

ZONAL STRUCTURE IN PLAGIOCLASES

BY

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With plates 24—27.

The purpose of this paper is to record the results of a series of observations on zonal plagioclases made with the aid of the Fedorow-stage. Some of these results may add to our present knowledge of zonality in general.

It is necessary, first of all, to give a definition of what we mean by zonal structure.

On first thought the expression seems to explain itself. When we observe a zonal felspar through the microscope between crossed nicolls, we generally see several more or less concentric zones. Their being visible is due to differences in extinction-angles, in their turn caused by differences in chemical composition. In certain rocks, that do not show any signs of stress, there are plagioclases which show an extinction somewhat similar to that of an undulose quartz-crystal. The change in composition from centre to border is so gradual, that no separate zones can be distinguished. In this case one cannot speak of zonality. On the other hand it seems obvious, that these plagioclases belong to the same class of crystals showing the above-mentioned phenomenon. In the definition I therefore propose to lay no particular stress on whether the zones show regular and abrupt borders or not, or on the conditions that prevented the forming of homogenous crystals, for these conditions can be fundamentally different. Thus the definition could be formulated:

By zonal structure in mix-crystals we mean a structure, which is the result of gradual or abrupt changes in the chemical composition during the process of crystallization.

We will now proceed to describe some examples of zonal structure.

Case 1.

The first case, which I have already alluded to, is that of an unhomogeneous crystal, in which no zonality is visible. Here we may speak of zonality on an extremely minute scale. I have studied such felspars from a proterobase (Stiebitz, Bautzen) with the aid of an oil-immersion, and did not succeed in finding the least indication of zones. The centre is the more calcic, the felspar becoming slightly more sodic towards the border. The molecular structure of each submicroscopic zone is a homogeneous discontinuum differing only slightly from that of the neighbouring zones. The measuring of such a felspar with the Fedorow-method is rendered difficult by the absence of distinctive marks. In this case one cannot be quite sure whether the measurements have

always been made for one and the same spot. I managed, however, to measure some plagioclases from this rock, where the difference in extinction between centre- and borderparty was comparatively large. The result showed a composition of the centre of 83 % to 84 % of anorthite, of the borderparty of 80 % to 81 % of anorthite. Thus the difference in composition may be 2 % An. at the least, 4 % An. at the most.

The crystallization of this rock must have been slow, not interrupted by abrupt changes in the physico-chemical conditions: the change in these conditions must have been slight and gradual.

Case 2.

This has not been the case in the second example, represented by fig. 1, a felspar from a vitrophyric tuff from the Tresa-valley (Porphyry-district of Lugano).

It consists of three individuals: 1, 2 and 3, forming the usual twinning-law combination:

- 1—2 Albite.
- 2—3 Karlsbad A.
- 1—3 Roe Tourné.

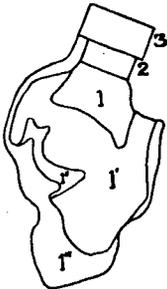


Fig. 1.
Sketch of plagioclase
with irregularly
shaped zones.
Enlargement 12 X.

The individual 1 shows four very irregularly shaped zones of the following compositions:

- 1 67 % An.
- 1' 55 % An.
- 1'' 44 % An.
- 1''' 39 % An.

The composition of 2 and 3 is 55 % An., or exactly the same as that of zone 1'.

It seems obvious, judging from the irregular shapes of the different zones, that, after the crystallization of a felspar with a composition of 67 % An., resorption took place, which was probably caused by a rise in temperature. Then a new felspar, more sodic, was formed round what remained of the former. The same process was repeated several times, whereby each newly-formed felspar became more rich in soda.

The forming of the individuals 2 and 3 must have begun, judging from their chemical composition, simultaneously with that of zone 1' and was terminated before 1'' began to crystallize, as this zone partly surrounds 2 and 3.

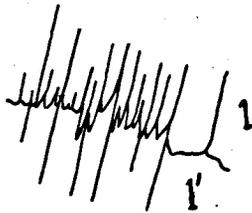


Fig. 2.
Enlargement of the border
of zone 1 of the plagioclase
represented on fig. 1.
Enlargement 70 X.

By „it seems” I mean that, although I am inclined to accept this explanation as the more probable, I am by no means sure as to its being the right one. Several questions namely remain to be answered.

First of all we must account for the fact, that 2 and 3 were not resorbed, as was the case with 1. Secondly a minute examination of the borders (fig. 2) of each of the zones shows that their aspect does not

resemble the rounded forms, that are so typical of resorption. It seems, on the contrary, that we have to deal with mechanically broken pieces. On the other hand it is difficult to account for the fact, if mechanical forces were really responsible for these forms, that the crystals were not split up along cleavage-planes, and that they were repeatedly broken.

Whatever may have been the cause of these irregular shapes, we may thus describe the conditions under which this crystal was formed: the general trend from calcic to sodic from centre to border points to the normal change in composition of the liquid phase during crystallization. The crystallizing matter itself would have changed its composition along similar lines as the liquid phase, but for a repeated interruption by certain occurrences which I am unable to ascertain more clearly.

The essential difference with the first-mentioned case exists in the fact, that the crystallization was repeatedly interrupted, or, in other words, shows a discontinuity, for a certain lapse of time must be allowed for between the forming of two subsequent zones. There is no difference, in principle, between the two cases, as regards the general trend of change in chemical composition. For, although in case 2 the composition of the liquid phase must certainly have been affected, especially if the interruptions were caused by resorption, the fact remains, that in both cases the compositions show the same trend from calcic to more sodic. I may here add, that in representatives of the cases 1 and 2, I have never observed recurrence in the composition of the zones.

In passing on to the next example I should like to point out, that this case is also interesting from the point of view of twinning. I am inclined to agree with Dr. KUENEN's supposition, that certain twins in feldspars might best be explained by supposing that a mutual attraction, caused by molecular forces, has brought the separately formed crystals into contact in twinned position.

Case 3.

Case 3 is represented in fig. 3, which shows a plagioclase from the same vitrophyric tuff. It consists of the individuals 1, 2 and 3. The twinning-laws are:

- 1—2 Roc Tourné.
- 2—3 Albite.
- 1—3 Karlsbad A.

All individuals consist of a calcic centre and a more sodic border. The compositions are:

- 1, 2, 3 { centre 69 % An.
- { border 54 % An.

