ON THE FORMATION OF AUGEN STRUCTURE-II

by

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(with 23 text-figures and 1 plate)

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Contents

Introduction

Porphyroblastic texture exhibited by various minerals is one of the most characteristic features of metamorphic and metasomatic rocks (HIBBARD, 1965. SCHERMERHORN, 1956). These porphyroblasts may have been formed in the solid state under strain, in which case the mechanism of growth is quite different from that of crystal grown from liquid or gas in free space. The growth mechanism on the surface of a crystal in free space has been the subject of many laboratory studies, and the physical background has been provided by recent theories of structural dislocation (BUCKLEY, 1951. READ, W. T. 1953). We have very little knowledge, however, on the mechanism of crystal growth in the solid state, particularly in the field of petrology.

The present author hopes to throw some light on this problem and has begun his studies with a petrographic description of augen feldspar porphyroblasts, because feldspar porphyroblastesis is one of the most important problems in plutonic petrology, and " augen " gneiss is a typical example of porphyroblastic fabric.

Detailed description of feldspar porphyroblasts

1. *Occurrence of the Samples*

The samples used in this study have been taken from the augen gneiss of the basement metamorphic terrain, which is called " *The Hida metamorphic complex* " in Japan (MINATO et al., 1965). This basement complex is composed of two different types of rocks. The older ; gneisses and migmatites mostly belonging to the amphibolite facies, rich in hornblende gneiss and crystalline limestone. The younger ; granites, granodiorites, hornblende diorites and the associated metamorphic rocks. The augen gneiss occurs in the younger metamorphic area (OHTA, 1959 and 1961) (Fig. 1).

The effect of the emplacement of the younger granites can be traced gradationally from the unaffected older gneisses into the younger granite itself and this transitional area may be divided into three zones ; the granulated older gneiss zone with concordant intrusions of gneissose aplites, the zone of augen gneiss, and the gneissose porphyritic granite zone. Each zone is bounded by mylonites or sheared faults.

The potash feldspar augens were formed under componental movement of individual layers of the granulated older rocks, owing to the emplacement of the younger granite. This tectonic movement was pure granulation of the pre-existing rocks with introduction only of a small amount of quartz in its earlier periods. In some part of the augen gneiss area, the tectonic movement continued after the porphyroblastesis, and thus mylonites developed.

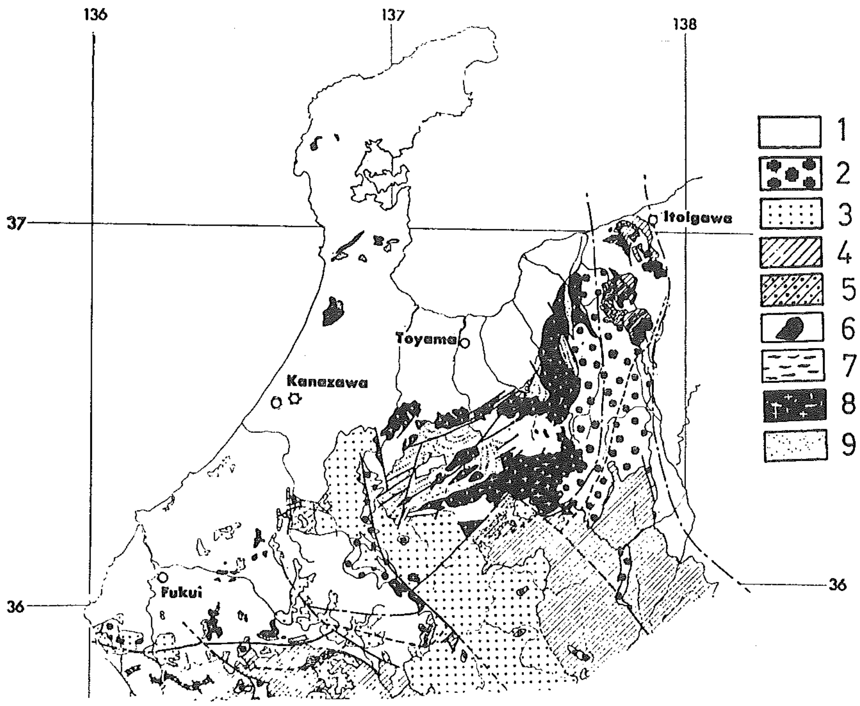


Fig. 1
Geological map of the central part of Japan.
1 ; younger sedimentary rocks. 2 ; Cretaceous granite. 3 ; quartz porphyry. 4 ; Permian sediments. 5 ; Carboniferous and Devonian sediments. 6 ; ultrabasic rocks. 7 ; crystalline schists. 8 ; younger granite and metamorphiscs. 9 ; Hida gneiss proper. (Minato et al., 1965)

2. *Megascopic features of the augen structure*

Several typical augens are illustrated in Fig. 2. In most cases, the potash feldspar porphyroblast and its accompanying material form an independent unit in the gneissose groundmass. This independent augen unit is the subject of the present study.

An augen unit can be subdivided into 4 domains as illustrated in Fig. 2-A. These subdivisions are readily distinguished in the measured specimens (Fig. 2-B, 2-C and Fig. 7-A).

The first domain in the augen unit (1 in Fig. 2-A) is the " *eyeball* ", being constructed of a single potash feldspar crystal, often idiomorphic, and with numerous inclusions. In the porphyritic granite, the long axis of the idiomorphic potash feldspar lies roughly in the plane of the general gneissosity or flow structure, but in the augen gneiss and in the strongly gneissose porphyritic granite, the diagonal of the idiomorphic cystal lies in this plane (Fig 21). This indicates that in the latter case the crystals have been rotated by componental movements after their formation.

The preferred orientation of the potash feldspar porphyroblasts on the gneissosity plane is designated as lineation of the rock. It would appear, however, that no differential movement took place during growth, since, in spite of numerous inclusions, the porphyroblasts show no rotational structures like snowball (Spry, 1963). Consequently, the " eyeball " crystallized during an intermediate period when stress was reliesed. The componental movement activated again after the formation of the " eyeball ".

The domain marked 2 (Fig. 2-A), *the dragged domain*, was formed during the reactivation of the componental movement. This domain is composed of one or several grains of potash feldspar, which, in some cases, are optically continuous with the " *eyeball* ", but usually are unoriented forming a mosaic of medium grained crystals. At the boundaries between each crystal, there are small relics of plagioclase and mafic minerals which are remnants of the fabric existing prior to the porphyroblastesis of the potash feldspar.

The third domain (3 in Fig. 2-A) is located at *the pressure shadow* of the " *eyeball* ", being composed of a mosaic aggregation of potash feldspar and quartz with

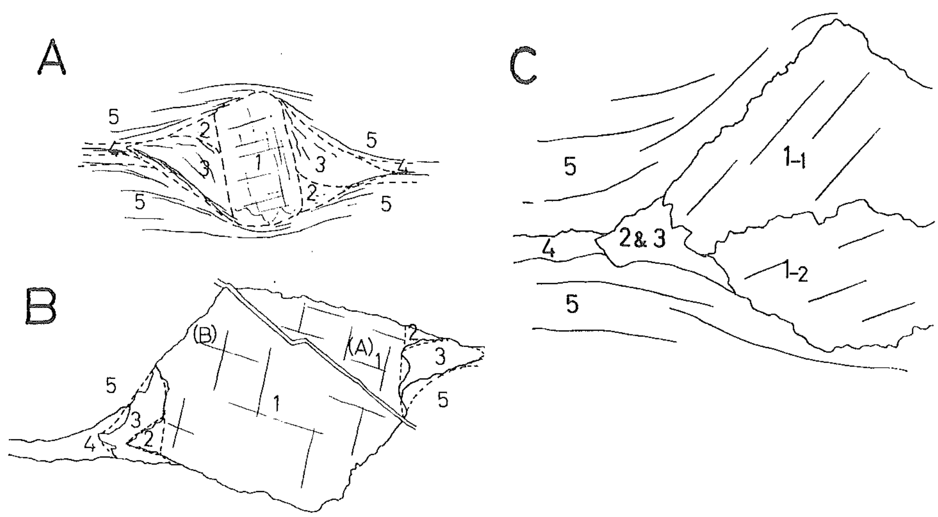


Fig. 2
Diagrams of the augen feldspar.
A ; subdivisions of the augen structure, explanations are in the text.
B ; augen with a single crystal eyeball, the " single augen " of the present paper.
C ; an augen unit with twinned eyeball. The whole shape is roughly symmetric to the gneissosity. This is the " twinned augen " in the text.

many relics of the pre-existing granulated groundmass. This domain was formed later than the second domain, possibly with some overlap. During this period, the supply of potash feldspar material decreased, and quartz is sometimes the main constitutent of the introduced material.

The fourth domain (4 in Fig. 2-A), *the tail* of the augen unit, crystallized in the last period of growth of the augen is composed of a medium-grained mosaic of potash feldspar and quartz unaffected by granulation.

In contrast to this, the quartz and plagioclase outside the augens are strongly fractured and strained in harmony with the granulated texture of the pre-existing minerals (5 of Fig. 2-A). It represents therefore a relict texture. However, small discontinuous pools and veinlets of quartz and potash feldspar in the groundmass represent recrystallized material. They contain many plagioclase porphyroclasts and porphyroblasts.

The " *eyeball* " potash feldspars are often composed of Carlsbad twins, but are never composed of more than one grain. Some twinned augen units show roughly symmetrical form against the gneissosity plane, thus blurring the distinction between the domains 2 and 3 (Fig. 2-C).

3. *The methods of investigation*

Almost all of the augen potash feldspars show intense undulatory extinction which may be due to small variations in the crystallographic orientation and also to changes in the optic axial angle from one place to another in a single crystal. Optic measurements by the universal stage and petrofabric analysis (Sander, 1950) are the only means by which such variations can be traced from place to place in a crystal.

Three typically augen-shaped crystals approximately of 3 cm.×2 cm. each, were selected for the study and were sectioned parallel to the elongation of the augen unit, that is nearly parallel to the general lineation of the rock, and vertical to the gneissosity plane. The eyeball of one of the augens (Fig. 2-C) is twinned, and that of the second (Fig. 2-B) is not. The third represents the beginning stage of an augen formation (Fig. 7-A). They will be referred to subsequently as " *the twinned* augen ", " *the single augen* " and " *the embryonic augen* ", respectively.

The thin sections of these three augen units were photographed, enlarged to 25 cm.×30 cm. and sketched. Optic measurements of the thin sections were made on the universal stage. An L-ruler was used for the parallel shift of the thin section on the stage and each point of measurement was checked on the photograph and the sketch. The optic axes and optic axial angles were measured at each point together with the orientation of the cleavages, microcline twin plane, and perthite veinlets if possible. All plagioclases included in the potash feldspar were also measured in order to establish their optic orientation and determination of An-content, based on the Köhler angles and Tröger's diagram. One hundred plagioclases from outside the augen unit were also measured.

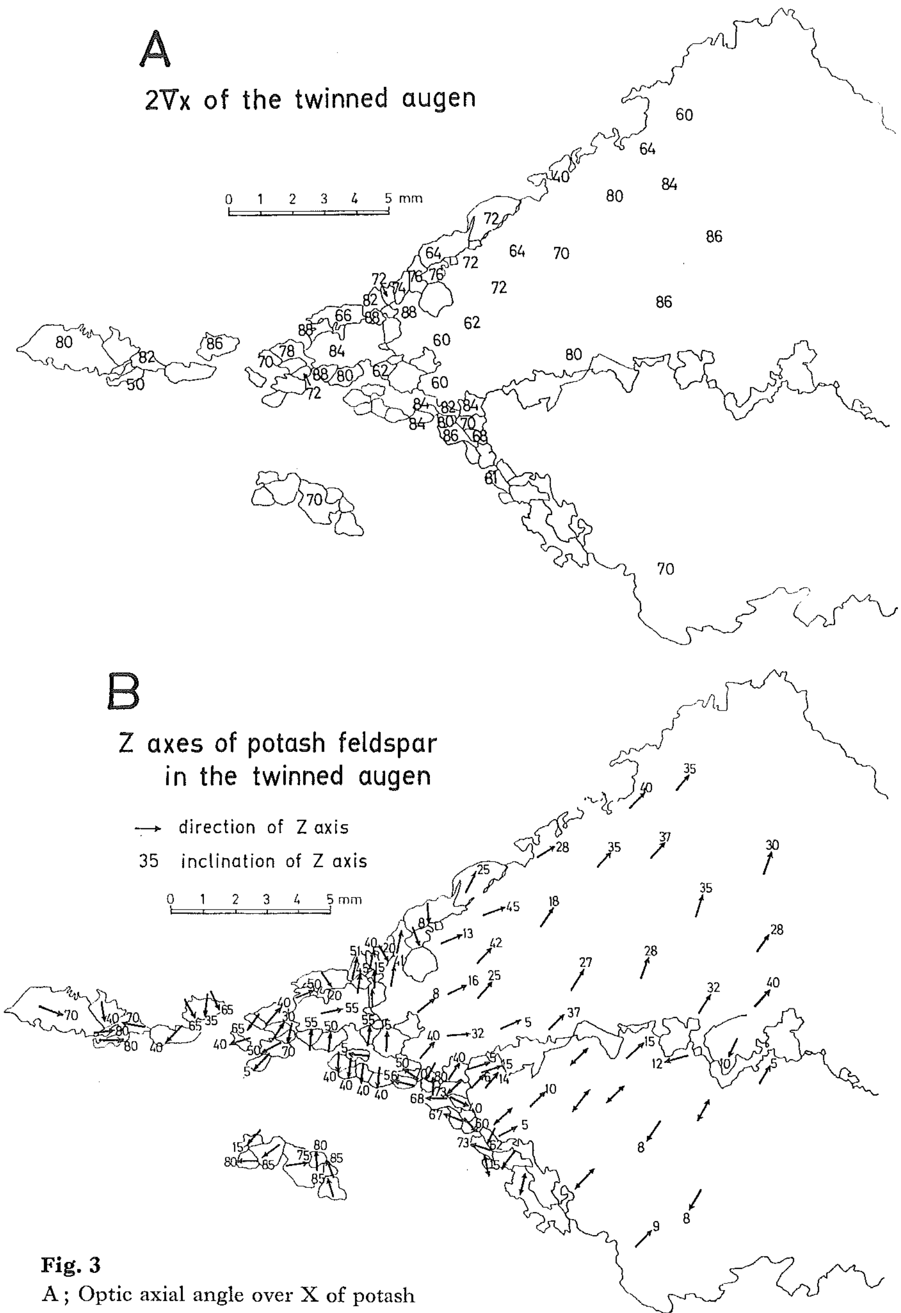


Fig. 3
A; Optic axial angle over X of potash feldspar eyeball in the twinned augen.
B; Optic orientation of potash feldspar eyeball of the twinned augen unit.

