

THE ALKALI FELDSPARS VI. SANIDINE AND ORTHOCLASE  
PERTHITES FROM THE SLIEVE GULLION AREA,  
NORTHERN IRELAND\*

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ABSTRACT

Detailed field and mineralogical studies of the associated porphyritic felsite and granophyre ring dykes of Slieve Gullion, N. Ireland, have been made to elucidate the genesis of the rock and of the alkali feldspars. Central, acentric subsidence of country rock within the ring fracture allowed the partially-crystalline magma to rise. Upon crystallization of one-third of the magma the roof shattered to form agglomerate, and the loss of volatiles led to rapid crystallization of the felsite. A subsequent subsidence without roof shattering led to formation of the granophyre.

The majority of the alkali feldspar phenocrysts fall between the sanidine and orthoclase series, consisting of intergrowths of monoclinic K-feldspar, anorthoclase and sodium-rich plagioclase. Two crystals from the granophyre consist of intergrowths of orthoclase, microcline and low-temperature plagioclase. It is thought that the majority of the phenocrysts are true phenocrysts formed slowly at considerable depth. During the cooling period they changed from homogeneous sanidine into their present assemblages through a sequence of unmixing and ordering reactions. It is thought that the local content of volatiles was probably the dominant factor in determining the extent of adjustment to the low-temperature assemblages. The occurrence of microcline is remarkable in hypabyssal rocks. It is thought probable that it results from fragments of Newry granodiorite caught up in the magma, although it might have arisen from plagioclase crystals by ionic exchange.

INTRODUCTION

Earlier papers of this series have been mainly concerned with obtaining a comprehensive catalogue of the structural changes to be found in the alkali feldspars, and, for convenience, attention has been focussed on well-crystallized specimens for which analyses were available. No attempt was made to obtain a representative coverage of rock types, the majority of the specimens being derived either from pegmatites or volcanic rocks. The remaining papers will deal mainly with the alkali feldspars from the common igneous rocks and two objectives will be kept in mind: obtaining a more balanced viewpoint on the distribution of the various structural types, and correlating the mineralogy of the alkali feldspars with the petrology of the host rocks.

The study has been confined to igneous<sup>1</sup> rocks and has concentrated

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<sup>1</sup> Possibly the larger bodies might arise from metamorphic or metasomatic reactions.

mainly on the Tertiary rocks of Britain. The relative youth of these rocks has helped to reduce the likelihood of later complicating metamorphic effects, and the detailed mapping of British rocks has helped in the estimation of the conditions of their consolidation. Tuttle and Keith (1954) in a study of the Beinn an Dubhaich granite have provided a useful signpost in demonstrating the coexistence of orthoclase and sanidine perthites. These feldspars have been re-examined by the more refined methods now available and the results will be presented in a later paper. To extend the data for the feldspars transitional between those from volcanic rocks (papers III and IV) and the Beinn an Dubhaich granite, the Slieve Gullion composite ring dyke of porphyritic felsite and porphyritic granophyre was chosen. The ring dykes vary in width from a few feet to over a mile, and a wide variation in conditions was thereby anticipated. To extend the coverage to include larger masses, the Arran and Mourne granites (both about 7 miles in diameter) were chosen and a further extension was obtained by a study of the older and much larger Dartmoor pluton and the Tertiary S. California batholith. Additional information has been obtained by a study of the larvikites from Norway (Muir and Smith, 1956; Smith and Muir, 1958).

The appearance of the feldspar in these rocks is quite different from that of the feldspars studied in the earlier papers. In contrast to the clear euhedral crystals obtained from the pegmatites and volcanic rocks, the specimens from the granites, granophyres and felsites are usually anhedral and turbid. The cleavage is irregular and the optical properties of grains large enough for single crystal work (ca. 0.2 mm.) are difficult to measure. Consequently some refinement of the simple techniques described in paper II has been necessary as will be described separately.

#### *The Petrology of the Slieve Gullion Ring Dyke Rocks*

In order that the conditions of crystallization and subsequent history of the feldspars may be assessed, it is necessary to give an outline of the petrology of the ring dykes. The general structure and petrology of the ring complex was described by J. E. Richey and H. H. Thomas (1932) and certain other aspects of the complex by D. L. Reynolds (1941, 1950, 1951, etc.), E. M. Patterson (1953) and E. B. Bailey and W. McCallien (1956). A full account of the western part of the ring dyke complex is in preparation by one of us (C.H.E.). A simple sketch map of the Slieve Gullion dykes is shown in Fig. 1; reference should be made to the excellent maps prepared by Richey and Thomas if further details are required.

The Porphyritic Felsite ring dyke, the older of the two acid intrusions, is a conspicuously porphyritic rock with phenocrysts of feldspar and quartz set in a fine-grained and often flow-banded matrix. In hand

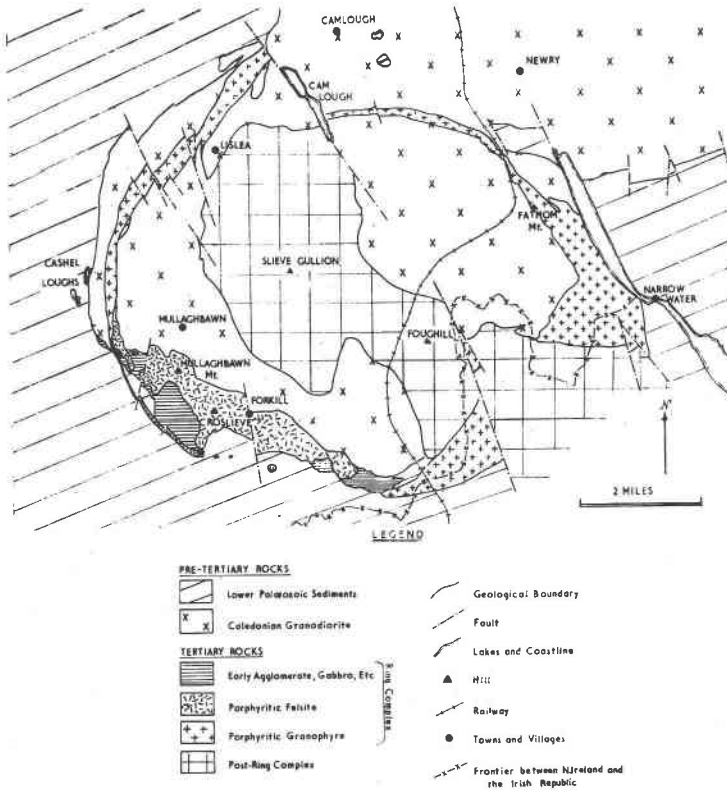


FIG. 1. Geological sketch map of the Slieve Gullion area.

specimens the felsite varies from a dark, semi-vitreous rock near the margins to a light-colored gray or buff rock in the more central parts of the intrusion. Phenocrysts are usually not more than 3 mm. in diameter and include, in addition to alkali feldspar and bipyramidal quartz, plagioclase ( $An_{25-35}$ ), hedenbergitic clino-pyroxene and fayalite. The groundmass of the marginal felsite consists of innumerable minute octahedra of magnetite in a dark crypto-crystalline base whereas the groundmass of the more central parts is a finely granular aggregate of quartz, alkali feldspar, subordinate amounts of plagioclase, magnetite and green amphibole. The amphibole occurs as poikilitic crystals enclosing grains of quartz and feldspar; frequently it develops as a mantle about clino-pyroxene and fayalite phenocrysts. Occasionally the groundmass consists of spherulitic growths of turbid alkali feldspar and quartz. The phenocrysts tend to be rounded and resorbed in appearance; many sections also contain fragments of original euhedral crystals (Fig. 2a).