In this example we notice:

1. The border which separates both zones is well defined.

2. The border-zone shows everywhere the same thickness, with the exception of the individual 3, which shows one direction, in which it has evidently grown

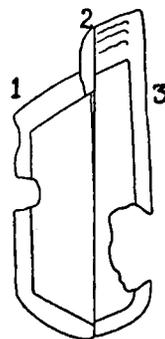


Fig. 3.

Sketch of plagioclase with regular zones.

Enlargement 12 X.

quicker than in all other directions. The centre, too, reaches further in this direction than that of individual 1.

3. The individual 2, wedged in between 1 and 3, does evidently "belong" more to 3 than to 1. Its association plane (010) is more sharply defined on the side of 3. Their twinning-law (Albite) being a far more common law than that of the Roc-Tourné also seems to point in the same direction.

4. Within the border zone of 3, where the rapidity of crystallization was greater, one is able to discern a subdivision into some smaller zones with recurrent chemical composition.

The difference with the former case is evident. First of all the rigorous parallelity of the inner zone to the border of the crystal here, the irregular forms there: this fact in itself seems to be sufficient proof that no time interval can have existed between the forming of both zones. The difference in composition must be due to another cause than in case 2, for instance to an abrupt change in the chemical composition of the liquid phase, or a fall in temperature. It seems, too, that there must have been a difference in rapidity of crystallization between the two zones. The border zone seems to have grown quicker, just where the Albite-lamella is present, the broadening of which begins simultaneously with the crystallization of the more acid border zone.

Case 4.

Plate 24, fig. *a* shows a plagioclase from the well known vitrophyre from Grantola (Porphyry-district of Lugano). In this case we notice:

1. Repeated recurrence in the chemical composition.
2. The zones run more or less parallel to each other. This parallelity, however, is not so pronounced as in case 3. Most zones show rounded forms. The border zone only has well defined crystal planes on both sides.
3. We discern two kinds of zones: main zones, which can be subdivided in subzones (Anwachsstreifen of BECKE). Usually these sub-zones are not to be observed in the centre; they begin to show themselves where zonality becomes more prominent. They may vary in thickness. In the left-hand lower corner of the figure, where crystallization has been quicker during the forming of the border zone, sub-zonality is very distinct. Six sub-zones may be counted, which, although narrower, persist throughout the whole of this main zone. We will see, later on, that this sub-zonality must be regarded as fundamentally different from the main zones.

In this case I will also draw attention to the peculiar twin-forming. The first impression is that we have to deal with two individuals. In reality there are three, of which number 3 happens to have the same orientation as 1, but is a separate crystal, as it has a zonality of its own. The zones of no. 2 are not visible on the photograph, but indicated by dotted lines. The composition of the centres of 2 and 3 are the same as that of 1. To all the zones of no. 1 can be found the corresponding zones of 2 and 3, which points to their having grown simultaneously.

The individual 2 maintained its dimensions during the crystallization of the centre of 1. It broadens, however, as soon as a pronounced zonality sets in. The fact however remains to be accounted for, that, during the crystallization of the central parts, the individuals did not yet touch each other, but are now seen to be in contact in twinned position.

The same subdivision in main zones and sub-zones must be made for the plagioclases represented on Plate 24, fig. *b* and Plate 25, fig. *a*.

The zones show their broadest dimensions in the directions of quickest crystallization. In this direction they are usually separated from each other by well defined borders. In other directions the zones cannot even be distinguished the one from the other.

Sub-zonality is only distinct in the same direction of quickest crystallization. The sub-zones cease quite abruptly, where crystallization-rapidity was at its minimum. It also appears, that the sub-zones are the chief formers of crystal planes. In Plate 25, fig. *a* can be observed distinctly, how, in the course of crystallization, crystal planes originate, disappear and reappear according to the directions, which, temporarily, have been favoured by crystallization-rapidity. The main zones can be quite independent in their forms from the sub-zones. Fig. 4 (text) shows the centre of the plagioclase represented on Plate 24, fig. *b*. Here the main zones show rounded forms. Within these zones sub-zones can be distinguished running almost perpendicular to the borders of the main zones. From this fact we may draw the conclusion, that each main zone must be merely regarded as a product of a certain composition of the liquid phase during a certain time interval in the process of crystallization. The presence of sub-zones is dependent on the manner, in which this crystallization occurs, i.e. from the rapidity of crystallization. A careful examination of these sub-zones shows calcic zones alternating with sodic zones. It seems, as if these alternating zones must be due to a rhythmically occurring process in the immediate surrounding of the growing crystal. When crystallization exceeds a certain rapidity, the part of the solution, which immediately surrounds the crystal, becomes relatively more rich on soda, as more calcium is withdrawn from it, while the rapidity of diffusion in the liquid phase cannot keep pace with the rapidity of crystallization, to re-establish the original concentration on calcium. 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 the 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 on calcium in the liquid phase, where it borders immediately on the crystal, resulting in the crystallization of a new sub-zone, with a composition



Fig. 4.

Sketch of zonal plagioclase showing sub-zones and main-zones. Within the innermost main-zone the sub-zones stand almost at right angles to the border of the former.

above the average composition of the main zone, which it forms part of. 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.

It may be of some interest, to illustrate this phenomenon with an experiment, which, in itself, must be well known.

A solution of NaCl in water, brought on an object-glass, is warmed a little, and the crystallization of NaCl is subsequently observed through the microscope. A rapid crystallization produces crystal skeletons. During a relatively slow crystallization the forming of the regular cubes can be followed. Their growing may be seen to be intermittent, for each time, after a new layer has been formed, there is a time interval, in which the water in the immediate neighbourhood of the crystal is not saturated with Na- and Cl-ions; as soon as evaporation and diffusion have re-established the necessary concentration, the crystallization proceeds. In this case the time-interval, in which there is no crystallization, corresponds to the crystallization of an acid sub-zone in the case of a growing plagioclase.

From this difference between main zones and sub-zones we may conclude, that each of these two kinds of zonality can occur without the other. When we observe Plate 25, fig. *a*, and leave the centre out of consideration, we are very near to the case, where only sub-zones occur, for main zones are not very well pronounced in this feldspar. Of the reverse case we have an example in Plate 26, fig. *b* and Plate 27, fig. *a*.