All measurements were firstly projected on the Wulff net to obtain the optic parameters and afterwards transfered onto the Schmidt net for the convenience of fabric comparison. The symbol " *G* " in both projection diagrams indicated the direction of the gneissosity plane of the rocks

As the first step, the twinned augen was measured to obtain general information on the optic variation. The results are illustrated in Figs. 3-A and 3-B and shown separately in Figs. 4-A, 4-B and 4-C.

Subsequently, a detailed study was made on the single augen and the embryonic augen. The results are presented in Figs. 5, 6, 7 and 8.

4. *Optic orientation of potash feldspar in the augen unit*

Fig. 3-B shows that there is considerable variation in the orientation of the optic axes even in a single potash feldspar. The data are plotted on the Wulff net, for each side of the twinned eyeball crystals separately (Fig. 4-A and 4-B).

The dragged and pressure shadow domain of this augen unit are not distinct. The examination of Fig. 3-B suggests that differences in orientation of potash feldsspars in these domains are greater than those in the eyeball domain.

The optic Y axes of the potash feldspar mosaics in the tail part of the augen unit have been plotted in Fig. 4-C. The projected points show a small girdle symmetrical to the gneissosity plane. This evidence suggests that they have a close relation with the outline of the eyeball crystal.

These observations were confirmed by detailed measurement of the single augen. This specimen has unfortunatly a large crack across the thin section. Though there is no large dislocation between these two fragments, they were illustrated as separate diagrams on the Schmidt net (i.e., areas (A) and (B) in Fig. 2-B).

Plots of the orientation of the optic axes of the eyeball potash feldspar of the single augen show very heavy concentrations on the Schmidt net about given orientation with a small amount of scattered plots (about 10%) showing a distinct deviation trend (Figs. 5-A and 5-B).

The same optic elements, plotted from the pressure shadow domain, are shown in Fig. 6. This domain is composed of several medium-grained homogeneous potash feldspars with no undulatory extinction and a fine-grained mosaic. The diagram from the pressure shadow domain of the (A) area (Fig. 6-A) shows a rather irregular pattern. The Y axes form two groups, one of which coincides with that of the eyeball, whilst the X and Z axes show girdle-like variation whose general trend is the same as the incipient trend of the eyeball. The medium-grained crystals in this domain show, however, a quite different orientation (Fig. 6-B), and are relatively homogeneous. They may be regarded as grains of the dragged domain and have therefore been excluded from Fig. 6-A.

A steadily increasing deviation of the optic orientation from that of the eyeball

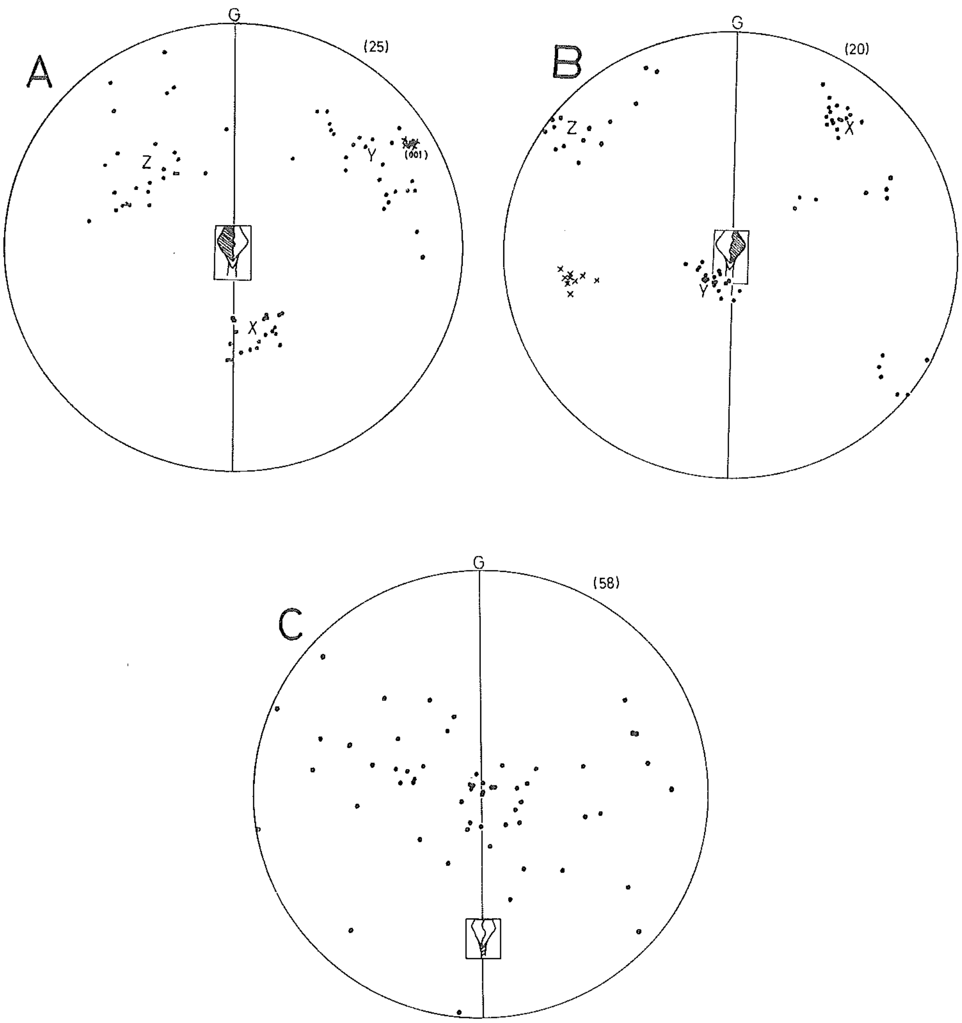


Fig. 4
Deviation of the optic axes of the twinned augen.
A; I-1 area of Fig. 2-C.
B; I-2 area of Fig. 2-C. Both on the lower hemisphere of the Wulff net.
C; Orientation of the Y axis from the tail domain (4 area of Fig. 2-C) of the twinned augen, on the lower hemisphere of the Wulff net.

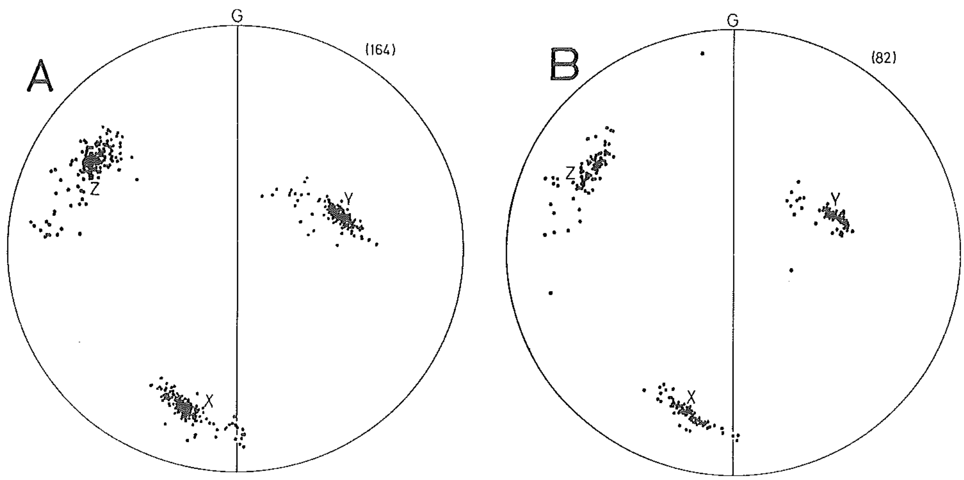


Fig. 5
Deviation of the optic axes in the eyeball of the single augen, on the lower hemisphere of the Schmidt net.
A; (A) are in Fig. 2-B.
B; (B) area of Fig. 2-B.

crystal is clearly traceable in the pressure shadow domain of the (B) area (Fig. 6-C). This domain is composed of 2 quartzes, 3 chloritized hornblendes and 4 medium-grained potash feldspars, along whose grain boundaries, several fine-grained plagioclases are present. The optic axes of the potash feldspars show a markedly different orientation from that of the eyeball. Besides these medium-sized grains, there are many fine grains forming a mosaic in the outermost part of the pressure shadow domain. The latter shows the same trend, the Y axes being scattered around the centre of the diagram on a small girdle, while the X and Z axes form a large girdle distribution (Fig. 6-D).

To summarize, the variation in optic orientation of the potash feldspars in the pressure shadow domains follows the same trends as deviations observed in the eyeball feldspar, but the range of variation is considerably large.

Distribution of potash feldspar in the embryonic augen is illustrated in Fig. 7-A. About a half of the augen unit is occupied by dusty plagioclase, chlorite, sericite, sphene and opaque minerals. The potash feldspar replaces these granulated plagioclases, but in general they occupy the interstitial spaces of the pre-existing minerals. This figure suggests that the central part of the augen shows independent domain from the pressure shadow domain. Dragged domain is not distinct.

The optic orientations of these potash feldspars were projected for these

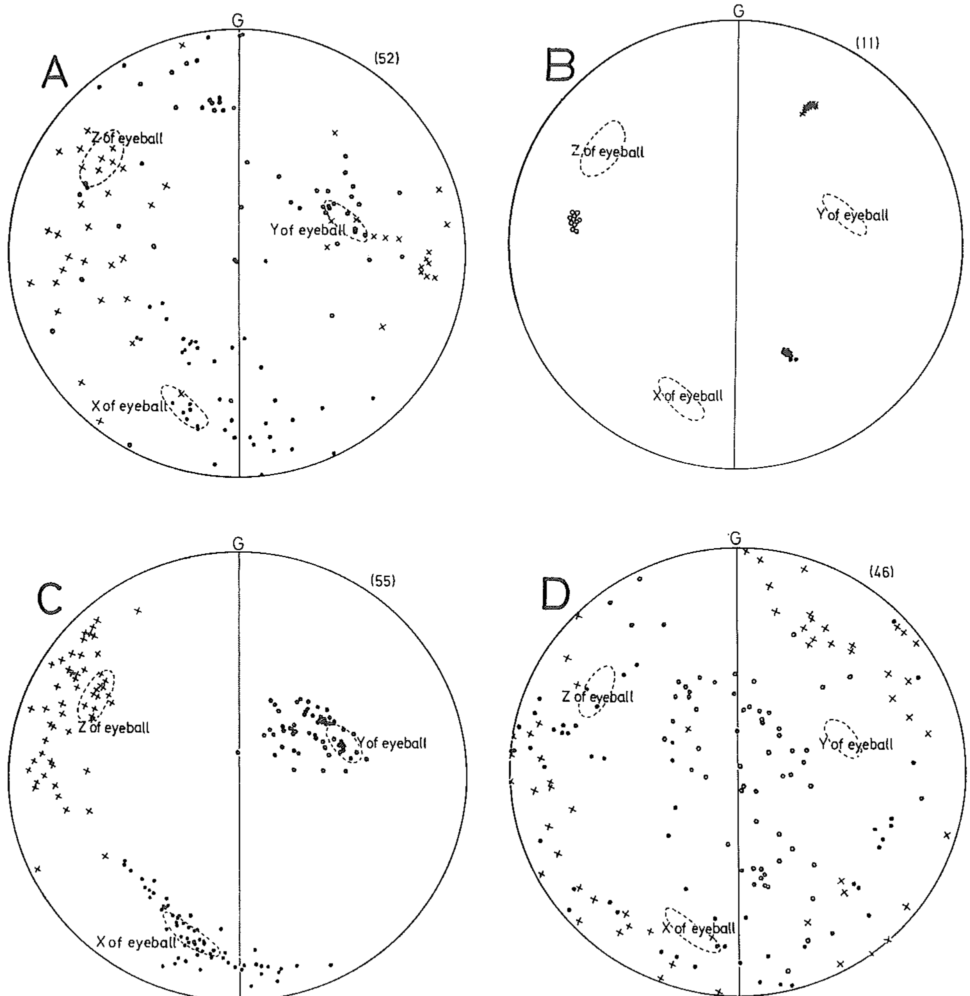


Fig. 6

Deviation of optic axes in the single augen unit.

