Zoning in plagioclase felspar.

(With Plate XXII.)

By James Phemister, M.A., D.Sc.
H.M. Geological Survey.

[Read January 25, 1934.]

During the examination of the basalts of Calciferous Sandstone age which are mapped on the one-inch Sheet 23 (Hamilton, Lanarkshire) Scotland, the peculiarities of zoning exhibited by the porphyritic felspar were studied in some detail. As only a summary of the details is possible in the memoir explanatory of the geology of this Sheet, the description of the zoning is offered here, and some conclusions regarding the magmatic history of the zoned felspars are presented.

The basalts are all olivine-basalts, in some of which felspar is the only porphyritic constituent (Markle type), while others carry phenocrysts of augite and olivine in addition (Dunsapie type); all three minerals may be only microporphyritic (a transitional type lettered $vyBd^1$ on the geological map). The groundmass of the basalts is composed essentially of laths of labradorite, which is usually not zoned and contains about 50 % An, together with grains and crystals of augite and iron-ore, interstitial serpentinous material, and more or less felspathic cement of oligoclasic composition.

In Section I of the paper the zoning is described and three types of zoning, termed here normal, simple reverse, and oscillatory, are distinguished. The complicated problem presented by oscillatory-zoned plagioclase is discussed in Section II.

I. *Zoning of felspar in Scottish basalts.*

According to the theory of continuous reaction between crystal and magma the plagioclase separating out from a magma of basaltic composition should show, in the event of incomplete establishment of equilibrium, a progressively more albitic composition towards the periphery. This change in composition is observed in many igneous rocks and may take place continuously so that the crystal shows no clearly separated zones. The change may also proceed discontinuously, with the consequence that the crystal exhibits more or less sharply separable zones within each of which the composition remains constant, while the zones become more sodic towards the exterior. Zoning, whether continuous or discontinuous, which effects a change from calcic to less calcic plagioclase outwards from the centre of a crystal may be considered normal zoning. Cases are, however, found in which the felspar of the outer zone is more calcic than that of the inner zone. This zoning is reverse zoning. No observation has been made of continuous outward change from less to more calcic felspar, but occurrence of more calcic shells around and sharply demarcated against cores of less calcic plagioclase felspar is frequent in the basalts under consideration. Reference in the following pages to zoning of this kind will be made under the term simple reverse zoning.

Almost as common as normal and simple reverse zoning is a complex zoning (pl. XXII, figs. 1, 2, 3, 6) in which there is greater difference in composition between adjacent than between the alternate zones. The felspar crystal is built of thin shells alternately less and more calcic, and is said to be zoned in an oscillatory manner. The zones are usually sharply demarcated from one another. Oscillatory zoning is typically discontinuous and in detail consists of repetitions of discontinuous normal and discontinuous reverse zoning. The mean composition of two adjacent zones may remain steady over several zones, but in most cases eventually shows progressive change along the crystal. This change may be towards a more sodic plagioclase in the outer part, and the crystal has then oscillatory-normal zoning; the change may, on the contrary, be towards more calcic plagioclase, and the crystal has then oscillatory-reverse zoning.

In 135 thin sections of basalts in which zoning of felspar might be expected on account of coarseness of texture or presence of phenocrysts, it was found that normal zoning was present in 34, simple reverse zoning in 41, while oscillatory zoning was observed in 18 of this aggregate number. In some of the remaining 60 sections zoning was not present, in others it was too obscured by decomposition or by included material for specific determination.

Normal Zoning.—The simplest type of normal zoning is shown by felspar laths which constitute the groundmass of coarse-textured basalts (19640, 21195)[1] and by phenocrysts of idiomorphic prismatic

[1] The numbers refer to registered slices in the Geological Survey Collection of Scottish rocks.

habit (19386, 23987). The zoning is continuous in these specimens and occurs towards the termination of the laths or prisms, that is, in the direction in which growth was most rapid. Usually the zoned portion forms from one-quarter to one-half the total length of the crystal. On rotation between crossed nicols the zoned portion shows continuous and unidirectional change in position of extinction.

