic origin, a few types of plagioclase-phenocryst of different origin are frequently found. For example, it is assumed that a volcanic rock has three kinds of plagioclase phenocryst of different origin. Among them, the first type of the phenocryst has a mean chemical composition nearly the same as that of the marginal zones of the crystal; in the second type, the inner part is different in its mean composition from the outer part of the crystal, indicating that both parts have grown under different chemical conditions; and the third type of the phenocryst is surrounded by a more or less wide reaction zone around its periphery, proving that it is a xenolithic felspar. In such a case at least three typical phenocrysts of each type and some microlites in groundmass have to be measured, if the research on the evolution of magma which included these crystals is to be undertaken.

After this work has been done, the crystals suitable for measuring are selected under the microscope.

In order to carry out the exact measurements, it is necessary to find a crystal that shows a distinct zonal structure having at least three zones with measurable widths, usually wider than the thickness of the thin slide. Of course, these three zones should not be of the same composition, but two of them must have nearly a maximum and minimum composition in the whole range of the crystal, while the remaining one should have an intermediate composition. As there is no relation between the changes of the extinction-position and the anorthite percentage in the plagioclase to be expressed with

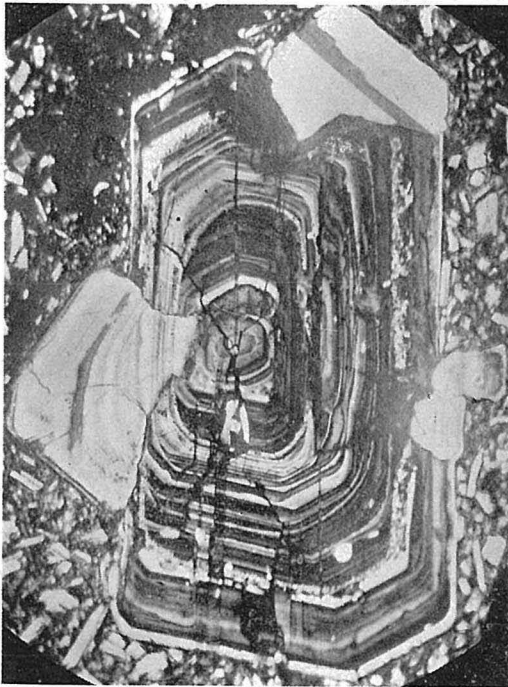


Fig. 1. A plagioclase phenocryst in the lava of 1657 of Unzen. (the long diameter of the crystal is ca. 3 mm. (+ nicols))

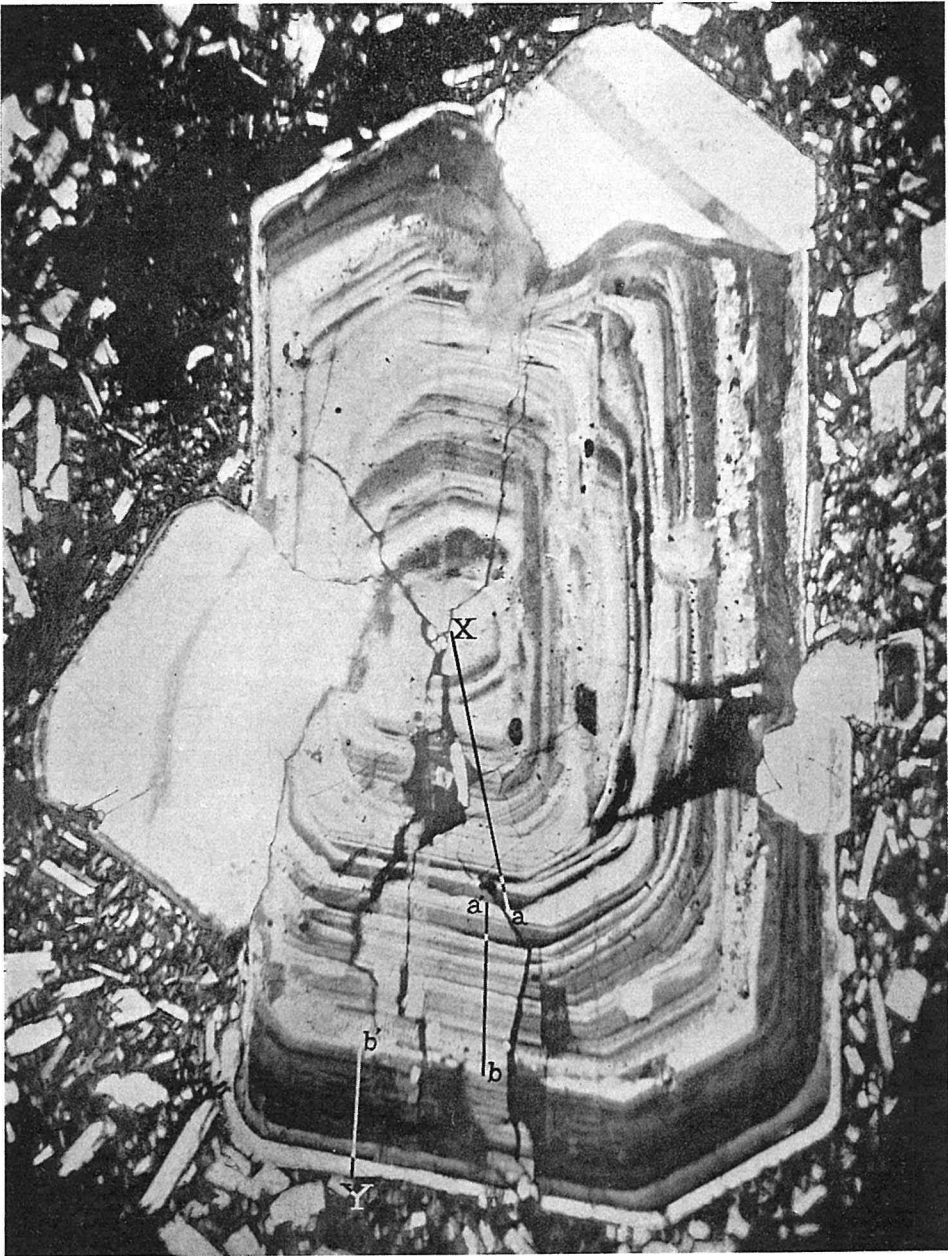


Fig. 2. The same crystal, illustrated as fig 1. (Xa-a'b-b'Y) shows the section along which the extinction-variation curve and the composition-variation curve are made. (+ nicols).

a straight line, the greater the number of zones actually measured, the more accurate will be the result. If the difference of the anorthite percentage between the most calcic and sodic zones is more than 20%, it is necessary to measure four or more zones by the universal stage method.

