PRELIMINARY OBSERVATIONS ON THE FELDSPARS FROM THE PILANESBERG ALKALINE COMPLEX, TRANSVAAL, SOUTH AFRICA

By

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Microcline and plagioclase from a suite of alkaline rocks are described. The evidence obtained from obliquity and $2V$ values, and the feldspar association point towards metastable crystallisation of orthoclase below ca. 500 °C, in some rocks, and subsequent inversion to microcline. The presence of cryptoperthite in other rocks suggests formation of orthoclase under stable conditions. The inversion (ordering) process is thought to have been accompanied by exsolution of excess Fe_2O_3 in the form of aegirine microlites. Microcline contains about 3–8 wt. % Ab dissolved. A variety of feldspar textures are also described.

Description

The Pilanesberg Complex was first described by Molengraaff in 1905. Following the discovery of these nepheline-bearing rocks, Brouwer described them petrographically in his work on the Transvaal nepheline syenites (1910), and the area was mapped by Humphrey in 1911. In order to resolve the lack of correlation between the observations of earlier workers, in 1923 Shand decided to remap the Complex and his work on the area was published in 1928.

From May to September of 1960 the present author remapped about 120 square miles (310 sq.km.) in the southern and north-eastern parts of the Complex. At present the collected material is being investigated petrologically and mineralogically at the Department of Geology and Mineralogy, Oxford.

A study of the feldspars provides information which is invaluable

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Table 1. Geological Section of the Pilanesberg Alkaline Complex.

Main rock type	Approximate mineral composition
Intrusive	
Syenitic dykes	Not investigated
Alkali granite (?) *	Anorthoclase, plagioclase, quartz, riebeckite, ore and sphene
Ledig foyaite	
Green foyaite and lujaurite	Variable for a given rock type; mainly alkali feldspar, pyroxene of the aegirine-augite series, nepheline; with
Tinguaite	or without any of the following:
White foyaite	sodic amphibole, biotite, sodalite,
Microfoyaite (?)	fluorite, analcite, cancrinite and ac-
Nepheline-feldspar porphyry (?)	cessories
Red foyaite	Alkali feldspar and liebnerite with or without biotite or nepheline
Syenite	Alkali feldspar, pyroxene of the aegirine-augite series, biotite, calcite with or without cancrinite, zeolite and accessories
Extrusive	
Lavas, tuffs, porphyries and breccias	Not investigated

* Data from Cloete (1957, pp. 7–16).
(?) Denotes uncertainty of relative age.

for an understanding of the conditions of crystallisation of the rocks, and also for possible relationships between different varieties.

The main rock types which occur in the Complex are listed in Table 1 in chronological order. Under the name white foyaite is included a diversity of rocks which differ mineralogically as well as texturally from each other. Chilled and pegmatitic phases of the main rock types are invariably present. Karroo dolerite, which occurs as intrusive sills in the Complex, is not listed in the Table.

The investigated feldspars were obtained in the pure state by handpicking phenocrysts or coarse crystals from a number of selected rock specimens. This method excludes small grains of feldpar which may occur in the groundmass, intergrown with other minerals. Several

large phenocrysts ranging in size from ca. 10 mm. to 100 mm. have also been studied. These large crystals occur sporadically in most rocks in the Pilanesberg. Descriptions of the rock types from which the feldspars were separated are given in Table 2.

X-*ray investigation*: Filtered Cu radiation was used to study smear mounts of powdered feldspar specimens. Obliquity values (Table 2) were determined on a Phillips high-angle diffractometer.

The term "obliquity" (Δ) is defined as the angular difference between 131 and 1$\bar{3}$1, and this is assumed to depend on the Al/Si distribution.

The obliquity of microcline was determined by measuring the distance between the 131 and 1$\bar{3}$1 reflections. In most cases it could be decided, from a study of the diffractometer pattern in the 29° to 31° and 20.5° to 24.5° 2θ regions, whether the specimen showed any gradation in obliquity (MacKenzie (1954) p. 362). Microcline shows a complete range of structural states, ranging from nearly monoclinic to almost maximum microcline. This Δ-range is very common in the porphyries (nos.32–41) as well as in "normal" red foyaite (nos. 42 and 43) and chilled phases of other rocks.

Optical properties: Due to the absence or poor development of (010) cleavage in microcline in thin sections, extinction angles have been determined on only a few of the investigated feldspars. The values for $\perp(010)/\gamma$ and $\perp(001)/\beta$ range from 1.5°–18° and 4°–11°, respectively. However, it has been possible to measure optic axial angles on most microcline grains. The determination of $2V$ is affected by the fine microperthitic character of some feldspars as well as the very finely-developed grid-twinning in certain microclines. Both these factors may tend to increase the $2V$ of the "crystal". A range in $2V\alpha$ from 50°–87° was measured on the investigated feldspars (Table 2). Microcline from a particular rock may give either a series of values or two definite readings.

Habit: Tilley (1956, p. 407) attached considerable importance to the habit of microcline in the green foyaite, and he pointed out that the phenocrysts are flattened on {010}, which is the characteristic form of sanidine. In 1961 (p. 69) he noted that microcline in nepheline syenite dykes from the Vredefort area have a similar habit. The development of grid-twinning, together with the habit of the feldspar, led him to

Table 2. Obliquity and $2V$ data of microcline in alkali rocks from the Pilanesberg Complex.