In many sections, however, zoning of a discontinuous type is exhibited by the phenocrysts. The bulk of the crystal is often of homogeneous calcic plagioclase which is bordered by a narrow homogeneous but less calcic zone, usually broader in the direction of the *c*-axis but distinct all round the crystal. There is no transition from the inner to the outer portion. The line of separation is parallel to the idiomorphic crystal outlines (19313, 19316) and is, in a narrow beam of light, shown up by the Becke line. Variants of this type are found in which the outer and inner portions show other differences besides the difference in composition. Thus the inner portion may be built of zones oscillating over a small range of composition, while the outer is homogeneous (19639, 24607, 24617), or in which the outer portion shows oscillatory (23131) or continuous normal zoning (24607, 24617, 25259).

Continuous normal zoning is in accord with the theory of crystallization from a melt of two components which form solid solutions in all proportions, and we may regard it as the normal product of crystallization in an undisturbed magma, cooling slowly but not sufficiently slowly for the attainment of complete equilibrium. Discontinuous change in composition such as described above, accompanied in some cases by change in the mode of growth, must then imply some departure from these ideal conditions of crystallization. Yet the crystal, despite these anomalies, appears to be a unit; the inner portion shows no appearance of corrosion such as is described later under the heading of simple reverse zoning. It seems that we should postulate some change in physical or chemical conditions which would cause a sudden change in the composition of the material precipitated without affecting that already crystallized. Removal of the crystal to a hypothetical less calcic part of the magma does not appear to be a probable explanation. Presumably this would involve an upward movement effected against gravity by convection currents, for the sudden origin of which it would still be necessary to provide an explanation. Further, unless the transportation were very rapid there should be continuous change between the inner and outer portions. Influx of more sodic magma may be suggested, but if the temperature remained the same, corrosion of the crystallized material should be expected to take place. A possible explanation which appears to give the required suddenness and proper direction of change in the physico-chemical conditions is that the magma, owing to relief of pressure consequent on eruption of overlying magma with which it is in hydrostatic communication, loses some of the volatile constituents. Experiment has shown that the melting-points of potassium silicates are lowered by about 50° C. by the presence of 1 % of water. Lowering of the melting-points of the alkali-felspars is possibly of the same order.[1] It may be expected, therefore, that the liquidus and solidus of the plagioclase series will be lowered, though probably not by a constant amount from end to end, by the presence of water and other volatiles. If this is the case, then sudden release of volatiles from a magma depositing a medium plagioclase will cause sudden change towards a more sodic composition in the material crystallizing out. An objection to this hypothesis is that the lowering of the solidus temperature might be sufficient to cause crystallization of the whole magma. As this has not occurred we must suppose that the amount of volatile constituents lost is quite small, and that, therefore, communication between the chamber of erupting magma and the lower chambers is very incomplete.

Simple reverse zoning.—Sections showing reverse zoning without oscillation are numerous (23073, 25757, &c.). The boundary between the zones is always sharply defined. The central portion of the crystal has, as a rule, rounded, and sometimes irregularly corroded outlines (pl. XXII, fig. 5), while either the outer zone may be idiomorphic (pl. XXII, figs. 4 and 5) or it may form a ring of fairly constant width around the inner portion (pl. XXII, fig. 3). Occasionally either the core or the border may possess a zoning not shared by the other, and the zoning of the core may be transgressed by the border zone as shown in the photograph last mentioned. In few cases can the composition of the zones be determined, but section 23996 shows a crystal cut parallel to (010) which possesses three sharply demarcated zones in which the extinction-angles against the (001) cleavage are 7° (core), 17° (intermediate zone), and 10° (border zone), corresponding to 37, 50, and 42 % An respectively.

In attempting to trace the history of such zoned felspars due

[1] Compare N. L. Bowen, The evolution of the igneous rocks. Princeton, 1928, Chap. xvi and p. 289.

attention must be paid to the existence of rounded or corroded outlines of the inner portion and to such allied features as zone truncation and differential distribution of inclusions. Some crystals, for example, show a core crowded with inclusions from which the surrounding zone is quite free (pl. XXII, fig. 4). Others show inclusions grouped along, and sometimes penetrating, the outline of the core. As a general rule there is some essential difference, such as those mentioned, between a less calcic core and a more calcic surround. It is therefore clear that in most cases of simple reverse zoning the cores are in a sense xenocrystic to the rock of which it now forms a part. This, however, does not imply that they are fragments of a previously consolidated rock detached by rising basaltic magma. They are probably early-formed crystals in a magma similar to or cognate with the rock now enclosing them. Since they are comparatively rich in albite it seems doubtful whether they are direct crystallizations from basaltic magma, and in this connexion it may be recalled that many of the lavas of the district are trachybasalts and trachyandesites in which porphyritic and groundmass felspars with low anorthite content are common. The simple reverse zoning described above may thus indicate active communication between magma chambers which contain liquids of different composition, and in some of which crystallization is in progress. The line between the zones is thus comparable with an unconformity and represents a period during which corrosion and transportation may have taken place.