Flow banding is a persistent feature of the felsite and varies considerably in character. The marginal felsite has a very fine-scale banding frequently associated with elongated drusy cavities rimmed with coarsely crystalline rock (Figs. 2*b* and *c*). Felsite away from the margins has coarser banding which becomes progressively less obvious until, in the central felsite, it is rather uncommon. The flow banding in the central parts consists of layers 5–10 mm. thick of relatively coarsely crystalline rock, often markedly spherulitic.

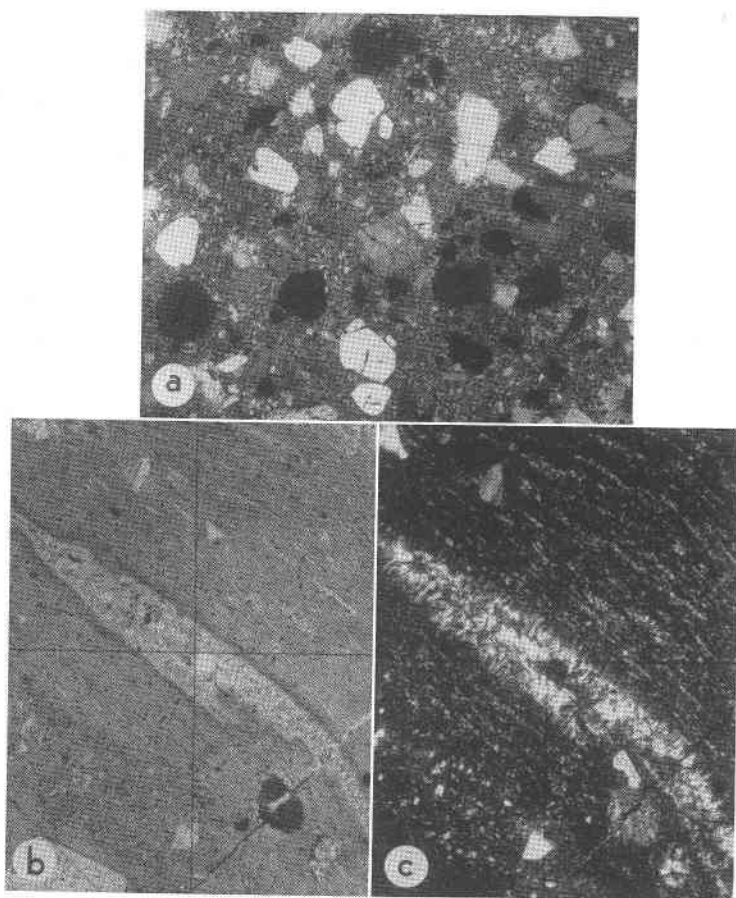


FIG. 2. Photomicrographs of Porphyritic Felsite. (a) shows resorbed and fragmented character of some of the phenocrysts. Specimen number G45, crossed nicols,  $\times 3$ . (b) shows fluxion structure outlined by trails of magnetite granules. Specimen G4, ordinary light,  $\times 13$ . (c) shows coarse crystallization about a drusy cavity. Specimen G4, crossed nicols,  $\times 13$ . By comparing the last two photographs, encroachment of the coarsely-crystallized part on the fluxion-banded part of the rock may be seen.

The flow banding and phenocrysts provide direct evidence of late stage recrystallization within the felsite. Originally the flow banding consisted of magnetite granules concentrated into trails and streaks. Where the bands adjoin druses associated with the coarsely crystalline felsite, and especially where the growth has been spherulitic, they may be traced through the relatively large crystals of quartz and feldspar (Compare Figs. 2*a* and 2*b*), or they may be interrupted, with the minute magnetite crystals replaced by larger grains or by amphibole in irregular, poikilitic crystals of small size. Away from the margins the small-scale banding dies out as the minute magnetite octahedra give way to larger grains or are replaced by the poikilitic amphibole. Where magnetite and amphibole occur together, the groundmass in the immediate vicinity of the amphibole is depleted in ore; evidently much of the finely disseminated amphibole developed at the expense of original ore. A similar feature was clearly demonstrated in the Porphyritic Felsite of Dibidil, Isle of Rhum (Hughes, 1956). There is also textural evidence for the replacement of fayalite and clinopyroxene by amphibole for the amphibole occurs as rims about the olivine and clinopyroxene. In the Porphyritic Granophyre replacement in this manner appears to be complete.

The Porphyritic Granophyre is extremely variable in hand-specimen and thin section. The marginal granophyre is fine-grained with phenocrysts of quartz and feldspar set in a dark-colored matrix which is sometimes flow-banded. The grain size of the groundmass increases rapidly away from the margins and in much of the intrusion the rock is, in effect, a porphyritic microgranite. The phenocrysts include quartz (with indications of bipyramidal habit in the marginal granophyre), alkali feldspar, plagioclase ( $An_{15-30}$ ), hedenbergitic clinopyroxene, fayalite and a green, hastingsitic amphibole. The approximate modal proportions are given in Table 4. Unlike the felsite, the granophyre contains amphibole as the dominant mafic mineral; biotite also occurs while magnetite, apatite, zircon and orthite are present in accessory amounts.

Texturally the groundmass may vary from a granophyric intergrowth of quartz, turbid alkali feldspar and plagioclase to a microgranitic aggregate of these minerals accompanied by green amphibole and sparse flakes of greenish-brown biotite. The olivine and pyroxene phenocrysts are almost invariably rimmed by amphibole, a relationship particularly well developed in the marginal granophyre. Towards the central parts of the intrusion the proportion of amphibole increases with the eventual exclusion of olivine (which is never common) and pyroxene. The marginal granophyre may be felsitic or aplitic in texture. Typically the Porphyritic Granophyre is drusy, the small cavities being lined with quartz, feldspar, dark mica, and, rarely, green epidote.