No. of spec.	Collection no.: EAR	Type of Rock	Obliquity (Δ)	$2V\alpha$
		Ledig foyaite		
1	340	"normal" †	0–0.64	77
		Green foyaite		
2	281	chilled	0–0.63	54–77
3	304	dyke rock	0–0.71	52–62
4	312	"normal" LP	0–?	53/77 *
5	317	dyke rock	0.86	81
6	471	chilled	0–0.74	53–68
7	611 b	"normal" LP	0.96	77–83
8	657	pegmatitic	0–0.75	—
9	699 c	pegmatitic	0.97	75–78
10	709	"normal" LP	0.98	83–86
11	813	"normal"	0.91	78
12	829	"normal" LP	0.89	81
		Tinguaite		
13	271	"average"	0.88	—
14	296	"average"	0	—
15	326	"average"	0–0.61	52–78
16	550	"average"	0.96	75
		White foyaite		
17	308	pegmatitic	0.93	71–74
18	342	"normal"	0.88	75
19	355	chilled	0–0.85	82–86
20	377 a	"normal"	0.86	—
21	419	chilled	0.90	76–81
22	424	pegmatitic	0.85	72–77
23	428	chilled	0.88	60–72
24	479	"normal"	0–0.74	53/70
25	546	poikilitic	0.90	78
26	660	pegmatitic	0.78	—
27	661	"normal"	0–0.86	87
28	692	"normal" LP	0.96	78–81
29	722	"normal"	0.88	64–84
30	755	pegmatitic	0–0.25	50/79
31	779	"normal"	0–0.75	56/84
32	785	"normal"	0–0.69	53–66
33	853	poikilitic	0–0.90	52/72

Table 2 (*continued*).

No. of spec.	Collection no.: EAR	Type of Rock	Obliquity (Δ)	$2V\alpha$
		Porphyry		
34	298	chilled	0.84	—
35	299	chilled	0–0.80	68–78
36	496	"normal"	0–0.60	59/79–82
37	531	"normal"	0–0.65	63–69
38	727	chilled	0–0.83	55–64
39	733	"normal"	0.83	—
40	735	"normal"	0.68	70–75
41	736	"normal"	0–0.69	52–56/70
42	798	chilled	0–0.64	—
43	1044	chilled	0–0.64	55
		Red foyaite		
44	252	"normal"	0–0.76	52/72
45	638	"normal"	0–0.84	50/67
46	651	pegmatitic	0.88	—
47	754	pegmatitic	0.84	—
		Syenite		
48	425	"normal"	0.89	78–82
49	783	"normal"	0.89	77
50	793	"normal"	0.90	—
51	835	"normal"	0.88	70–74
52	983	"normal"	0.90	—

†: The term "normal" is used to designate a medium to coarse grained rock with a wide-spread occurrence, which can be regarded as representative of a particular type.

*: If two definite values for $2V$ have been measured for microcline in a specimen, the readings are thus indicated.

LP: Large phenocryst.

the conclusion that the phenocrysts crystallised originally as sanidine and have since inverted to microcline.

In all the Pilanesberg rocks, microcline from the green foyaites and the porphyries shows the best development of a sanidine habit. This characteristic of the crystals renders the parallel orientation on insets very conspicuous. Some phenocrysts consist of nearly pure potash feldspar, but small quantities of microperthitic plagioclase are often present. The other rocks are essentially non-porphyritic and the tabular habit of the feldspar is less conspicuous.

Plagioclase occurs as individual laths or as antiperthitic and microperthitic intergrowths with microcline.

Twinning: Microcline crystals which are flattened on {010} are twinned after the Carlsbad law. The development of this type of twin is rather restricted in perthitic or antiperthitic intergrowths. Examples of Baveno and Manebach twins are also found.

It has been found that the pole of the Carlsbad composition plane coincides with the Z axes of both components, of the majority of twinned "crystals" measured. Since some of the morphological units of potash feldspar undoubtedly consist of triclinic phases, it is clear that the composition plane cannot be parallel to (010) of microcline, but coincides with another plane, the indices of which have not been determined. This plane probably represents the (010) of the original monoclinic crystal.

Several examples of multiple twinning after the Carlsbad law have been observed amongst the phenocrysts from the porphyries. A twinned "crystal" in specimen 36 consists of six components related to each other according to this law. Oftedahl (1948, pp. 38–9) observed similar features of multiple twinning after the Carlsbad law in feldspar from syenite in the Oslo region.

Microcline nearly always shows irregularly developed albite-pericline grid-twinning. The size and relative amounts of the domains may vary greatly in the same morphological unit (see Figure 1).

Plagioclase is mostly twinned on the Albite Law, but parallel and complex twins have also been observed.

Composition: The position of the $20\bar{1}$ reflection was used in order to obtain an estimate of the composition of microcline. Several authors (Bowen and Tuttle, Tuttle and Bowen and Orville) have produced curves for this method, which were determined for high-temperature synthetic feldspars. Koritnig (1961, p. 665), however, provides curves for the microcline-low-albite and sanidine-high-albite series. A copy of Goldsmith and Laves' paper (1961, pp. 81–96) came to hand, unfortunately, too late for their method to be used.

Shand (1928, pp. 132–3) analysed a large phenocryst of microcline from the green foyaite, and Tilley (1956, pp. 407–9) presents a complete analysis of microcline separated from the same type of rock. These results, together with the albite content of the investigated specimens,

Table 3. Composition of microcline in Pilanesberg Rocks as determined by X-ray and chemical methods.

Spec.[1] no.	$2\theta_{20\bar{1}}$ CuK_{χ}[2]	Wt.% $NaAlSi_3O_8$ [3]		
		I	II	III
53	20.973	3.5	4.4	3.5
54	20.989	5.0	6.1	5.2
4	20.987	5.0	6.0	5.0
5	20.979	4.0	5.3	4.0
7	20.983	4.5	5.7	4.5
10	20.987	5.0	6.0	5.0
11	20.990	5.5	6.3	5.5
55	20.985	5.0	5.7	4.7
56	20.990	5.5	6.6	5.5
23	20.997	6.3	6.8	6.5
24	20.988	5.0	6.0	5.0
28	21.012	7.5	7.7	8.0
33	21.006	7.5	7.7	7.5
37	20.997	6.3	6.8	6.5
39	20.983	4.5	5.7	4.5
41	20.998	6.5	6.8	6.5
43	20.988	5.0	6.0	5.0
57	21.008	7.5	7.7	7.6
44	20.984	4.6	5.7	4.7
58	21.010	7.5	7.7	7.6

A: $Or_{96.1}$ $Ab_{2.2}$ $An_{0.9}$ $Cn_{0.8}$.