Oscillatory Zoning.—Many plagioclase crystals show between crossed nicols that they are built of a large number of thin shells which can be shown by differences in extinction-angle and in refractive index to be alternately less and more calcic. The crystal is in effect built of two plagioclases which are deposited alternately. The zoning has therefore been called oscillatory. The change from one zone to another is not, however, truly oscillatory as it is not gradual but abrupt, and the zoning would be better described as alternating or rhythmic. In addition to the alternation in composition of the shells, each series of alternate shells changes in composition from centre to periphery. In some crystals the outward change is towards more albitic plagioclase, and such a zoning is here termed oscillatory-normal. On rotation between crossed nicols a wave of extinction passes from centre to margin, and under a low power the crystal seems normally zoned. In other crystals the outward change is towards more calcic plagioclase, and the zoning is oscillatory-reverse. The two cases are shown diagrammatically in fig. 1 *a* and *b*, which have been constructed from measurements made on crystals in sections 18574 and 23996 respectively. In those figures abscissae represent distance from the centre of the crystal, and the ordinates give the extinction-angles of the zones. Horizontal lines indicate

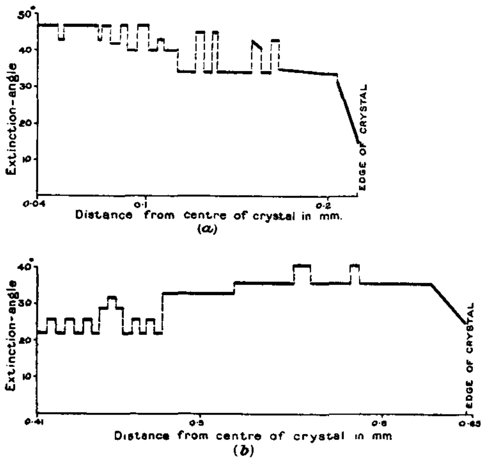


FIG. 1.

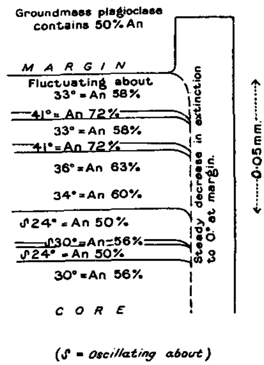


FIG. 2.

FIG. 1. Types of oscillatory zoning in plagioclase felspar.

(*a*) The zoning though oscillatory is normal, that is, the progression of zoning is more sodic outwards. (Compare pl. XXII, fig. 1.)

(*b*) The zoning is oscillatory-reverse, that is, the progression of zoning is more calcic outwards. Approximate compositions of the zones are shown in fig. 2.

FIG. 2. Approximate composition of zones of plagioclase felspar represented in fig. 1 *b*.

constant extinction and inclined lines varying extinction (within a zone). The general change to more sodic plagioclase in fig. 1 *a* and to more calcic in fig. 1 *b* is readily seen, and it may be observed that it takes place both by change in composition and by change in relative width of the more or less calcic zones. Both crystals show the rapid marginal variation towards oligoclasic felspar which is universal in the Calciferous Sandstone basalts of Scotland. Usually it is not possible to determine the composition of the zones without special apparatus, but in the case of the crystal which is illustrated by fig. 1 *b* the section was at right angles to the bisectrix γ, and in addition showed an ill-defined multiple twinning. On the assumption that this was on the albite-law the compositions of the zones were obtained from the curve of extinctions published by Duparc and Reinhard[1] for such orientated sections, and the variation in composition[2] is represented diagrammatically in fig. 2. The crystal represented by fig. 1 *a* is shown in pl. xxii, fig. 1. It is not a phenocryst, but a rather large groundmass crystal.