The crystals satisfying the above mentioned conditions are photographed under the microscope. Usually at least three photographs for each crystal are needed to give a



Fig. 3. The same crystal, illustrated as fig. 1, showing the zonal structure due to the inclusions and differences of indices of neighbouring zones.

correct impression of the zonal structure of the crystal; one of them is to be taken between the crossed nicols at the position where the whole structure is seen most clearly, while the second one is taken in a position that intensifies the most characteristic feature in the zonal structure or that clearly reveals the zones which the first photograph failed to show. The microscopic photograph reproduced herein as fig. 1, which shows the zonal structure of a plagioclase phenocryst in the olivine bearing biotite-hornblende andesite of Unzen volcano, the lava flow of 1657, or the "old lava", gives an impression that the dark zones have nearly the same extinction positions, but fig. 2 makes it plain that the outer dark zones next to the bright peripheral zone have extinction-positions which on the whole differ considerably from those of the inner zones. The actual difference of the extinction-positions between these dark outer and inner groups of zones in fig. 1 is on an average ca. 6° , as seen in fig. 4.

If the zonal structure is complicated by a wide range of variation in its composition, a few more photographs between the crossed nicols may sometimes be necessary.

The third photograph is taken under the microscope, with the upper nicol opened. It shows the presence of the zone of inclusions as seen in fig. 3 and sometimes even the zonal structure, if the indices of refraction of the neighbouring zones are considerably different.

A heavy line is next drawn on the first or second photograph to indicate where the extinction- and the composition-variation curve were constructed. But as shown in fig. 2, in cases in which the crystal is broken or in which many zones appearing partly because of intervening corrossions cannot be omitted in the curve, two or more lines will be drawn, the inner line being succeeded at its outer end by an outer line at a different point in the same zone.

As shown in fig. 1, even in a crystal which shows comparatively weak effects of corrossion some zones are always omitted in any section which has been made by cutting through the center of the crystal. Therefore, from the petrological point of view, having ascertained the history of the growth of the crystal by collecting as much concrete material as is possible, the composition-variation curve should be made preferably on the abscissa, formed by the connections of a few successive lines, which would include a greater number of zones than another composition-variation curve which can be drawn along a single straight line from the centre to the periphery.

III Plotting the Extinction-Variation Curve

After the work described in the above chapter has been completed, the extinction-variation curve is plotted. The four-axial universal stage of E. LEITZ is enough to carry out this work, but the objective lens of UM 3 or 4 and the upper hemisphere with parallel leading apparatus for the thin slide are indispensable for exact measurements. The refractive index of the hemisphere most desirable is 1.557, since, in this case it is not necessary to correct the measurement except when the thin slide of the mineral, having the composition of albite or anorthite, is inclined more than 30° around H or K axis after REINHARD.¹⁾

Now the thin slide is mounted on the universal stage and the crystal to be measured is laid in the position at which it is photo-

1) M. REINHARD, *Universaldrehtischmethoden*, 1931, pp. 30—31.

graphed. The work of constructing the variation curve is begun by measuring the width of each zone along the line XY, drawn on the photograph to establish the abscissa as shown in fig. 4. By the term "zone", used here temporarily and called the "section" in the curve (fig. 4), is meant only the light or dark band distinguishable in the photograph.

The relative width of each zone between X and Y is measured by the ocular micrometer to represent itself on the abscissa successively rightward from the origin. These zones have been numbered to facilitate the location of their positions in the photograph. In the course of this measurement an examination is made as to (1) how each inner zone passes to the outer; that is to say, continuously or discontinuously, (2) where the traces of resorption are, (3) whether or not further minor zonal structures, which are not seen in the photograph,

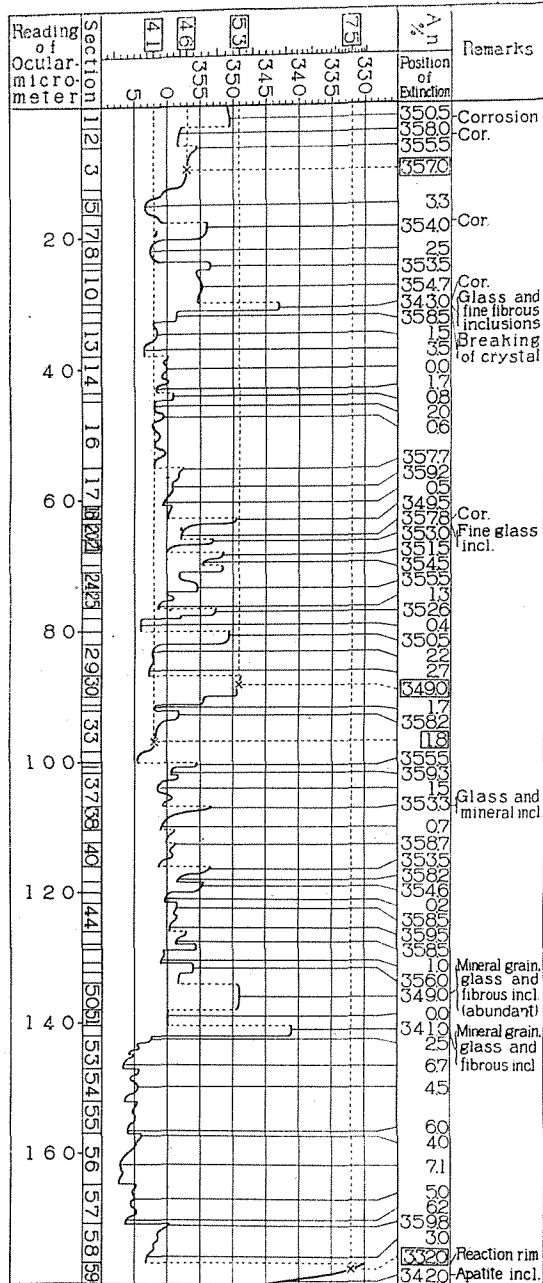


Fig. 4. Extinction-variation curve along XY in fig. 2. (x are measured points by the universal stage method.)

are observable in an individual zone and (4) how the various kinds of inclusion are distributed.

