

The Classification of the Zonal Structure of Plagioclase

By

Fujio HOMMA

(Geological and Mineralogical Institute, Kyoto Imperial University)

With 25 Text-figures

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I Introduction

The physical chemistry concerning the crystallization of plagioclase from a melt was explained by N. BOWEN through his study of the chemical equilibrium of the binary system anorthite-albite. The processes of the crystallization of the same mineral series from molten magma were discussed first in his paper,⁽¹⁾ "The Later Stages of the Evolution of Igneous Rocks", using the bases of subsequent investigations on a few ternary systems as diopside-anorthite-albite, forsterite-anorthite-silica and forsterite-diopside-silica. His first explanation for the zoning of plagioclase, that it is due to supersaturation by the rapid cooling and sinking of crystals in a magma reservoir, was, however, a view taken only from the chemical side. In his recent work,⁽²⁾ "The Evolution of the Igneous Rocks", he has extended his idea over the geological field to cover the complicated conditions in nature.

Founded on the practical observations of plagioclase under the microscope, prior to BOWEN's last work, C. FENNER,⁽³⁾ discussing the problem in his paper on Katmai Magmatic Province, pointed out that the oscillatory zoning which is most frequent in the phenocrysts in volcanic rocks in intermediate acidity seems to be looked upon as a record of changes of composition of magma brought about by external causes. He has supposed that, in the intratelluric reservoir, processes of differentiation have tended to change the composition in a certain direction, while at intervals ascensions of original magma

have carried the composition back a certain distance toward the starting point. Or, as an alternate process, that the crystals settle into a more calcic portion of the magma and are carried upward again into sodic layers. Thirdly he considered also the possibility that escape of volatiles, perhaps during an eruption of overlying magma, changes either the form of combination of constituents in the liquid or the relative solubilities to such a degree that the ratio of albite to anorthite deposited is considerably affected.

C. FENNER has further noted that, apart from the oscillatory zoning, the change of composition of zoned phenocryst through a wide range, as from labradorite to oligoclase suggests that the crystals remained suspended while corresponding changes in the liquid occurred.

During the practice of the measurement of zoned plagioclase under the universal-microscope the writer has confirmed that such remarkable changes of anorthite percentage as over 20~30% occur frequently between both parts of a corroded zone, while the parts form again oscillatory zoning. Moreover even in the same slide many phenocrysts manifest very different chemical compositions and different types of zonal structure. These complicated facts show clearly that each crystal has grown by its own career which is different each from the other.

It seems therefore that in the origin of the zonal structure of plagioclase the dynamical causes, magmatic and geodynamic, play a competitive rôle with the chemical differentiation of magma by crystallization.

From the genetical point of view, assuming the above conditions, the writer has classified the zonal structure in the following three orders in his paper,⁽⁷⁾ "über das Ergebnis von Messungen an zonaren Plagioclasen aus Andesiten mit Hilfe des Universaldrehtisches":

1. The general tendency in changing the composition from the core of the crystal to the periphery.
2. The mode of succession of zones.
3. The minute structure found in each individual zone.

Recently J. PHEMISTER⁽¹⁰⁾ has counted the following conditions as the cause of the formation of zonal structure:

(a) Movement of crystals in the magma, whether by gravitative settling or by convection currents.

(b) Movement of the magma as a whole into a region where different conditions of temperature and pressure prevail.

- (c) Irruption of additional magma into the crystallizing liquid.
- (d) Loss of volatile constituents.

He regarded all of these incidents as probable events in magma which is awaiting eruption.

Admitting that the formation of the zonal structure is restricted to the above mentioned conditions, it is still not easy to discern the origin of each zone observed under the microscope.

A systematic measurement of zoned plagioclase to accumulate examples of different types of zonal structure and to classify them according to the proper order and kind would be the first step to take in solving the problem concerning the origin of the zonal structure.

In recent years A. RITTMANN,⁽⁴⁾ S. KÔZU,⁽⁵⁾ S. WATANABE, T. NEMOTO,⁽⁶⁾ F. HOMMA,⁽⁷⁾ G. PAULIC,⁽⁸⁾ Ed. WENK⁽⁹⁾ and J. PHEMISTER⁽¹⁰⁾ have made many measurements of the zoned plagioclase in effusive rocks and the writer has added some more examples from plutonic rocks, which are not yet made public. The writer has thus gathered a sufficient examples to make a classification of zonal structure of plagioclase.

It must be remembered here that the zonal structure, or the mode of succession and of chemical change of zones is only the direct manifestation of the growing history of the crystal. Fundamental importance will be laid, in future petrology, on the exact observation of the zonal structure to elucidate the dynamical and chemical evolution of magma.

It is noted by the way, that the correct observation of the mode of succession may be attained only under the universal microscope with the objective U. M. 3 or 4 by E. LEITZ; under the ordinary microscope the discontinuity of zone would be missed, if the boundary plane of the zone does not lie parallel to the axis of the tube of the microscope. With the ordinary objective lens the magnification of image is much lowered than is the case with objective U. M. 3 or 4.

II The Theoretical Basis of the Classification

An illustration of zoned plagioclase, after a microscopic photograph given in IDDINGS' "Rock Minerals", 1911, is drawn as figure 1 and a hypothetical variation curve of An% corresponding to the section along the heavy line is expressed as figure 2. In the zonal structure in figure 1, we recognize three zones of remarkable corrosion, which divide the crystal into four groups of zones; they are again divided into many zones.