The great majority of crystals exhibiting oscillatory zoning are idiomorphic and the zones show the same crystal faces as the crystal. Specially fine examples are seen in sections 23996 and 23074, in each of which a phenocryst contains about forty idiomorphic zones (pl. xxii, figs. 2 and 6). In the latter the crystal clearly consists of a core only faintly zoned and three broad main zones which are themselves built of a number of thin shells developed most conspicuously in the direction of strongest growth. Each main zone is oscillatory-normal, but a sharp return to more calcic plagioclase is shown by the next outer main zone. The innermost main zone is, however, less calcic than the core. This crystal then has a complex zoning consisting of oscillatory-normal combined with discontinuous normal and repeated reverse zoning.

It is common to find one or more of the zones rich in inclusions. The inclusions being confined to a particular shell have clearly been trapped during growth of the shell and are not due to corrosion or permeation at a later stage in the history of the crystal. Good oscillatory zoning is found in many sections.

II. *Discussion of the origin and significance of oscillatory zoning.*

Before proceeding to the general discussion attention is drawn to the systematic investigation of the zoning in felspar with the aid of the Fedorov stage which has recently been undertaken by workers in the Mineralogical and Petrological Institute at Basel.[3] The papers

[1] L. Duparc and M. Reinhard, La détermination des plagioclases dans les coupes minces. Mém. Soc. Phys. Hist. Nat. Genève, 1924, vol. 40, p. 32. [M.A. 3–34.]

[2] According to C. Harloff (Zonal structure in plagioclases. Leidsche Geol. Mededeel., 1927, vol. 2, p. 111) it is not possible to obtain the exact percentages of anorthite in the minute zones of oscillatory-zoned plagioclase by this method, and the compositions shown in the diagram must be regarded as approximations.

[3] F. Homma, Über das Ergebnis von Messungen an zonaren Plagioklasen aus Andesiten. Schweiz. Min. Petr. Mitt., 1932, vol. 12, pp. 345–352. [M.A. 5–436.]

G. Paliuc, Untersuchungen der Plagioklase einiger tertiärer Ergussgesteine Siebenbürgens (Rumänien). Ibid., 1932, vol. 12, 423–444. [M.A. 5.]

S. Ghika-Budesti, Les plagioclases des banatites. Ibid., 1931, vol. 11, pp. 12–26. [M.A. 5–436.]

quoted contain much detailed quantitative work on the composition of the zones in oscillatory zoned crystals, and those by Homma and Paliuc show the results graphically as in fig. 1 *a* and *b*. The types to which the writer has referred as oscillatory-normal and oscillatory-reverse are conspicuous in the diagrams, but equally important is zoning in which the average composition of the less and more calcic series remains practically constant. Though many of the crystals investigated by those authors are built of homogeneous shells abruptly separated from the contiguous ones, crystals are also common in which continuous transition to more acid plagioclase is the rule within the shells. The change from the less calcic plagioclase of one shell to the more calcic plagioclase of the next shell is, however, always discontinuous. In a considerable number of crystals some of the more calcic zones are homogeneous while others are continuously zoned. Since those types are not illustrated in the rocks studied by the writer, examples are reproduced in fig. 3 from the paper by Paliuc. In a small number of the diagrams main zones which are oscillatory-normal zoned can be easily identified and the diagrams represent crystals of the type illustrated in pl. XXII, fig. 6. Those authors call attention also to evidence of corrosion between contiguous zones. In twenty crystals in which the zoning is represented diagrammatically, Paliuc observes corrosion in eight. In seven of those the corrosion has affected a shell of the more acid set; in only one has a shell of the more calcic set been attacked. It should, however, be emphasized that the contact of a calcic shell with its inner more acid neighbour is in the great majority of cases idiomorphic and shows no sign of corrosion.

Crystallization under steadily falling temperature and without complete establishment of equilibrium from a magma of two components which form a continuous series of solid solutions in all proportions results as we have seen in the formation of crystals continuously zoned from more calcic to more sodic felspar. When the same change takes place in stages represented by zones of increasingly albitic composition sharply separated from one another it has been supposed that periodic resorption has been operative.[1] In certain of the crystals under consideration the general outward change from more to less calcic plagioclase is effected by compound stages each of which involves precipitation of two very thin shells, one of more and one of less calcic composition. The alternation of such very

[1] A. Harker, Natural history of igneous rocks. London, 1909, p. 232.

thin zones (sub-zones) has been explained by Harloff as a consequence of lack of balance between the rate of diffusion and the rate of crystallization. If the rate of deposition in the region immediately surrounding the growing crystal, or shortly the *domain of crystallization*,