Generally speaking there are comparatively few feldspars, that do not show at least some indications of sub-zonality. When I stated, that both kinds of zonality are fundamentally different, this difference only concerns the direct cause of their forming.

Indirectly there obviously exists a causal link between the two, for circumstances which force a magma to crystallize rapidly are generally at the same time the cause of more or less abrupt changes in the physico-chemical conditions in the liquid phase. If, for instance, a magma suddenly loses part of the gasses which it holds in solution, this loss of "agents minéralisateurs" results in a swift crystallization of the liquid phase, while at the same time the matter that crystallizes, will have a different composition from that, which crystallized before the disturbance. Especially in the neighbourhood of eruptive centres such changes are liable to recur periodically and their influence will make itself felt, though less markedly, in deeper regions. After each eruption, which means a loss of gasses, there will be a tendency to restore the former conditions, till the next eruption occurs.

The more the character of the eruptions is intermittent and explosive, the more we may expect to see this character reflected in the mineral habitude of the rock concerned (basic recurrence in the zones of plagioclases, resorption, etc.). If, on the other hand, the loss of gasses is continual, no such structures are to be expected.

Zonal plagioclases, however, also occur in intrusive rocks, which, so far as we know, have not had any communication with the earth's surface. In such a case the possibility remains, that we have to deal

with what were once the deeper regions of an eruptive centre, referred to above, where the effects of extrusions made themselves felt, though less markedly. Often the denudation of such intrusive bodies has reached a stage, where there are no geological data to establish this possibility as a fact. Much also depends on the mechanism of the intrusion. If the process of de-roofing (DALY) keeps pace with the assimilation of the intruded rock, and the intrusion goes on gradually, the intruded rock will already have assumed a temperature that does not differ much from that of the intruding magma, when it has actually been reached by the latter. The loss of heat by the assimilation and conduction is supplied from the inner body of the batholith both by conduction and convection-currents.

On the other hand an abrupt intrusion means the coming into contact of the magma with rocks much lower in temperature, which may lead to a disturbance in the above mentioned heat equilibrium. Local losses of gasses may be the result of such disturbances. In fact, the possibilities for the occurring of a number of disturbing influences in the border regions of intrusive bodies are so manifold, that one may expect the frequent occurring of structures otherwise typical of effusive rocks.

The theory of HERZ, (Bibl. 8) that zonality in plagioclases is due to currents which bring the crystals into contact with parts of the magma, where felspar-substance has not yet crystallized, has been rejected by BECKE as improbable. It is unlikely, that a current would bring the crystals into contact with new parts of the magma, for the magma surrounding the plagioclases must have been included in the movement. Another question is why only part of the magma should have begun to crystallize. Plate 25, fig. *b* represents a plagioclase from an augite-andesite (Mount Elias, Santorin). The centre shows inclusions of ore and augite and is obviously a resorption remnant. After the resorption crystallization once more set in, producing a more acid border zone with many sub-zones. Many of the sinuous resorption-inlets were wholly or partly filled up. The large gap on the left, reaching into the core of the section, shows this new border with sub-zones. It is remarkable that, almost everywhere the border zone shows good crystal planes. Plate 26, fig. *a* represents a small phenocryst from a hornblende-andesite of South-Mendoza, Argentine. Very narrow sub-zones are present, though not clearly visible on the photograph. Peculiar is the gradual loss of well defined crystal planes towards the border of the crystal, followed by the sudden recurrence of the crystal shape near the outer edge. A similar phenomenon has been described by BECKE (Bibl. 4) in a hypersthene-andesite from the isle of Alboran:

“Oft sind die inneren Anwachsstreifen (our sub-zones) der Durchschnitte unbestimmt rundlich und erst die äusseren streben der regelmässigen Gestalt zu, alsob ein durch Korrosion eines ältern Kristalles entstandener Kern durch Ausheilung Kristallform gewonnen hätte”.

There is, however, an essential difference in that our crystal cannot have been rounded off by resorption, as it has lost the normal crystal shape gradually, each approaching more nearly to the egg-shape, and that the recurrence is quite sudden.

Plate 26, fig. *b* shows a fine example of basic recurrence in the composition of the zones. The dark zones are the more calcic ones. They contain 84 % An. throughout the whole crystal. The acid zones contain 44 % An. Usually, in the case of recurrence, the composition of both calcic and sodic zones becomes more acid from centre to border. In this case, however, both compositions remain remarkably constant and show the unusually large difference of 40 % An., the largest I have yet found, when measuring plagioclases with recurrent zones.

Plate 27, fig. *a* shows a plagioclase from the same rock (a porphyrite) with similar zones, containing in this case 82 % and 44 % An. The V-shaped twin-lamella has the same zonality, though not visible on this figure. Plate 27, fig. *b* is a photograph of the same feldspar, made through the Fedorow-microscope. By tilting the slide it could be brought into a position, in which the zones show up. The twinning-law is Karlsbad A., the association plane running through the centre of the crystal. The other arm of the V is not on actual crystal plane. This is a remarkable fact, because its position could be ascertained fairly accurately, but it was found to be, not even approximately, that of any known association plane.

The examples I have mentioned, with the exception of those showing interruptions due to resorption, or any other cause, have one thing in common, so far as their crystallization is concerned. Although each of these plagioclases show discontinuities in their chemical composition, the crystallization was continual. The two last-mentioned cases I am inclined to regard as exceptions, because of their unusual appearance. After the deposition of each zone the crystallization may have halted for a certain space of time. Another reason in favour of this supposition will be given later on.

As regards the optical properties of zonal plagioclases, I will proceed to draw attention to the fact, that, in special cases, an unexpected optical behaviour is to be observed.

It is known, that the ellipsoid, or Indicatrix, of which the three main axes are represented by the refraction-indices n_α , n_β , and n_γ , (n_p , n_m , and n_g of DUPARC and REINHARD) has a special position with regard to the crystallographic elements of the crystal, for each composition of a plagioclase. Diagrams have been composed showing the shifting of the positions of n_α , n_β , and n_γ along certain lines, migration lines, with regard to one or more crystallographic planes. The reverse method has also been followed: for the different compositions the position of the poles of crystallographic planes and of twinning-axes have been set out while a fixed position is given to n_α , n_β , and n_γ .