Thus the abscissa of the extinction-variation curve is established. Then the three axes of the universal stage (N. H. & K axes after M. REINHARD or A_1 , A_2 & A_3 axes after M. BEREK¹⁾) will be rotated to find a position where the zonal structure can be seen more clearly as a whole than under the ordinary microscope. When the best position is determined, it is fixed on the universal stage and noted in the note book by the co-ordinates of N. H and K axes.

Then, rotating the objective stage or M axis after REINHARD, the extinction position of each zone is measured and represented by the degree which coincides with the zero point of vernier, fixed directly outside the objective stage. As it is shown in the ordinate in the extinction-variation curve, the necessary numbers of degree between $0^\circ \sim 360^\circ$ will be marked with an equal interval on the ordinate. The approximate values of the degrees corresponding to the extinction-positions of both ends, the most and least calcic zones, can easily be determined by a precursory observation of the crystal. There is therefore no practical difficulty knowing how many divisions on the ordinate are necessary to represent the extinction-position of all zones.

The measurement of the extinction-position of each zone will now be made. A normal line will be drawn from each measured zone to the abscissa and a dot will be marked on each normal line to indicate its extinction-position. Connecting each point, thus made, a preliminary extinction-variation curve along the section XY will be delineated.

The measurement of the extinction is necessarily carried on in a dark room where the light illuminating the thin slide will be so equipped as to fall only upon the mirror of the microscope. Rotating the objective stage or M axis both clockwise and counter-clockwise, the positions of the beginning and ending of the extinction will be observed at first, then, the measurement of the extinction-position will be repeated many times in order to get for the result an average value that will be within $\pm 0.5^\circ$ of correctness.

To complete the delineation of the extinction-variation curve, the following characteristic features of the mineral, enumerated already in the preceding pages, must be observed again very carefully, during the process of connecting the measured points.

1) M. BEREK, Mikroskopische Mineralbestimmung mit Hilfe der Universaldrehtischmethoden, 1924. pp. 9—12.

(I) As shown in the photograph, some inner zones seem to pass continuously to the outer ones, while others appear to be succeeded discontinuously by zones of different composition. Strictly speaking, whether or not an inner zone passes continuously to the outer can only be proved when the boundary zone or plane is brought parallel to the axis of the tube of the microscope. Otherwise, the neighbouring zones will be piled over each other wedgewise at their ends, giving an appearance that they pass always continuously from one to the other.

Genetically considered, it is very important to distinguish these cases, because the phenomena would be the reflections of the physico-chemical condition of the magma during crystallization.

(II) It is also often the case that a zone is bounded from the outer one by an irregular curving face, caused by magmatic corrosion, making it impossible to bring the face parallel to the axis of the microscope-tube. But the presence itself proves, that there took place a considerable change in the physicochemical condition of magma. Therefore it must necessarily be noted in the extinction-variation curve.

(III) Even in an individual zone, it is observed sometimes that the extinction-positions of different parts display a little but nevertheless an appreciable change under the microscope, though they are not discernible in the photograph. The change from the inner to the outer side in an individual zone is often directed towards a certain definite point, while in other cases, it is expressed in an oscillatory manner yielding faint light and dark bands between the crossed nicols. Such modifications in an individual zone would be liable to the local heterogeneity, the oscillatory change of pressure or volatiles in the magma, in which the crystal was moving in some way during its growth.

(IV) Lastly, the inclusions in the crystal must be looked for very carefully. When they are found, their distributions are to be examined and if it is observed that they are apparently limited only to some specific zones, they should be inspected further. This can be done by bringing the zone parallel to the microscope-tube. This is effected by rotating the three axes of the universal stage, then by ascertaining whether or not they are really limited only to a face or to a very narrow belt in the observed zone. Almost half of the inclusions which formerly have been believed to be scattered in a zone of considerable width, will be proved to be distributed only

along the face or on a very narrow belt in a specific zone if they are inspected under the universal microscope. It will not be forgotten on this occasion, to examine the composition of the substance of which they are composed and the chemical composition of the zones including them.

Zonal inclusions, found even in a relatively inner zone, are occasionally an aggregate of fine minerals which are produced around a xenolithic felspar fragment by a reaction with the magma. On the contrary, if the inner part rather than the zone of inclusion is proved to be crystallized from the same magma of the outer part, the presence of the zonal inclusions shows that there occurred a considerable change in the physicochemical condition of the magma at the period when they were formed.

To illustrate the causes resulting in such a change, the following cases are enumerated.

On such an occasion as during the injection of magma into the surrounding crust an opportunity for a rapid temperature decrease of the magma may be afforded, resulting in spontaneous crystallizations of numerous crystal grains, some of which may attach themselves to the existing plagioclases to constitute a zone of inclusions. A release of pressure in the magma reservoir due to certain causes,



Fig. 5. An honey-combed structure of plagioclase, illustrating that a phenocryst was formed by accumulations of minute ones. (No. 341091, Shin-Také, Kuchierabu-Jima.) (Diam. 0.5 mm.)

such as the explosion of an overlying volcano, would liberate gas bubbles which might yield a zone of gas inclusions in consequence of the subsequent growth of the plagioclase. Thirdly, if the fluidity of magma happens to increase due to such a cause as a release of the pressure or an increasing concentration of volatiles, many small crystals, suspended in the magma, would segregate around the large crystals of the same

mineral. In this case the former would be arranged in some crystallographic orientations as to form an outer zone of the large crystal. But between the small crystals there remain many spaces, filled with magma, and they subsequently constitute a zone of glass inclusions.

In an example from the basal lava,¹⁾ two pyroxene andesite, of New Cone of Kuchierabu volcanoes, in the Kirishima zone of southwestern Japan, the writer identified plagioclase, augite and magnetite that were crystallized from the occluded drops of magma in plagioclase phenocrysts in consequence of the subsequent fall in temperature of the magma. Among these, the plagioclase was absorbed to the wall while others remained as fine crystals in brown glass in which many crystallites and sometimes fine gas bubbles were also discerned (fig. 5).

The above descriptions afford some basis for the belief that the investigation of zonal inclusions is important to petrogenetic study.