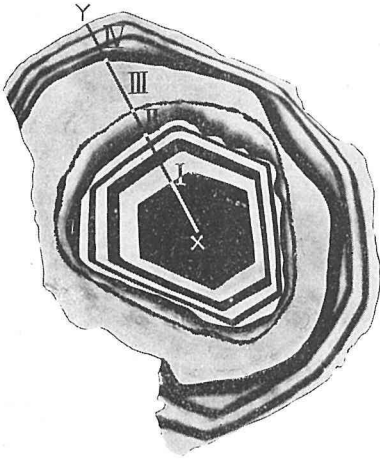


Fig. 1. A zoned plagioclase (simplified fig. 44 in IDDINGS' "Rock Minerals".)

clase in the surrounding rocks of the magma reservoir happen to sink into the magma as accidental inclusion or xenocryst, they may be partially molten or dissolved to form a round core of the crystal, surrounded by the subsequent outer shells of plagioclase, crystallized out from the magma.

(2) Plagioclase, crystallized out from a kind of magma A, may be affected when a new magma B of the higher temperature, or of the different chemical composition, is injected into the magma A reservoir. The outer zones of the crystal, formed after the injection of magma B, may show remarkable differences from the inner zones in respect to the mode of succession of the zones or the chemical compositions.

(3) Plagioclase might be corroded if the temperature of the magma were raised, affected by the injection of a new magma of the higher temperature in the country rocks, surrounding the magma reservoir. In this case the outer shells, succeeding the zone of corrosion, may be rather similar in the mode of succession or in the chemical compositions.

It is usual that under the microscope we find sometimes such crystals as illustrated above, suggesting that they have been affected during their growth by remarkable changes in the physical and chemical environment, due to such causes as considerable rises of temperature or changes of chemical composition, including the volatiles, in the magma.

Geologically considered, the following cases are expected to cause such a remarkable resorption:

(1) If fragments of plagioclase

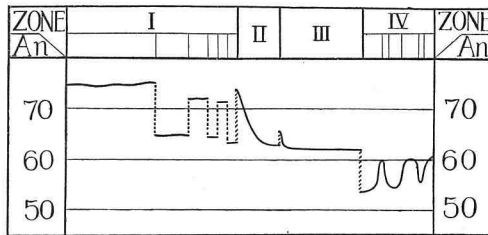


Fig. 2. A hypothetical composition variation-curve along XY in fig. 1.

(4) If the magma reservoir has a vertical elongation, the plagioclase, crystallized out from the upper acidic partial magma of low temperature may sink down into the lower basic magma of the higher temperature, which might then be able to resorb the crystal. In this case it is, however, doubtful whether or not there might be formed always a remarkable zone of resorption. If the reaction proceeds gradually during the whole course of sinking, it might also be expected that a tendency towards increasing An% to the outer shells may be only the result.

(5) Plagioclase might be affected by some unknown change occurring in the chemical system of magma in the course of differentiation. Even if such may be the case it is still doubtful that a remarkable zone could be formed.

Summarizing the five conditions above mentioned, the first three seem to be most responsible for forming the remarkable zone of corrosion. A much inferior degree of corrosion, such as is expressed only by the rounded edges of the zone, is observed in almost every case in the zonal structure and may be formed by many other different causes than those above stated.

Genetically considered, in the classification of the zonal structure, the zones of remarkable corrosion hold the highest position, dividing the whole structure into a few "groups" of zones.

Looking back to figure 1, we find in it that the structure of each group of zone is very different. If we assume that the corresponding variation curve of An% would be like figure 2, the first group forms an oscillatory normal structure, the second a non-oscillatory normal (continuous normal), the fourth again an oscillatory normal and the third forms a non-oscillatory even (no zonal structure).

These oscillatory structures, bounded within one group, are characterized by the parallel pile of shells representing the crystallographic faces of plagioclase. This may be regarded as positive evidence that the crystal was not disturbed during its growth by remarkable changes in its physico-chemical environs. Such a distinct shell is the "zone" generally referred to.

As already stated, some writers have noticed the general tendency toward a changing composition from the core to the periphery of the crystal, the mode of connection of successive zones and the variation of An% in an individual zone, but none has made yet a general survey over the whole field of the zonal structure.

As may be found later, the forms of the zonal structure within

one "group" were classified into eighteen types which are made up of the six standard types in reference to the manner of continuation of successive zones; each one, being divided into three forms according to the general tendencies toward the increasing, decreasing and unchanging An% from the inner to the outer side of the group.

Among the eighteen types of the zonal structure, the so-called "oscillatory", including fifteen types, is most usual.

If the question be considered from the physico-chemical point of view, the oscillatory zoning is only due to the change of chemical environment surrounding the crystal, but so far as the practical conditions of geology are concerned, the origin should be considered from two sides, space (1) and time (2):

(1) If the different parts of the magma reservoir are not the same in regard to the physico-chemical conditions, oscillatory zoning may be formed in a crystal by the circulation of the crystal in the magma or by some differential current, or movement, of the magma which includes the crystals flowing with an unequal velocity.

(2) If the physico-chemical condition of the magma changes in an alternative manner in the course of time, the oscillatory zoning may be naturally formed.

Among the four geological conditions on the origin of oscillatory zoning supposed by J. PHEMISTER, the first two are related to the "space" element and the last two, to the "time" element. But as the magnitude of the movement remains unlimited, under these conditions, zones of remarkable corrosion as well as rather inconsiderable minor oscillations of zone (illustrated as the microzone of zone 12 in figure 17, p. 149) might also be formed. These conditions are therefore of no use practically to explain the actual phenomena, appearing under the microscope.

In order to give the adequate explanations on the origin of zonal structure it is, then, more important to collect and to arrange every kind of zonal structure to a proper order than to look for such abstract conditions forming them.

For their arrangement, having first brought the order of magnitude of phenomena into the consideration, as illustrated in the several figures of this paper, the writer designated five orders: These are group, subgroup, zone, subzone and microzone.

As already stated, the criterion by which to distinguish a "group" is a trace of profound resorption. It is generally the case that within one group several zones succeed, in parallel, from the

inner to the outer side forming a certain type of oscillatory zoning. But it is also frequent, that even within one group, the different parts display different appearances as to the mode of succession of zones, the form of each zone, or the average An% of some successive zones. In such a case the group is divided into a few "subgroups", which are sometimes bounded by a trace of weak corrosion, being roughly parallel to the zones on both sides.