A certain restriction must be made in the application of the diagrams, as they chiefly concern *separate* individuals without zonal structure. In that case two or more plagioclases with different compositions, compared to one another, show different positions of n_α , n_β , and n_γ , that all fall on the constructed migration lines. The same can be said for the cases represented in Plate 26, fig. *b* and Plate 27, fig. *a* and *b*. In all these cases the positions of the Indicatrices of the different zones show differences, which are in accordance with the rule.

In the case of zonal structure it appears, however, that there are examples, where a deviation from this rule can be observed. This is especially the case where sub-zones are present (in other words: where the crystallization of differently composed zones was a continual one). Here the Indicatrices of the zones shift their position in quite a different way: A notable tendency is observed for the vectors n_γ , to maintain a position very nearly parallel. In two cases I even found them to be exactly parallel: in the well known vitrophyre from Grantola and in an augite-andesite from Santorin. In both rocks, therefore, the zones of the plagioclases have n_γ in common. When, for instance, a plagioclase in the slide was given such a position, that the optical plane of symmetry, which contained n_α and n_β , corresponded to the line of vision (axis of the microscope), no zonality whatever could be observed. On the other hand it is clear, that, if the section was placed at right angles to this plane (namely n_γ being parallel to the line of vision) the zonality was most pronounced.

This circumstance enables us to find out, without the aid of a compensator for obtaining the optical character, which one of the three main axes of the Indicatrix we have to deal with, when it has been brought parallel to the axis A 4 (BEREK) of the universal stage.

In the case of this main axis being n_β , this always appears immediately, as it is the pole of the optical plane of symmetry, which contains n_α , n_γ and the optic axes.

In the case of n_α being parallel to A 4, only the zone (or zones, in case of recurrent composition), which is being measured, shows extinction.

In the case of n_γ being parallel to A 4, all the zones extinguish simultaneously. I must add, that, although this method has never failed me, I have always checked it by using the gypsum plate.

Thus the optical behaviour of such a zonal plagioclase can be described in the following way: the mutual position of the indicatrices of the zones is such, that all ellipsoids are rotated round a common axis, which is identical with the direction of n_γ . I must emphasize the fact, that only the directions of the different n_γ 's are identical, or show a tendency to become so: their actual values naturally differ from each other, according to the chemical composition of the zones. Fig. 5 is a sketch, showing the positions of the three main indices in three different zones: the centre, *a* and *b*.

Searching for an explanation for this abnormal conduct, I thought at first, that the presence of a chemical constituent, other than the Albite- or Anorthite molecule might be held responsible. The presence of potassium probably affects the position of the indicatrix considerably, as has been supposed by Prof. Dr. REINHARD. Dr. KUENEN has applied this explanation to the cases he describes in rocks of the porphyry-district of Lugano (L. G. M., dl. 1, Afl. 1, 1925), in which all three ellipsoid-axes for the various zones have a position unknown for pure Albite-Anorthite feldspars. So the possibility of another component causing the abnormal conduct mentioned here, might not be overlooked.

Prof. Dr. REINHARD, who kindly discussed this subject with me,

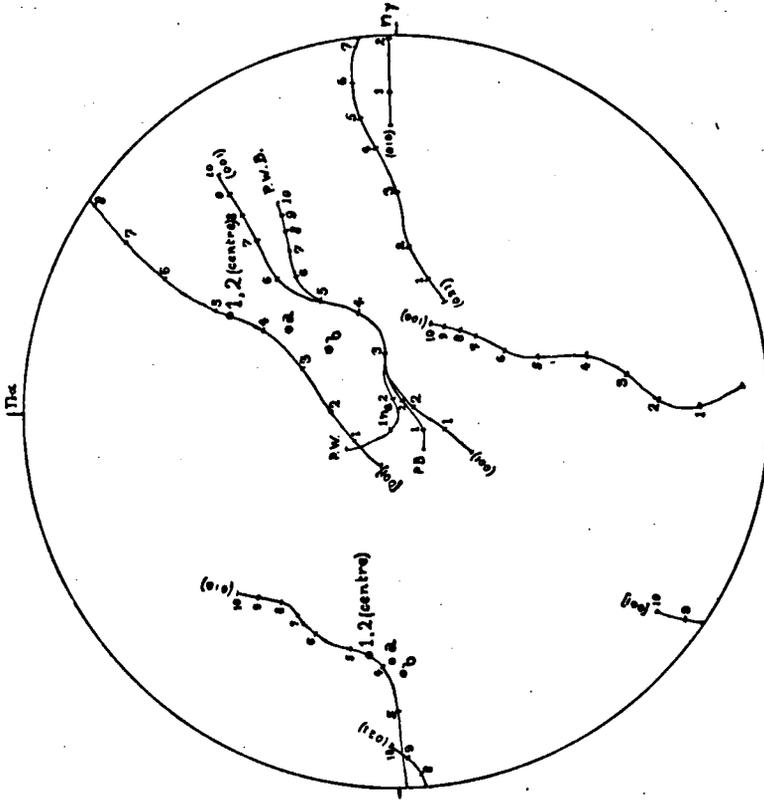


Fig. 6.

Diagram showing the normal conduct of the centre and the abnormal deviation from the migration lines of the zones *a* and *b* of a zonal plagioclase. Twinning law Karlsbad A; association plane (010); twinning axis [001]. Diagram of Reinhard and Duparc.

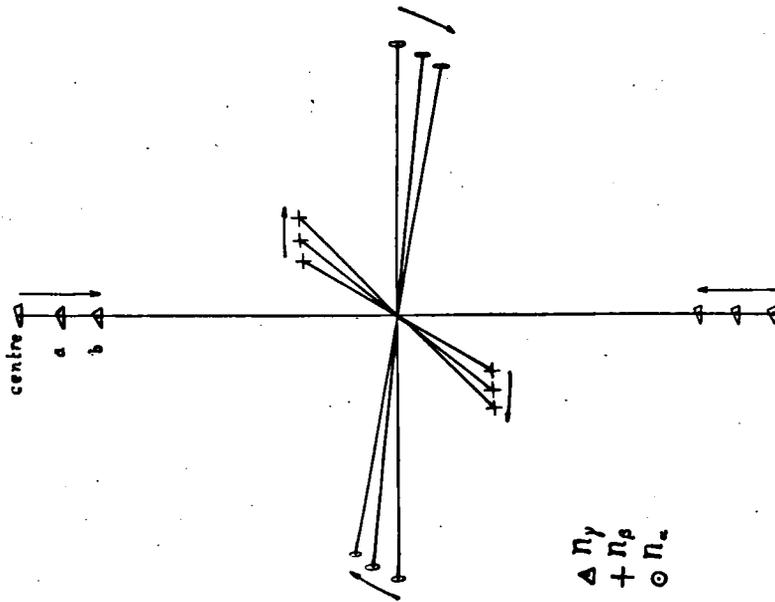


Fig. 5.