TABLE 1. CHEMICAL ANALYSES OF ROCKS FROM THE SLIEVE GULLION RING DYKE

|                                | (1)   | (2)    | (3)    |
|--------------------------------|-------|--------|--------|
| SiO <sub>2</sub>               | 71.91 | 74.66  | 76.91  |
| Al <sub>2</sub> O <sub>3</sub> | 13.42 | 12.62  | 11.79  |
| Fe <sub>2</sub> O <sub>3</sub> | 1.62  | 1.52   | 1.00   |
| FeO                            | 1.96  | 1.24   | 0.99   |
| MgO                            | 0.27  | 0.31   | trace  |
| CaO                            | 0.84  | 0.66   | 0.68   |
| Na <sub>2</sub> O              | 3.65  | 3.62   | 3.33   |
| K <sub>2</sub> O               | 5.49  | 5.02   | 4.98   |
| H <sub>2</sub> O <sup>+</sup>  | 0.21  | 0.20   | 0.23   |
| H <sub>2</sub> O <sup>-</sup>  | 0.35  | 0.13   | 0.12   |
| CO <sub>2</sub>                | nil   | nil    | nil    |
| TiO <sub>2</sub>               | 0.07  | 0.16   | 0.16   |
| P <sub>2</sub> O <sub>5</sub>  | 0.07  | 0.05   | 0.02   |
| MnO                            | 0.07  | 0.04   | 0.04   |
|                                | 99.93 | 100.23 | 100.25 |

- (1) Porphyritic Granophyre. Cashel Plantation, 7 miles WSW of Newry, 4 miles NW of Forkill. (Approx. same as G. 70).
- (2) Porphyritic Felsite. Scarp,  $\frac{1}{2}$  mile NW of Forkill. (Approx. same as G. 315.) Analyst for (1) and (2): E. M. Patterson (Patterson, 1953).
- (3) Porphyritic Felsite. Knoll just south of Mullaghbawn Lough. Analyst: F. Harwood, unpublished analysis done for J. E. Richey. (Approx. same as G. 31.)

In the granophyre, the phenocrysts are larger than in the felsite, particularly the alkali feldspar and plagioclase which may reach as much as 1 cm. across. The number of individual phenocrysts in a given volume is less than in the felsite, although the modal proportions of phenocrysts and groundmass are similar (Table 4). A further difference between the phenocrysts is that in the granophyre they generally occur as aggregates; usually the groups are monomineralic but sometimes they may be composite. It is noticeable that plagioclase and alkali feldspar enter readily into the aggregates, quartz almost never does and participation of mafic minerals is uncommon but by no means unknown. A more detailed description of the aggregates is given later.

Three chemical analyses are available for the ring-dyke rocks (Table 1) Both intrusions are typical of the majority of the British Tertiary granites, granophyres and felsites in their high silica, high FeO/MgO ratio, low absolute amount of magnesia, and in having potash in excess of soda. The felsite is somewhat more siliceous than the granophyre while the latter is appreciably richer in total iron and total alkalis. (Alkali determinations on six specimens from each intrusion show that a

slight relative alkali enrichment characterizes the granophyre.) Amongst the other acid Tertiary rocks, the felsite compares closely with the more acid of the Mourne Mountain granites (Brown, 1956) while the granophyre is closely comparable with the more mafic facies of the Mourne Feldspathic granite, G1 (Richey, 1928; Brown, 1956). This similarity extends to the mineralogy for hastingsitic amphibole is abundant in both, the analysis of the Mourne amphibole revealing an extreme FeO concentration (Brown, 1956).

### THE ALKALI FELDSPARS

#### *Techniques and Data*

Pure specimens of the alkali feldspar phenocrysts were obtained by crushing, magnetic separation and centrifuging the porphyritic felsite, and by hand picking the crushed porphyritic granophyre.

Only the felsite phenocrysts have been analysed so far. The alkalis were determined by the flame photometer using sodium oxalate and potassium nitrate for calibration, and the standard granite G1 and diabase W1 for checks. The results were reproducible to 0.03% of the weight quoted in Table 2, representing a spread of about 0.2 wt. % on the calculated orthoclase and rather less on the albite. Semi-quantitative spectro-

TABLE 2. CHEMICAL COMPOSITION OF ALKALI FELDSPAR PHENOCRYSTS AND THE HOST ROCK

| Specimen Number | Alkali                 |                   | Feldspar |      | Phenocrysts |     | Total | Host Rock        |                   |  |
|-----------------|------------------------|-------------------|----------|------|-------------|-----|-------|------------------|-------------------|--|
|                 | K <sub>2</sub> O       | Na <sub>2</sub> O | CaO      | or.  | ab.         | an. |       | K <sub>2</sub> O | Na <sub>2</sub> O |  |
|                 | <i>Weight per cent</i> |                   |          |      |             |     |       |                  |                   |  |
| G.45            | 7.54                   | 5.60              | 0.59     | 44.6 | 47.4        | 2.9 | 94.9  | 5.07             | 3.23              |  |
| G.31            | 7.06                   | 5.93              | 0.41     | 41.7 | 50.1        | 2.0 | 93.8  | 4.52             | 3.23              |  |
| G.105           | 10.5                   | 4.0               | 0.63     | 62.1 | 33.8        | 3.1 | 99.0  | 6.98             | 2.67              |  |
| G.106*          | 9.51                   | 4.72              | 0.69     | 56.2 | 39.9        | 3.4 | 99.5  | 5.90             | 3.03              |  |
| G.107           | 8.45                   | 5.25              | 0.66     | 50.0 | 44.4        | 3.3 | 97.7  | 5.66             | 3.35              |  |
| G.108           | 8.30                   | 5.25              | 0.72     | 49.1 | 44.4        | 3.6 | 97.1  | 5.48             | 3.19              |  |
| G.109           | 9.30                   | 4.70              | 0.63     | 55.0 | 39.8        | 3.1 | 97.9  | 4.46             | 3.01              |  |
| G.111           | 7.67                   | 5.58              | 0.93     | 45.3 | 47.2        | 4.6 | 97.1  | 4.46             | 3.01              |  |
| G.313           | 7.44                   | 5.81              | 0.61     | 44.0 | 49.1        | 3.0 | 96.1  | 5.96             | 3.85              |  |
| G.314           | 7.95                   | 5.50              | 0.65     | 47.0 | 46.5        | 3.2 | 96.7  | 5.39             | 4.50              |  |
| G.315           | 7.66                   | 5.76              | 0.38     | 45.3 | 48.7        | 1.9 | 95.9  | 4.54             | 3.23              |  |
| G.317           | 7.41                   | 5.60              | 0.67     | 43.8 | 47.4        | 3.3 | 94.5  | 5.23             | 3.47              |  |
| G.396           | 8.70                   | 4.92              | 0.40     | 51.4 | 41.6        | 2.0 | 95.0  | 4.57             | 3.23              |  |
| G.398a          | 8.70                   | 5.20              | 0.44     | 51.4 | 44.0        | 2.2 | 97.6  | 4.79             | 3.26              |  |

\* Additional data on alkali feldspar in G.106: SiO<sub>2</sub>, 65.22; Al<sub>2</sub>O<sub>3</sub>, 19.92; Total: 100.06. Analyst for SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and CaO: E. A. Vincent.

graphic determinations, using  $\text{SrCO}_3$  as an internal standard, were made of CaO, yielding fairly reproducible results with a variation corresponding to  $\pm 0.1$  wt. % calculated anorthite.