The difference of An% between neighbouring zones, or between the inner and outer parts of one zone is usually 5~10%. Within one zone minor oscillations are further observed very frequently, creating the necessity of making further minute classification of the zone into "subzone" and "microzone"; the technical standard for classifying them is analogous to that for the subgroup and zone within one group.

To give the genetical explanation of the five orders above mentioned is not easy at least and would be perhaps the last aim in studying the zonal structure. The writer postulates, however, the following supposition as to the genetical meaning of the five orders:

(1) For the trace of remarkable resorption dividing two groups, it is supposed that the growing crystal is forced to enter into a condition quite different from any it has ever experienced due to the movement of the crystal itself or the magma as a whole, or the irruption of new and different magma into the existing reservoir as already suggested.

(2) The differences corresponding to the subgroup would be caused by the shifting of the magma as a whole, due to the eruption to the surface or injection into the roofing earth crust of the overlying part of the magma, or to an analogous event.

(3) Each zone forming an oscillatory structure would be due to the up- and downward circulation of the crystal on a large scale in the magma reservoir, or to some other cause of a similar nature.

(4) The formation of the subzone would be due to changes in physico-chemical conditions which took place in the magma reservoir when affected by the different activities of the volcano, when it was connected with the reservoir, or to other similar events.

(5) The microzone is supposed to be formed by the direct or indirect effects of the local heterogeneity of the physico-chemical conditions of the magma due to unequal distribution of the minerals and volatiles or the irregular shape of the magma reservoir and to other minor causes.

All the conditions above mentioned are to be expected in the ordinary course of magmatic differentiation, but there may be also many unexpected or accidental events such as showers of rock and mineral fragments due to the collapse of the roofing rock of the magma reservoir. The zonal structures produced by the effect of accidental events would be identified by their irregular and abnormal appearances which are found in a smaller number than those due to the ordinary course of events.

Though the exact explanation for each kind of zonal structure will be left for the future, the preceding description seems to be sufficient to suggest how important is the detailed study of the zonal structure to the elucidation of the growing history of the crystal or the evolution of the magma. It suggests too that the detailed study must be made only through the proper classification of the structure.

III The Classification and Nomenclature of the Zonal Structure

Under the implicit assumption that the form of the individual zone and the mode of succession of the zones are dependent upon the up- and downward movement of the crystal in the magma reservoir and the tendency toward a varying composition from the inner to the outer side within one group or subgroup is due to the resultant migration of the crystal, up- or downward, the writer has classified six types as to the serial characters of successive zones and three tendencies as to varying composition as follows.

For the types of zonal structure, the followings are established as the standard forms ;

- I. Non-oscillatory structure.
- II. Wavy-oscillatory structure.
- III. Normal-oscillatory structure.
- IV. Reverse-oscillatory structure.
- V. Even-oscillatory structure.
- VI. Irregular-oscillatory structure.

For the chemical tendencies, (n) Normal, (e) Even and (r) Reverse tendencies are adopted.

The non-oscillatory structure is the term applied to the type in which the change of composition takes place continuously in a certain definite direction as illustrated in figure 3, while the other five type show some oscillatory or alternative structure due to a varying composition.

Thus the wavy-oscillatory is a type in which the migration to

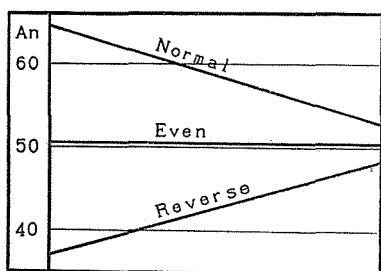


Fig. 3. I. Non-oscillatory structures.

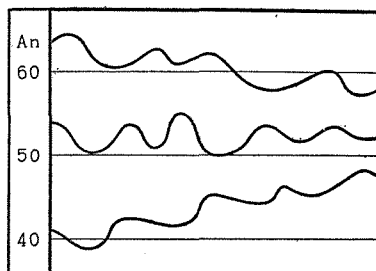


Fig. 4. II. Wavy-oscillatory structures.

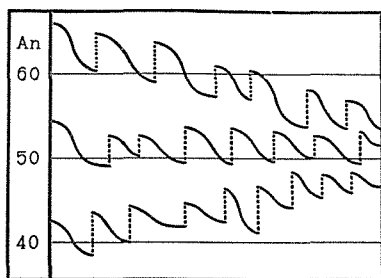


Fig. 5. III. Normal-oscillatory structures.

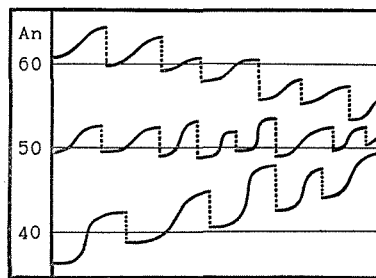


Fig. 6. IV. Reverse-oscillatory structures.

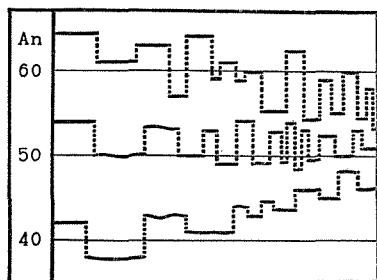


Fig. 7. V. Even-oscillatory structures.

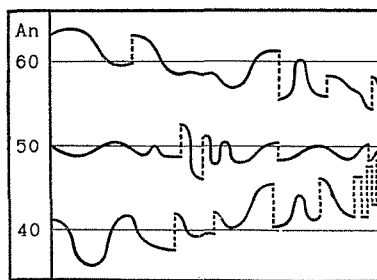


Fig. 8. VI. Irregular-oscillatory structures.

the neighbouring zone is continuous with a wavy form due to the alternate succession of acidic and basic zones (fig. 4) while in the even-oscillatory type, the mode of succession of the zone is discontinuous due to the alternate appearance of acidic and basic zones (fig. 7).