A ; from the pressure shadow domain of the (A) area.

B ; from the dragged domain of (A) area.

C ; from the pressure shadow domain of the (B) area.

D ; from the margin of the pressure shadow domain, being composed of fine grained potash feldspars, of the (B) area of single augen.

All are on the lower hemisphere of the Schmidt net. solid : Y, open : X, cross : Z.

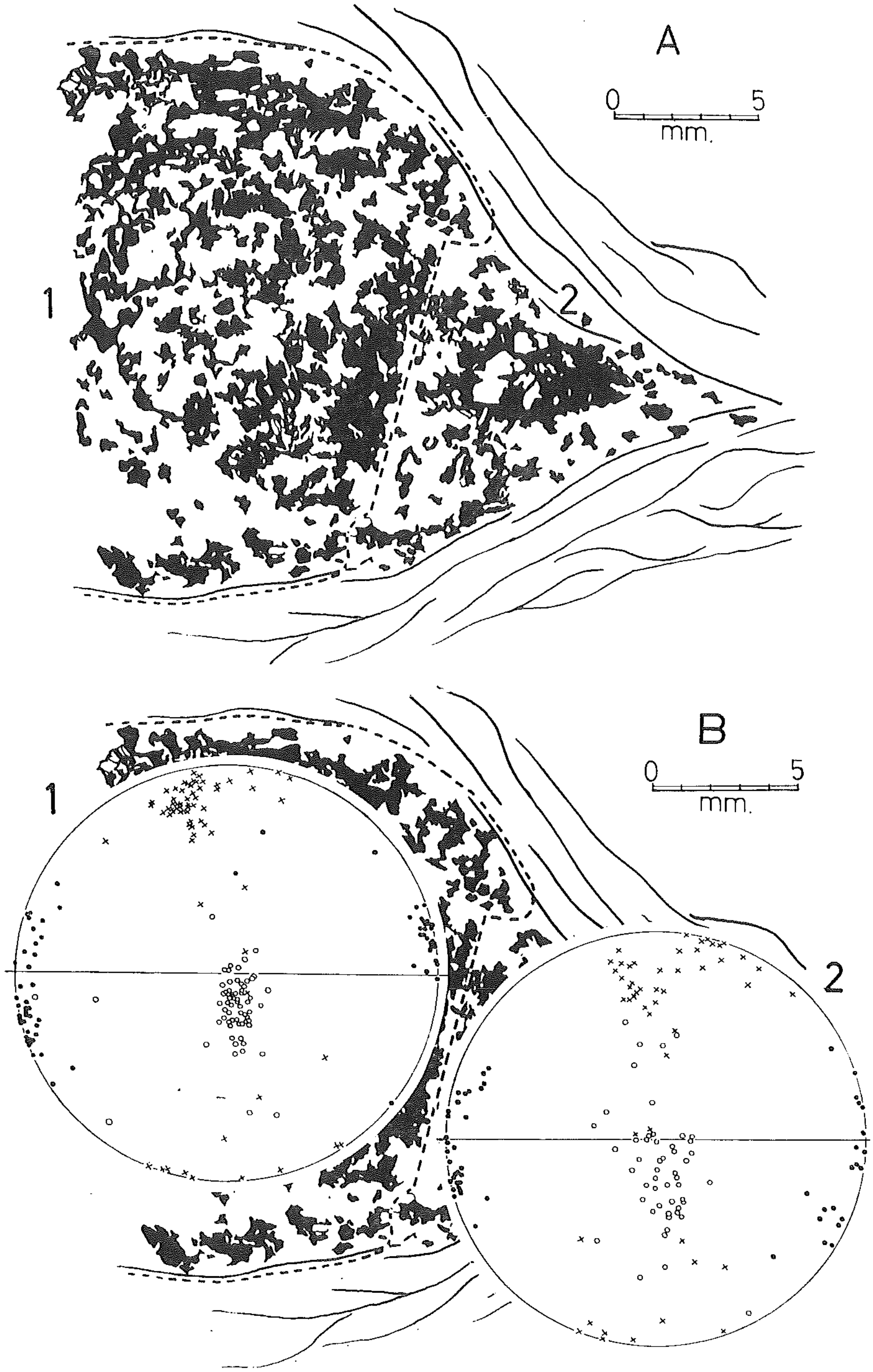
Fig. 7 (on p. 253)

A ; Potash feldspars in the embryonic augen.

black ; potash feldspar. 1 ; central part, 2 ; pressure shadow domain.

B ; Optic orientation of the potash feldspars in the embryonic augen.

1 ; central part. 2 ; pressure shadow domain.


A
0
5
mm.
1
2
B
0
5
mm.
1
2

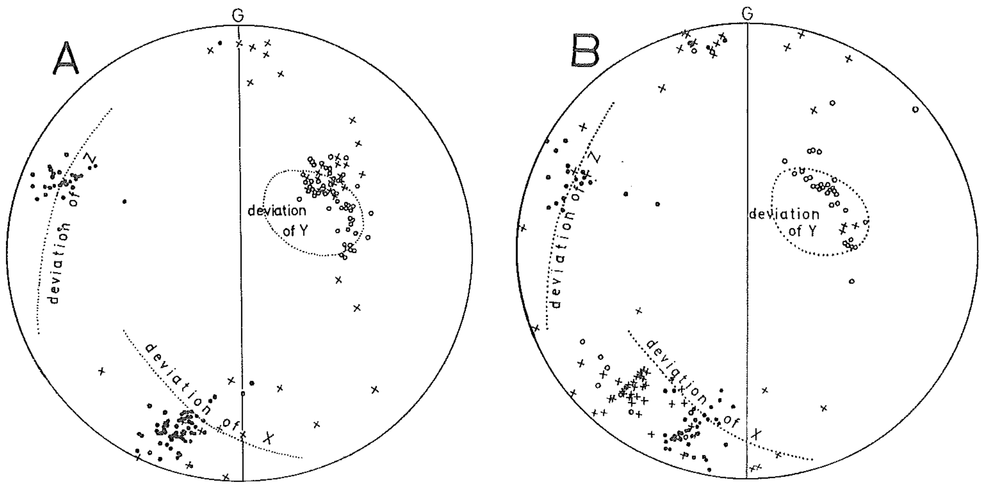


Fig. 8
Orientation of the crystallographic elements and perthite veinlet in the single augen on the lower hemispher of the Schmidt net.
A ; from the (A) area.
B ; from the (B) area.
solid ; microcline twin plane pole. open ; orientation of perthite veinlet. cross ; cleavages and cracks.
Dotted line means the deviation of optical axes of the single augen eyeball.

two domains as illustrated in Fig. 7-B. The results again appeared as a partial girdle on the Schmidt net. The Y and Z axes deviate on a large girdle in both domains, and the deviation is smaller in the central part than in the pressure shadow domain.

Cleavages and twinning planes in the eyeball crystal of the single augen were also plotted on Schmidt nets (Figs. 8-A and 8-B). The precision of the twin plane projection may be less accurate than that of the other determinations. These planes also show slight differences in orientation and the general trends are roughly vertical to the variation trends of the otpic orientation. This means that the variation of the optic axes is independent from that of the crystallographic elements. It may be related to the internal structural strain of the crystal.

The poles of the perthite veinlets were also plotted in Figs. 8-A and 8-B. They show deviation trend diagonal to that of the Y axis, or more precisely, they intersect it at an angle of about 50°.

The tail domains of the single and embryonic augen have not been measured yet, but that of the twinned augen show that the Y axes deviate on a large girdle (Fig. 4-C)

In conclusion, all optic orientations of the potash feldspars belonging to the augen unit show two different types of rotation ;

1. The rotation around Y axis ; the right half of the twinned augen eyeball and the eyeball and pressure shadow domains of single augen. The rotation axis is 25° from Y towards Z, roughly c-axis of the eyball crystal and the prismatic planes of the crystal rotated in full circle (Fig. 20-A).
2. The rotation around X axis ; the left half of eyeball and tail part of the twinned augen, and the embryonic augen. The rotation axis is roughly a-axis of the crystal (Fig. 20-B).

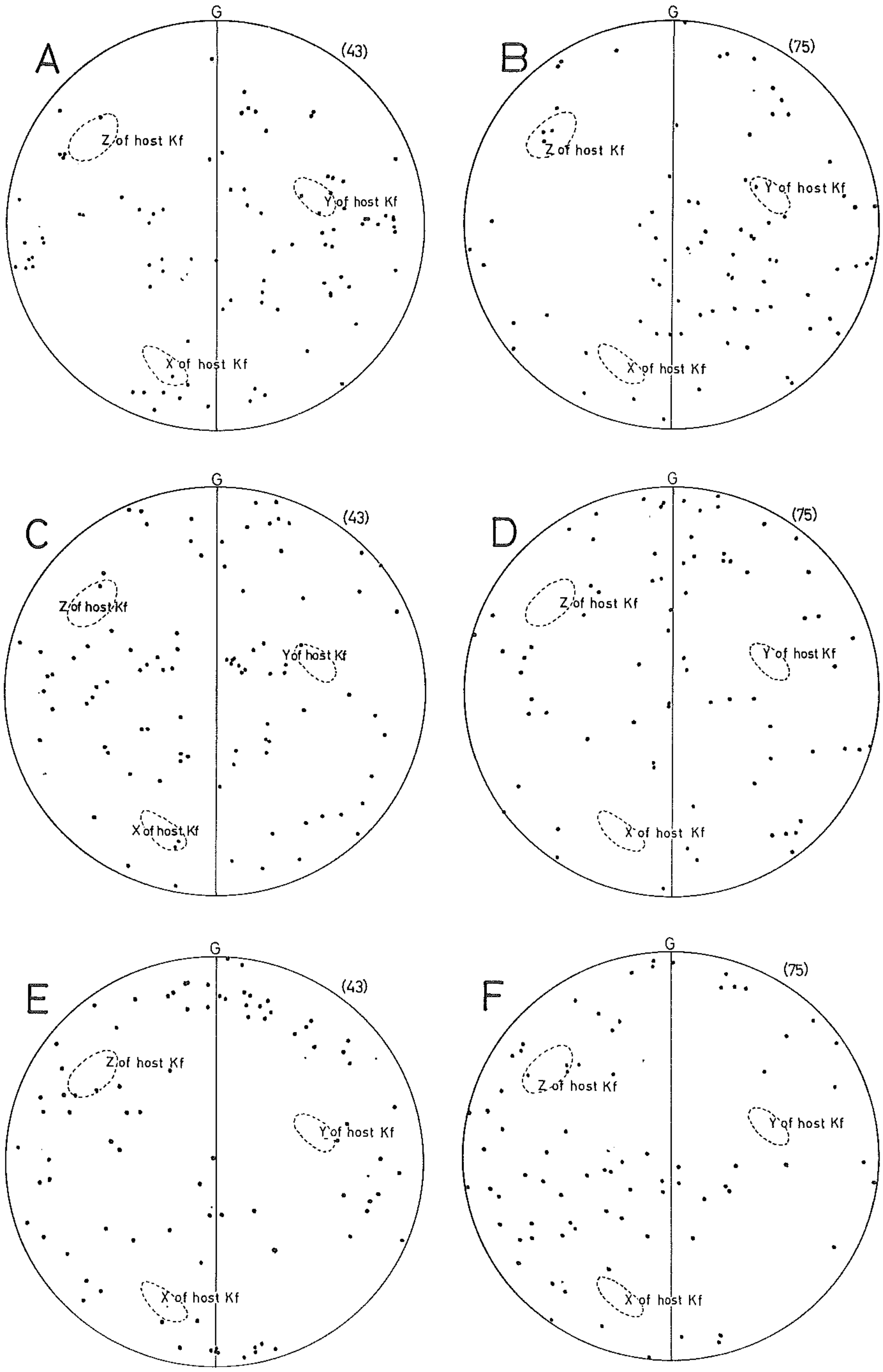
The degree of rotation in the augens which have a definite eyeball crystal, is very small in the eyeball crystal, but increases more than 60° in the pressure shadows, and in the outermost parts of the pressure shadow domains, the rotation is almost complete. It is clear from the close relationship of the optic orientation of potash feldspars in the different domains of an augen unit that both pressure shadow and and tail domains were formed under the influence of the same dynamic field caused by the eyball potash feldspar, that is to say, the eyeball porphyroblast was already present when the pressure shadow and the tail domains were formed. Accordingly, it is clear in these cases that the formation of the eyeball is a different problem from the formation of a whole augen unit, the latter being characterized by the existence of the pressure shadow and tail domains. Without these, the eyeball crystal would be an idiomorphic or subidiomorphic porphyroblast as in the porphyritic granite.