For several of the alkali feldspars the total of Or+Ab+An (Table 2) calculated from the figures for  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$  and CaO falls short of 100% by as much as 5%. This deficiency is thought to be genuine in view of the reproducibility of the chemical methods. Microscopic examination of mounted grains did not reveal the presence of anything like enough macroscopic impurity, such as quartz, to account for the discrepancy. The feldspars, however, are very turbid and at first sight it was thought that the turbidity arose from an alteration involving the loss of alkalis. Detailed analysis of G106, an exceptionally turbid specimen, tends to

TABLE 3. OPTICAL PROPERTIES OF THE ALKALI FELDSPAR PHENOCRYSTS

| Specimen Number | Distance from Margin* | or. content † | $n_o \pm 0.001$ | Optic axial angle, $2V\alpha$ |       |                    |
|-----------------|-----------------------|---------------|-----------------|-------------------------------|-------|--------------------|
|                 |                       |               |                 | average                       | range | number of crystals |
| G.31            | 150 yards             | 44.5          | 1.520           | 58                            | 56-59 | 6                  |
| G.45            | 300 yds.              | 47.9          | 1.522           | 57                            | 51-63 | 8                  |
| G.105           | at contact.           | 62.8          | 1.520           | 50                            | 40-72 | 23                 |
| G.106           | 1'                    | 56.5          | 1.520           | 49                            | 37-72 | 7                  |
| G.107           | 2'                    | 51.2          | 1.521           | 48                            | 38-66 | 14                 |
| G.108           | 3'                    | 50.6          | 1.520           | 48                            | 43-58 | 9                  |
| G.109           | 14'                   | 56.2          | 1.520           | 55                            | 44-66 | 10                 |
| G.111           | 30-40 yds.            | 46.6          | 1.522           | 49                            | 41-55 | 10                 |
| G.313           | 45 yds.               | 46.8          | 1.524           | 63                            | 56-68 | 7                  |
| G.314           | 25-30 yds.            | 48.6          | 1.523           | 64                            | 55-70 | 9                  |
| G.315           | ca. 300 yds.          | 47.3          | 1.522           | 59                            | 55-67 | 7                  |
| G.317           | 70 yds.               | 46.3          | 1.522           | 62                            | 60-63 | 6                  |
| G.396           | 9"                    | 54.2          | 1.521           | 47                            | 38-53 | 8                  |
| G.398a          | 18"                   | 52.7          | 1.521           | 49                            | 44-55 | 8                  |
| G.407           | ca. 120 yds.          | —             | —               | 53                            | 37-64 | 6                  |
| 79085           | 50 yards              | —             | —               | 53                            | 48-57 | 8                  |
| 79086           | at contact.           | —             | —               | 58                            | 49-68 | 4                  |
| 79087           | 2 yds.                | —             | —               | 53                            | 48-57 | 10                 |
| 79090           | 15 yds.               | —             | —               | 53                            | 45-56 | 6                  |
| 79091           | 60 yds.               | —             | —               | 53                            | 39-61 | 10                 |
| 79092           | 1'-2'                 | —             | —               | 57                            | 48-63 | 5                  |
| 79094           | 350 yds.              | —             | —               | 56                            | 45-60 | 9                  |
| 79099           | 220 yds.              | —             | —               | 60                            | 54-66 | 9                  |
| 79102           | 80 yds.               | —             | —               | 59                            | 44-65 | 6                  |
| 79105           | ?                     | —             | —               | 54                            | 46-62 | 7                  |

\* Distances over 5 yds. are estimated.

† Wt. per cent or./total feldspar.



discredit this possibility, for gravimetric measurements of CaO, SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> made by Dr. E. A. Vincent along with photometric estimation of the alkalis yielded a calculated content of feldspar close to 100%. The cause of the turbidity is also uncertain for the data for G106 would indicate that loss of alkalis was not the reason and that some other factor, perhaps an iron-bearing impurity, was the culprit. It is worth noting that many past analyses have recorded a deficiency of calculated feldspar that has been ascribed to solid solution with silica. The present data should not be used to support this idea.

The  $\alpha$  refractive index (Table 3) was measured on a number of grains using a single-variation (temperature) method. Little spread was observed about the mean value of 1.521 (Na light). Measurement of the optic axial angles was carried out on a five-axis Universal stage employing the extinction method for thin sections and the conoscopic method for separated grains. Measurements were made only when both optic axes were accessible. As the turbid character of the feldspars rendered difficult the determinations on grains, thin sections were much the more satisfactory, particularly as variation within single crystals could be detected and correlated with morphological features. An accuracy of about 2° was obtained in the values listed in Table 3.

From the separated phenocrysts about forty fragments were selected and thirty of these gave good x-ray oscillation photographs (details of techniques given in paper II of this series, Smith and MacKenzie, 1955). Values of  $\alpha^*$  and  $\gamma^*$  were determined for the triclinic sodium-rich components and plotted on Fig. 3. There is no point in giving a detailed account of each specimen for the structural states found in these 30 specimens are so varied that only a much larger number would have any statistical significance. It is sufficient to list the type and nature of the different assemblages in the following table:

|                               |   |   |   |    |   |   |
|-------------------------------|---|---|---|----|---|---|
| Monoclinic potassium feldspar | x | x | x | x  | x | x |
| Triclinic potassium feldspar  |   |   |   |    |   | x |
| Sodium-rich sanidine          | x |   | x |    |   |   |
| Anorthoclase                  |   | x |   | x  |   |   |
| Albite-oligoclase             |   |   | x | x  | x | x |
| Number of crystals            | 1 | 2 | 3 | 17 | 5 | 2 |

Some typical photographs are shown in Figs. 8–12 and described in the final section.

#### *The Alkali Feldspars of the Porphyritic Felsite*

The composition of the alkali feldspar phenocrysts ranges from Or<sub>62</sub> to Or<sub>44.5</sub>. At contacts there is a variation in the composition as is especially well shown in the series G105–109 taken at the contact with the earlier

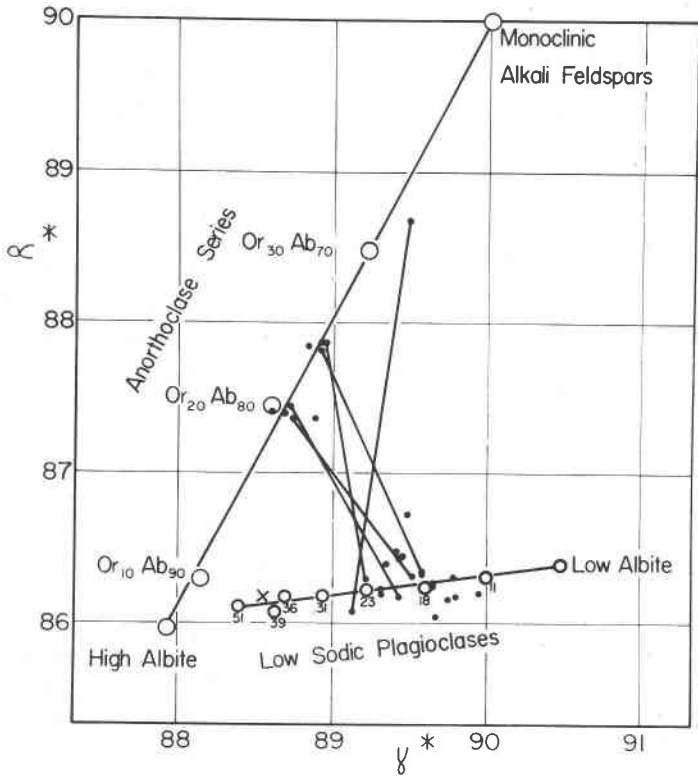


FIG. 3. Values of  $\alpha^*$ ,  $\gamma^*$  determined from sodium-rich components of the alkali feldspars from the felsite and granophyre. Circles give reference values measured for homogeneous feldspars of known composition (see earlier papers in series for source of these data) Dots show values from the Slieve Gullion alkali feldspars. The lines join values obtained for anorthoclase and albite-oligoclase in the same specimen. The duality between anorthite content and structural state should be remembered when the  $\alpha^*$ ,  $\gamma^*$  values of the plagioclase specimens are considered. The indicated An-content is the maximum value and corresponds to a low structural state. Lower An-contents are possible if the structural state is not fully low. However, even if the An-content is zero, which is most unlikely, the structural state cannot be more than half-way towards the extreme high state. Consequently the designation low-temperature is used for the specimens. An uncertainty in the use of  $\alpha^*$ ,  $\gamma^*$  angles as indicators of composition and structural state has recently arisen from the demonstration by Schneider (1957) and other workers at Zürich that crystals become monoclinic at room temperature following prolonged heating just under the melting point. However, it is thought that this work does not affect conclusions reached for natural specimens, for deductions made for a large number of specimens, such as the Slieve Gullion ones, have been very reasonable.