Scheme showing the migration of the vectors n_α , n_β and n_γ of the central part and the zones *a* and *b* of a zonal plagioclase (abnormal conduct).

did not, however, agree with this supposition and pointed out, that, in all probability, the cause must be sought merely in a great rapidity of crystallization, which usually originates from the same causes (undercooling, oversaturation, loss of gasses) that give birth to zonal structure. At the time I only had observed this optical behaviour in zonal plagioclases from the Grantola vitrophyre.

Since then, to test Prof. REINHARD's supposition, I have studied zonal plagioclases from other rocks, chiefly andesites, in order to see, if they showed the same phenomenon.

The observation of 122 plagioclases with the aid of the Fedorow-stage has given strength to Prof. REINHARD's supposition.

In cases, where interruptions had evidently influenced the process of crystallization, the position of the Indicatrices of the different zones was normal. These interruptions were in some cases caused by resorption, (case 2; Plate 25, fig. *b*), in others there were indications of periodes in which crystallization ceased, without resorption taking place, however. (Plate 26, fig. *b* and Plate 27, fig. *a* and *b*). There was no evidence of the crystallization having exceeded a certain degree of rapidity, whereby sub-zones would have been formed, as we have seen.

In all other zonal plagioclases the above mentioned tendency for the different n_{γ} 's to become identical was observed more or less distinctly, more clearly, where other facts also pointed to a rapid crystallization (sub-zones).

The plagioclase represented on Plate 24, fig. *a* (vitrophyre, Grantola) shows the optical behaviour mentioned, with the exception of the outermost border zone, which is clearly defined on both its sides. It is of importance, that nearly all the feldspars in this rock possess this border zone. It seems to belong to a later period of the crystallization, separated from of the inner part of the crystal by a period, during which crystallization was probably suspended. In other plagioclases (hypersthene-andesite, Cerro de los Lobos, Cabo de gata, Spain) I observed, that two neighbouring zones (1 and 2) had n_{γ} in common. The position of n_{γ} of the next zone (3) differed slightly from that of n_{γ} in the zones 1 and 2; while n_{γ} of zone 4 again coincided with n_{γ} of zone 3. Usually in such a case the zones 2 and 3 were separated from each other by a somewhat better defined border than 1 and 2, or 3 and 4, pointing to a break in the crystallization. I must add, however, that, in many cases, I observed the same conduct without this better defined border.

It is also necessary to mention that in many plagioclases the position of n_{γ} was not directly obtainable because of an unfavourable position of the section, so that it had to be derived from the positions of n_{α} and n_{β} . Although I made use of plagioclases in a good state of preservation, the accuracy of the measurements did not reach below a maximum of error of one degree. This error is still too large to give a satisfyingly exact position of n_{γ} , when the latter has to be obtained by this indirect method. Apart from this, difficulties arise when the zones in question are very narrow, a circumstance which cannot but have an unfavourable effect upon the exactness of the measurements.

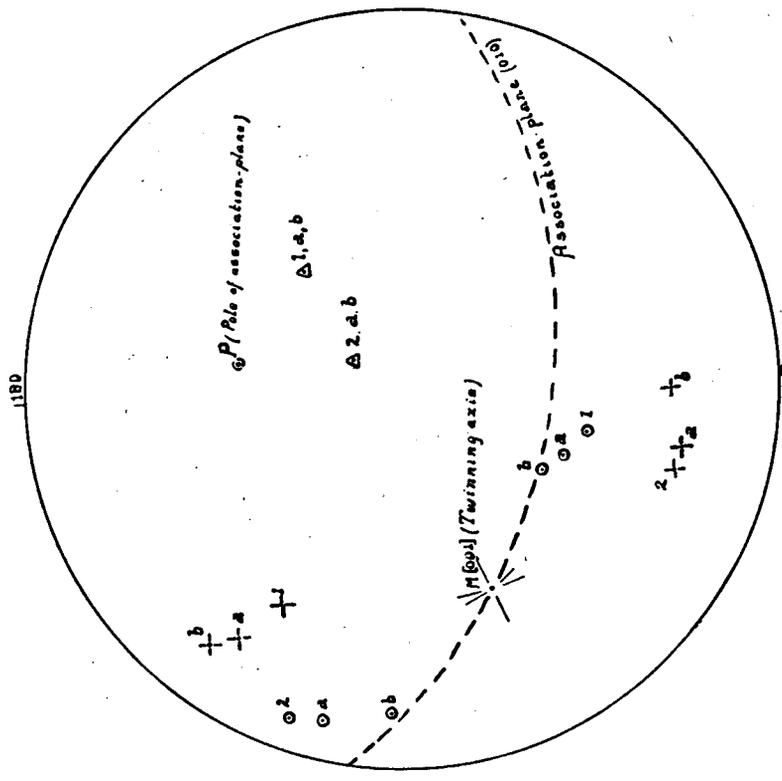


Fig. 8.

Diagram showing the position of n_a , n_b and n_γ of the centre and the zones a and b of two plagioclase individuals in twinned position with regard to the plane of the thin section. M ($= [001]$) is the twinning axis and is the point of intersection of the three great circles connecting the homonymous vectors of the centres. The spheric distances of the vectors of the zones a and b were measured with regard to the same point M and to P . (Pole of the association plane). The plane of the diagram is identical with that of the thin section.