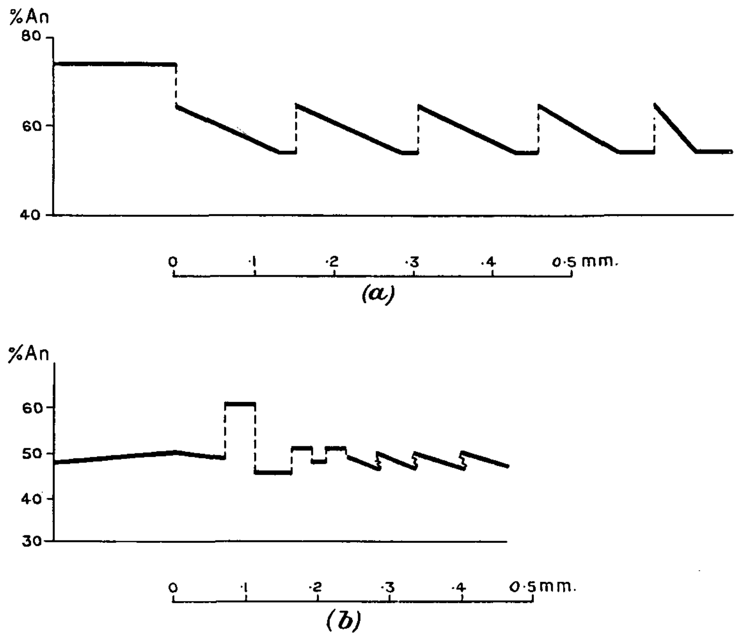


FIG. 3. Types of oscillatory zoning in plagioclase felspar.

(*a*) The change from the more to less calcic felspar is continuous, from less to more calcic felspar discontinuous.

(*b*) The crystal shows both continuous and discontinuous change to less calcic, but always discontinuous change from less to more calcic felspar. Zigzag vertical lines indicate evidence of corrosion.

There is no general progression towards either less or more calcic felspar. (After G. Paliuc, 1932.)

exceeds the rate of diffusion into this domain the composition of the residual liquor must become more albitic. According to Harloff (loc. cit., pp. 103–104):

Thus the felspar grows on, becoming more acid. Meanwhile, the rapidity of diffusion increases, because of the growing difference in concentration between the part immediately surrounding the crystal and the other parts of the liquid phase. Calcic ions, that were intended by diffusion to re-establish the former concentration in the acid part, now meet the growing crystal surface, before having succeeded in fulfilling their original intention. This causes a surplus of calcium in the liquid phase, where it borders immediately on the crystal, resulting in the crystallization of a new sub-zone, with a composition above the average composition of the main zone, of which it forms part. The sub-zones are thus the result of a reciprocal influence of the rapidities of crystallization and of diffusion, causing the crystallization of alternating calcic and sodic zones.

The writer, while agreeing with Harloff that the alternation of minute zones indicates some rhythmic process occurring within the domain of crystallization, is unable to follow in detail the modus operandi as outlined above. On theoretical grounds it is to be expected that deposition will halt when the concentration of anorthite in the domain of crystallization is reduced, unless there is at the same time a drop in temperature. From figures given by Bowen (loc. cit., p. 46) the drop in temperature between the crystallization of $Ab_{20}An_{80}$ and $Ab_{25}An_{75}$ from a melt of plagioclase $Ab_{50}An_{50}$ and 15% of diopside is 75° C. If figures of the same order hold for temperature and composition during crystallization from a basaltic magma, Harloff's explanation of alternating more or less calcic sub-zones requires temperature oscillations of a magnitude which is very improbable. Indeed it would seem likely that temperature change within the domain of crystallization should, owing to release of heat on crystallization, be in the direction of a slight rise. If, therefore, the rate of diffusion is considerably less rapid than the rate of crystallization, deposition should cease and there is a possibility that resorption may ensue or that the crystal margin may be changed-over into less calcic felspar by reaction with the surrounding more albitic liquor. The rhythm of events may thus be: (i) deposition of plagioclase with a much higher An:Ab ratio than in the magma, and concomitant concentration of albite in the liquor within the domain of crystallization; (ii) reaction of the crystal periphery with the more albitic liquor to form a less calcic plagioclase, and concurrent rise of the An:Ab ratio in the liquor both through reaction and through diffusion; (iii) deposition of calcic plagioclase once more. As the magma cools both the more and the less calcic zones will progress towards more sodic compositions.