The cross (X) shows values of  $\alpha^*$ ,  $\gamma^*$  determined for an albite-twinned plagioclase crystal. The x-ray photograph also revealed the presence of a very weak monoclinic potassium-rich phase.

agglomerate on the south-west side of the Croslieve. The potash content is highest at the contact falling to a minimum after about three feet, and then rising slightly. A similar but smaller drop in potash content was found at the contact west of Mullaghbawn mountain (G396-G401). The variation could be caused by an early potash-rich phase of the Porphyritic Felsite grading imperceptibly into the normal variety away from the margins. The alkali contents of a number of felsite specimens were determined (Table 2). As might be expected there is a sympathetic variation in alkalis between phenocrysts and host rock with the phenocrysts the more potassic.

TABLE 4. MODAL COMPOSITIONS

|                             | Porphyritic Felsite | Porphyritic Granophyre |
|-----------------------------|---------------------|------------------------|
| Groundmass                  | 68.8                | 72.7                   |
| Phenocrysts                 |                     |                        |
| Quartz                      | 9.1                 | 6.0                    |
| Alkali Feldspar             | 19.7                | 19.4                   |
| Plagioclase                 | 0.5                 | 1.3                    |
| Pyroxene, Olivine Amphibole | 0.9                 | 0.6                    |
| Inclusions                  | 1.0                 | nil                    |

Note: All modal analyses determined on thin sections using a point counter. Felsite is average of 32 specimens, granophyre average of 9. The granophyre specimens are from the chilled marginal parts. In the center differentiation between true phenocrysts and groundmass is rendered difficult by the general coarse crystallization.

A considerable range of optic axial angles was found from specimen to specimen, crystal to crystal, and in a single crystal. The variation scheme was similar in nearly all the single crystals. In thin section many of the crystals are inhomogeneous; water-clear areas are bordered by turbid feldspar, and spindles and small areas of perthitic plagioclase are common. In perthitic crystals the feldspar immediately adjacent to the plagioclase spindles almost invariably gave the maximum value of  $2V_{\alpha}$  for the crystal. This area commonly was the most turbid although some exceptions occurred. Two examples illustrate the variation:

specimen G108. Perthitic crystal. Major part turbid with  $2V$   $58^{\circ}$ . Small clear area  $2V$   $43^{\circ}$ .

specimen G109. Crystal not visibly perthitic. Turbid part  $2V$   $55^{\circ}$ . Small clear area  $2V$   $44^{\circ}$ .

A small number of crystals show zoning with a core of lower optic axial angle, presumably attributable to compositional variation, (c.f. Muir and Smith, 1956). The variation from crystal to crystal in the same hand

specimen appears to be caused by effects similar to those producing the variation within single crystals, for clouded crystals generally give higher values of  $2V$  than clear ones. This was especially noticeable in the marginal specimens. The average values of  $2V$  for marginal and internal specimens are not sufficiently different to have statistical significance although the average of the marginal values is actually lower in accordance with expectation.

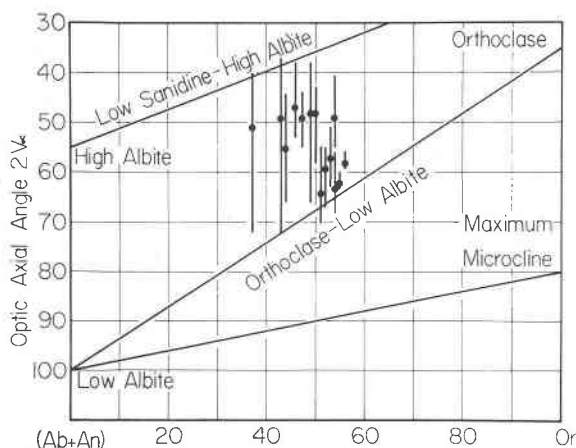


FIG. 4. The relationship between the bulk chemical composition and the optic axial angle,  $2V_{\alpha}$ , of the Slieve Gullion alkali feldspars. The length of the line shows the measured variation for each specimen and the dot gives the average. The nomenclature and position of the lines for the various series of feldspars has been slightly modified from Tuttle (1952).

The combination of the chemical, optical and  $x$ -ray data shows that the alkali feldspars lie between the low sanidine-anorthoclase and orthoclase-low albite series as defined by Tuttle (1952). The spread of optical properties (Fig. 4) is very similar to that found in the Tertiary granite of Beinn an Dubhaich, Isle of Skye by Tuttle and Keith (1954).

#### *The Porphyritic Granophyre*

Study of the granophyre has been less detailed and at present there are no chemical data for the separated alkali feldspars. The optical properties of the feldspar phenocrysts were very similar to those of the felsite. Where the groundmass alkali feldspar was sufficiently coarse grained to permit determination, the optic axial angle was generally larger than in the associated phenocrysts (*e.g.* 79086; phenocrysts  $2V_{\alpha}$   $46^{\circ}$ ,  $47^{\circ}$ ,  $55^{\circ}$ ; groundmass  $55^{\circ}$ ,  $55^{\circ}$ ,  $56^{\circ}$ ,  $62^{\circ}$ .) While many of the feldspars

in the granophyre are not strongly perthitic, the development of coarse perthite is much more common than in the feldspars of the felsite.

The aggregated, or glomero-porphyritic habit of the phenocrysts is common, especially among the feldspars. Within an aggregate the individual crystals develop good crystal faces where they adjoin the groundmass but against each other the outlines are irregular and rounded (Fig. 5). The optical break between crystals may be accentuated by a line of quartz blebs. The individual crystals often contain

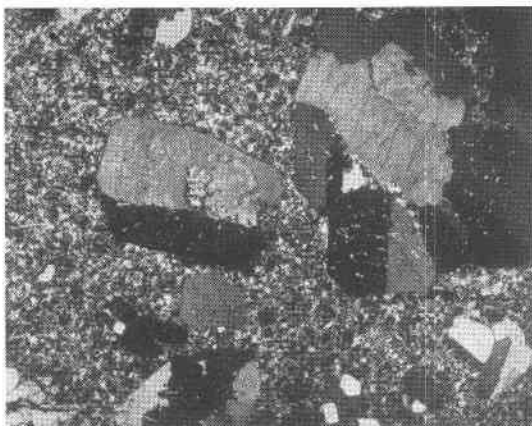


FIG. 5. Photomicrograph of porphyritic granophyre showing the aggregated habit of alkali feldspar phenocrysts. Note the irregular boundaries within the aggregate and the well developed crystal faces towards the granophyric matrix. Specimen G76, crossed nicols,  $\times 3$ .