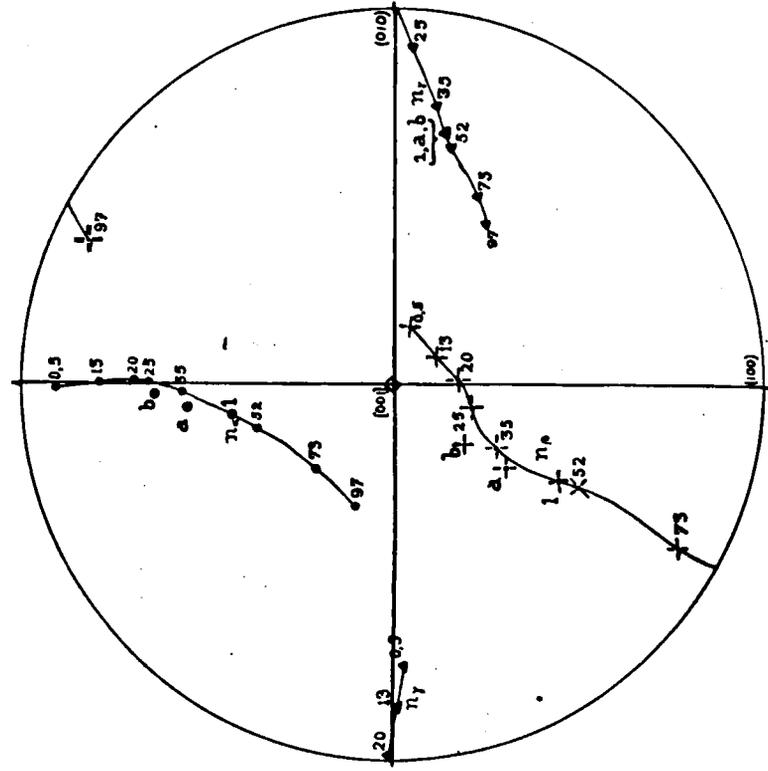


Fig. 7.

Diagram showing the normal conduct of the centre and the deviation from the migration lines of the zones a and b in one of two individuals of a zonal plagioclase. Diagram of Reinhard and Duparc.

It is clear, that, in consequence of this abnormal conduct it is not possible to obtain the exact percentages of An. with the aid of the diagrams of REINHARD and DUPARC or BEREK. This can only be done approximately, for n_α and n_β necessarily change their positions according to that of n_γ . The same can be said for the composition planes and twinning axes. In fig. 6 the position of these crystallographic elements is shown on the diagram of REINHARD and DUPARC, for the three percentages of the centre and the zones *a* and *b* of two individuals (1 and 2) in twinned position. The next fig. (7) shows the centre and the two zones *a* and *b* of one of these individuals on a diagram \perp (001). On both diagrams the position of the centre appears to be normal, while that of the two zones shows an increasing deviation from the migration lines with the increasing percentage of Albite.

Recapitulating it appears, that, if a plagioclase grows with a rapidity exceeding a certain value, which occurrence is usually accompanied by, or the result of, circumstances favourable to the forming of zones, this rapidity of crystallization is apt to influence the optical orientation of the different zones in the manner which has been indicated. A decrease in the rapidity of crystallization for a certain space of time shows as a result tendency to re-establish the normal conduct for the following zones. This re-establishment will be actually reached when there has been a break in the crystallization.

By optical orientation is meant the position of the Indicatrix with regard to one or more crystallographic elements; in most cases an association plane is used. Now if such a plane changed its position in accordance with the chemical composition of each zone, we should still have a normal conduct, though not in the same sense as in the other cases mentioned as normal. We observe, however, that association planes as well as cleavage planes run through the zones without showing the slightest deviations. According to the diagrams represented in fig. 6 and 7 the position of the association plane (010) and the composition plane (001) is only normal for the centre of the crystal; the zones *a* and *b* deviate from the curves.

In the case of normal twins (Albite, Manebach, Baveno) the association plane is identical with the composition plane, the pole of the latter being the point of intersection of the three great circles which connect the homonymous vectors of the centres of both individuals (1 and 2). The pole of the association plane, found by direct measurement, always coincided very nearly with this point of intersection; which shows that the optical orientation of the centre part is always normal (fig. 8, where the percentages of the centre and the zones *a* and *b* were obtained by measuring the distances from the different vectors to *P* and *M*.) Now the question arises, if it should not have been better to measure the distances of n_α , n_β and n_γ of the zones *a* and *b* of each individual from their own points of intersection.

Fig. 9 shows a schematic sketch, in which this manner of proceeding has been illustrated on somewhat exaggerated scale. In that case, however, we should have obtained the position, which the pole of the association plane should have had, if the conduct were normal. This is

not the true state of affairs, for the position of the crystallographic elements remains constant for all the zones. Therefore the said distances were always measured with regard to one point only (fig. 8), which happened at the same time to have the normal position with regard of the Indicatrix of the centre. Thus it appears, that, after the forming of the central part, the immediately following zones, notwithstanding the difference in chemical composition, are forced by rapid crystallization to adapt themselves to the crystal planes assumed by the centre. In the case of no association planes being present, or in the case of rounded forms, this adaption concerns the planes, which the centre would have had, if it had grown separately.