If the change of An% in one zone is from acidic to basic the zone is called normal as it accords with the general tendency of the magmatic evolution, though the reverse is also not infrequent. By the normal-oscillatory type is meant that a group or subgroup is formed by the repetition of the normal zone, the successive outer zones being carried back to nearly the same composition as the inner (fig. 5). The reverse-oscillatory type is a similar structure formed by the repetitions of the reverse zones (fig. 6). Under the irregular-oscillatory, are gathered the remaining structures which do not accord with the preceding five categories (fig. 8).

These six types will be divided into three kinds according to their tendencies in varying the chemical composition. Thus, in the normal-oscillatory normal (III_n), the outward succession of the zone forming a normal-oscillatory structure shows a general tendency toward decreasing the An% and, in the normal-oscillatory reverse (III_r), the tendency is toward increasing the An%, while in the normal-oscillatory even (III_e) it remains unchanged. In the same way the other five types may be divided each into three kinds, for example, non-oscillatory normal (I_n), non-oscillatory reverse (I_r), non-oscillatory even (I_e), wavy-oscillatory normal (II_n) etc.

If there is no trace of remarkable resorption in a zoned crystal it is said to be of "simple" structure, as it is formed by a single group of zones while if there is one it is of the "double", as the zones are grouped to two, and so on.

Genetically considered it is very important to observe what change of composition has occurred in the zone crystallized out directly around the trace of remarkable resorption; if there occurs no significant change of An% it is said to be of "ordinary" (O) structure in reference to the manner of continuation of the groups while if the tendency in varying the An%, exhibited in the inner group, is significantly advanced by the outer zone around the trace of the resorption, the structure is "promoted" (P). On the contrary if the tendency is carried back to a significant extent, the structure is called "retarded" (R). For the group composed of even structures the exceptions are made as follows: if the outer group begins

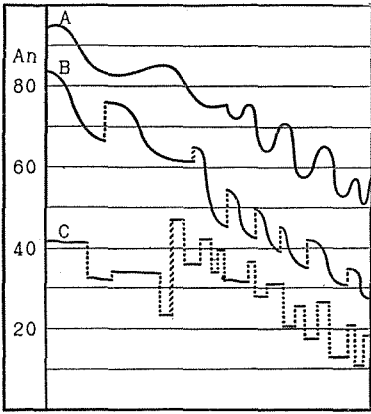


Fig. 9. Multiple structures.

- A. Ordinary M. S. of wavy-oscillatory normal, IIn-(O)-IIIn.
- B. Promoted M. S. of normal-oscillatory normal, IIIIn-(P)-IIIn.
- C. Retarded M. S. of even-oscillatory normal, Vn-(R)-Vn.

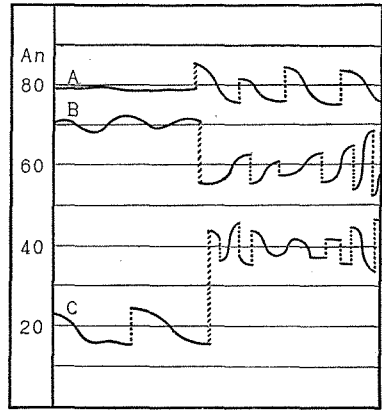


Fig. 10. Composite structures.

- A. Ordinary Cs. S. of non-oscillatory and normal-oscillatory even, Ie-(O)-IIIe.
- B. Promoted Cs. S. of wavy-oscillatory and reverse-oscillatory even, IIe-(P)-IVe.
- C. Retarded Cs. S. of normal-oscillatory and irregular-oscillatory even, IIIe-(R)-VIe.

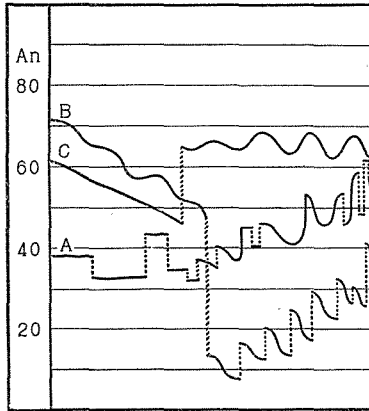


Fig. 11. Complex structures.

- A. Ordinary Cx. S. of even-oscillatory even and irregular-oscillatory reverse, Ve-(O)-VIr.
- B. Promoted Cx. S. of wavy-oscillatory normal and normal-oscillatory reverse, IIn-(P)-IIIr.
- C. Retarded Cx. S. of non-oscillatory normal and wavy-oscillatory even, In-(R)-IIe.

with a zone of a significantly lower An% than the inner, it is defined as "promoted" while if it begins with a zone of higher An%, it is called "retarded".

Thus if a zoned plagioclase be composed of two groups, the inner having a wavy-oscillatory normal form while the outer, a normal-oscillatory reverse form and, at the same time, the outer group begins with a zone of significantly lower An% than the last zone of the inner group, the structure is called a "promoted (complex) structure of the wavy-oscillatory normal and normal-oscillatory reverse" or expressed with a notation, II_n(P)-III_r (fig. 11, B), or the structure illustrated as figure 1 will be expressed, V_n(O)-In(O)-Ie(P)-I_{le}.