The processes of constructing the extinction-variation curve will be completed with making an entry of the above stated characteristics in the column of remarks.

IV Delineation of the Composition-Variation Curve

After the construction of the extinction-variation curve, two of the three optic-elastic axes, and one or two optic axes of broad zones and poles of some cleavage and those of composition planes of twinning are measured under the universal microscope. As briefly stated in the foregoing pages, the zones necessary for the measurement are those whose reading for the extinction-position are nearly maximum, minimum, or medium in all zones of the crystal; and if the difference in composition between the most calcic and sodic zones is as large as 20% of anorthite, four zones or more should be measured to get reliable data on the chemical compositions of all zones. The measurement is always possible if the width of the measured zone is not less than the thickness of the thin slide. The homogeneity of this zone is very desirable, although, even if the composition of a zone varies within a narrow limit, it can nevertheless often be measured easily and accurately, while if the composition of the neighbouring zones is very different from the measured one, optical disturbances are caused by the neighbouring zones falling wedgewise on the

1) F. HOMMA, On the Zonal Structure of Plagioclase Phenocryst in the Basal Lava of the New Cone of Kuchierabu (in Japanese), 'Chikyū,' Vol. XXIV, 1935, pp. 243—263. (Full informations will be given in near future.)

measured one, during the rotation of the thin slide around the axis K or H. In such cases the exact measurement of α , β or γ are practically impossible.

As already stated, the refractive index of the upper hemisphere is preferably 1.557, as it occupies the middle position of the whole scale of the refractive indices of the plagioclase, ranging from 1.525 to 1.590. In this case, if the inclination of the K or H axis is small, correction of the apparent position of the pole to the real one is practically unnecessary, and even if the plagioclase having nearly albite or anorthite composition has been inclined so much as 30° around the K or H axis, the correction of 1.5° only will be necessary; the real inclination for albite being nearly 31.5° , or 28.5° for anorthite.

The method employed by the writer for an exact measurement of α , β or γ is as follows:

Table 1.

k	m.		
	I h=10.6	II h=8	III h=10
325°	3.0	0.5	2.5
335°	1.6	0.5	1.5
345°	1.2	0.3	1.1
0°	0.8	1.2	0.6
15°	0.6	2.5	1.1
25°	0.6	3.5	1.5
35°	1.4	4.1	2.4

α $n=277$
 $h=10.6$ } Approximate values

α $n=277.6$
 $h=10$ } Exact values

First an approximate measurement of n and h for α , β or γ is made under the universal microscope; then, the position, as for an example $n=277'$, $h=10.6'$ for α , being fixed, the exact positions of extinction are measured at each position on the K axis, such as $325'$, $335'$, $345'$, $0'$, $15'$, $25'$ or $35'$, by the rotation of the objective stage, or M axis. If the mean measurement of the different positions of K should be 3° , 1.6° , 1.2° , 0.8° , 0.6° , $0.6'$ and 1.4° respectively, as tabulated in table 1, the value of h will be a little too large and the value of n slightly smaller. Then

the position for h will be shifted to $h=8$, leaving n unchanged. The same measurement will be carried on again at the above mentioned positions around K, resulting in the value tabulated in column II of table 1, in which we find that h is too small. Thus we can look systematically for an exact value for h , where the extinction-position of the opposite points on both sides of $k=0$ are the same, but the apparent value for m becomes incorrect if the inclination of K axis is considerably large, as is seen in table 1. Thus taking into consideration all possible errors, the error in the measurement for α , β or γ , carried out through the above stated method, would be restricted to $\pm 1^\circ$ at its maximum.

The optical angle ($2V$) is determined usually by doubling the measured angle between one of the optic axis and γ or a . The exact determination of the optic axis is not easy in the least though it would seem to be so theoretically. The maximum error for k may attain $\pm 2^\circ$ around an optic axis if the inclination of the K axis is considerably great. Thus if the error for a or γ should be added the total error of $2V$ may be as large as $\pm 6^\circ$. Therefore, even if the other conditions be neglected, the determination of $2V$ for the purpose of estimating An% is practically of no value.

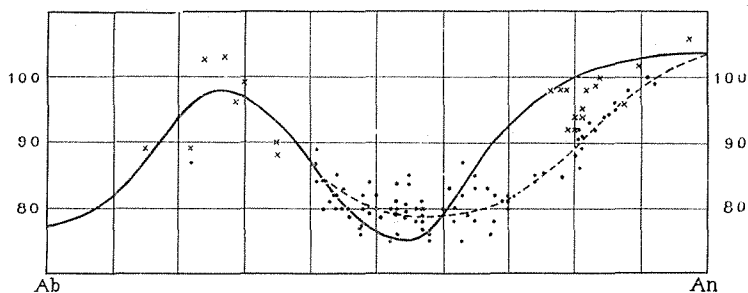


Fig. 6. Optic axial angles ($2V$) of plagioclase measured by the universal stage method by the writer. (The solid curve is BERER's curve. The broken line is a probable trace of mean values of $2V$ for Japanese effusive rocks.)
 • Effusive rocks x Plutonic rocks

Recently the writer confirmed the fact that the variation-curve of the optical angle of plagioclase in calc-alkaline effusive rocks is unlike those illustrated in many text-books, in spite of having considered all the possible errors in favour of the current curve. The probable curve for calc-alkaline effusive rocks is illustrated with a dotted line between andesine and anorthite in figure 5. Such a deviation of the optical angle may be caused first by the dissolution of some molecules other than albite and anorthite in the crystal and second by the physical conditions under which the crystal was formed, a conclusion suggested by the relation between orthoclase and sanidine. Whatever be the origin, however, the radical causes are the smallness of $\beta - a$ and $\gamma - \beta$ in $\tan V = \frac{\gamma}{a} \sqrt{\frac{(\beta + a)(\beta - a)}{(\gamma + \beta)(\gamma - \beta)}}$ in plagioclase.

The writer does not insist that the measurement of $2V$ is meaningless. On the contrary, he believes that future researches will prove that the serial variation of $2V$ produced by the composition changes of plagioclase in different igneous districts, explains important characteristics of these igneous series.