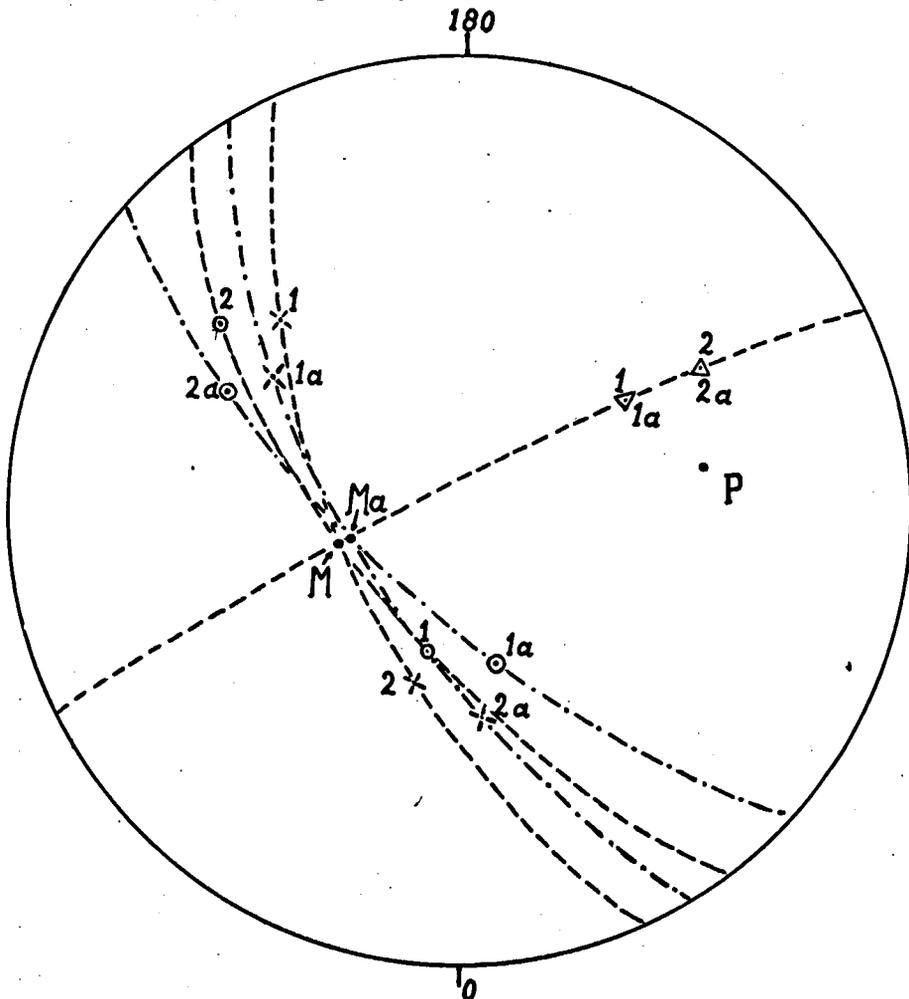


Fig. 9.

Diagram illustrating the second possibility of proceeding, namely by measuring the distances of the vectors of the centre with regard to M and P; of the zone *a* with regard to Ma and P. The plane of the diagram is identical with that of the thin section.

At the end of this paper I wish to express my gratitude to Prof. Dr. B. G. ESCHER and to Dr. PH. KUENEN for their advice and counsel during my investigations on this subject; to Prof. Dr. GRUTTERINK of Delft University for his allowing the use of his apparatus for microphotography, and to Dr. F. KRUIZINGA for his kind help in manipulating the apparatus.

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T. M. P. M. = Tschermaks Mineralogische und Petrografische Mittheilungen.

L. G. M. = Leidsche Geologische Mededeelingen.

¹⁾ Only part of the works mentioned in this Bibliography have been referred to in the text. The other works I recommend for the minute descriptions of zonal feldspars, which they contain.

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- Plate 24. fig. *a*. Zonal Plagioclase from Vitrophyre, Grantola, Porphyry-district of Lugano. Main-zones and sub-zones.
The largest individual (1) is in twinned position with the individuals 2 and 3, of which 3 has the same orientation as 1.
- fig. *b*. Zonal Plagioclase from vitrophyre, Grantola. Note the apparent asymmetry in the zoning of the left and the right individual. Main- and sub-zones. Inclusions of magnetite and apatite.
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- fig. *b*. Plagioclase from augite-andesite, Santorin. The centre is a remnant of a resorbed plagioclase. The border shows a composition different from that of the centre and sub-zones.
- Plate 26. fig. *a*. Zonal Plagioclase from hornblende-andesite, South Mendoza, Argentine. Rounded shape of the inner zones; sudden recurrence of the crystal shape near the outer edge.
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- Fig. 2. Enlargement of the border of zone 1 of the plagioclase represented on fig. 1. Enlargement 70 \times .
- Fig. 3. Sketch of plagioclase with regular zones. Enlargement 12 \times .
- Fig. 4. Sketch of zonal plagioclase showing sub-zones and main-zones. Within the innermost main-zone the sub-zones stand almost at right angles to the border of the former.
- Fig. 5. Scheme showing the migration of the vectors n_α , n_β and n_γ of the central part and the zones *a* and *b* of a zonal plagioclase (abnormal conduct).
- Fig. 6. Diagram showing the normal conduct of the centre and the abnormal deviation from the migration lines of the zones *a* and *b* of a zonal plagioclase. Twinning law Karlsbad A; association plane (010); twinning axis [001]. Diagram of Reinhard and Duparc.
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- Fig. 9. Diagram illustrating the second possibility of proceeding, namely by measuring the distances of the vectors of the centre with regard to M and P; of the zone *a* with regard to Ma and P. The plane of the diagram is identical with that of the thin section.

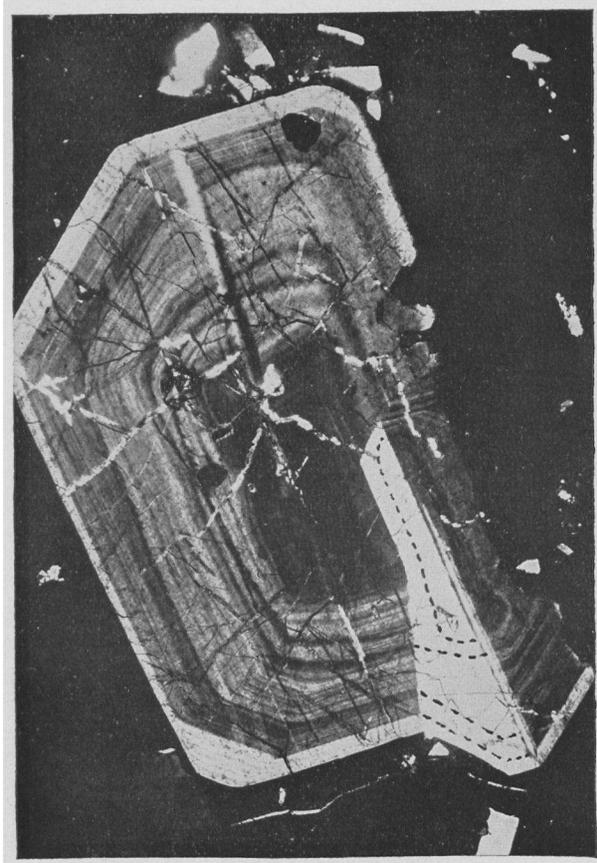


Fig. a.

Zonal Plagioclase from Vitrophyre, Grantola, Porphyry-district of Lugano. Main-zones and sub-zones. The largest individual (1) is in twinned position with the individuals 2 and 3, of which 3 has the same orientation as 1.