The embryonic augen, which represents an earlier stage of eyeball formation process, also shows the same rotation pattern of the constituent potash feldspars which occupy the interstitial spaces of the pre-existing minerals as anhedral amoeba-like shape. This indicates that the material to form the eyeball potash feldspar might have initially precipitated in these interstitial spaces with orientated direction. Judging from the distribution of the potash feldspars in this augen unit, the formation of the pressure shadow domain is not so later than the formation of the eyeball domain.

5. *Optic orientation of the plagioclases included in the eyeball potash feldspar*

We have often encountered large potash feldspar porphyroblasts with a lot of inclusions which show zonal arrangement inside the host potash feldspar (MAUCHER, 1943, SMITH, 1965). This phenomenon is also found in some augen feldspars including those described here. The included plagioclases sometimes appear to have the same optic orientation as the host crystal.

A preliminary examination of the twinned augen of the present study showed that the included plagioclases were arranged roughly parallel to the (001) cleavage of the host eyeball crystal. However, such regularity was not found in the single augen. The optic orientation of all plagioclase inclusions was, therefore, measured in the single augen. The X and Y axes (Fig. 9) do not show any clear relationship to the host crystal. However, the Z axis (Figs. 9-E and 9-F) shows a girdle-like pattern on the Schmidt net and the plots of the albite twin planes show the same


A
G
(43)
Z of host Kf
Y of host Kf
X of host Kf
B
G
(75)
Z of host Kf
Y of host Kf
X of host Kf
C
G
(43)
Z of host Kf
Y of host Kf
X of host Kf
D
G
(75)
Z of host Kf
Y of host Kf
X of host Kf
E
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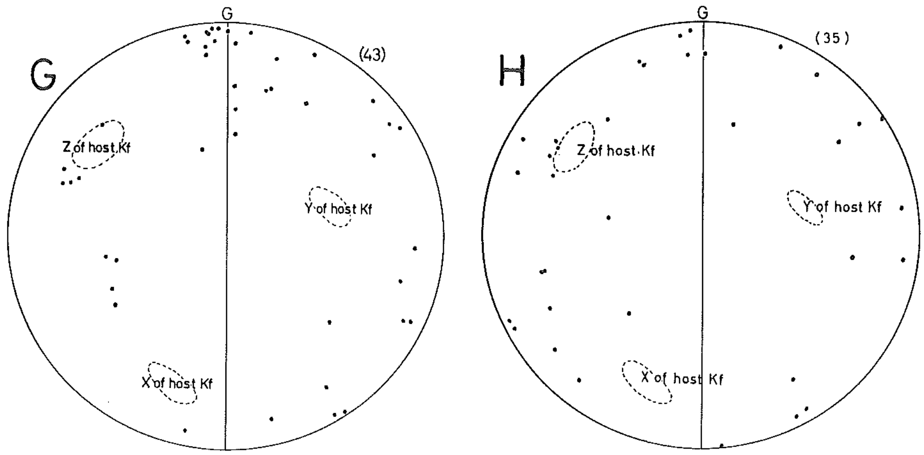


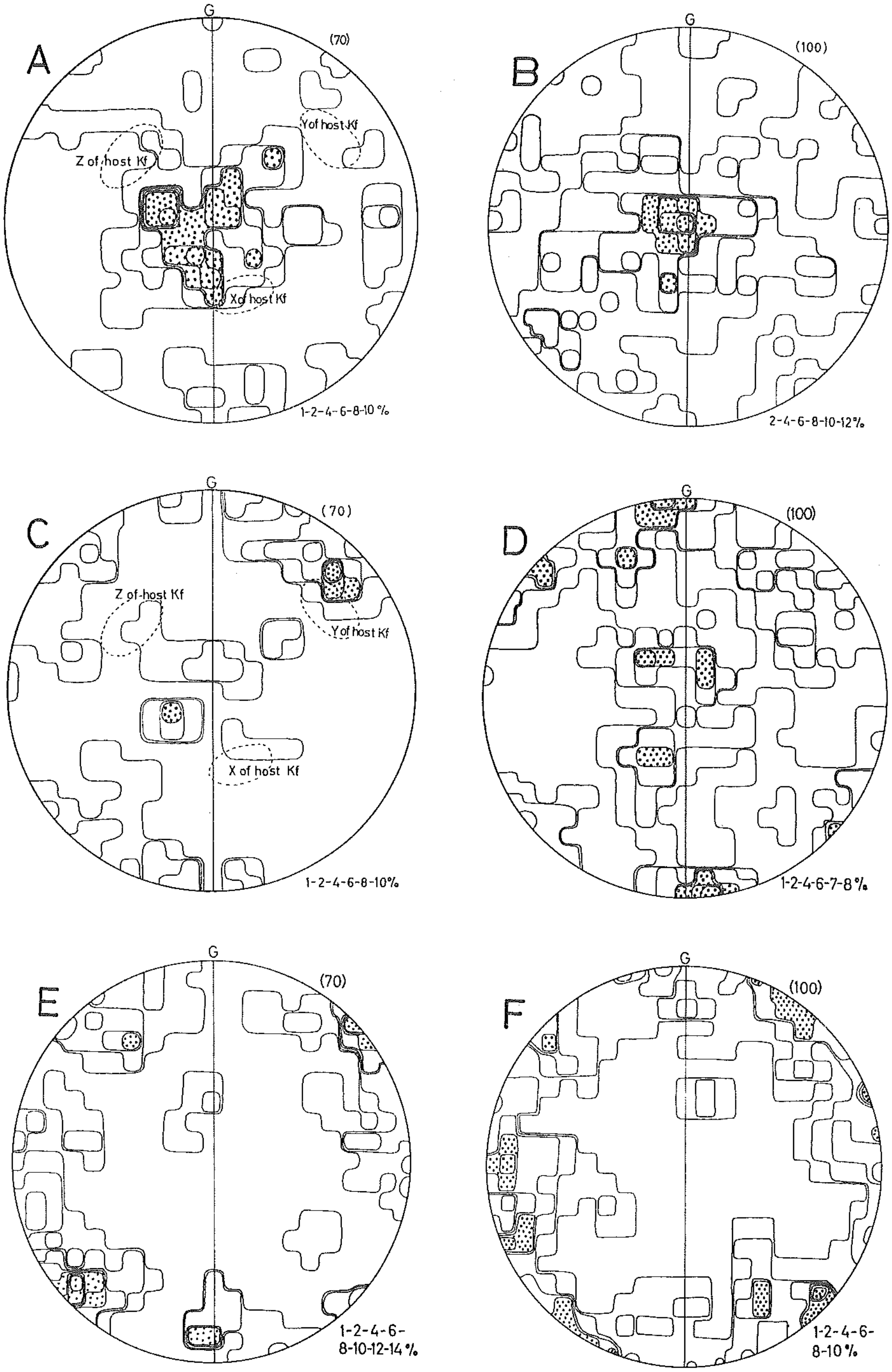
Fig. 9
Orientation of the plagioclase inclusions in the eyeball of the single augen.
A. X axis, (A) area. B. X axis, (B) area.
C. Y axia, (A) area. D. Y axis, (B) area.
E. Z axis, (A) area. F. Z axis, (B) area.
G. albite twin plane pole, (A) area. H. albite twin plane pole, (B) area.
Dotted circle shows the position of optic axes of the host potash feldspar.

pattern (Figs. 9-G and 9-H). It should be remembered that in the case of the albite twin plane projection, the technical restriction, that the flat laying twin planes are impossible to measure, might effect the projected pattern. Nevertheless, the fact that girdlelike pattern of the Z axis is roughly the same as the general rotational deviation trend in the host potash feldspar suggests a rotation of the planes nearly parallel to the (010) plane of the included plagioclases around the same rotation axis of the host potash feldspar.

Very small plagioclase inclusions, which have already been albitized, often show the same optic orientation as that of the perthite vein albite of the host potash feldspar. These plagioclases have been completely replaced by albite material segregated from the host potash feldspar and were recrystallized into the same orientation.

6. *A comparison of the optic orientation of the plagioclase inclusions and that of the plagioclases outside the augen unit*

This comparison has been made using the thin section containg the twinned augen. The optic axes of all plagioclases (70 grains) in the left half of the twinned potash feldspar eyeball (I-1 area of Fig. 2-C) and 100 grains of plagioclase outside the augen unit (5 of Fig. 2-C) were measured and their X, Y and Z axes were plotted on a Schmidt net (Fig. 10). Comparison of these data (Figs. 10-A and B, and Figs. 10-C


A
G
(70)
Z of host Kf
Y of host Kf
X of host Kf
1-2-4-6-8-10 %
B
G
(100)
2-4-6-8-10-12 %
C
G
(70)
Z of host Kf
Y of host Kf
X of host Kf
1-2-4-6-8-10%
D
G
(100)
1-2-4-6-7-8 %
E
G
(70)
1-2-4-6-
8-10-12-14 %
F
G
(100)
1-2-4-6-
8-10 %

and D), indicated that both the Y and Z axes patterns of the plagioclase inclusions are simpler than those of the plagioclases outside the augen unit. The positions of the maxima do not differ greatly, though not identical. There is no indication in this augen of rotation of the Z axes of the plagioclase inclusions around the rotation axis of the host potash feldspar.

There are two possible interpretations of the statistically valid differences of optical orientations in these plagioclases ;

1. Selective replacement and absorption of the plagiocalse inclusions by the host potash feldspar.
2. Reorientation of plagioclase inclusions during the growth of the host potash feldspar.

Evidences to support both these interpretations can be found in the eyeball

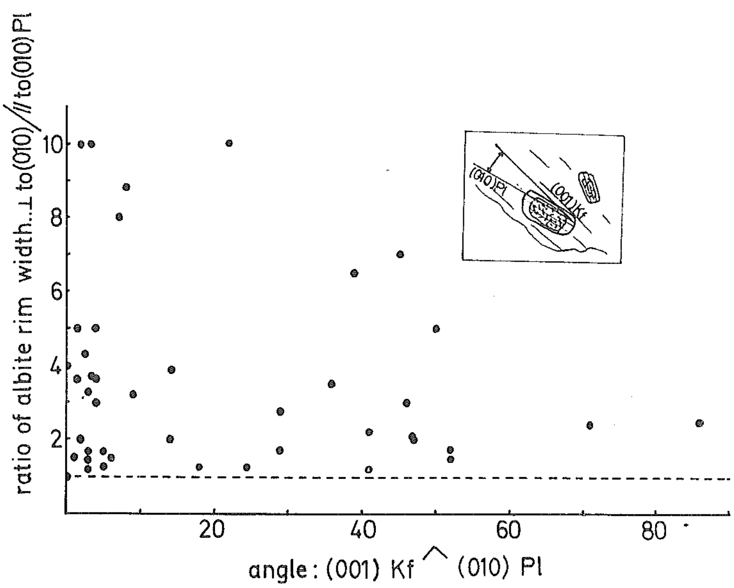


Fig. 11
Selective replacement of the plagioclase inclusions in the eyeball potash feldspar of the twinned augen (I-1 area of Fig. 2-C). Interpretations are in the text.

Fig. 10 (on p. 258)
Comparison of the optic orientation of plagioclases inside and outside the augen unit of the twinned augen.
A ; Y axis of plagioclase inclusions in the eyeball (I-1 area of Fig. 2-C).
B ; Y axis of plagioclases outside the augen unit (5 domain of Fig. 2-C).
C ; Z axis of plagioclase inclusions in the eyeball.
D ; Z axis of plagioclases outside the augen unit.
E ; X axis of plagioclase inclusions in the eyeball.
F ; X axis of plagioclases outside the augen unit.

potash feldspars. For example, some plagioclase inclusions in the single augen have clean albite rims around the margin, the width of the rim being the greatest along the margin perpendicular to the (010) of the plagioclase. This is particularly emphasized when the (010) of the plagioclase is parallel to the (001) plane of the host potash feldspar (Fig. 11). These phenomena support the interpretation of selective absorption or replacement. In the twinned augen, however, several prismatic plagioclase inclusions are arranged parallel to the (001) of the host potash feldspar and the (010) twinning plane of these plagioclases is also roughly parallel to the (001) cleavage plane of the host. Moreover, many plagioclase inclusions are arranged along the contact surface of the Carlsbad twinning of the eyeball crystal. This supports the second interpretation.