The last attempt at classifying the zonal structure is based on what kind of type is followed as the outer group to the inner one, when a zoned crystal is composed of two groups of zones. If the same type among the eighteen as that of the inner group is repeated in the outer group, it is called "multiple" (fig. 9) and if the only same tendency toward changing the composition is inherited by the outer group, it is called "composite" (fig. 10) while, if the outer group is of a different changing tendency from the inner, the structure is termed "complex" (fig. 11). Genetically considered, the multiple structure would be produced if, at the second stage of growth of the crystal, the same dynamical conditions and the similar chemical tendencies as those of the first stage should prevail in the magma reservoir; while the composite structure would be due to a subsequent change in dynamical conditions at the second stage in spite of its similar chemical tendency. If the physico-chemical conditions were entirely renewed at the second stage of growth, a crystal of complex structure should be the result.

The further nomenclature for the inferior orders concerning the zonal structure will be dealt with in the future, whereas the present attempt only covers to the third order of the phenomenon.

To explain the geological meaning of all the individual types is a difficult problem. The writer hopes to treat the problem elsewhere in the near future. In this paper several examples will be given in the next chapter.

IV Examples of Zonal Structures Actually Measured

Through the examples given in this chapter the writer wishes to show how the zonal structures of plagioclases differ according to

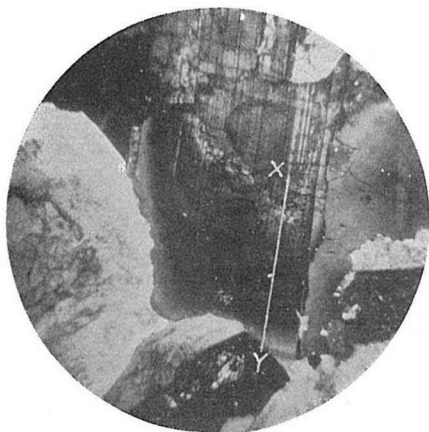


Fig. 12. Plagioclase in the adamellite near Kyoto.

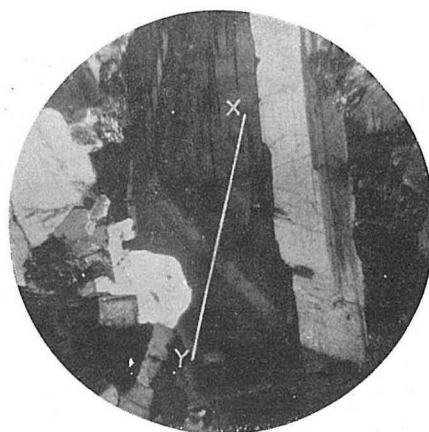


Fig. 14. Plagioclase in the porphyritic quartz-diorite north of Kyoto.

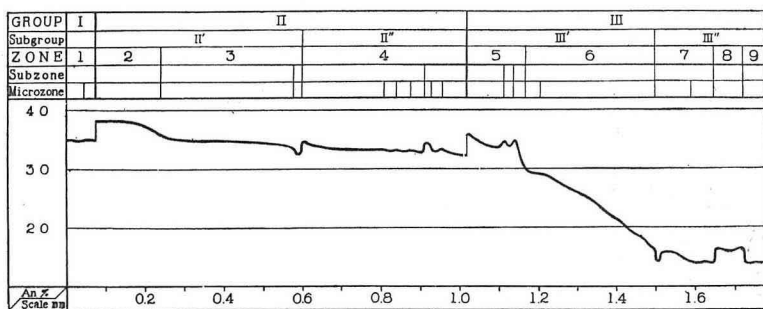


Fig. 13. Composition variation-curve along XY in fig. 12.

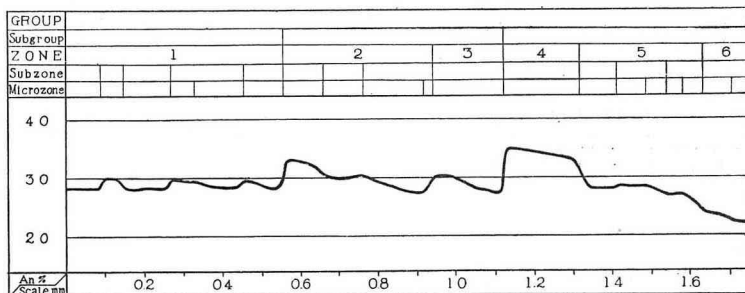


Fig. 15. Composition variation-curve along XY in fig. 14.

the kind of rocks that include them and therefore to suggest an explanation of the origins of the structures.

(a) *A Plagioclase in Adamellite.*

A hypidiomorphic crystal of plagioclase in the adamellite which intruded into the Paleozoic group near Kyoto, forming a stock with an areal extension of more than 25 sq. km, was measured under the universal microscope.

The actual measurement was done along the heavy line XY in figure 12. The general changing tendency of the composition follows roughly the normal course of the magmatic evolution but with some modifications, among which two traces of considerable resorption are most noticeable, (the outer zone is not visible in the photograph). By these traces the structure is divided into three zonal groups as shown in the variation curve (fig. 13). As may be seen from the photograph there may occur some differences of the curve according to the different sections. The first zones of the second and third groups are begun by considerably basic zones, among them zone 2 is so basic as to be partly decomposed and the remaining zones possess also more or less complicated structures, having been necessarily divided into subzones and microzones.

The resorptions during the growth of the crystal can not be explained geologically but it seems that the chemical composition of the magma did not change considerably, suggesting that the resorption was partly due to some thermodynamical effects. The structure of this curve will be roughly expressed $Ie\text{-}(R)\text{-}In\text{-}Ie\text{-}(R)\text{-}VI\text{-}In\text{-}Ve$.

(b) *A Plagioclase in Porphyritic Quartz Diorite.*

Several kilometers north of Kyoto a dyke-like mass is found injected into the Paleozoic group (Anthracolithic). This is a kind of basic quartz diorite and under the microscope the holocrystalline porphyritic texture with sporadic large crystals of plagioclase reveals the character of a rock forming a rather small injected mass (fig. 14). The plagioclase measured is hypidiomorphic as seen in the photograph and the mode of succession of the zones is typically a simple structure of the wavy-oscillatory normal type (II_n) with a slight decrease of An% towards the periphery (fig. 15). Such a structure is supposed to be due to the growth of the crystal in a reservoir of the quartz diorite magma with a very large dimension or rich in volatiles, suggesting it as a product in the batholithic stage.