inclusions of quartz and groundmass, both with cusped outline. Rather rare crystals contain such a high proportion of included material that they resemble sieve-textured plagioclases described from acid rocks in the Central Layered Complex of Slieve Gullion (Reynolds, 1950, fig. 7). Part of the apparently included material probably represents groundmass crystallization within a sieved and "corroded" crystal. In a number of the alkali feldspar aggregates, a rim of alkali feldspar or plagioclase, often in optical continuity, separates the aggregated crystals from the groundmass (Fig. 6a,b). A few aggregates of plagioclase of similar properties are also found (Fig. 6b) but in none of these is quartz found in any significant quantity. The quartz that does occur in these aggregates is almost wholly confined to small bleblike or cusped inclusions within the feldspar or along their mutual boundaries. Only one example (G347) was found of an aggregate of equal quantities of quartz or feldspar and one (G374) of alkali feldspar and fayalite. In one specimen, 79105,

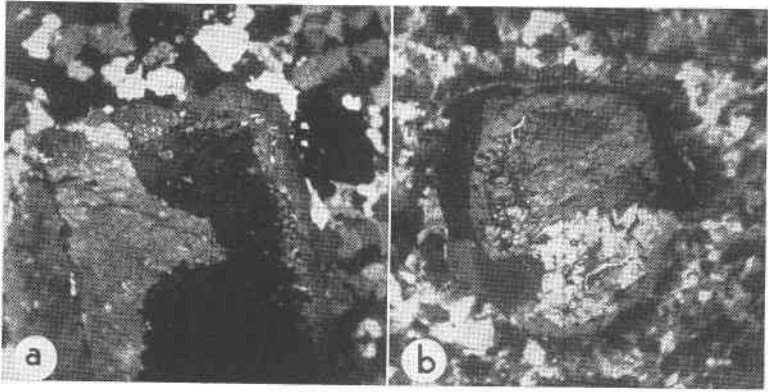


FIG. 6. Photomicrographs of porphyritic granophyre. (a) Aggregated alkali feldspar phenocrysts with a rim of plagioclase between core and groundmass. Specimen G62, crossed nicols,  $\times 8$ . (b) Aggregated plagioclase phenocrysts with a rim of alkali feldspar between aggregate and groundmass. Specimen G74, crossed nicols,  $\times 8$ .

aggregates of plagioclase, hornblende, mica and a little alkali feldspar occur, which are almost certainly fragments of Newry Granodiorite.

#### *Discussion*

From the respective settings of the two intrusions in the composite ring dyke, it is possible to obtain a probable explanation of the mode of emplacement and the reasons for the marked textural differences between the felsite and granophyre. The close spatial association between the felsite and agglomerate was noted by Nolan in 1877, and a close connection in time was advocated by Richey (1928) who considered that gases responsible for the formation of the agglomerate were derived from the acid magma which then consolidated to give the Porphyritic Felsite. This suggestion is accepted, but with the reservation that the the gases largely escaped before the magma was intruded into the present level. The Porphyritic Granophyre, the later intrusion, is regarded as having consolidated in the presence of its own volatiles. Hughes (1956) has come to a similar conclusion for the felsite and granophyre of South East Rhum, and regards the two as originating from a common magma.

The detailed sequence of events is thought to begin with an initial rise of acid magma into the lower parts of the ring fracture, followed by a period of crystallization. Central, acentric subsidence of the country rock within the ring fracture allowed the partially crystalline magma to advance to higher levels in the south-western part of the complex, the rate of crystallization increasing. After crystallization of about one-third of the magma, the vapor pressure proved too great for the covering rocks

and the roof shattered to form the agglomerate. The rapid escape of volatiles caused the fragmentation of some of the early-formed crystals. Subsequent rise of the acid magma into the higher parts of the ring fracture led to a rapid chilling in the marginal parts without noticeable thermal effects on the country rocks. The high viscosity caused considerable heterogeneity within the felsite with segregations of volatile-rich material trapped within volatile-poor parts producing a drusy structure with the cavities lying in the direction of the flow.

After the emplacement of the felsite a further subsidence occurred, this time acentric to the southeast, allowing acid magma to rise around three-quarters of the circumference. This time the volatiles did not escape, as is attested by the abundance of amphibole and the numerous small drusy cavities, leading to the relatively coarse microgranitic and granophyric textures of the groundmass, and replacement of pyroxene and olivine by amphibole. The alteration of the country rocks was marked, the granodiorite being baked and some of the crush rocks converted into fine-grained biotite-quartz-plagioclase hornfelses.

The formation of the aggregated phenocrysts, which comprise one-third of the rock, is a matter for speculation. If they are true phenocrysts, some mechanism must have caused them to aggregate together, followed by further crystallization both inside and outside the aggregate. Alternatively they could consist of fragments of pre-existing acid rocks of granitic composition. Although fragments of Newry granodiorite can be recognized clearly, and some of the phenocrysts resemble the altered granodiorite crystals in part of Slieve Gullion, the Newry Granodiorite would not seem to be a suitable source for the bulk of the aggregates, because a very large metasomatic transformation of plagioclase ( $An_{20}$ ) into alkali feldspar would be needed. Furthermore, there is a fundamental difficulty in deriving the aggregates from any holocrystalline granite parent. The aggregates strongly tend to be mono-mineralic instead of having "granitic" texture: also fayalite and hedenbergite are found only occasionally in granodioritic rocks. As the phenocrysts of the aggregates have compositions which would be expected to be in equilibrium with a melt of granitic composition, and because the phenocrysts of the felsite and granophyre are very similar in properties it is regarded as highly probable that the majority are true phenocrysts. The aggregation may have been the result of eddy currents produced around the phenocrysts by movement of the magma, causing the crystals to come together like bubbles on a water surface.

The nature of the alkali feldspar formed the second main interest of the investigation. Initially, it was hoped that it would be possible to show that the thicker the ring-dyke, the more the feldspar would have pro-

gressed to the low-temperature structural state. This would be the obvious result if the state of the feldspar was governed solely by the cooling rate of the rock. However, it soon became clear that this was apparently not more than a small factor for the correlation between the structural properties, as measured by the optic axial angle, and the local thickness of the ring-dyke was rather small, certainly near the border line of having any significance at all.

Examination of Fig. 4 shows that there is a wide variation of properties in each hand specimen, closely comparable to that found by Tuttle and Keith (1954) in the Beinn an Dubhaich granite. The majority of the optic axial angles fall between the sanidine and orthoclase series but a few lie just the other side of the orthoclase series in the area occupied by the microcline series. The single-crystal  $x$ -ray study of the phenocrysts shows a wide variation of properties as described earlier, but with the majority of crystals containing albite-oligoclase, anorthoclase and a K-phase. The extreme specimens are three which contain no low-temperature plagioclase, and two which contain microcline in association with monoclinic potassium feldspar (orthoclase) and low-temperature plagioclase. Both of the microcline-bearing rocks are Porphyritic Granophyre (specimen 79105 and 79102). Occurrence of microcline in these hypabyssal rocks is remarkable, for microcline is regarded as the low-temperature form of potassium feldspar by most observers (but see Ferguson, Traill and Taylor, 1958, and later discussion by MacKenzie and Smith, 1959) and has not previously been recorded in hypabyssal rocks. Indeed many recent granites contain only orthoclase as will be shown in later papers of this series.