7. *Optic axial angle of the potash feldspar in the augen unit*

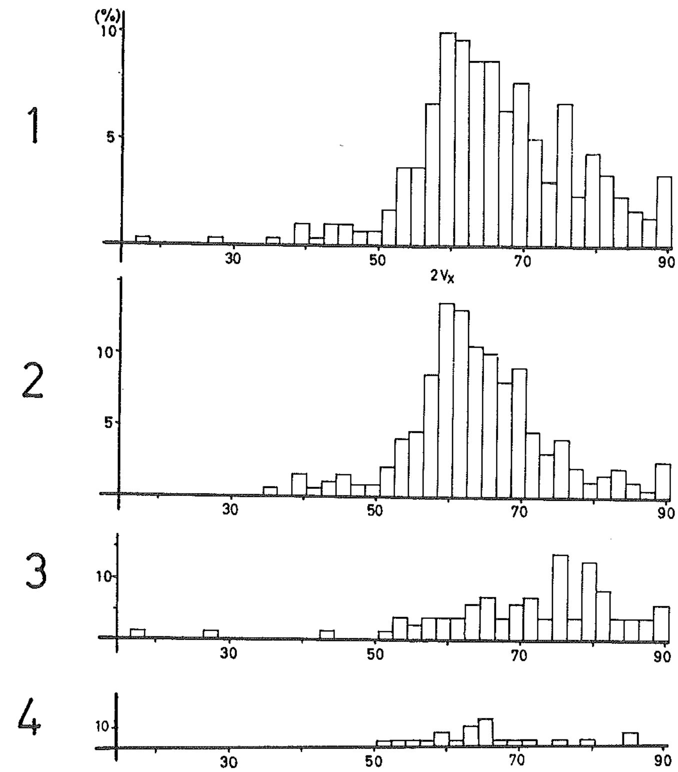


Fig. 12
The histograms of the optic axial angles obtained from the augen unit of the single augen.
1 ; all measurements from the augen unit.
2 ; 2V× from the inner part of the eyeball.
3 ; 2V× from the marginal part of the eyeball.
4 ; 2V× from the pressure shadow domain.

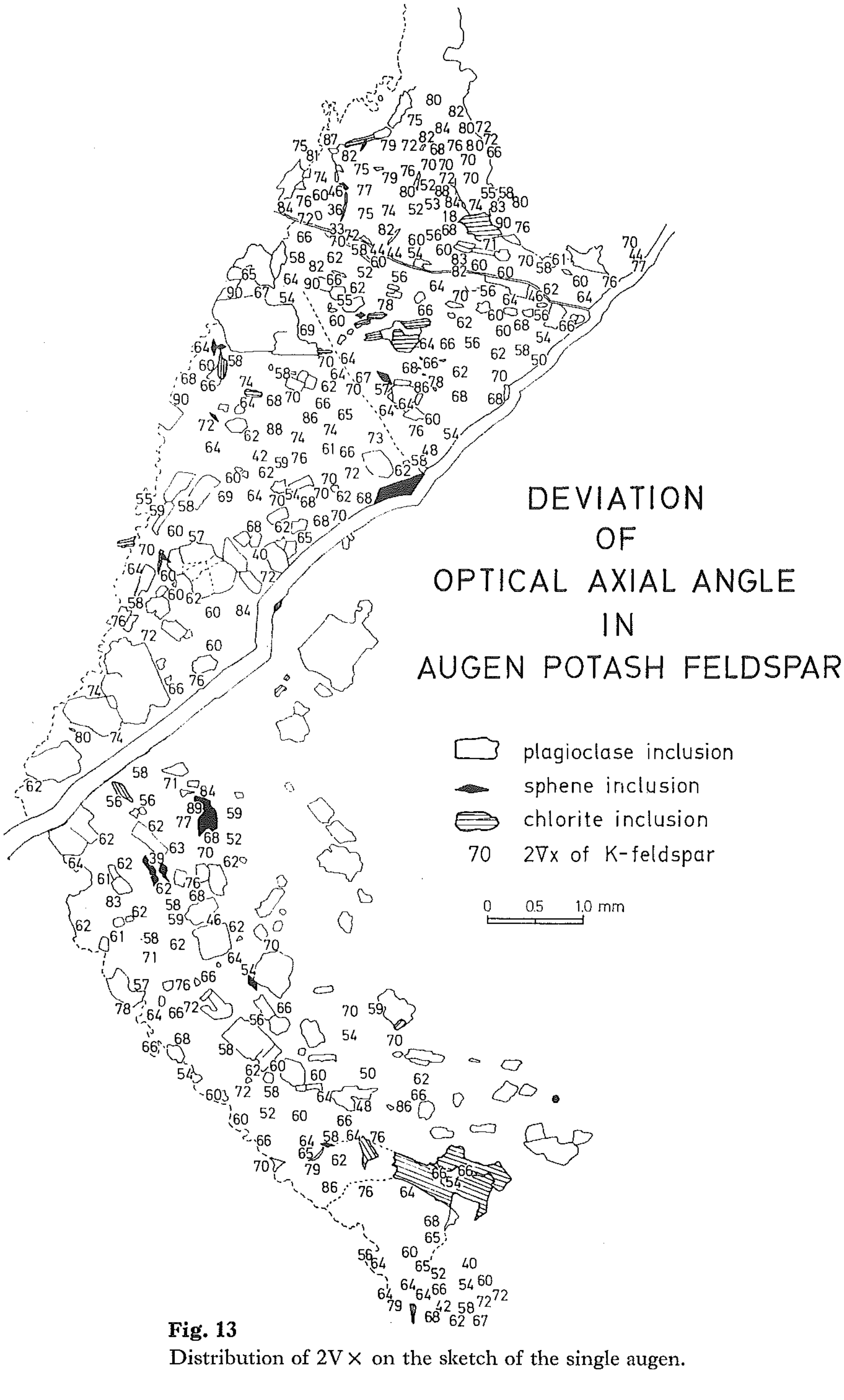


Fig. 13
Distribution of 2V× on the sketch of the single augen.

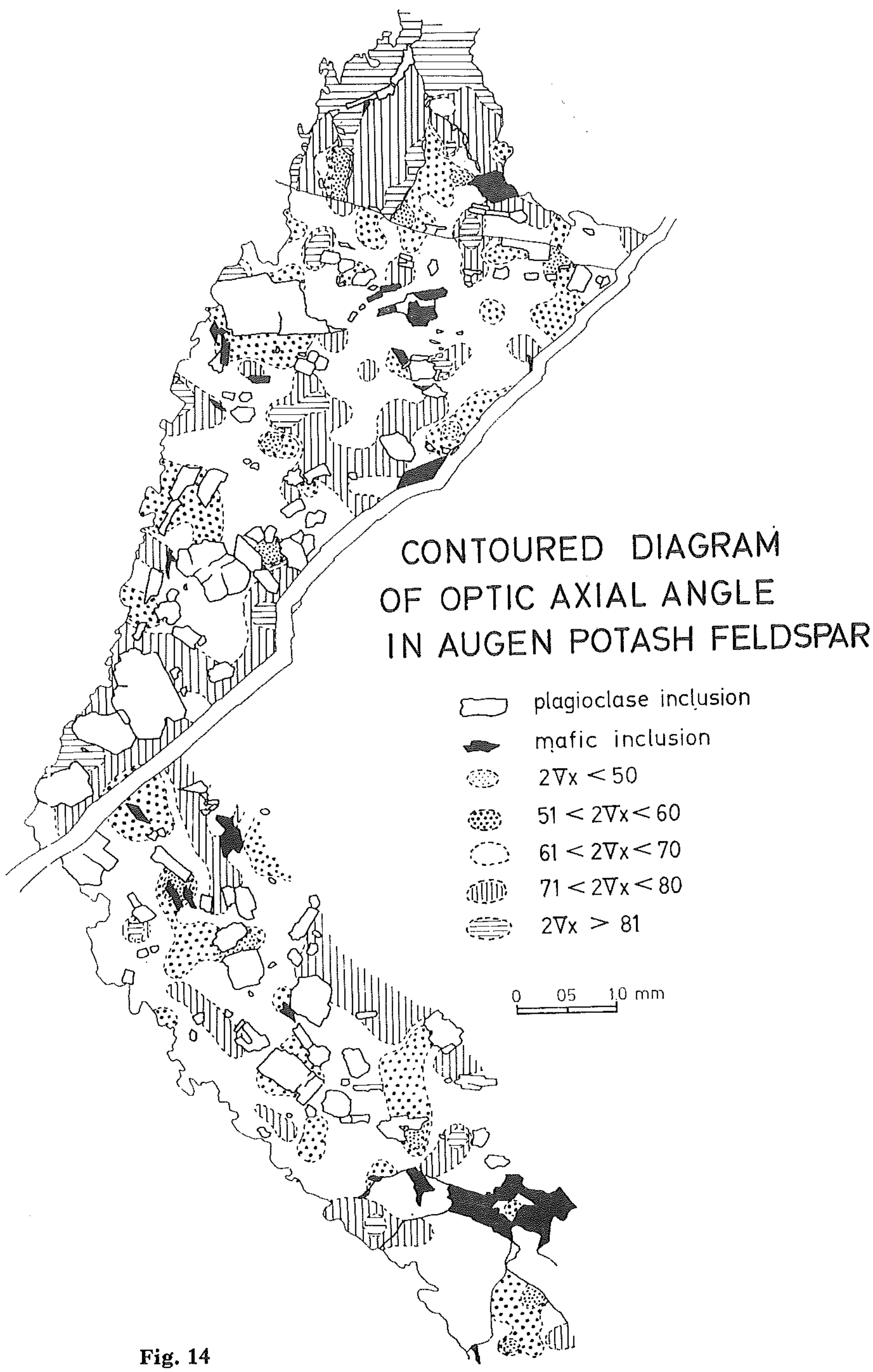


Fig. 14
Distribution pattern of 2V X on the sketch of the single augen.

According to the preliminary measurement of the twinned augen (Fig. 4), the central part of the eyeball shows a 2Vx of more than 80°, while that of the marginal part lies between 40° and 76°. The 2Vx of the mosaic potash feldspars in the pressure shadow and tail domain are variable (50°–88°).

This tendency has not been confirmed yet in the single augen specimen, because the measurements have only been made around the marginal part which occupies about a half of the whole augen unit. However, a large range of variation in 2Vx from 18° to 90° and a difference between the eyeball and the pressure shadow domain is clear (Fig. 12). In this case, in contrast to the twinned augen, the 2Vx of the centre of eyeball is smaller than that of the marginal part. Some medium-grained potash feldspars in the pressure shadow domains have the same 2Vx range as the eyeball crystal.

The 2Vx data were also plotted on a sketch of the measured crystal (Fig. 13) and were simplified to a contoured figure (Fig. 14). From these it can be deduced that there are no regular patterns of the distribution of the 2Vx in the eyeball. The writer, however, expects to find some general differences of 2Vx between the marginal part and the central part of this eyeball when the measurement over the whole crystal of the eyeball has been completed.

An X-ray powder photograph of this potash feldspar obtained with a Guinier focussing camera shows a wide band-like reflection for (131) and ($1\bar{3}1$) which is typical for a "*randomly ordered*" structure.

8. *The compositions of the plagioclase inclusions in the eyeball*

Many plagioclases, for instance, 70 grains in the left half of the twinned augen

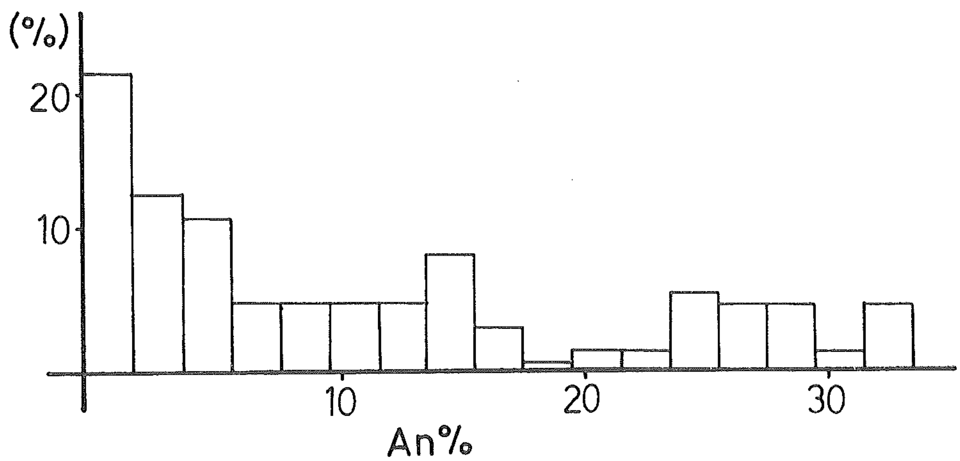


Fig. 15
The histogram of An-content of plagioclase inclusions in the single augen eyeball (123 measurements).