(c) A Phenocryst of Plagioclase in a Dacite.

The dacite forming Mae-yama was erupted upon the eastern foot of the Unzen volcanic group, as a lava dome at the earlier period of the activities of Kunimi and Myôken Volcanoes, representing the third stage of the construction of the Unzen group. The zonal structure of the plagioclase phenocryst is beautifully shown in the photograph (fig. 16); the variation curve of the composition is rather regular (fig. 17). As shown with distinctly bright lines in the photograph, there are two basic zones (19 and 23), which appear directly outward from the traces of significant corrosion while the remaining zones show no considerable difference of composition.

The zones are grouped into three for the sake of convenience, by the traces of resorption preceding the distinctly basic zones though in the photograph the oscillatory zones of the first group show nearly parallel to the outlines of the crystal, contrary to the definition of

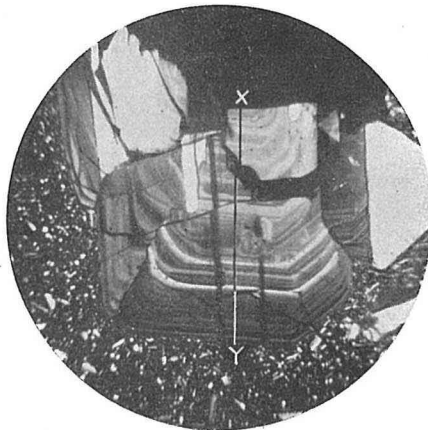


Fig. 16. Plagioclase in the dacite of Mae-yama, Unzen.

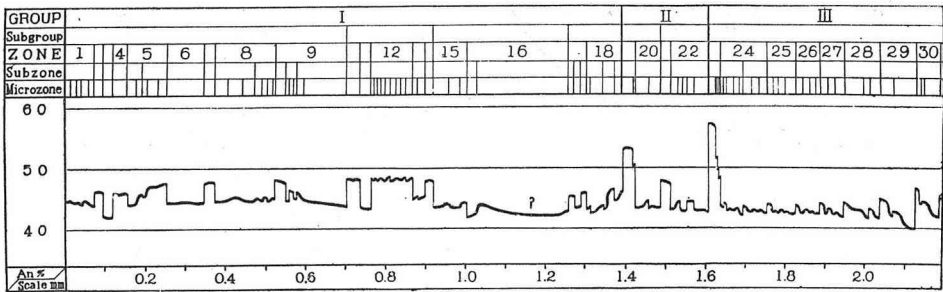


Fig. 17. Composition variation-curve along XY in fig. 16.

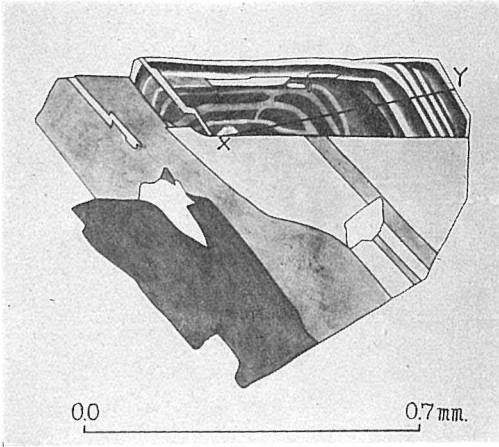


Fig. 18. Plagioclase in a biotite hornblende andesite at Simpura Peninsula, Northern Borneo.

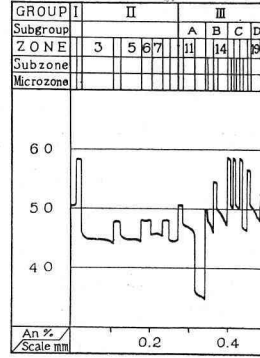


Fig. 19. Composition variation-curve along XY in fig. 18.

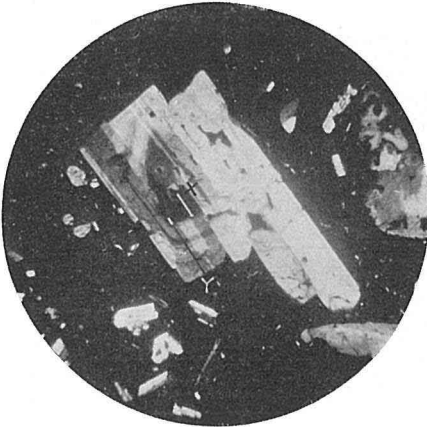


Fig. 20. Plagioclase (type 1) in the two pyroxene andesite of Shin-take, Kuchierabu.

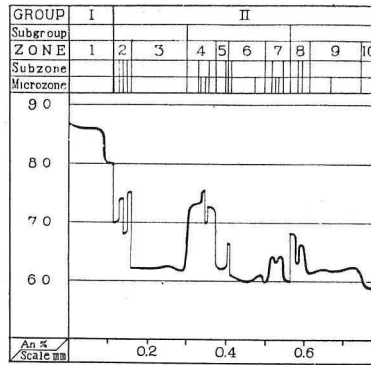


Fig. 21. Composition variation-curve along XY in fig. 20.

diving the group. Besides the two, there are also some traces of resorption, by which the groups are again divided into subgroups. In the first and second groups the mode of succession of the zones is mostly of the even-oscillatory even type having the composition of nearly 48~46 and 45~43% of An, while the third group forms a normal-oscillatory even type having the mean composition of 43% of An. The whole structure will be noted as Ve-(O)-Ve-(O)-IIIe.