B: $Or_{97.2}$ $Ab_{1.6}$ $An_{0.8}$ $Cn_{0.4}$.

NOTE: [1] Specimens: 53 and 54 (EAR 470 and 472)—Ledig foyaite.

4–11; 55 and 56 (EAR 656 and 1040)—green foyaite.

23–28—white foyaite.

33–43; 57 (EAR 901)—porphyries.

44—red foyaite.

58—syenite.

[2] Internal standard used: $KBrO_3$ ($2\theta_{101}$ 20.205° Cu $K\alpha$).

[3] Composition determined with the aid of curves of various workers. An error of ca. ± 0.3% should be allowed for converting 2θ to Ab content.

I: Koritnig (1961)—curve for sanidine-high-albite series.

II: Orville (1958)—curve for high-temperature synthetic alkali feldspars.

III: Tuttle and Bowen (1958)—curve for high-temperature synthetic alkali feldspars.

A: Analysis of large phenocryst in green foyaite (Shand (1928) pp. 132–3).

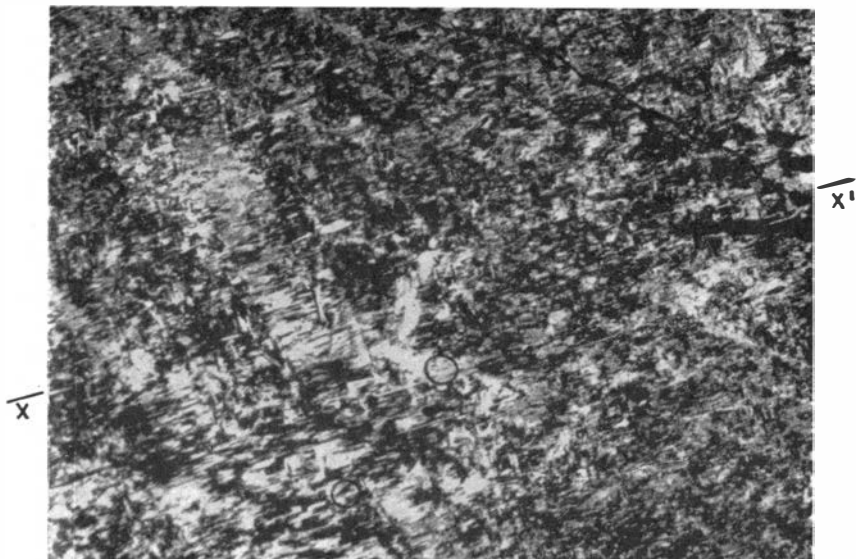B: Analysis of phenocrysts separated from green foyaite (Tilley (1956) pp. 408–9).

Figure 1. Cross-hatched twinning of the albite-pericline type, in microcline. Size and relative amounts of domains are variable. Section $\sim //(001).X - X' -$ trace of (010). Crossed Nicols, magnification $41 \times$. (Large phenocryst in green foyaite: EAR 709; spec. 10).

obtained by means of the $(20\bar{1})$ spacing method, appear in Table 3. It is clear from these data that microcline has very little albite (ca. 3–8 wt.%) in solid solution.

The composition of plagioclase was determined by means of the Rittmann zone method and in some cases the values thus obtained have been checked against $2V$. The extinction angle $\varepsilon(= X'/\langle\rangle(010))$, for plagioclase from most rocks, varies from $-16°$ to $-19°$. A problem arises in deriving from these readings the composition of the feldspar, since the curves for ε vs. An-content vary according to the individual author (e.g. the data of Winchell (1951, p. 262) and Tröger (1959, p. 111)). If the maximum value of $-19°$ is taken into account, the curve of Winchell should be used. The values correspond to 0–ca. 6 mol.% An.

Textures: In general, it can be said that the textural relationships between the feldspars are controlled either by replacement, or exsolution, or both. However, the possibility of albitisation affecting earlier

Figure 2. Primary plagioclase crystal replaced by albite component of an anti-perthite, which also attacks an "antiperthite" unit (upper right). Crossed Nicols magnification 36×. (Syenite: EAR 726).

textures is not excluded. A variety of relationships between microcline and plagioclase is illustrated in Figures 2–6.

Intergrowths that qualify for the description of a true perthite have a very limited development in the Pilanesberg rocks, and occur only in a chilled white foyaite, which outcrops over an area of about 3 square km. on the farm Doornhoek 91 JQ. Two varieties of the texture are illustrated in Figures 5 and 6. Figure 5 shows albite forming stringers in the microcline host as well as a rim around the perthite grain. This type of texture has been described by Tuttle and Bowen (1958, Plate 1, Figure 3). The above stage, where a definite rim of plagioclase is present, has not yet been reached in the texture shown in Figure 6. However, there is a slight tendency towards plagioclase concentrating on the border of some crystals. The exsolution plane makes an angle of 74° with the pole of the (001) cleavage plane, which is the normal crystallographic orientation of exsolved albite (Smith (1961)).