The next step is the measurement of the poles of cleavages and

those of the composition planes of twins. The N and H axis are adjusted merely to bring these planes parallel to both the longitudinal wire of the ocular and the axis of the microscope tube. But their measurement is so difficult, that an accurate result can be secured only by taking the mean of ten or more readings. If there are fine lamellae of albite twin, the parallel position to the axis of the microscope tube will be easily determined by the equal lumination of all lamellae while the K axis is rotating. Thus the maximum differences of these poles may not be larger than $\pm 1^\circ$.

The accuracy of the measurements was greatly increased since the discoveries of UM 3 and UM 4 in 1931, which introduced a new epoch for the universal stage method. As we know that α , β and γ must stand normal to each other, we can easily determine the error of the measurements by finding that the angular distance between two of them is not 90° in WOLF's net. On the other hand, the total range of shifting of α , β and γ from An 100 to An 0 is nearly as large as 90° . Accordingly, we believe that the error may be less than 2% of An in most cases, if the diagrams, employed for the

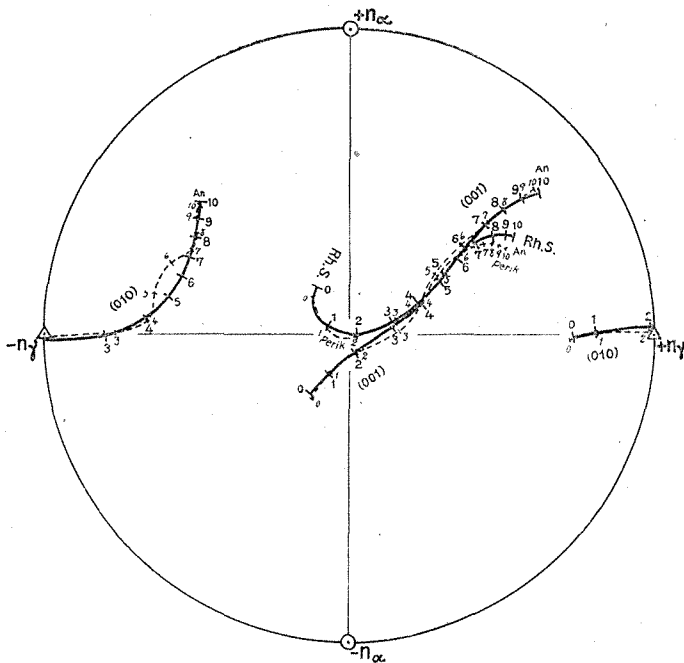
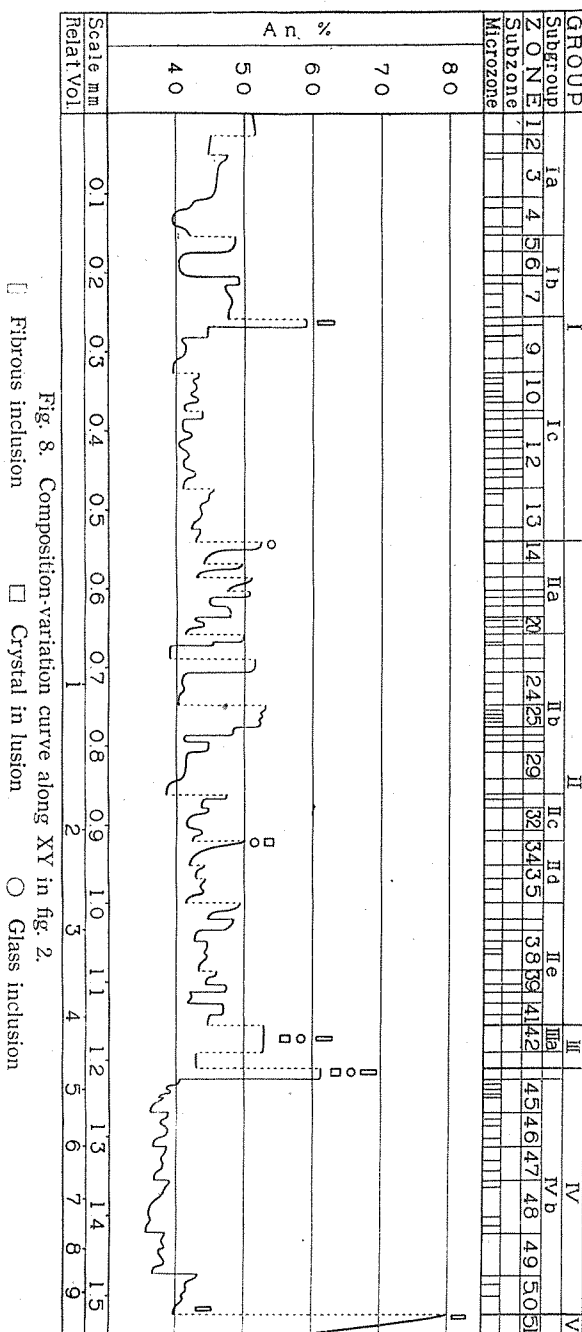


Fig. 7. The traces of the poles of (010), (001) and those of the composition planes of the pericline twin. After M. BEREK (solid lines) and M. REINHARD (broken lines).

determination of An%, are correct; and the relative differences of An% for different zones in a crystal, whose determinations are of the utmost importance, will be made far more exactly than the actual determination of An%, if in a given diagram only the same curve concerning a crystallographic plane, say (010), is used through the whole course of the measurements. For the determination of the An% based on the actual measurements of optical and morphological elements, we usually use the diagrams given by BEREK or M. REINHARD. But it is a matter of regret that the curves of both these authors show a considerable difference between An 70~40%, though they do not differ so greatly in the determination of An% as they appear to. On the other hand the most measured poles



do not fall on any of the curves, so far at least as the Japanese calc-alkaline effusive rocks are concerned. Consequently, for the determination of An%, the writer is forced temporarily to employ BEREK's curve whose intersecting point with a normal line drawn to it from the measured pole is considered to represent the composition of the zone. The writer uses only (010), (100) or Rh.S curves because at least one of them is always present in any plagioclase. The maximum difference of An% between BEREK and REINHARD is found at the point designated as 60% of anorthite on the former's curve whereas the point for 60% of the latter is estimated at 65% if a normal line is drawn from the point to the former curve, while around the points of 90% and 10% they practically coincide.

By the theoretical and mechanical descriptions above given, the results obtained under the universal microscope can be correctly judged.