The minor structure is characteristic in this crystal, especially in the third group, in which every zone is modified by the wavy-oscillatory normal or normal-oscillatory normal of the inferior order. The two basic zones include minute glass inclusions which contain always a very fine round hollow having been filled by some liquid or gas; they are accompanied sometime by finest apatite prisms, while other zones are quite free from inclusions.

For the genesis of such a structure the explanation may not yet be made with certainty but the structure seems to be generally characteristic of such rocks as dacite, hornblende or biotite andesite, suggesting that the structure is due to the rapid growth of the crystal having an active movement, probably, of a circulating nature, in thin fluidal magma.

Another example having a similar structure is given as figures 18 and 19 which may be noted as Ve-(P)-Ve-(P)-IIIr. The crystal is a phenocryst in a quartz-bearing hornblende biotite andesite (110BR), collected from Simpura Peninsula district of British Northern Borneo by Prof. M. REINHARD at Basel, Switzerland, under whom the writer made its measurement.

(d) *A Phenocryst of Plagioclase in a Pyroxene Andesite* (1).

Pyroxene andesite including the measured plagioclase is from the basal lava of Shin-take, or New Cone, in the Kuchierabu volcanic group which is composed of a multitude of small cones, situated on the Kirishima volcanic zone.

The structure observed under the crossed nicols is given as figure 20 and the corresponding variation curve is shown as figure 21. The mode of variation of the chemical composition of this crystal is very irregular, but it can be distinctly divided into two groups of zones, the inner of which consists of a nearly homogeneous composition of 86% of An excepting the transitional periphery while the outer sodic zone having a general tendency toward decreasing An% may be again divisible into three subgroups by the traces of

resorption. The general tendency of each of the three subgroups is toward decreasing the An%, or normal, and the mode of succession of the zones is irregular. Thus the whole structure will be described as "IIn-(P)-VIe and for the 2nd group, VIIn-(R)-VIIn-(R)-VIIn".

The rock is one of the most acidic ones in this volcanic group, including a kind of olivine basalt as its basic end. The plagioclase phenocrysts are roughly classified into two kinds, one of which, as here mentioned, has the composition of about 70~50% An with the peripheral rim of 59% An and is characterized by being nearly free from inclusions, while the other is more basic, with the composition of about 88~70% An having the periphery of 77% An and is characterized by abundant inclusions, gas, glass and pyroxenes; both kinds of phenocrysts exist in nearly equal quantity. Thus the writer has supposed as an extraordinary case for the explanation of the coming together of both kinds of phenocryst that, just before the effusion of the lava, the basic magma, possessed of a powerful inner expansive force by the volatiles in it, came to rise into the acidic magma chamber, stirring up the magma with an explosive violence.⁽¹⁾ Connected with this line of assumption, the basic core of the crystal here treated may be imagined to have been derived from the basic magma in some way.

(e) *A Phenocryst of Plagioclase in a Pyroxene Andesite (2).*

The microscopic photograph, here given (fig. 22), is the second kind of plagioclase in the rock mentioned above. It is characterized by the exceptionally abundant glass inclusion at the core and the outer zone of the crystal. The variation curve of composition along section XY having more basic composition than the former is rather simple (fig. 23), though the minor modifications are made around the inclusion which are neglected in the curve as they could hardly be measured.

Because of the considerable differences in appearance under the microscope, the zonal structure was divided into three groups, contrary to the definition, in spite of the absence of the noticeable traces of resorption between the groups. Thus it can be noted as Ie-(O)-Ve-(O)-Ie for the group.

Careful observation under the microscope reveals that sometimes the glass inclusion is nothing more than the remaining space which was made when the swarming small crystals happened to gather to form the central part or the outer part of the crystal. In this

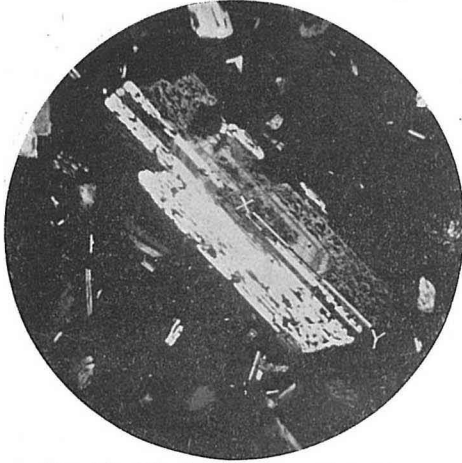


Fig. 22. Plagioclase (type 2) in the two pyroxene andesite of Shin-take, Kuchierabu.

occluded drop of the magma, the crystallization seems further advanced due to the falling temperature with the separation of plagioclase and pyroxenes; among them the plagioclase attached to the wall while the pyroxenes and clear brown glass with minute bubbles remained as inclusions. The zone of the abundant inclusions seems to be therefore due to the thin fluidity of the magma rich in volatiles.

(f) *A Phenocryst of Plagioclase in a Pyroxene Andesite* (3).

This is also a phenocryst of the pyroxene andesite forming the basal lava of Shin-take of Kuchierabu Volcanoes. A remarkable zone

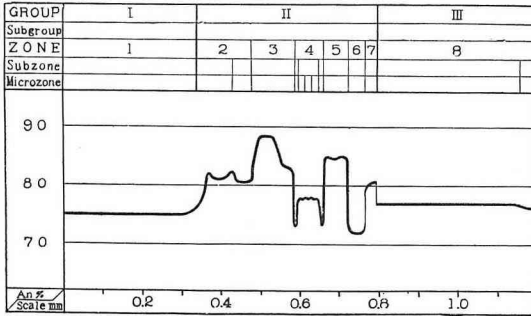


Fig. 23. Composition variation-curve along XY fig. 22.

of the abundant inclusions giving a dusty appearance is most characteristic in this crystal as illustrated in figure 24. As may be seen from the variation curve (fig. 25), the core inside the zone of inclusions is exceptionally sodic, suggesting that it would be quite

foreign to the magma underlying Shin-take, while the outer zone has the ordinary composition of the second kind of phenocryst in this rock. The fine dusty inclusion is therefore due to the reaction between the magma and the felspar fragments derived from a rock of a much lower temperature than the magma.