The antiperthitic textures are extremely complicated owing to the
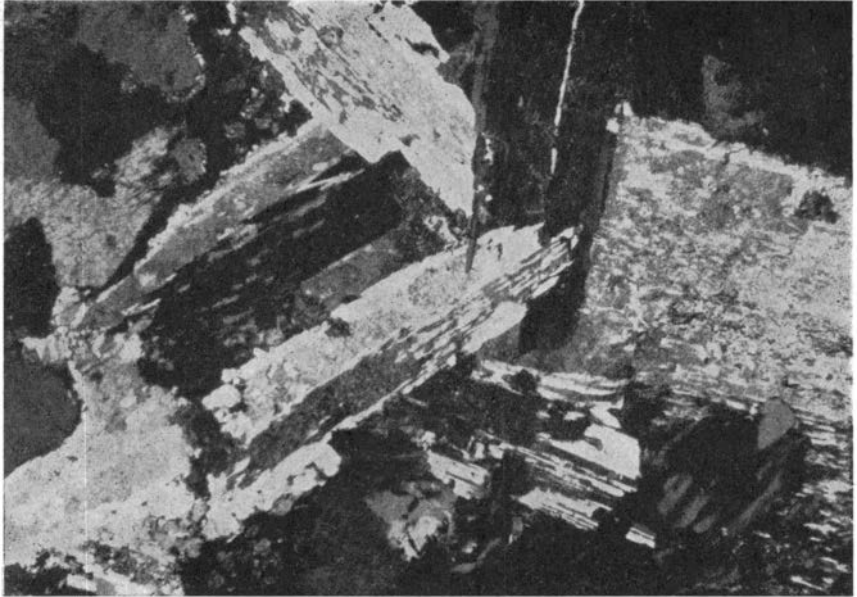
Figure 3. "Antiperthite" formed through replacement of microcline by albite. Solid sheaths of plagioclase surround replaced core of microcline. These units cut across others of the same type (centre). Dark grains (upper right): nepheline. Crossed Nicols, magnification 19×. (White foyaite: EAR 342; spec. 18).

fact that they have been formed through the replacement of microcline by albite, which results in a series of intergrowths ranging from potash feldspar with only isolated specks of soda feldspar to patches of microcline sporadically distributed in an albite host (see Figures 2, 3 and 4). This variety of relationships can be observed in a single thin section; however, textures of an intermediate nature predominate. The intergrowths are commonly flanked or surrounded by broad laths of pure plagioclase which is in optical continuity with the "perthitic" albite (see Figure 3).

The replacing nature of plagioclase practically eliminates all traces of a texture, which is presumed to have resulted through true exsolution, because of the orientation of the lamellae, as can be seen in Figure 4, where a perthitic texture has been partially destroyed.

Microcline is replaced mainly on the (010) plane, but irregular replacement is also observed. The nature of the feldspar textures in the Pilanesberg rocks does not support the theory that a true perthitic
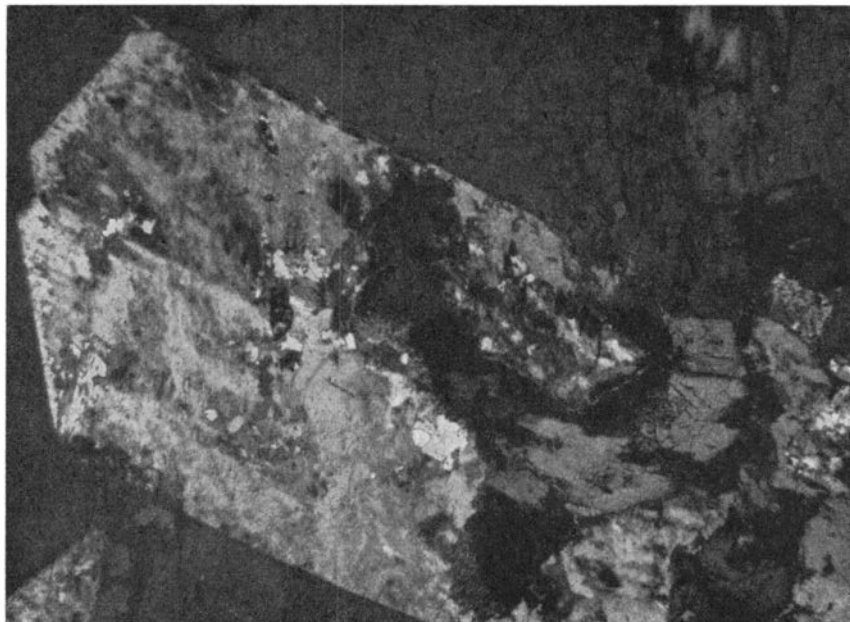
Figure 4. "Crystal" with remnants of "original" perthite, which is replaced by plagioclase (light grey). Another generation of albite (white grains) transects the unit. Other minerals are: nepheline (dark grey, upper and lower grains); sodalite (dark; left) and inclusions of soda amphibole and sphene. Composition plane: (010). Crossed Nicols, magnification 48×. (White foyaite: EAR 722; spec. 29).

relationship can be formed by a replacing mechanism (Emmons *et al.* (1953)).

Resorbed crystals of plagioclase, which seem to be primary, are very common in the syenites (Figure 2). The corroding agents are both components of antiperthite grains, but mostly the soda feldspar phase, and later albite. However, due to the lack of sufficient data, this suggestion should be regarded as only tentative.

Orthoclase-microcline inversion: The occurrence of microcline showing two phases with different $2V$'s within a single "crystal" has been described (for data see Table 2). A very good example of this relationship was found in a large phenocryst from the green foyaite (no. 4) and this type of texture is illustrated in Figures 7 and 8. The diffractometer pattern in the region $29°–31°\ 2\theta$, of specimen 4, shows a broadening at the base of the monoclinic 131 reflection, whereas specimen 3
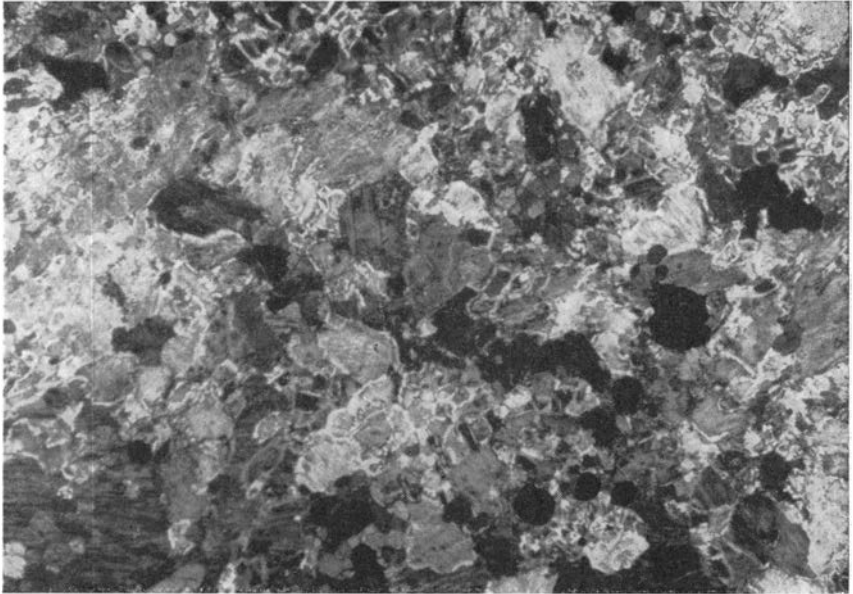
Figure 5. Microcline microperthite in chilled white foyaite. Stringers of albite in the host coalesce into rims round the "unit". Small crystals enveloped by larger units. Nepheline present. Crossed Nicols, magnification $32 \times$. (EAR 355; spec. 19).