Because the extinction-variation curve has been constructed already, the composition of each zone can easily be inferred by interpolation, if some points corresponding to different extinction-positions have been actually measured. In this manner the ordinate can be scaled with An% as shown in the left column of ordinate in fig. 4, though the intervals corresponding to each 1% of anorthite are not equal.

Thus the transformation of the extinction-variation curve into the composition-variation curve is easily done. In the composition-variation curve the ordinate is scaled by An% with an equal interval for each 1%, and the abscissa is doubly scaled by 0.1 mm, representing the actual length of the crystal measured along the section XY and by the volumetric ratio, the total volume being assumed as 10. The volumetric scale serves to show the approximate mean composition of each group or of the crystal as a whole. However, the latter scale is not applicable to the comparison of the volume of each individual zone. Moreover it does not treat some zones which failed to appear on the line XY, affected by corrosion. If the thin slide does not made cut through the centre of the crystal, the scales for the inner part in the abscissa are quite meaningless. Here it should be noted that, while some unfavourable conditions in the inner part may be excluded from consideration, the outer is usually far more important, in every respect, than the inner part of the crystal.

V The Classification of the Zonal Structure and Some Genetical Explanations

The plagioclase illustrated in this paper is contained in the lava flow called "Furu Yaké" or old lava, which was effused in 1657 near the summit of Fugen-Daké in Unzen Volcanoes, Western Kyûshû, Japan. The chemical analysis of the rock is tabulated in table 2.

The rock is characterized chemically by the most basic composition found in Unzen Volcanoes¹⁾. Under the microscope, it shows a remarkable mineral association in the phenocrysts and the zonal structures of the plagioclase, in which was revealed an olivine-bytownite-basalt magma injected into the lava basin of biotite-hornblende-andesine dacite.

The phenocrysts in the rock are plagioclase, biotite, hornblende olivine and quartz. Among them, plagioclase, biotite and hornblende are as large as 2~4 mm, while olivine is usually 0.3~0.5 mm in size. The smaller crystals and microlites in the groundmass are plagioclase, pigeonite, hypersthene, olivine, augite and magnetite; but biotite and hornblende are quite rare. Though the general features of the rock are demonstrated briefly in table 3, some important information is given in the following.

Almost all rocks making up the Unzen volcanoes, contain hornblende and biotite as phenocryst with additional quartz in acidic ones and hypersthene and augite in basic ones; olivine is never found in the normal type of rock in the volcanoes. The mean composition of plagioclase is nearly An 38~48, despite its complex zonal structure with numerable traces of corrosion; and the composition from the core to the periphery of the phenocryst shows no appreciable change or tendency to slightly decrease of the An%.

Contrary to these general features of the phenocryst in the rocks of Unzen, the rock under consideration contains many olivine pheno-

Table 2

SiO ₂	58.15	Q	15.58
Al ₂ O ₃	17.69	or	10.11
Fe ₂ O ₃	2.72	ab	21.17
FeO	4.41	an	32.57
MnO	0.11	di	2.28
MgO	3.45	hy	12.44
CaO	7.20	mt	3.98
Na ₂ O	2.52	il	1.54
K ₂ O	1.63	ap	0.34
TiO ₂	0.75		
P ₂ O ₅	0.12	Class	II
H ₂ O+	0.34	Oder	4
H ₂ O-	0.60	Rang	4
Total	99.74	Subrang	4

Analysist: U. USHJIMA

1) "Unzen-Daké", Bul. of Volcan. Soc. of Japan, Vol. III, 1936, p. 109. (edited by F. HOMMA), (in Japanese).

crystals and an abnormal kind of plagioclase, which abruptly increases in An% in its peripheral zone. The inner part of plagioclase is quite similar in its composition and the structural feature to those of ordinary rocks in Unzen. In most cases hornblende is altered to opacite; and biotite is bordered always with a wide black reaction rim, often containing brown hornblende grains. Corroded quartz grains are found also. All these characteristics give the appearance that these minerals are foreign to this rock.

In the groundmass, there are abundant small crystals of plagioclase, whose composition is mostly 78~55% of anorthite. They sometimes exhibit a distinct zonal structure, with a rapidly decreasing tendency of An% towards the periphery.

Next to plagioclase, small crystals of augite, olivine and pigeonite are also abundantly present in groundmass, the refractive index of the glass in groundmass is 1,503, which is normal for andesite. If the outermost basic zone of the phenocryst (group V in fig. 8) is reexamined, we will find that the anorthite percentage of this zone decreases very rapidly towards the periphery of the crystal from 80% to 56% An. This is the most characteristic feature of the plagioclase phenocryst in this rock. Let us recall here that in 1793 the new lava, or Shin-Yaké, flowed out a distance of 1 km from the vicinity of this old lava, whereas its mineralogical and chemical characteristics are quite similar to the older rocks which compose the main body of Unzen. The fact affords almost conclusive evidence that the magma of Unzen underlying this locality was in a fluid state in 1657.

From these facts we can conclude that a basic magma of olivine basaltic composition injected itself into a branch of magma reservoir of Unzen when the plagioclase, together with other kinds of phenocryst, had grown to group IV in figure 8. As the olivine basalt did not affect the lava of a later eruption from a close vicinity, it is supposed to have been injected as a dike which happened to cross only a branch of the magma basin of Unzen.

By this injection, besides the strong reaction against the existing phenocrysts, the microlite in the acidic magma might be entirely resolved, due to the higher temperature of the invaded magma, while, with these changes, the crystals suspended in the basic magma might have grown rapidly, accompanied by a considerable change in composition, as shown in zone V of figure 8. The eruption in 1657 is considered to have occurred before the magma had restored equi-

Table 3.