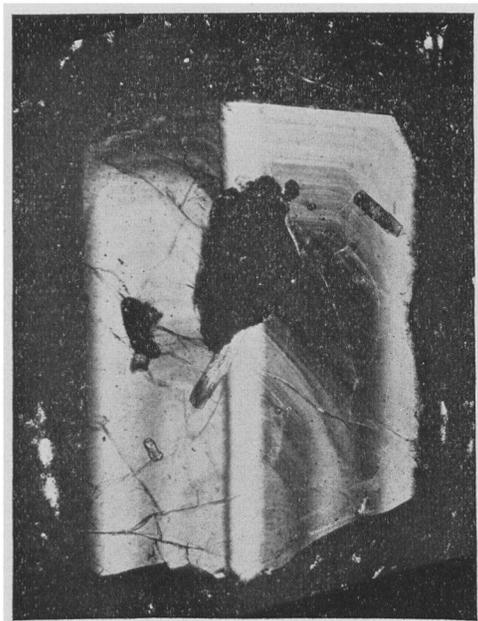


Fig. b.

Zonal Plagioclase from Vitrophyre, Grantola. Note the apparent asymmetry in the zoning of the left and the right individual. Main- and sub-zones. Inclusions of magnetite and apatite.

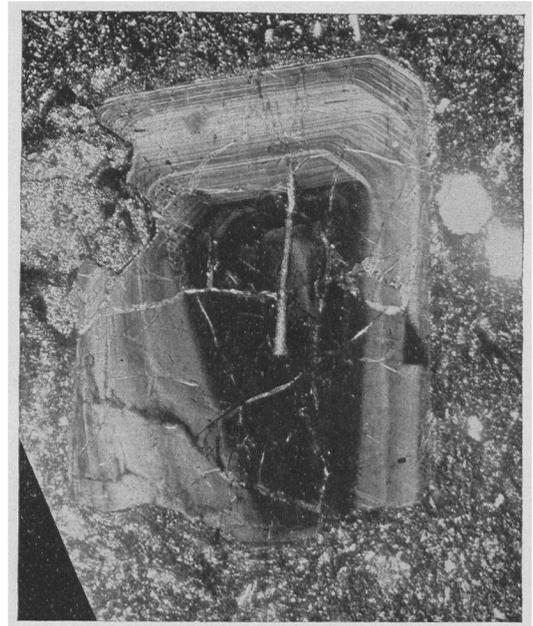


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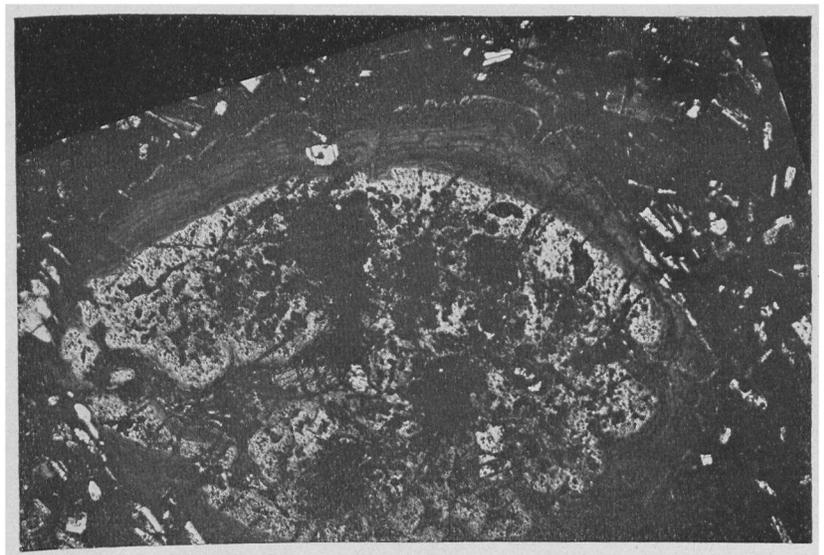


Fig. b.

Plagioclase from augite-andesite, Santorin. The centre is a remnant of a resorbed plagioclase. The border shows a composition different from that of the centre and sub-zones.

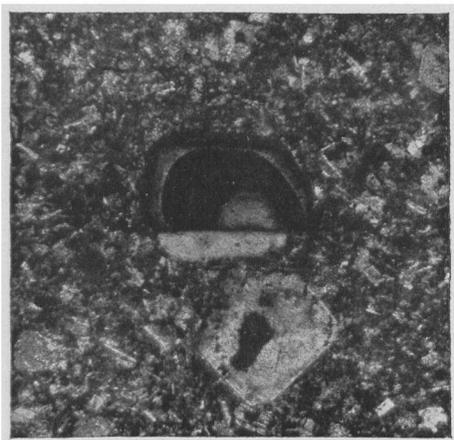


Fig. a.

Zonal plagioclase from hornblende-andesite,
South Mendoza, Argentine.
Rounded shape of the inner zones; sudden
recurrence of the crystal shape near the
outer edge.



Fig. a.

See Plate 26, fig. b.
Note peculiar form of twin-lamella.

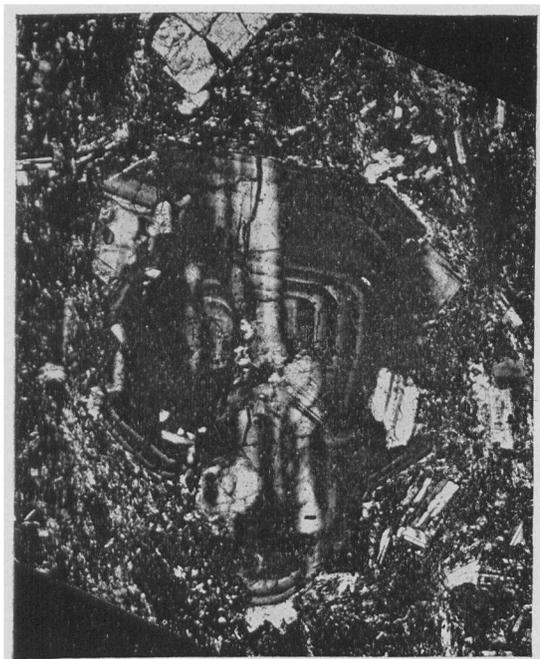


Fig. b.

Zonal Plagioclase from porphyrite, locality unknown.
Regularity in the recurrence of alternating sodic and
calcic main-zones.



Fig. b.

The plagioclase of fig. a, photographed through
the Fedorow-microscope.
Note the symmetry in the zoning.