gives a trace with a strong monoclinic peak and weaker, but definite triclinic peaks (Figure 9).

In specimen 4 the main part of the crystal consists of a clear homogeneous monoclinic phase ($2V\alpha = 53°$) which has inverted to a triclinic phase ($2V\alpha = 77°$). This phase develops as definite bands parallel to (010) or as feathery streaks in other directions which were not determined. Thin lamellae form in (001) cleavage fractures. The transformation in specimen 3 has taken place mainly $\perp$(010); the triclinic phase also shows irregularly developed twinning, of the albite-pericline type.

The bright, disoriented, short laths between the broad bands of microcline in Figure 7 have a $2V\gamma = 86°$, and presumably represent exsolved plagioclase. The presence of plagioclase in specimen 4 is indicated by a $20\bar{1}$ reflection in the diffractometer pattern (Figure 9c), but this soda phase could not definitely be detected optically. During the preparation of an artificial plane, nearly at right angles to (010) and (001), on a chip from the specimen, a pearly schiller was noticed on the
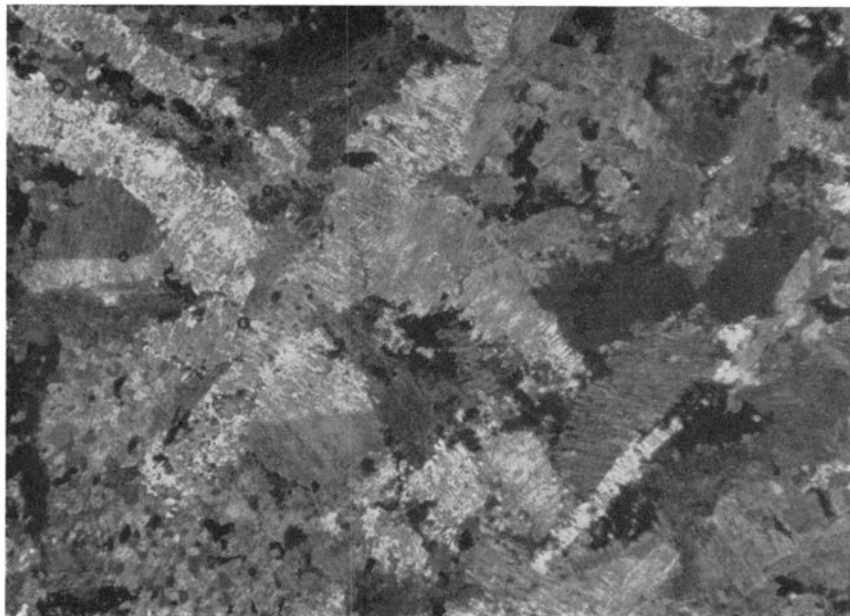
Figure 6. Herringsbone texture formed by twinning of microcline microperthite after the Manebach law. Limited development of albite rims round the perthite crystals. Dark grains: nepheline. Crossed Nicols, magnification 30×. (Chilled white foyaite: EAR 372b).

polished surface of the fragment. Oftedahl (1948, pp. 42–4) took into account the theories put forward by Brøgger (1890) and Spencer (1930) on the origin of labradorization, and came to the conclusion that iridescence in alkali feldspars in the Oslo area is dependent on a crypto-perthitic structure. The finely exsolved plagioclase lamellae are nearly parallel to ($\bar{8}$01). The indices of this plane were determined as ($\bar{6}$01) by Smith (1961).

Another interesting feature in specimen 4 is the association of very fine aegirine (?) microlites with the triclinic phase: the monoclinic host does not contain a single microlite. It seems as if the sanidine holds Fe_2O_3 in solid solution, which is exsolved during the inversion to form aegirine. Microlites of sodic pyroxene occur in practically all microcline crystals showing grid-twinning, and they are usually orientated parallel to (010). Small crystals of aegirine-augite are also enclosed by potash feldspar.
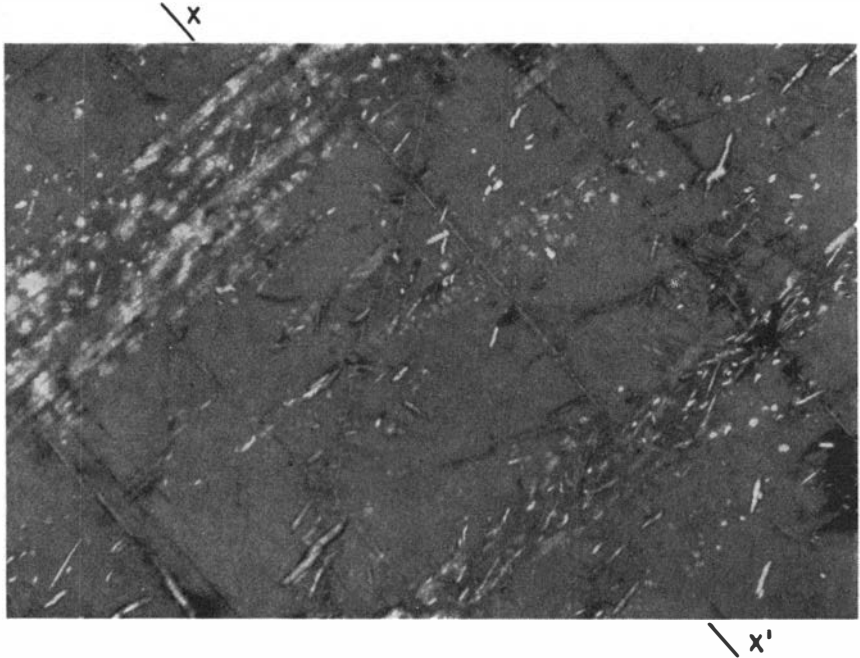
Figure 7. Inversion of orthoclase (host: $2V\alpha = 53°$; $\perp(010)/\gamma = 1°$) to microcline ($2V\alpha = 77°$; $\perp(010)/\gamma = 14°$); laths mainly parallel to the trace of (010) cleavage, but other orientations also present. Microcline contains aegirine(?) microlites. Disoriented, short laths between broad microcline bands, are presumably plagioclase ($2V\gamma = 86°$). Section $\sim\perp(010)$ and (001); $X-X'$—trace of (001) cleavage. Crossed Nicols, magnification 25 ×. (Large phenocryst in green foyaite: EAR 312; spec. 4).