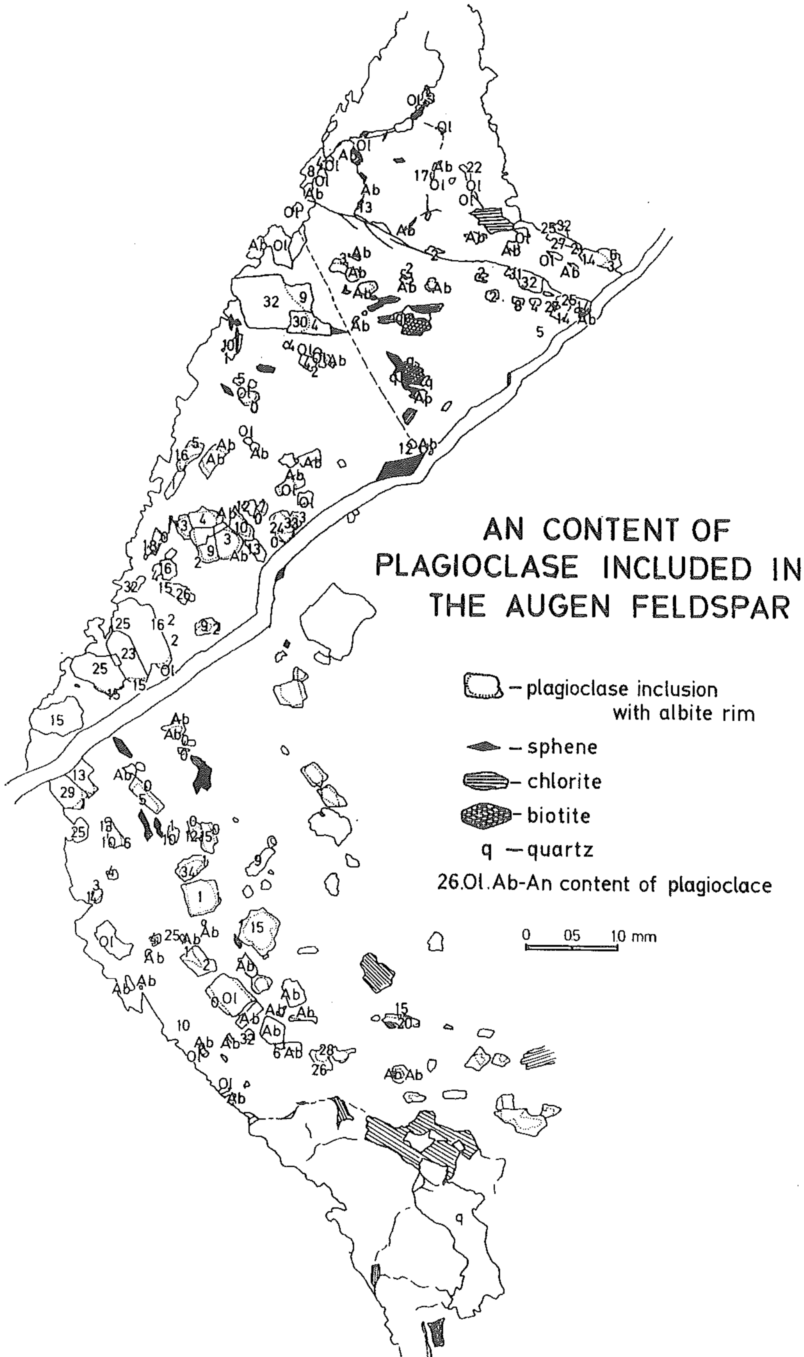


Fig. 16
Distribution of An-content of plagioclases in the single augen.

(I-1 of Fig. 2-C) and 170 in the surveyed area of the single augen, are included in the eyeballs. It appears from general observation that these plagioclase inclusions are concentrated in zones, arranged parallel to the outline of the eyeball crystal.

It was possible to determine the An-content of 123 plagioclases in the eyeball of the single augen. The frequency of the An-content is illustrated in Fig. 15 and data are also plotted on a sketch of the crystal (Fig. 16).

The coarse-grained plagioclases always have a dusty core consisting of sericite and carbonate minerals. They sometimes show fractured texture and have kept their original oligoclase composition. Clear narrow albitic rims are common, but are not invariably present.

On the other hand, some small grains have been completely albitized, and are free from any dusty inclusions. Some of them are continuous with the perthitic patches, having the same optic orientation as the perthitic albite.

In the pressure shadow domain of the single augen unit, plagioclases occur along the grain boundaries of the mosaic potash feldspars. Myrmekitic texture is often developed in these plagioclases which are never included within the mosaic of the potash feldspars. The mode of emplacement of the plagioclase in this domain is different from that in the eyeball potash feldspar where the emplacement took place as a progressive encroachment of an albite rim from the margin of plagioclase inclusions.

The An-contents of plagioclases in the host rock of the augen feldspar and in other granitic variaties of the younger metamorphics and an older biotite gneiss of Hida metamorphic complex, are illustrated in Fig. 17. Fifty grains of plagioclase were measured from each of the younger rocks and 130 grains from the older biotite gneiss, using one thin section of each rock. These data do not contain any plagioclase inclusions in the potash feldspar, but all are independent grains.

The plagioclases of the biotite gneiss have somewhat higher An-content than the granitic rocks and augen gneiss, and the pegmatite, aplite and mylonite contain some albites. In these rocks, the peristerite gap (Brown, 1962) from An 5 to An 18 is quite distinct.

The An frequency histogram of the plagioclase inclusions in the single augen unit shows a larger variation range of composition than that of these metamorphic rocks. This suggests that there was some replacement of plagioclases under solidus circumstances.

Using the XX′-YY′ angle diagram (Uruno, 1963) and Tröger's diagram (Tröger, 1959, Kano, 1955) for the determination of the plagioclase composition, the degree of order of the crystalline state was also estimated (Fig. 18).

The degree of order was tentatively divided into 10 grades from 0.0 to 1.0 in these diagrams, and was grouped into the ordered group (1.1–0.8), transitional group (0.8–0.3) and disordered group (0.3–0.0). The total number of the albite twinned plagioclase was 114 and the ratio of the ordered-transitional-disordered

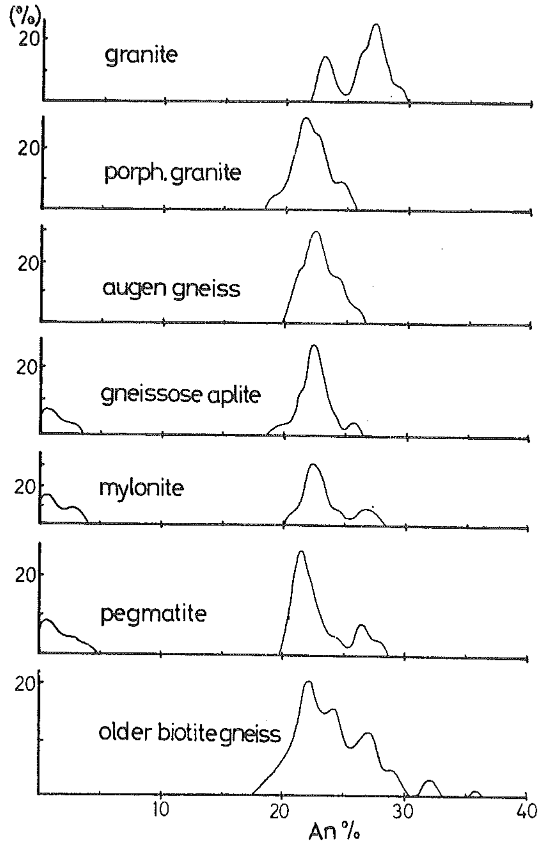


Fig. 17
An-content of plagioclases in various kinds of the younger granites and metamorphics of the Hida metamorphic terrain.

group grains is 8–82–24, i.e., the percentage of the O-T-D ratio is 6% : 73% : 21%.

9. *Optic orientation of the feldspars in the mylonite*

The augen gneiss sometimes alternates with mylonitic layer where both plagioclase and potash feldspar were fractured and granulated. This evidence supports the idea that the differential movement took place simultaneously with the growth of potash feldspar in the augen gneiss, while the movement continued after the formation of potash feldspar porphyroblasts in the mylonite. During the granulation of feldspars in the mylonite, sodium and silica were introduced instead of potassium. The fractured potash feldspars were replaced by albite along the margin and crack (ORVILLE, 1963). New albite often show a flame perthite (Figs. 19-A, 1, 2, 3, 4)

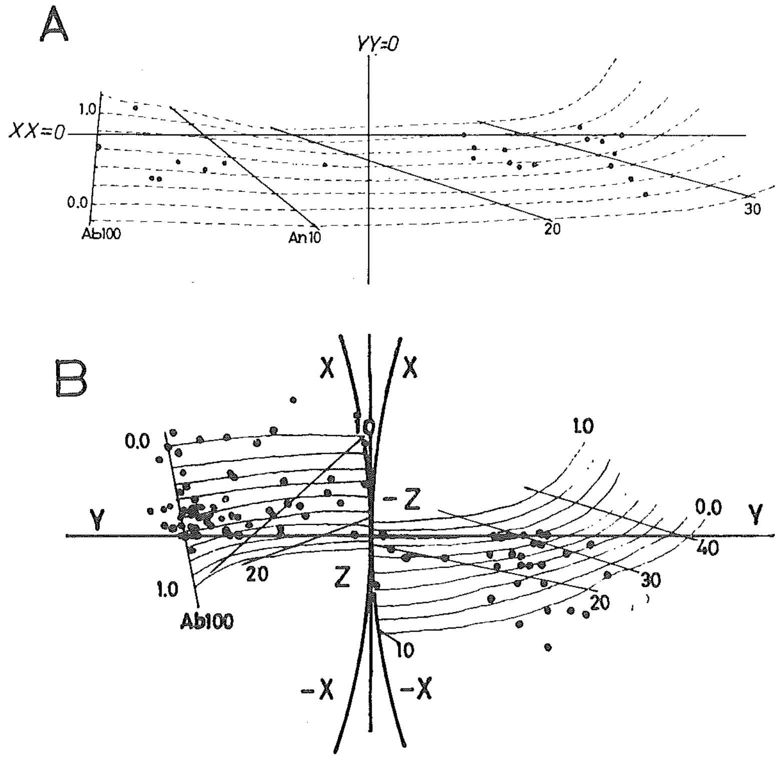


Fig. 18
Wulff net projection of the albite twin plane pole and the XX′-YY′ diagram of plagioclase inclusions in the single augen.
A ; Wulff net projection (91).
B ; XX′-YY′ diagram (23).

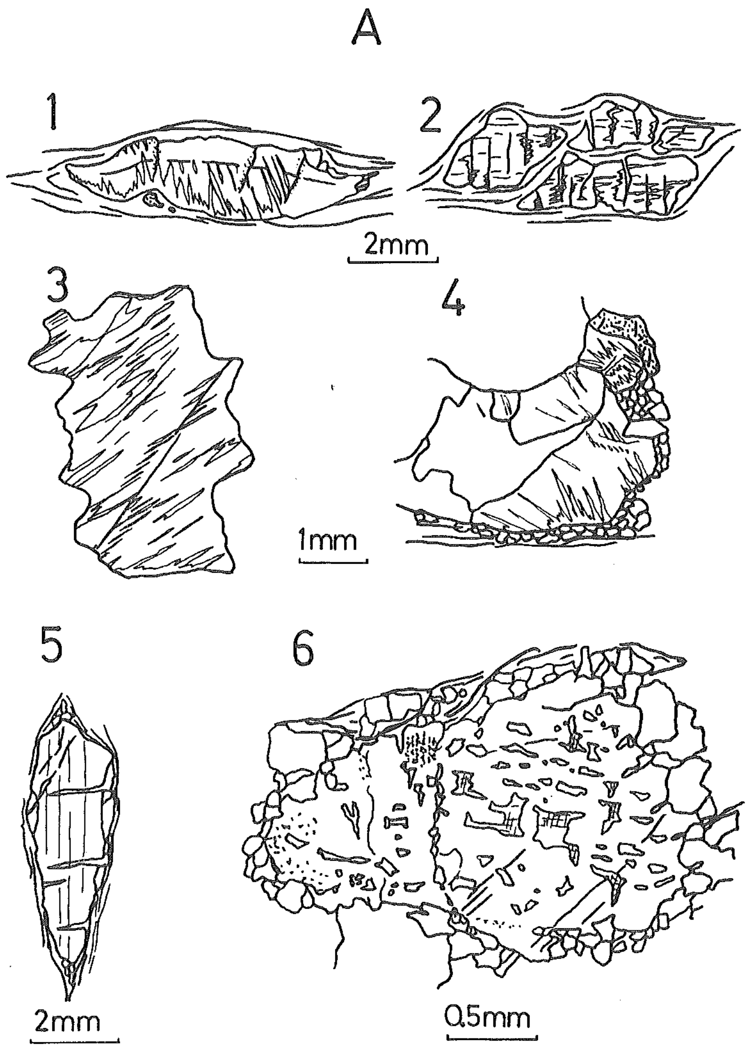
and antiperthitic texture (Fig. 19-A, 6) in the potash feldspar, and at last whole grain was completely replaced by albite showing faint albite polysynthetic twin lamellae (Fig. 19-A, 5).