The reactions which have led to the present assemblages of alkali feldspars are thought to be as follows. Phenocrysts in the true sense grew to a large size while the magma was at considerable depths. Upon movement to higher levels the temperature would begin to fall and crystallization become more rapid. After consolidation of the rock, cooling continued and the feldspar began a structural readjustment to the states stable at the lower temperatures. The extent of this readjustment would depend on three main factors: the cooling rate, the local content of volatiles and the chemical composition. It is thought likely that the most important factor may well have been the local content of volatiles thus explaining the great variability of the structural states in a single hand specimen and the poor correlation between the mean optic axial angle and the cooling rate inferred from the local width of the ring dyke. The rare crystals now occurring as two sanidines would probably have occurred in a drier portion of the rock. Those occurring in the wetter portion would have proceeded further, passing into the stage where the



sodium-rich sanidine was partially inverted into a low-temperature albite-oligoclase. (For a detailed account of the reaction sequence and the probable temperatures see Smith and Muir (1958)). It is thought to be extremely unlikely that the rare microcline-bearing specimens are the product of unmixing and inversion of an original single-phase sanidine. The Newry granodiorite contains microcline as is shown in Fig. 7, and small xenoliths of the granodiorite can be definitely identified in the felsite and granophyre. The microcline-bearing phenocrysts therefore could reasonably be regarded as being xenocrysts and not true

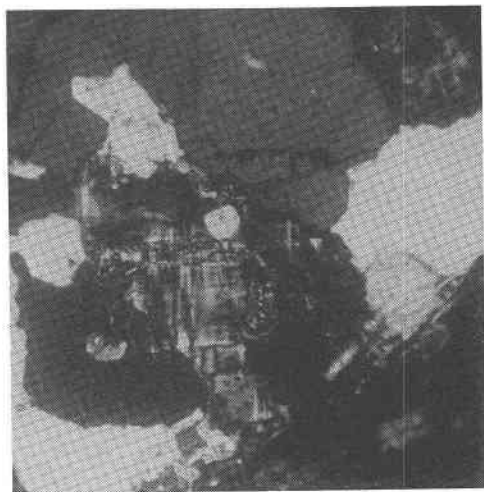


FIG. 7. Photomicrograph of Caledonian Newry Granodiorite showing the familiar cross-hatched twinning of microcline. Specimen G 171, crossed nicols,  $\times 4$ .

phenocrysts and their reaction scheme would be the following: some of the xenoliths caught up in the intrusion of the magma would be disrupted so that separate crystals were produced. The resistance of microcline to conversion into high-sanidine by heating is strong, for prolonged heating at temperatures of about  $1050^{\circ}\text{C}$  in the dry state and not less than  $500^{\circ}\text{C}$  in the presence of high-pressure water (Goldsmith and Laves, 1954) is needed. Thus it seems reasonable to suppose that the microcline would remain essentially unchanged during the short period required for the intrusion. During the period of cooling it would remain in much the same state, possibly undergoing some further slight unmixing. An alternative mode of formation of the microcline is based on the experimental work on ionic exchange in alkali feldspars. According to Laves (1951), Wyart and Sabatier (1956), Hafner and Laves (1957), microcline

can be produced from low-albite by exchange of the sodium and potassium ions. Laves produced microcline by heating a specimen of albite in contact with a glass of potassium feldspar composition. Wyart and Sabatier used fused potassium chloride as the source of the potassium. Thus it would not be inconceivable that microcline could be produced from plagioclase in rocks by a process of potassium metasomatism. Possibly then, the microcline in the Slieve Gullion rocks has been produced by a metasomatic process from a true phenocryst following an earlier inversion from a sodium-rich sanidine to a low-temperature albite-oligoclase. Alternatively a xenocryst of plagioclase might have undergone ionic exchange. Of the three origins for the microcline, the xenocrystal origin without ionic exchange is thought to be much the more likely. Thus the sanidine and orthoclase-perthites are regarded as the truly characteristic alkali feldspars of these hypabyssal rocks and are considered to represent the type of feldspars to be found in conditions lying between the very rapidly-cooled volcanic and the slowly-cooled granitic rocks.

#### DETAILS OF THE X-RAY PHOTOGRAPHS

In order not to break up the main discussion of the paper technical details concerning the x-ray data are given here. Figure 8 is a typical photograph showing a monoclinic potassium phase and two sodium phases, dominant anorthoclase occurring as pericline superstructure and weak albite twinned albite-oligoclase. The reflections from the anorthoclase occur in two closely-spaced clusters which may be merged in the reproduction. Figure 9 shows a different type in which one monoclinic potassium phase and three sodium phases occur. One of the sodium phases is pericline twinned anorthoclase. The other two are both albite-twinned, one being anorthoclase and the other albite-oligoclase. That there are two albite-twinned phases is most clearly seen in the group of reflections for the  $40\bar{5}$  planes, shown at the right of the enlarged portion. The outer reflections of the five that lie on the row line come from the albite-twinned albite-oligoclase, the central reflection from pericline-twinned anorthoclase, and the other two from albite-twinned anorthoclase. The other reflection of the group comes from the K-phase. On the left-hand side of the main photograph, the reflections for the two albite-twinned components overlap, giving the impression that only one albite-twinned phase occurs. Fig. 10 is a photograph of a perfect example of albite twin-type superstructure. The distinction between this photograph and Fig. 9 is obvious: but when superstructure is poorly developed or when reflections from twins are distorted for some reason or another, it may be appreciated that distinction is not so easy and may be impracticable. In fact, a certain identification was not possible

for one or two specimens from this and other rock areas. Two details are illustrated in the enlargements. In insert one, the wing shape of two of the clusters is well illustrated. In the other the occurrence of satellite reflections about the potassium-phase reflections and the presence of streaks connecting the reflections from the two phases is shown. Figure 11 shows a monoclinic potassium phase together with anorthoclase occur-