There are thus two possible origins for pyroxene needles in potash feldspar in rocks from this area; firstly, exsolution from an orthoclase during inversion to microcline, and secondly, inclusion of small aegirine-augite crystals.

In a study of the structural and optical orientation of K–Na feldspars, Marfunin (1961, p. 108) arrived at the conclusion that unmixing, ordering and twinning in potash-soda feldspars occur almost simultaneously as interdependent processes. If this statement is correct, it is reasonable to assume that the same mechanism operates in the case of aegirine microlites.

Some indication of the behaviour of Fe_2O_3 in microcline is provided by the experimental data of Rosenqvist (1951) who found that the powdered feldspar could take up to 0.21% Fe_2O_3 into the structure at
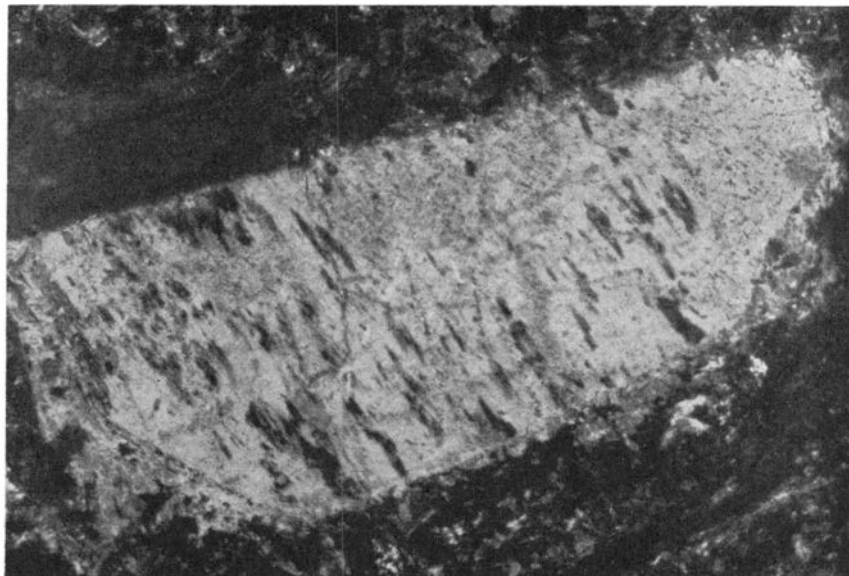
Figure 8. Orthoclase phenocryst from green foyaite dyke, partially inverted to microcline; lenticular patches orientated $\sim\!\perp$ (010). Crossed Nicols, magnification 40 ×. (EAR 304; spec. 3).

980 °C. At lower temperatures, much smaller quantities were taken up. Coombs ((1954) p. 422) states: "The fact that microcline normally does not carry large amounts of iron in solid solution, although micro-cline-perthites frequently contain oriented and presumably exsolved lamellae of haematite (Andersen (1915)), indicates the possibility that the ordered structure may be incapable of holding much iron. If so, the presence of iron in a sanidine should have the effect of retarding the ordering process."

Following the nomenclature used by Tuttle (1952), the monoclinic potash-feldspar described above would be defined as orthoclase. In Laves' (1960) nomenclature, it would be described as low sanidine.

Discussion and conclusions: In this short note an attempt has been made to describe briefly the salient features of the feldspars in the Pilanesberg rocks. Although the data presented are of a preliminary nature, some conclusions can be drawn from the observations.

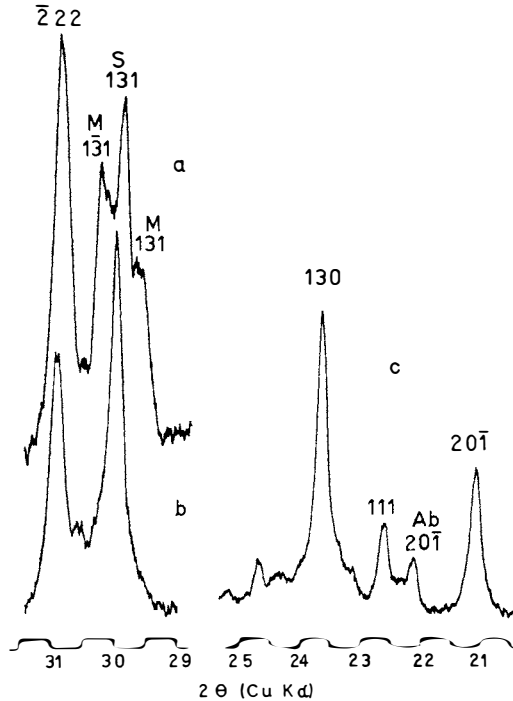Table 2 shows a considerable range of values in both obliquity and

Figure 9. Parts of the X-ray diffractometer patterns of orthoclase (or low sanidine) partially inverted to microcline: (*a*) specimen 3 (EAR 304); (*b*) and (*c*)—specimen 4 (EAR 312). Trace (*a*) shows a gradation between a strong 131 sanidine peak (*S*) and istrong 131 and 1$\bar{3}$1 microcline peaks (*M*). The presence of a triclinic phase in specimen 4 s indicated by the broadening of the bases of the 131 and 130 monoclinic peaks in traces (*b*) and (*c*), respectively. A perthitic intergrowth is suggested by the 20$\bar{1}$ albite reflection in trace (*c*).