No. of Thin Slide	351024, 351037, 351205—351207.							
Name of Rock	Biotite-hornblende andesite with quartz and olivine.							
Locality	Hatonoana, the lava flow of 1657 of Fugen Daké, Unzen Volcanoes.							
PHENOCRYSTS (volume % ca. 9.2)								
Mineral	Composition	Volume (%)	Size (mm)	Indices of refraction	2V	Color & Pleochroism	Remarks	
Plagioclase	Inner An 61~37 Margin An 80~56	61	4 × 3 0.6 × 0.3	mostly 1.5500(α) ~1.5600(γ)	47° (An 41) 79.5° (An 53) 85° (An 75)	Colorless	A remarkable reaction zone with abundant inclusions between the inner and marginal zones. Some remarkable traces of corrosion in the inner part of the crystal.	
Quartz		9	1.4 × 1.4 0.4 × 0.4		Uniaxial	Colorless	Corroded and fractured.	
Biotite		12	2 × 1.5 0.4 × 0.4	Ca. 1.6890(γ)	2E \div 20°	X, light yellowish brown Y \div Z, dark reddish brown	Wide dark reaction rim, in which brown hornblende is formed.	
Hornblende		13	4 × 1.7 0.6 × 0.3			X, yellow. Y, brown. Z, deep reddish brown	Most ones are entirely opacitized. Sometimes it is altered into long prismatic pyroxene.	
Olivine	Fo 83	5	1.0 × 0.7 0.4 × 0.3	α < 1.673 γ > 1.694	-81° ~ -88°	Colorless		
GROUNDMASS (volume % ca. 90.8)								
Plagioclase	An 80~55	Small crystals (vol. % 26)	65	0.3 × 0.1 0.05 × 0.01	1.5580(α) ~1.5730(γ)		Colorless	Short prismatic crystals.
Augite			20	0.3 × 0.2	Ca. 1.7090(γ)	+44° + 63°	Pale dull green	Octagonal or grain form. Undulatory extinction due to hour-glass structure.
Olivine	Fo 83	Microfites & glass (vol. % 74)	12	0.3 × 0.3 0.02 × 0.02	α < 1.673 γ > 1.694	Ca. -83°	Colorless	
Hypersthene			1	0.4 × 0.2 0.05 × 0.01			X, pale brown. Y, pale yellowish brown. Z, colorless	Crystallized later than augite. Long prismatic form.
Magnetite		2	0.05 × 0.05 0.02 × 0.02			Black and opaque	Always small grain form.	
Pigeonite		24				Pale brown	Fine needles.	
Magnetite		8				Black and opaque	Fine grains.	
Plagioclase		4				Colorless	Fine needles.	
Apatite		+				Colorless	Fine long prismatic forms.	
Glass with crystallites		61		1.5030 (glass)		Pale brown (glass)	Grobulites and belonites.	
Remarks	Phenocrysts of plagioclase (An 61~37), quartz, biotite and hornblende are crystallized from the Unzen magma proper, while olivine phenocryst and some of small crystals of olivine and plagioclase are crystallized from the olivine-bytownite-basalt which was injected into the Unzen magma basin. Small plagioclase crystals } Augite → hypersthene } are crystallized from the mixed magma.							

librium of its thermo-chemical state, for it is believed that, if an equilibrium corresponding to the temperature had been attained after the complete mixing of both basic and acidic magmas, a gentler manner of change in composition would have ensued around the margin of the plagioclase.

As stated above, it might be concluded from the study of any one of the few characteristics of this rock that it originated in the mixing of two magmas, but a study of the zonal structure in the plagioclase has given us a more complete history of its origin.

The inner part of the crystal (see fig. 2, 8 and 9), is divided into four groups of zones by traces of deep corrosion. Though each outer zone of corrosion begins with a basic zone and constitutes sometimes of a zone of inclusions, the mean chemical composition of each group is not much different. This characteristic is common to every kind of Unzen rock. Thus the deep corrosion is suspected to have been caused by some dynamic disturbance, such as an inner expansion due to volatiles in magma. If there occurred a power explosion in that part of the volcano

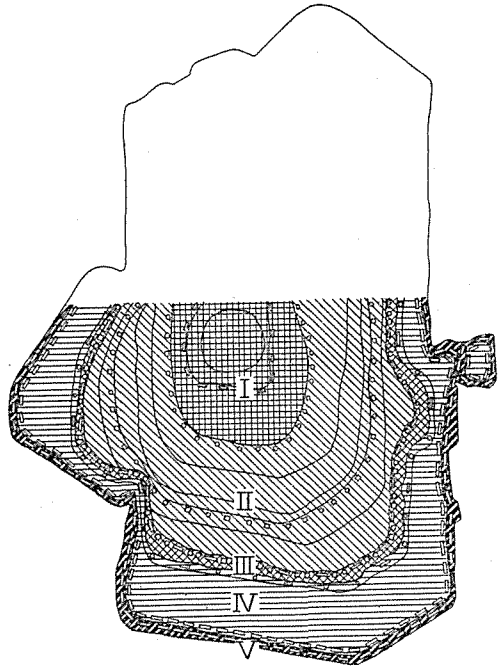


Fig. 9. Five groups of zones indicated in fig. 8.

connected with this magma basin, it is but natural that the underlying basic magma would be added to the magma basin.

The writer has divided the whole structure into five groups composed of 51 zones according to his own classification in order to make clear the history of crystal growth.

The first group is composed of three subgroups, of which Ia is an irregular oscillatory normal (VI_n), Ib is an even-oscillatory even, (Ve) and Ic a normal-oscillatory even modified by microzones, if zone 8 is excluded from consideration. As the relative volume of the first