For classifying the structure of this crystal the zone of inclusion will be left out of the consideration and noted as Ie-(R)-IIIe.

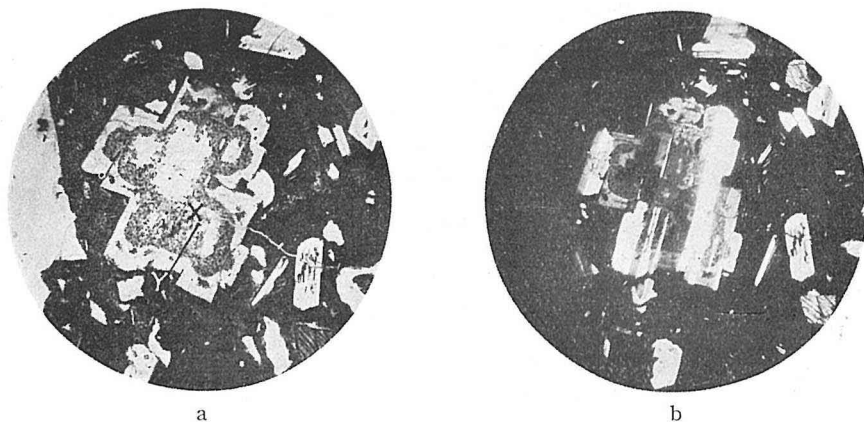


Fig. 24. Plagioclase (type 3) in the two pyroxene andesite of Shin-take, Kuchierabu.
a: open nicol. b: crossed nicols.

V Summary

It was pointed out in the first chapter that the zonal structure is the direct manifestation of the growing history of the crystal and the classification of it is the first step necessary to explain its history. It was noted also that the measurement may only be attained under the universal microscope.

Having given the theoretical basis for the classification in the second chapter, the writer tried to classify the zonal structure of the plagioclase in the third chapter, taking advantage of the many examples accumulated by himself; the results are as follows.

He divided the structure into the five orders as group, subgroup, zone, subzone and microzone.

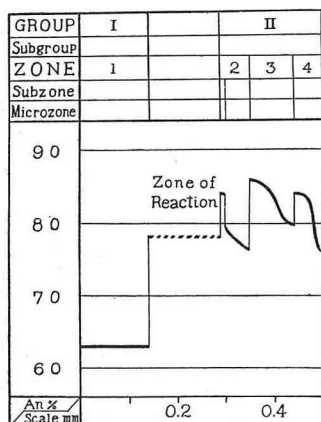


Fig. 25. Composition variation-curve along XY in fig. 24 (a).

For the mode of mechanical succession, multiple, composite and complex were defined, while for the chemical, ordinary (O), promoted (P) and retarded (R) were distinguished. The same kind of classification was alluded for the subzones.

Concerning the form of zone and the mode of its succession the group or subgroup was divided into the six standard forms, that is, (I) non-oscillatory, (II) wavy-oscillatory, (III) normal-oscillatory (IV) reverse-oscillatory, (V) even-oscillatory and (VI) irregular-oscillatory, while, from the tendency resulting from the varying chemical composition from the inner to the outer side, three tendencies were named as normal (n), reverse (r), and even (e). Thus the general method for the nomenclature and notation were exemplified.

In the last chapter seven examples were cited suggesting the genetical meaning of each structure.

The writer is much indebted to Prof. M. REINHARD, under whom his first steps in the study were made and he is also obliged to Honorary Prof. T. ÔGAWA, Prof. S. KÔZU and Prof. S. TSUBOI for their useful suggestions and encouragement in the investigation. To these the sincerest thanks of the writer are given.

Literatures

1. N. BOWEN, The later stages of the evolution of igneous rocks. Journ. Geol., 1915, XXIII, Supplement, pp. 32—39.
2. C. N. FENNER, The Katmai magmatic province. Journ. Geol., 1926, XXXIV, pp. 700—703.
3. N. BOWEN, The evolution of the igneous rocks, 1928, pp. 274—275.
4. A. RITTMANN, Geologie von Ischia. Zeitsch. f. Vulk., 1930, Ergänzt. Bd. VI, pp. 208—210.
5. S. KÔZU and S. WATANABE, Studies of the plagioclase phenocrysts in the pumice ejected from Komaga-take in 1929, (in Japanese). Journ. Jap. Assoc. Min. Petr. and Ec. Geol., 1931, VI, pp. 51—69.
6. T. NEMOTO, On the plagioclase in an andesitic basalt at Mitake near Sendai, (in Japanese). Journ. Jap. Assoc. Min. Petr. and Ec. Geol. 1931, VI, pp. 74—80.
7. F. HOMMA, Über das Ergebnis von Messungen an zonaren Plagioklasen aus Andesiten. Schweiz. Min. Petr. Mitt., 1932, XII, pp. 345—352.
8. G. PAULIC, Untersuchungen der Plagioklase einiger tertiärer Ergussgesteine Siebenbürgens. Schweiz. Min. Petr. Mitt., 1932, XII, pp. 423—444.
9. Ed. WENK, Statistische Drehtischuntersuchungen an Plagioklasen rumänischer Ergussgesteine. Schweiz. Min. Petr. Mitt., 1933, XIII, pp. 205—219.
10. J. PREMISTER, Zoning in plagioclase felspar. Min. Mag. 1934, XXIII, pp. 541—555.
11. F. HOMMA, On the zonal structure of plagioclase phenocryst in the basal lava of Shin-take, Kuchierabu Is, (in Japanese). Chikyû, 1935, XXIV, pp. 243—265.