This process of periodic resorption working under conditions of rapid crystallization and slow diffusion may be tentatively considered explanatory of the thin alternating more and less calcic shells, but it is not capable of explaining the appearance of zones more calcic than the plagioclase deposited at the beginning of crystallization. Neither can it account for the division of oscillatory-zoned crystals into main zones. For example, it may explain the thin alternating shells represented on the left-hand portions of the graphs, fig. 1 *a* and *b*, and those of the crystal shown in pl. XXII, fig. 6. It does not, however, seem applicable to the appearance of narrow calcic zones within a broad band of less calcic plagioclase as in fig. 1 *a*, right-hand portion, and is quite incapable of explaining the consistent progression towards more calcic plagioclase shown in fig. 1 *b* and the division of the crystal, fig. 6, into the broad main zones, which at their inner wall show abrupt return to calcic plagioclase. These features of oscillatory-zoned crystals must now be considered.

The problem is in part similar to that presented by simple reverse zoning, but while, as already pointed out, certain features such as corroded and rounded zone boundaries or differential distribution of inclusions within the zones accompany simple reverse zoning, it is found that the boundaries between the zones and particularly between the main zones, in oscillatory-zoned crystals are idiomorphic and that features such as corrosion or differential distribution of inclusions are more often absent than present. Therefore it seems probable that there has been no such hiatus in the growth of the crystal as has been postulated in the history of simple reverse zoned crystals. We may at this point review some hypotheses relating to the production of oscillatory-reverse zoning.

Reversal of the normal order of zoning in plagioclase felspar has been explained by Harker (loc. cit., p. 233) and by Iddings[1] as a consequence of supersaturation. According to this hypothesis crystallization does not begin until some time after the liquidus temperature has been passed and plagioclase more acid than would normally be deposited from a melt of the particular composition separates out. In virtue of the heat liberated by rapid crystallization the temperature rises permitting more calcic plagioclase to separate until temperature and crystal and magma compositions reach the equilibrium values, whereupon crystallization follows the normal course. It is possible on this hypothesis to have reverse zoning followed by normal zoning, but it does not seem probable that the *repeated* alternation of reverse and normal zoning exhibited by oscillatory-zoned crystals can be thus accounted for, since supersaturation can occur only once. Fenner[2] and Bowen (loc. cit., pp. 274–275) have both discussed the phenomenon of oscillatory zoning with particular regard to its

[1] J. P. Iddings, Igneous rocks. New York, 1909, vol. 1, p. 177.

[2] C. N. Fenner, The Katmai magmatic province. Journ. Geol. Chicago, 1926, vol. 34, pp. 700–703.

significance as an indicator of events in the history of the magma. Neither of these writers draws the distinction between main zones and the thin shell alternations, and Bowen alone makes the attempt to trace in detail the causes which lead to the rhythmic deposition of more and less calcic plagioclase. He considers that oscillatory zoning may 'find a probable explanation in several periods of sinking with intermittent surging forward of the mass'. During each period of sinking the crystal will reach portions of the magma which, being at a higher temperature, are able to deposit plagioclase more calcic than accrued to the crystal at a higher level. During suspension in this hotter region the surface layer of the crystal reacts with the magma and is either made over to more calcic plagioclase or taken into solution. In the latter event calcic plagioclase is deposited later when the temperature has fallen to the required value. Bowen conceives that in this way reverse zoning may arise, and, if the whole body is then carried to higher (cooler) levels, a new cycle of cooling and sinking will cause deposition of a second set of less and more calcic zones, and so on. As Bowen points out there should be on this hypothesis a general outward tendency to more sodic zones; the hypothesis may therefore explain the oscillatory-normal type of zoning in some cases, though it seems an impossibly intricate way of explaining the oscillatory-normal zoning of the groundmass crystal shown in pl. XXII, fig. 1, and in text-fig. 1 *a*.

Fenner suggests three explanations. First, oscillatory zoning is a reflection of changes of composition of the magma brought about by external causes; second, the crystals may settle into a more calcic portion of the magma and be carried upward again into more sodic layers; or lastly, the form of combination or relative solubilities of the constituents of the magma may be changed by escape of volatiles, perhaps during an eruption, to such a degree that the ratio of albite to anorthite deposited is considerably affected.