$2V$ of microcline; feldspar, from this area, in an optically monoclinic part, has a $2V\alpha = $ ca. 52°, while the triclinic parts have $2V$'s ranging up to 87°.

Smith pointed out in a comment on a paper by Heier (1961, p. 136) that there need not be a correlation between $2V$ and Δ, since $2V$ may depend on short range order and Δ on long range order. Lack of correlation between long range and short range order may be due to variability in domain structure caused by Ca.

Harker (1954) has established that orthoclase in granitic gneisses from the Carn Chuinneag-Inchbae complex, in E. Rossshire, inverted

to microcline during regional metamorphism. He concluded, from an X-ray study of this material, that orthoclase and microcline predominate over feldspar of an intermediate nature. However, Figure 2 of his paper shows a spread in $2V$ from ca. 56° to ca. 82°, and a range in $Z \wedge y^*(\perp(010)/\gamma)$ from ca. 2° to ca. 23°.

In their discussion on microcline with tabular habit after {010}, MacKenzie and Smith (1961, p. 57) state that it is known from laboratory studies that the composition of a liquid may affect the habit of the crystals formed. Referring to the occurrence of microcline as an almost pure potassium feldspar, along with almost pure sodium feldspar, they tentatively propose that this association requires rather a low temperature of crystallisation, perhaps as low as 500 °C. It must be noted in this connection, however, that the green foyaites, tinguaites and some specimens of the other rock types of the Pilanesberg, contain very little modal or normative albite. The bulk of this plagioclase is held in solid solution in the microcline, but minute exsolved grains can be observed in some specimens. X-ray investigation has confirmed the presence of cryptoperthite in some cases.

The existence of a monoclinic potash feldspar phase in these rocks may be questioned, since Laves and Goldsmith (1961, p. 72) state that the ability to observe the triclinic character of feldspars, in which the triclinicity is observable, depends on the resolution of the instruments available, on the degree of triclinicity (obliquity) of the twinned domains, and on the size of these domains.

Emeleus and Smith (1959, pp. 1200–4) failed to observe the expected correlation between structural state of alkali feldspar and the thickness of ring-dykes from the Slieve Gullion area. They came to the conclusion that the local content of volatiles played the most important role of the factors governing the adjustment of the structural state of the alkali feldspars. Smith (1960) and MacKenzie and Smith (1961) believe that the Na/K-ratio strongly influences the degree of Al/Si-order. However, their views are not shared by Laves (comment on the second paper, p. 65). They also express the idea (p. 63) that caution is needed in using the alkali feldspars to elucidate the genesis of the rocks in which they occur.

In the subsequent discussion of the crystallisation history of these rocks, only the main minerals, nepheline, alkali feldspar, aegirine-augite and sodic amphibole, are considered. Nepheline is, almost

without exception, the first mineral to have formed, followed by feld-spar, but in some rocks pyroxene may crystallise immediately after the feldspathoid. Sodic amphibole has a very limited distribution, reaching a maximum development in the various types of white foyaite and in the Ledig foyaite. An intimate relationship between aegirine-augite and amphibole exists in most rocks. Some accessory minerals separated from the magma at an early stage, whereas the minor constituents like sodalite, analcite, fluorite etc. formed fairly late.

In the syenites, primary plagioclase, which precipitated after pyroxene, was followed by a feldspar phase that exsolved to give an antiperthite. This association suggests hypersolvus crystallisation, but the presence of replacement "antiperthite" (microcline and plagioclase) infers that the solvus intersected the solidus during crystallisation. Experimental data on this aspect of feldspar crystallisation are lacking and the above conclusion is purely tentative.

Crypto- and microperthite intergrowths in the red foyaite, por-phyries, tinguaite and green foyaite indicate hypersolvus crystallisa-tion and subsequent unmixing.

The white foyaites display textures ranging from microperthite to replacement "antiperthite". The latter have been formed through direct crystallisation of microcline and plagioclase from the magma.

The Ledig foyaite shows much the same variety of textures as the white foyaites.

Sodic amphibole may be older or younger than pyroxene, which indicates fluctuation in volatile pressure conditions during cooling. The former mineral may occur as the sole mafic in some white foyaites. It is evident that a gradation between hyper- and subsolvus conditions of formation for feldspar existed in the white foyaites. In some rocks the solvus was intersected (for texture, see Figure 4), which resulted in unmixing of original homogeneous feldspar as well as direct precipita-tion of potash and soda feldspar form the magma.

The conditions that prevailed during crystallisation of the syenite, Ledig foyaite and certain white foyaites, seem to indicate that potash feldspar crystallised metastably below 500 °C (Goldsmith and Laves (1954 and 1961); Laves (1960) and Laves and Goldsmith (1961)) as ortho-clase and has since inverted to microcline. In some rocks this process has not proceeded to completion, as indicated by the fact that ordered and disordered phases exist side by side in the same morphological unit.

It is known from the work of Tuttle and Bowen (1958, pp. 135–6) that nepheline influences the temperature of crystallisation in the ternary feldspar system, and it can be expected that this mineral may have had some effect on the conditions under which feldspar has formed.

The Pilanesberg rocks, except perhaps the syenite, had fairly high concentrations of F, Cl, H_2O and CO_2 during their formation, and it is reasonable to assume that the local volatile content contributed a major share, not only in aiding the ordering process of potassium feldspar, but also in affecting the PT conditions during crystallisation of alkali feldspar.