One mylonite sample alternating with the augen gneiss was cut into a thin section parallel to the lineation and vertical to the gneissosity plane and the optic axes of 100 potash feldspar porphyroblasts were measured (Fig. 19-B).

The orientation of Z axis was projected on the Schmidt net, since the Z axis situated near the (010) crystallographic plane pole in microcline crystal. The diagram obtained shows cross girdles roughly symmetrical to the gneissosity plane. This result suggests that prism planes of the feldspars, including the (010) plane, were rotated about an axis parallel to lineration of the rock during the differential movement.

On the other hand, almost all of these feldspars have some cracks filled by quartz veinlets. The orientation of these cracks was also projected on a Schmidt net (Fig. 19-C). The diagram obtained show that most of them are nearly perpendicular to the gneissosity plane. This may suggest that the stress applied to the mylonite was a tension.

These results suggest a relationship between the differential movement and orientation of feldspar, since the mylonite is a extremely emphasized product of the augen gneiss in the sequence of the kinetic metamorphism.



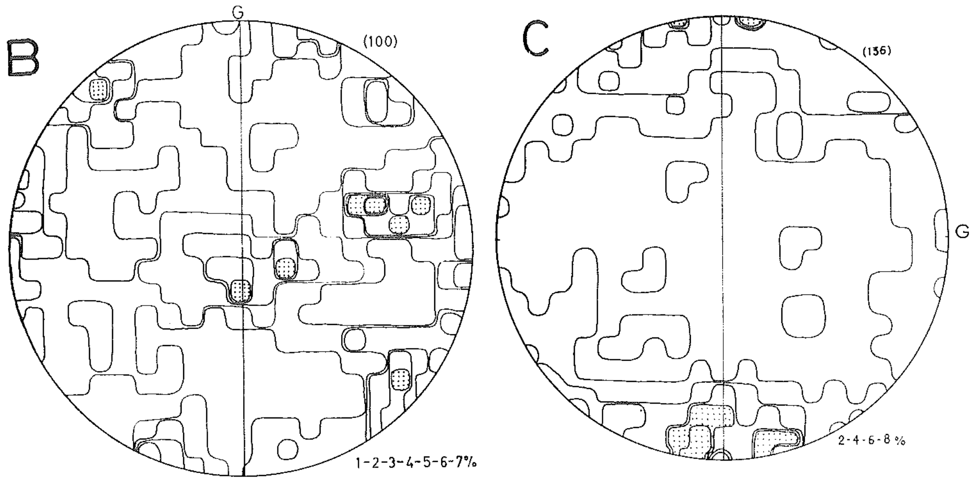


Fig. 19
Feldspars in the mylonite.
A ; albitization of potash feldspar, showing flame and antiperthite structures.
B ; Z axes of the potash feldspars in the mylonite.
C ; orientation of the cracks of the potash feldspars.

10. *The other inclusions in the eyeball potash feldspar*

Besids many plagioclases, green hornblende, mostly converted into chlorite, epidote and opaque ore minerals, chloritized biotite and idiomorphic sphene are all present as inclusions in the eyeball potash feldspar. Especially in the embryonic augen, these foreign minerals occupy more than a half of the augen unit. All these minerals were derived from pre-existing hornblende and biotite, which have been converted into the mineral paragenesis of the epidote-albite amphibolite facies.

The abundant existence of such inclusions suggests that the space at present occupied by the eyeball potash felspar was once an area of granulated mosaic of the pre-existing gneiss, and that the eyeball represents an advanced stage of replacement of these materials.

Discussions

1. *On the rotation of optic orientation of the potash feldspar in the augen unit*

The deviation trend of the optic axes in the eyeball feldspar is inherited in the rotation trend of the orientation in the pressure shadow domain. One type of rotation axis is about 25° from the Y to the Z axis and may roughly coincide with the crystallographic C axis which is 26° from the Y to the Z. This suggests that the

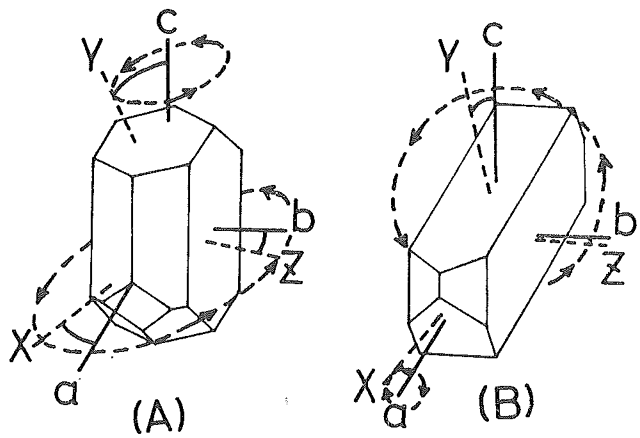
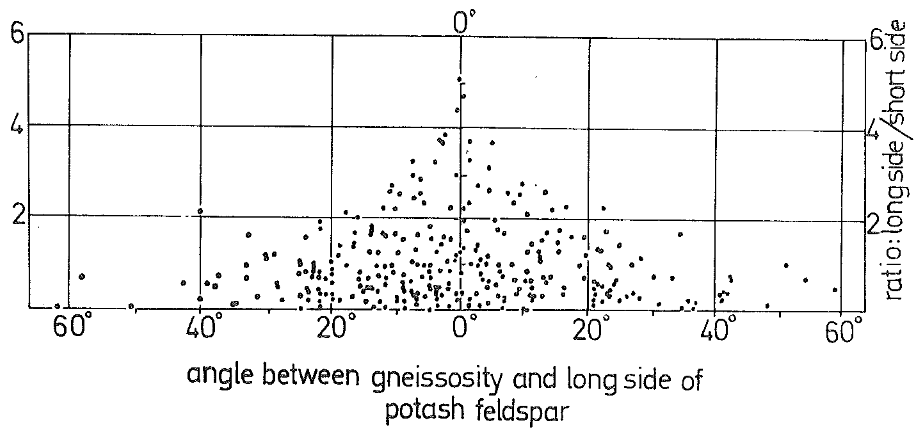


Fig. 20
Schematic illustration of the rotation of potash feldspar in the single augen unit.
A ; rotation about c-axis. B ; rotation about a-axis.



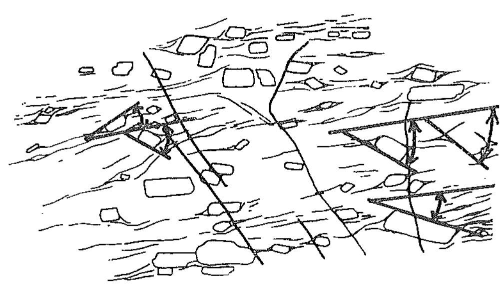


Fig. 21
Megascopic arrangement of potash feldspar porphyroblasts in the augen gneiss, showing rotation of the individuals. Interpretations are given in the text.

[001] planes might glide during the rotation of the potash feldspar (Fig. 20-A). The second type rotation has its axis about a crystallographic a axis and the [100] planes might have glided (Fig. 20-B).

These rotation movements was also proved by field observation. A good exposure of the augen gneiss, roughly perpendicular to the gneissosity plane and about 10 m×1 m in size was traced onto a transparent vinyl sheet, and both the long and short sides of all prismatic potash feldspar megacrysts and the angle between the long side of the prism and the gneissosity plane were measured. This angle was plotted against the ratio of the length of long and short sides of the megacrysts. (Fig. 21). The result shows clearly that the long prismatic crystals lie nearly prallel to the gneissosity plane, while the square shaped ones are situated diagonally. The gneissosity of the fine-grained groundmass bends around these crystals. This can only be explanined by a rotation of the megacrysts.

2. *On the significance of the rotation*

As already mentined in the augens which have well-shaped eyeball crystal, the idiomorphic or subidiomorphic megacrysts of potash feldspar existed prior to the formation of the augen under differential movement.

An important experiement had been carried out by O. Watanabe in the Geophysical Institute, Nagoya University, on ice blocks. He pressed an ice cylinder of a polycrystalline aggregate of ramdomly orientated fine crystals (about 10 micron in size) under $-18°\sim-20°C$. A 10 cm. high cylinder was pressed with 75 kg/cm^2 pressure at a constant compressing velocity of 0.02–0.03 mm./min., until its strain becomes 90%. The change of the ice texture of the polycrystalline aggregate was studied from the view point of the mechanics. Texturely, many " glide units " appeared (plate 1), bounded by diagonal " glide planes " whose angle to the direction of the compression was gradually increase with the increase of the compression (Fig. 22). When the ice was kept under a certain large load in a deformed state, the glide planes becomes nearly perpendicular to the direction of the compression. These textures of glide units and parallel glide planes in the ice are very similar to those observed in some porphyroblastic gneisses and crystalline schists. Many petrologists believe that pressure on a rock acts directly on individual grains and that the deformation of the rock is achieved by recrystallisation and reorientation of individual minerals. However, judging from the results of the ice experiment, actual deformation might be carried out through differential gliding of these units. of course, the units themselves were strained very much during the compression, but the direction and intensity of the stress in each glide unit differs from each other. Then the compression was maintained for a long time, the grains in the gluide unit granually recrystallized to release the strain. This work may have important implications for petrofabric studies.

The augen gneiss is clearly divided into spindle shaped domains of various size

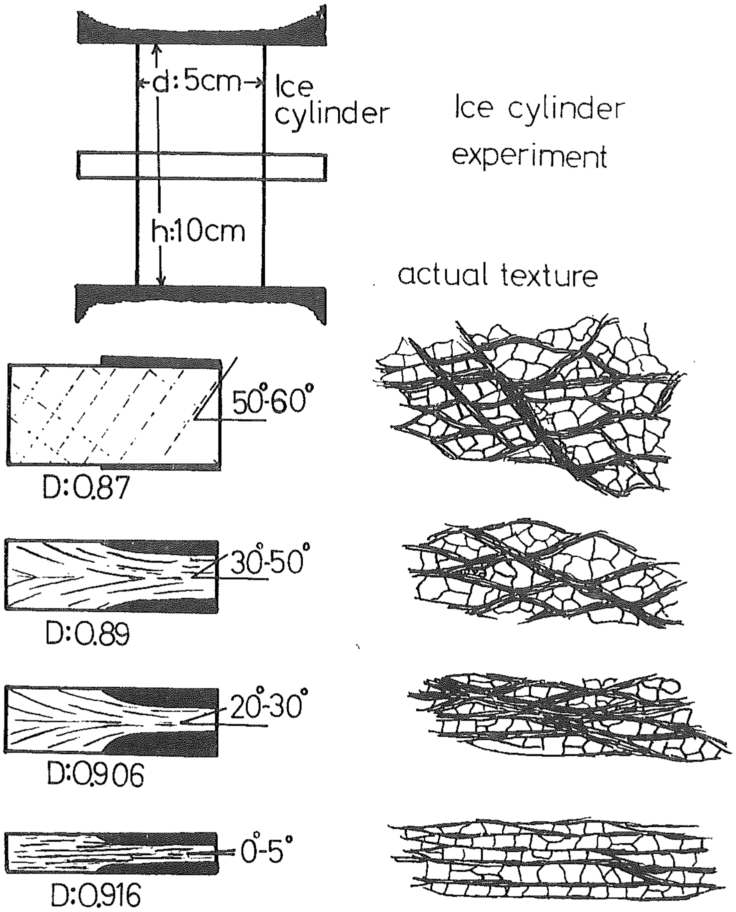


Fig. 22
Fabric development of the compressed ice cylinder. Interpretations are given in the text.

(Fig. 23). Let us assume that these augen domains are equivalent to " the glide units " of the ice fabric experiment. The borders of these augen units are composed of a concentration of phyllosilicate minerals and small granulated mosaics forming glide planes. If gliding movement took place along these planes, then the planes around the eyeball crystal become the most pronounced glide planes where intense granulation of the crystal might be expected.

These considerations bring us easily to the conclusion that the rotation of the optic orientations of the potash feldspar in the augen unit is the result of granulation of the eyeball crystal and the undulatory extinction observed in the eyeball potash

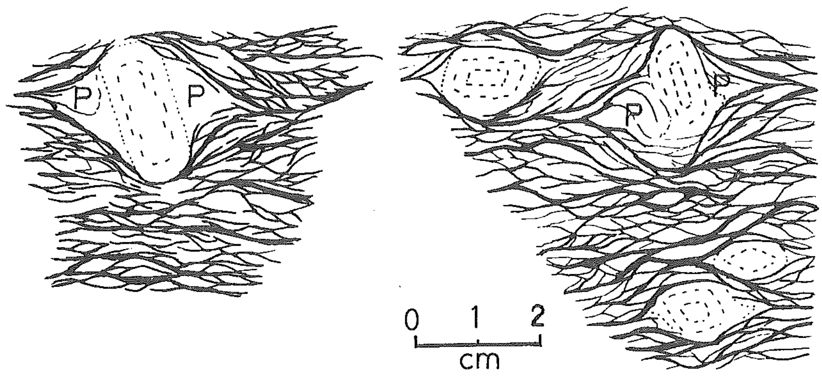


Fig. 23
Glide unit structures around augen unit of the augen gneiss. P in the figure is the pressure shadow domain.

feldspar is the result of strain in the glide unit.