Homma (loc. cit., pp. 350–351) favours the second explanation suggested by Fenner and considers that the movement of the crystal is due to convection currents in the magma chamber and is aided by escape of volatiles which, bubbling upwards, help to float the crystals to the top of the chamber whence they descend under gravity and in the downward convection stream. Harloff (loc. cit., p. 104) suggests that sudden escape of volatile constituents is the cause of rapid crystallization of zones of a composition different from those already deposited.

The various hypotheses invoke recurrence of the following incidents separately or in some combination:

(*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.

All of those incidents must be regarded as probable events in magma which is awaiting eruption. In judging which or which combination of them is probably effective in producing oscillatory zoning we must take into account the number of recurrences. Thus during the growth of a crystal with forty zones there must be twenty recurrences. It seems to the writer that the hypothesis put forward on p. 550 which involves rhythmic changes in anorthite concentration around a growing crystal is more probable than hypotheses based on a large number of recurrences of external influences, and that this hypothesis in combination with one involving a few recurrences of external influences is capable of explaining the phenomena of oscillatory zoning. The external influence which is most likely to affect magma at the roots of a volcano is relief of pressure consequent on eruption. Relief of pressure will result in loss of volatiles to an extent depending on the openness of communication between magma chamber and the throat of the volcano. So far as loss of volatiles can directly affect the nature of the plagioclase deposited the difference must lie towards the more sodic end. More calcic plagioclase cannot separate out as the direct result of loss of volatile components. Relief of pressure causing streaming upward of volatiles may, as suggested by Homma, aid circulation of crystals within the magma chamber. Whether movement of crystals from higher to lower levels in the chamber can achieve the observed difference in composition of plagioclase in contiguous zones the writer has been unable to decide, as too many unknown factors are involved, principally the thermal gradient, which must be small if convection currents are operative, the degree of homogeneity of the magma, the thickness of the magma chamber. Relief of pressure consequent on eruption must, however, find an echo in the tendency of magma at lower levels to ascend to higher. It is therefore possible and probable that ascending hot magma will be erupted into higher chambers in which crystals are forming. It is by periodic accession of such hot magma that the writer would explain the abrupt recurrence of the more calcic zones which form the inner shells of the main zones of oscillatory-zoned crystals, the abrupt appearance of thin highly calcic shells, and the phenomenon of outer zones more calcic than the core.

Summary.—The paper describes various types of zoning in plagioclase felspar in the Calciferous Sandstone basalt lavas in one district of Scotland. The zoning is classified as (*a*) normal, (*b*) simple reverse, (*c*) oscillatory. Simple reverse zoning is associated with other differences in the zones which point to important time intervals between the growth of the zones. Oscillatory zoning is classified as oscillatory-normal and oscillatory-reverse and attention is drawn to the occurrence of oscillatory-zoned crystals which show no general tendency towards either more calcic or more sodic composition. Distinction is drawn between the main zones and the thin shells of alternately more and less calcic composition within the main zone. The alternating composition of the thin shells is possibly the result of lack of balance between rate of growth of the crystal and rate of diffusion from the surrounding magma. Recurrence of calcic plagioclase in the inner part of main zones is explained as the result of irruption of hot magma into the crystallizing liquid, probably consequent on eruption of lava at higher levels.

This paper is published with the permission of Sir John Flett, Director of H.M. Geological Survey.

EXPLANATION OF PLATE XXII.

Photomicrographs of plagioclase crystals in Scottish basalts.

FIG. 1. Slice[1] 18574. An oscillatory-normal zoned crystal of plagioclase of groundmass size. There is a general progression outwards towards more sodic plagioclase. Compare text-fig. 1 *a*. Crossed nicols. ×76.

FIG. 2. Slice 23996. Oscillatory-zoned crystal showing main zones with general progression towards more sodic plagioclase within each main zone. The most calcic zones are in the extinction position. Crossed nicols. ×10.