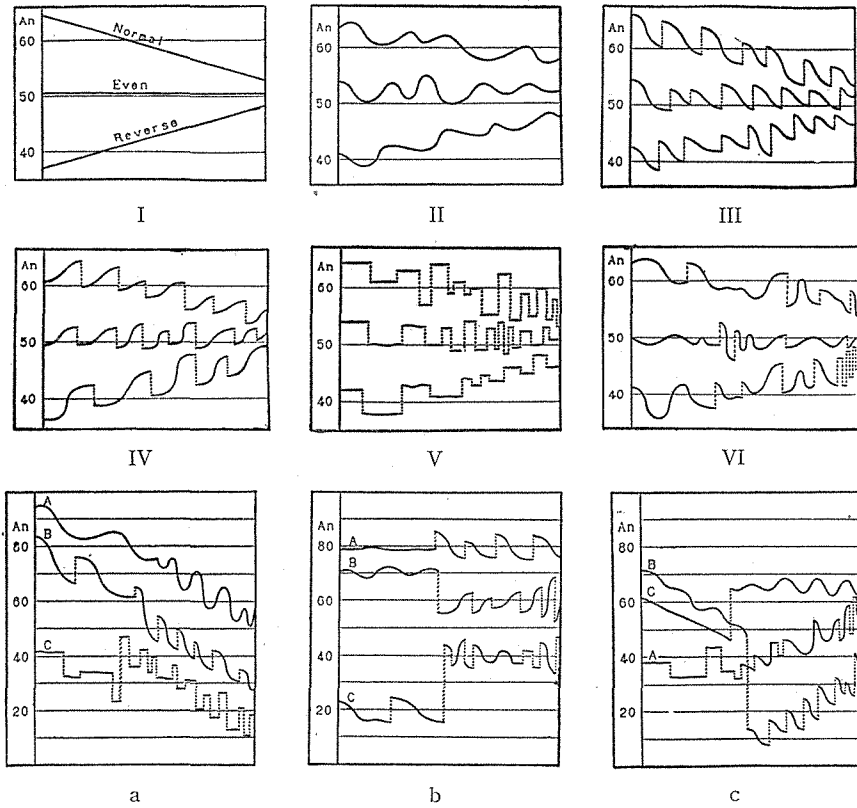


Fig. 10. Eighteen standard types of zonal structure and their combinations. I. non-oscillatory normal (In) even (Ie) and reverse (Ir). II. Wavy-oscillatory normal (II_n), even (II_e) and reverse (II_r). III. Normal-oscillatory normal (III_n), even (III_e) and reverse (III_r). IV. Reverse-oscillatory normal (IV_n), even (IV_e) and reverse (IV_r). V. Even-oscillatory normal (V_n), even (V_e) and reverse (V_r). VI. Irregular-oscillatory normal (VI_n), even (VI_e) and reverse (VI_r). a. Multiple structures; (A) Ordinary M. S. [In-(O)-In], (B) Promoted M. S. [III_n-(P)-III_n], (C) Retarded M. S. [V_n-(R)-V_n]. b. Composite structures; (A) Ie-(O)-III_e, (B) II_e-(P)-IV_e, (C) III_e-(R)-VI_e. c. Complex structures; (A) Ve-(O)-VI_r, (B) II_n-(P)-III_r, (C) In-(R)-II_e.

group is perhaps less than one tenth of the whole, the history of its growth does not throw much light on the general understanding of the crystal. If we use the notation = to show that the mean composition of Ia and Ib is nearly equal and the notation → to show that the mean composition of Ic is more sodic than Ib, the whole structure will be noted as VI_n=(R)=Ve→(o)→III_e, where (R) means a retarded continuance between zones 4 and 5 and (O) an ordinary continuance between zones 7 and 9 (fig. 8 and 10).

In the second group, IIa and IIb are irregular-oscillatory normal (VIIn), IIc and IId are normal-oscillatory normal (IIIIn) and IIe is irregular-oscillatory even (VIE); and at the same time the tendency of the composition to vary from IIa to IIe is hardly appreciable; that is, VIIn=(R)=VIIn=(R)=IIIIn=(R)=IIIIn=(R)=VIE.

The most characteristic feature of this group of zones is that the composition of the zones, directly surrounding the trace of corrosion, is carried back nearly to the same composition of the first zone of the preceding subgroup in spite of the decreasing tendency of An% in each subgroup. Such a phenomenon is clarified by C. FENNER's explanation¹⁾ that processes of differentiation have tended to change the composition to sodic, while ascensions of original magma have carried the composition back nearly to the starting point at the period of crystallization of the first zone in each subgroup.

The crystallization of the third group was begun by a considerable change in the conditions of the magma. Zone 42 is characterized by abundant inclusions of pyroxenes, apatite and glass, containing a fine bubble of gas. Such characteristic zonal inclusions in a basic zone, succeeding a trace of corrosion, is often observed in plagioclase in the rock of this volcano, though the amount of inclusion varies.

As has been explained, such a fact seems to show that a violent explosion took place in the volcano, connected with the magma reservoir, and caused temporary falls of temperature and pressure of magma, in which a small quantity of the underlying basic magma was supplied during a period of vigorous stirring.

The same event would be imaginable at the beginning of the fourth group, but soon after the magma seems to have been restored to its unruffled state, which was long held, till the fifth stage of crystal growth was begun with the mixing of olivine basalt magma.

The repeated normal-oscillatory structure in a gentler manner within only a few percent of anorthite will be understood if we suppose there was an up-and-downward circulation of the growing crystal in the magma reservoir. If a magma reservoir is connected to a volcano by a channel, as it is in the case in Unzen, gases in the magma will leak off through this channel to the surface of the earth, yielding a three-phase current, if it may be so named, of gas, liquid and solid phases. In this current the gas phase moves upward incom-

1) C. Fenner, *The Katmai Magmatic Province*, Journ. Geol., 1926, XXXIV, pp. 700—703.

parably faster than the other two, while the solid phase can only move upward by the aid of attached bubbles of gas. As the gas phase may pass freely into the liquid phase, the speed of ascension of the latter is almost negligible compared with those of the gas and solid phases when the volcano is in a state of inactivity.

The upper part of magma reservoir has a little lower temperature than the lower part, due to the natural gradient of geotherm and the endothermic action of the expansive gases at the upper part, as it is the fact that the pressure of the magma at the upper part is lighter than at the lower part. Consequently the crystal grows rapidly at the upper part of the reservoir, making the magma there more acidic than that of the lower part. Thus, if a plagioclase is carried upward by the aid of attached bubbles, it grows gradually, adding more sodic layers during the rise, while it can not do so or may be even a little reduced in sinking if it separates from the bubble. Such a movement of the crystal may take place repeatedly in a very gentle manner, effecting a normal-oscillatory normal structure as illustrated in the group IV of figure 8. Concerning the origin of the minor oscillatory structures, classified as microzone, a suggestion was given in the preceding pages. Recently E. S. HILLS¹⁾ discussed the origin of reverse and oscillatory zoning in plagioclase taking issue at certain points with PHEMISTER's explanation²⁾. He discussed the effect of pressure and volatiles in magma largely from the standpoint of physical chemistry, but according to the writer's considered opinion, as has been suggested in this paper, the effects of these factors are far more important when they are considered from the dynamical point of view.

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1) E. S. HILLS, Reverse and Oscillatory Zoning in Plagioclase Felspars, *Geol. Mag.* Vol. LXXIII 1936, pp. 49—56.

2) J. PHEMISTER, Zoning in Plagioclase Felspars, *Min. Mag.* XXIII, 1934, pp. 541—555.