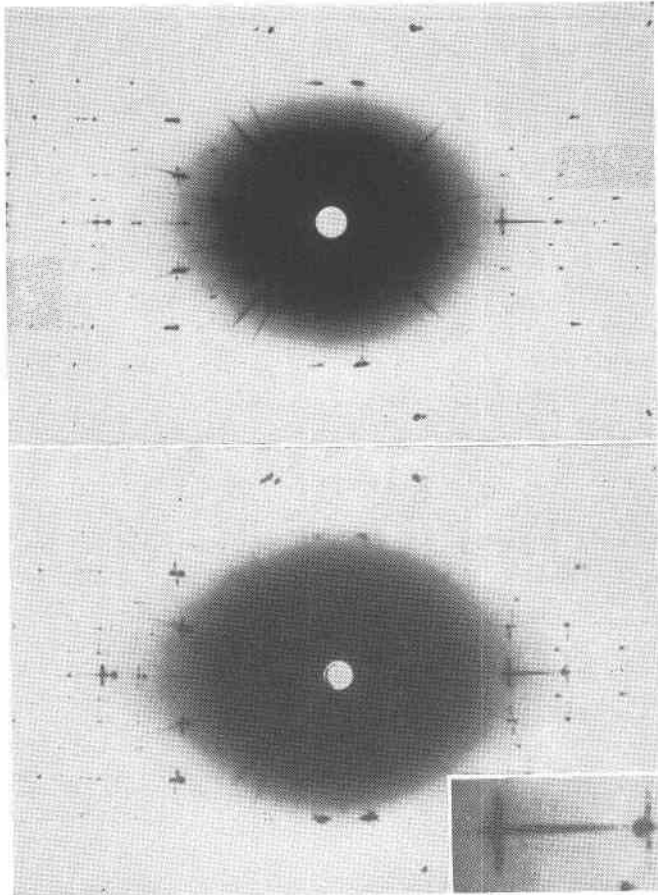


FIG. 8 (above). Oscillation photograph of monoclinic K phase-anorthoclase-albite/oligo-clase perthite taken about  $b$ -axis in standard orientation (Smith and MacKenzie, 1955). See text for detailed explanation.

FIG. 9 (below). Oscillation photograph in standard orientation of a perthite composed of a monoclinic K-phase and two Na-phases showing albite type superstructure. A portion of the photograph that contains the reflection  $40\bar{5}$  has been enlarged and shown in the bottom right hand corner. See text for detailed explanation.

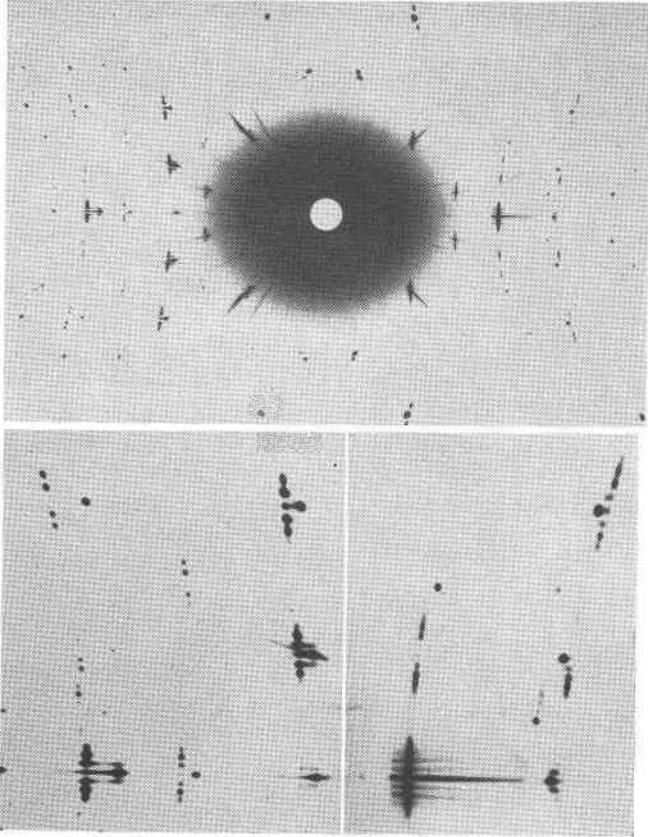


FIG. 10. Oscillation photograph in standard orientation of a perthite composed of a monoclinic K-phase and an Na-phase showing perfectly developed albite-twin type superstructure. Two portions of the photograph have been enlarged and shown below the main photograph. See text for detailed explanation.

ring both in albite and pericline orientations. As there are no sharp doublets characteristic of twinning, this type is best classified as both albite and pericline superstructure. If the ends of the streaks are imagined to correspond to reflections from twin-components, the  $\alpha^*$ ,  $\gamma^*$  angles measured from them correspond to anorthoclase. A streak connects the potassium-phase reflection to the cluster of sodium phase reflections as is most clearly seen for reflection 442. In Fig. 12, the reflections for the potassium phase show a strong sharp center lying in a weak diffuse streak elongated nearly along the row lines. The sodium phase gives reflections composed of two streaks with maxima lying near to the positions for albite and pericline twinning. Measurements of  $\alpha^*$ ,  $\gamma^*$  for the

sodium phase show that it is an albite-oligoclase from which it may be deduced that most of the potassium phase is orthoclase. The diffuse streaks of the potassium-phase reflections reveal the presence of a little intermediate microcline, which is almost in the orientation for albite twinning. The occurrence of streaking between the albite and pericline twinned components of sodium phases is very common and often the maxima on the streaks do not correspond exactly to those to be expected

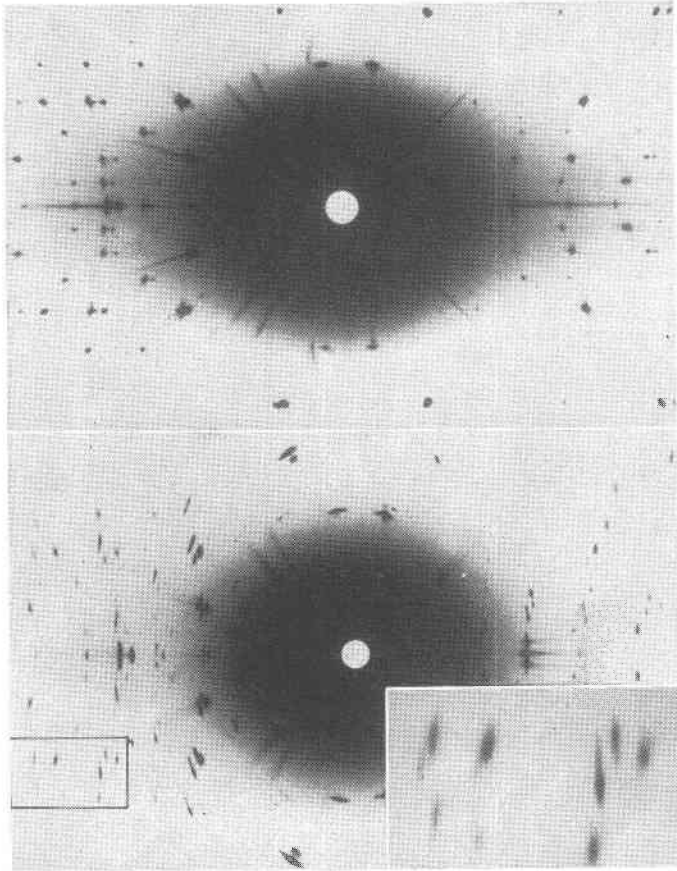


FIG. 11 (above). Oscillation photograph in standard orientation of a perthite composed of a monoclinic K-phase and of anorthoclase showing reflections that lie on both layer lines and row lines. See text for detailed explanation.

FIG. 12 (below). Oscillation photograph in standard orientation of a perthite composed of both a monoclinic and a triclinic K-phase and of a sodium-rich plagioclase both albite and pericline twinned. The inset is an enlargement of the area outlined in the main photograph. See text for detailed explanation of the photograph.

for a strict obedience of the albite and pericline laws. Intermediate positions of the streaks correspond to the "diagonal association" (see paper V of this series, Smith and MacKenzie, 1959, for a stereographic projection showing the angular relations).

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