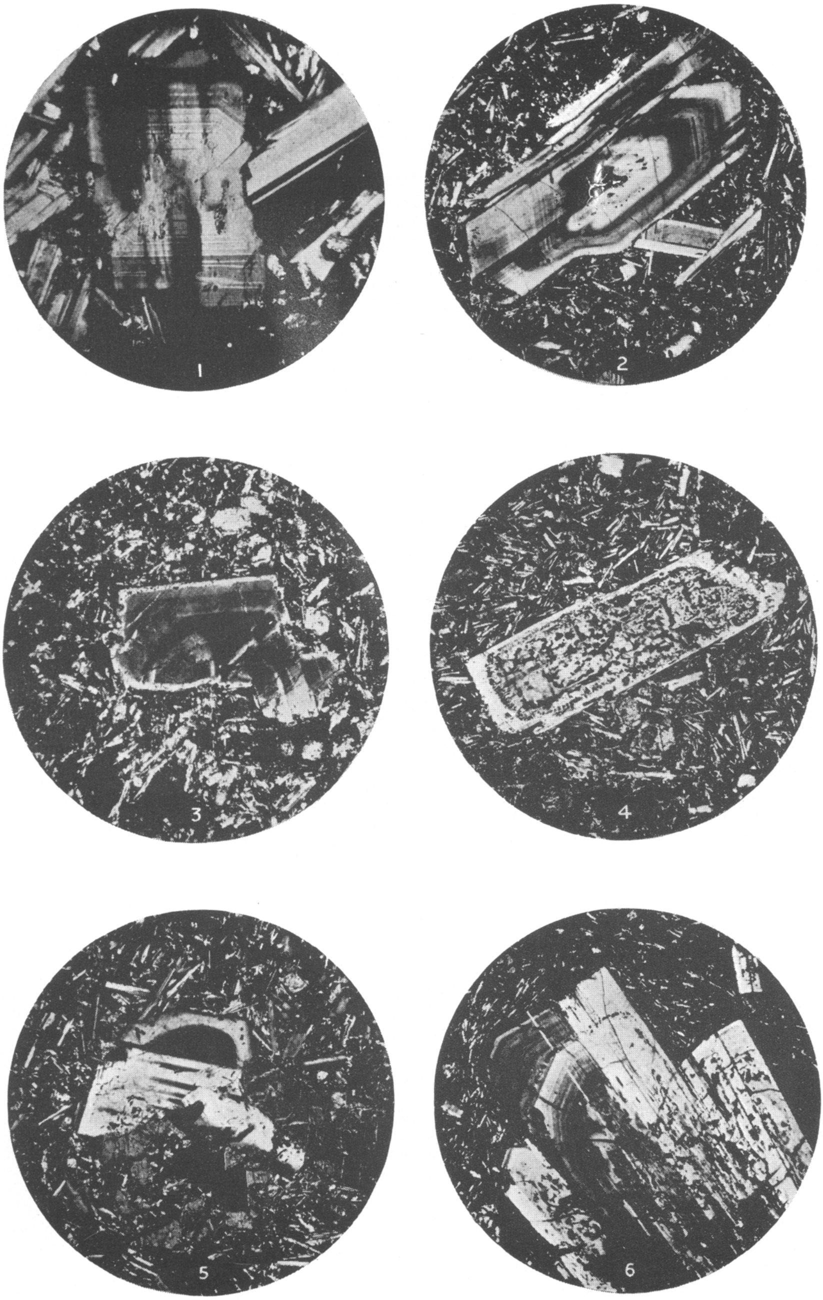
FIG. 3. Slice 23073. An oscillatory-zoned crystal has been corroded and more calcic plagioclase has been deposited after the corrosion as a narrow rim which truncates the zoning of the core. Exemplifies simple reverse zoning. Crossed nicols. ×25.

FIG. 4. Slice 25757. Exemplifies essential difference between core and outer shell in a simple reverse zoned crystal. The core is crammed with inclusions of ore, pyroxene, and serpentinous material and has a roundish outline. The outer shell, which is of more calcic plagioclase, is free of inclusions. Crossed nicols. ×18.

[1] Registered rock slices in the Geological Survey collection of Scottish rocks.

Fig. 5. Slice 23996. Exemplifies simple reverse zoning. The less calcic core has an outline rounded by corrosion. The more calcic plagioclase surrounding the core is idiomorphic and is normally zoned at the periphery. Crossed nicols. ×34.

Fig. 6. Slice 23074. The crystal exhibits very well the division into main zones which are composed of thin shells of alternately more and less calcic composition, and which show a general outward progression towards more sodic plagioclase, an abrupt return tolcalcic plagioclase being made in the next outer main zone. Inclusions of pyroxene, ore, and serpentine are confined to (*a*) the core and (*b*) the most calcic zone of the largest main zone. In this crystal the core has the most calcic composition. Crossed nicols. ×18.



J. PHEMISTER: ZONING IN PLAGIOCLASE FELSPAR.