However, the pressure shadow domain of the single augen is clearly inside the glide planes along the sides of the eyeball crystal. We have also met with exmples of augen whose pressure shadow domain is evidently inside the glide planes along the sides of the eyeball crystal as shown in Figs. 7-A, and 23. In these cases, the pressure shadow domain is no longer a region of granulation, but a domain of material accumulation. Actually, these domains are filled with feldspar and quartz, forming pools. The glide plane is a mean of material transport, but not a place of precipitation. The transported material and granulated fragments derived from the sides of eyeball crystal might accumulated in the pressure shadow domain. In such cases, the accumulated materials are hardly likely to have any regular orientation relative to the optic orientation of the eyeball crystal. In fact, however, the obtained variation pattern of the optic orientations of these grains in the pressure shadow domain had its rotation axis around the c- or a- axis of the eyeball crystal.

A positive example of this was found in the embryonic augen. The embryonic augen, which has no eyeball crystal and represents the beginning stage of an augen potash feldspar formation, also reveals the same types of rotation, both around c- and a axes as rotation axis.

The augen unit was already defined as a glide unit limited by some glide planes and the granulated materials within the glide unit were being replaced by the introduced potash feldspar material. The rotation patterns obtained from this augen suggest that the potash feldspar material was initially settled with somewhat regular orientation in the interstitial spaces of the pre-existing minerals. Therefore, the specific stress field to form an augen unit already existed there during the beginning stage of precipitation of potash feldspar materials.

By analogy with the ice experiment, the augen shaped glide unit might formed synkinematically with the differential movement of the pre-existing rock. Thus the precipitation of potash feldspar took place under differential stress. The rotation of the optic orientation suggests that the eyeball crystal itself was grown up by coalescence of differently orientated initial grains through the rotation of their orientation.

The same convergence of orientation can be expected in the pressure shadow domain of the single augen. Then the rotation pattern of the optic orientation indicated reorientation of the accumulated material into the most stable orientation i.e., the same orientation as the eyeball crystal. It is this process which makes up a large eyeball potash feldspar and modifies an idiomorphic crystal into the rounded augen shape. Therefore, the rotation pattern is not only a granulation pattern but also a growth pattern of the augen structure.

3. *On the variation of optic axial angle in an eyeball potash feldspar*

More than a hundred measurements of optic aixal angles in the single augen eyeball (Fig. 12) show a surprisingly wide range of variation from $2Vx=18°$ to $90°$ (OHTA and KIZAKI, 1966).

The optic axial angle of potash feldspar is a function of the structural state of a crystal as well as of the chemical composition (MACKENZIE, 1955). It is not certain whether the variation of the optic aixial angle in the eyeball potash feldspar in this case is due to structural state or chemical composition, since no chemical analysis of the material has yet been made.

However, it will be assumed for the purpose of the present discussion that the variation is mainly due to the structural state of the feldspar. The twinned augen shows a rough regularity in which the large optic axial angles are in the core part and the intermediate ones around the margin of the eyeball crystal (Fig. 3-A). But the single augen eyeball does not show any such regularity (Figs. 12 and 14).

REIDERER (1965) studied the optic characters of potash feldspars in the Mordanubischen granites, and measured several hundred optic axial angles in three potash feldspars. None of his three samples show any regular distribution of the optic axial angle.

The formation of triclinic potash feldspar is still an unsuccessful subject of experimental mineralogy. It is said that potash feldspar tends to crystallize in a disordered state even under a temperature lower than the transition point of the order and disorder modification, especially when the crystallisation is rapid (GOLDSMITH and LAVES, 1954. LAVES, 1950).

All known examples (the two examined here and the three of the mordanubischen granite) commonly have intermediate optic axial angles around the grain margin. This may indicate that such large porphyroblasts are formed as a result of relatively rapid precipitation of material. The material settles as metastable orthoclase and is gradually converted into microcline at the same or lower temperature than that of the precipitation.

Since, as already mentioned above, the distribution of the optic axial angles in a potash feldspar is in many cases completely random (NILSSEN and SMITHSON, 1965, SYLVESTER, 1963), the change of crystalline state might proceed from centres of ordering. It is unknown, at the present stage of this study, from which parts of a crystal the ordering has started (RAST, 1965, RAST and STURT, 1957). However, a suggestion may be made on the basis of the optic axial angle distribution observed in the twinned augen eyeball, where the central part of the crystal has large optic axial angles. This may means that the domains which were crystallized earlier tend to (Fig. have large optic axial angles. On the other hand as shown in the embryonic augen 7-A), some parts of potash feldspars, where initial anhedral grains were formed might become centres of ordering of the crystalline state (MACONNELL and MCKIE, 1960).

4. *On the plagioclase inclusions in the eyeball potash feldspar*

As already discussed in the foregoing chapter, the orientation of the plagioclase inclusions in an eyeball crystal was controled by the selective replacement and reorientation of the inclusions. The orientation of the host potash feldspar is an important controlling factor in the orientation of the plagioclase inclusions.

The zonal distribution of inclusions, often met with in megacrysts, is a result of change in the growth rate during the formation of such a large crystal. During rapid growth the inclusions are not absorbed by the host, while most of the potential inclusions are assimilated completely when the growth rate is small. The former then becomes a zone of abundant inclusions and the latter is free from them (SCHILING and WENSINK, 1962).

When the chemical equilibrium has been established between the host and inclusions, and the composition of the host potash feldspar is constant over the entire crystal, the An-content of the plagioclase inclusions should be constant (RUTLAND, 1961). However, the plagioclase inclusions in the single augen eyeball have in fact a wide range of compositional variation from An_2 to An_{33}. Among these plagioclases some oligoclases have thin albite rims at the margins of the grains, and sometimes, these albite rims are continuous with the perthite veinlets exsolved from the host potash feldspar keeping the same optic orientation. Some other oligoclases are however in direct contact with the host without any albite rim. Owing to the peristerite gap in the acidic plagioclase series, an albite and an oligoclase could be stable and co-exist with a host potash feldspar, but the oligoclases should not have the large compositional range as observed for the single augen eyeball where An-content varied from 18 to 33. If all these oligoclases are in stable co-existence with the host, the potash feldspar should also have large difference in composition from place to place within the crystal (THOMPSON, 1959). In other words, some oligoclases are in stable co-existence with the host, but others are not.

The optic axial angle of potash feldspar is a function of the crystalline state, which in turns is mainly a function of temperature. The compsotion of exsolved potash feldspar is ideally the function of temperature, thus the optic axial angle may give us some informations on the composition of potash feldspar. SMITH and MACKENZIE (1959) proposed a tentative diagram of optic axial angle of potash feldspar versus bulk potash felspar composition. If this diagram is applied to the present data of the single augen, the compositional variation in this feldspar covers all range of the exsolved potash feldspar series. These unstable parageneses should be carefully examined when element partition is to be discussed.

A problem also arose in the discussion of a bulk rock. As shown in Fig. 17, fifity independent plagioclases in a thin section of a rock commonly show a compositional range of 10 to 20% An-content (OHTA, 1961). When the minimum and maximum An-contents were used to calculate the formation temperature of the rock, following the method proposed by BARTH (1958), the estimated formation temperatures differed by more than a hundred degree C.. A formation temperature calculated from chemical analysis of the co-existing feldspars, using the material collected from a hand specimen, means only an average value, and such an average is not of great value in any attempt to understand the complicated formation history of the rock.

Conclusions

The occurrence of large porphyroblasts of various kinds of minerals is the most characteristic feature in different kinds of metamorphic rocks. The mechanism of formation of such a porphyroblast is one of the most important subjects of metamorphic petrology. The major factors controlling growth of a large crystal may differ from that in the scale of micron and angstrom. This study is an attempt to get some informations concerning the growth of porphyroblast with the scale of microscopic dimensions. It is also aimed to combine studies of crystal growth and petrofabric methods.

The present study of three potash feldspar porphyroblasts has yielded some informations on the growth of augen shaped porphyroblast;

1. The rotation of the optic orientation within an augen unit. This rotation is the result not only of granulation of a pre-existing idioblast, but also of the growth of a crystal through gradual coalescence of a number of small grains into a large porphyroblast.
2. The crystalline state of the single eyeball potash feldspar is not homogeneous, but very variable from place to place even in a single crystal. The ordering of the crystalline state might originate from the points where the feldspar material precipitated first. This means that the ordering may be a function of time after the crystallisation in the case of structural conversion of these large por-

phyroblasts.

3. Many inclusions of plagioclase in potash feldspar porphyroblasts show a characteristic distribution produced by selective replacement and re-orientation within the host. The An-contents of these plagioclases show a large range of variation. This means that either the host potash feldspar has large compositional differences within one crystal, or else these two feldspars are not always in chemical equilibrium.

It is to be regretted that in the present study no chemical information was obtained for each of the point measured in the potash feldspars. The integration of petrofabric methods and electron microprobe techniques is expected to offer a chance for great advance in the study of this kind.

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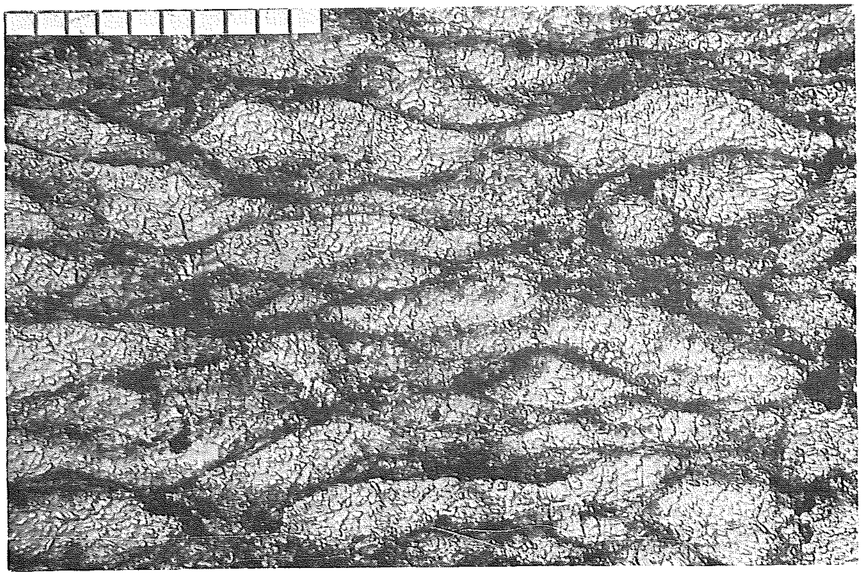
PLATE 1 AND EXPLANATION

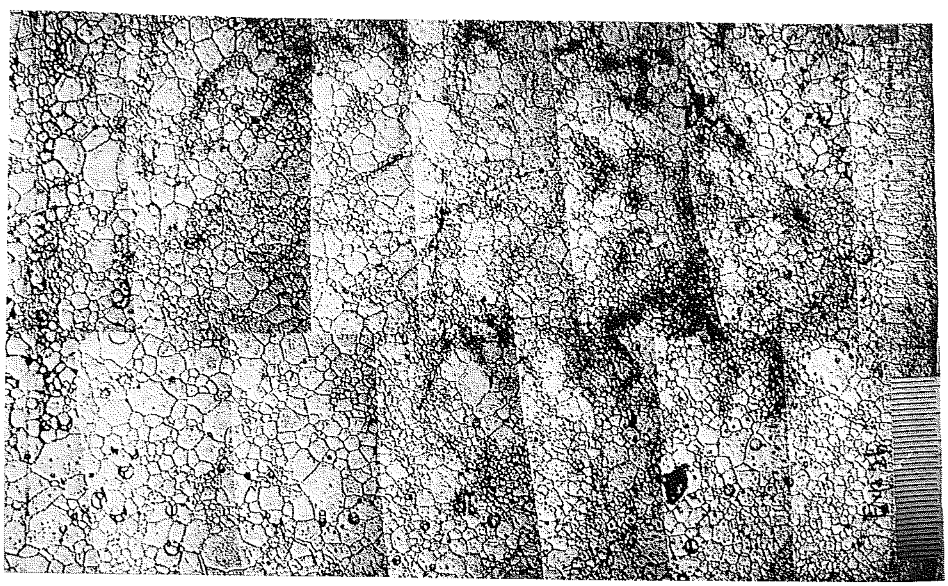
Explanation of Plate 1

Microphotograph of the ice fabric representing glide unit textures Scales in mm.
1; cross section. 2; ground plane.

Plate 1



1



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