Since little has been said about the petrography of the various rock types, the picture of the crystallisation history, given above, is incomplete and only tentative. However, various aspects of this problem are to be included in the present study of this interesting suite of alkali rocks.

REFERENCES

BRØGGER, W. C. (1890): Die Mineralien der Syenitpegmatitgänge der südnorwegischen Augit- und Nephelinsyenite. Zeitschr.Krist., vol. 16 (1890) pp. 1.

BROUWER, H. A. (1910): Oorsprong en samenstelling der Transvaalsche Nephelien Syenieten. Mouton and Co., 's-Gravenhage.

CLOETE, D. R. (1957): Die Dolerietvoorkomste van die Noordelike Pilanesberg. M.Sc. thesis, Univ. of Pretoria.

COOMBS, D. S. (1954): Ferriferous orthoclase from Madagascar. Mineral.Mag., vol. 30 (1953–55) pp. 409.

EMELEUS, C. H. and SMITH, J. V. (1959): The Alkali Feldspars VI. Sanidine and Ortoclase Perthites from the Slieve Gullion Area, Northern Ireland. Amer.Mineral., vol. 44 (1959) 1187.

EMMONS, R. C. et al. (1953): Selected Petrogenic Relationships of Plagioclase. Geol. Soc.Amer., Memoir No. 52.

GOLDSMITH, J. R. and LAVES, F. (1954): Potassium feldspars structurally intermediate between microcline and sanidine. Geochim.Cosmochim.Acta, vol. 6 (1954) pp. 100.

—— (1961): The Sodium Content of Microclines and the Microcline-Albite Series. Instituto Lucas Mallada, Cursillos y Conferencias, fasc. 8 (1961) pp. 81.

HARKER, R. I. (1954): The Occurrence of Orthoclase and Microcline in the Granitic Geneisses of the Carn Chuinneag-Inchbae Complex, in E. Ross-shire. Geol.Mag. (1954) pp. 129.

HEIER, K. S. (1961): The amphibolite-granulite facies transition reflected in the mineralogy of potassium feldspars. Instituto Lucas Mallada, Cursillos y Conferencias, fasc. 8 (1961) pp. 131.

HUMPHREY, W. A. (1912): The Geology of the Pilandsberg. Union of South Africa, Mines Dept., Ann. Reports for 1911, Prt. 3, Geol.Surv., pp. 75.

KORITNIG, S. (1961): Zur röntgenographischen Bestimmung von Alkalifeldspäten. Naturwiss., vol. 48 (1961) p. 665.

LAVES, F. (1960): Al/Si-Verteilungen, Phasen-Transformationen und Namen der Alkalifeldspäte. Zeitschr.Krist., vol. 113 (1960) pp. 265.

—— and GOLDSMITH, J. R. (1961): Polymorphism, order, disorder, diffusion and confusion in the feldspars. Instituto Lucas Mallada, Cursillos y Conferencias, fasc. 8 (1961) pp. 71.

MACKENZIE, W. S. (1954): The orthoclase-microcline inversion. Mineral.Mag., vol. 30 (1953–55) pp. 354.

—— and SMITH, J. V. (1961): Experimental and geological evidence for the stability of alkali feldspars. Instituto Lucas Mallada, Cursillos y Conferencias, fasc. 8 (1961) pp. 53.

MARFUNIN, A. S. (1961): The relation between structure and optical orientation in the potash-soda feldspars. Instituto Lucas Mallada, Cursillos y Conferencias, fasc. 8 (1961) pp. 97.

MOLENGRAAFF, G. A. F. (1905): Preliminary Note on the Geology of the Pilandsberg and a Portion of the Rustenburg District. Trans.Geol.Soc. South Africa, vol. 8 (1906) pp. 108.

OFTEDAHL, C. (1948): Studies on the Igneous Rock Complex of the Oslo Region. 9 The Feldspars. Norske Videnskaps-akad., Oslo, Skr. I Mat.Nat.vidensk.kl. (1948) No. 3. pp. 1.

ORVILLE, P. M. (1958): Feldspar Investigations. Annual Report, Director Carnegie Inst.Wash. pp. 206.

ROSENQVIST, I.T. (1951): Investigations in the crystal chemistry of silicates III. The relation haematite-microcline. Norsk.Geol.Tidsskr. vol. 29 (1951) pp. 65.

SHAND, S. J. (1928): The Geology of the Pilansberg (Pilaan's Berg) in the Western Transvaal: A Study of Alkaline Rocks and Ring-Intrusions. Trans.Geol.Soc. South Africa, vol. 31 (1928) pp. 97.

SMITH, J. V. (1960): Phase Diagrams for Alkali Feldspars. Report 21st. Intern.Geol. Congr., Norden, Prt. 31, pp. 185.

SMITH, J. V. (1961): Explanation of Strain and Orientation Effects in Perthites. Amer. Mineral., vol. 46 (1961) pp. 1489.

SPENCER, E. S. (1930): Contribution to the study of moonstones from Ceylon and other areas and the stability relations of the alkali-feldspars. Mineral. Mag. vol. 22 (1929–31) pp. 291.

TILLEY, C. E. (1956): Nepheline Associations. Verhandel. Konink. Ned. Geol. Mijnbouw Genoot. (Brouwer volume), vol. 16 (1956) pp. 403.

——— (1960): Some New Chemical Data on the Alkali Rocks of the Vredefort Mountain Land, South Africa. Trans. Geol. Soc. South Africa, vol. 63 (1960) pp. 65.

TRÖGER, W. E. (1959): Optische Bestimmung der gesteinsbilden Minerale. Teil 1. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

TUTTLE, O. F. (1952): Optical Studies on Alkali Feldspars. Amer. Jour. Sci., Bowen volume, pp. 553.

——— and BOWEN, N. L. (1958): Origin of Granite in the Light of Experimental Studies in the System $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O. Geol. Soc. Am., Memoir No. 74.

WINCHELL, A. N. (1951): Elements of Optical Mineralogy. Prt. 2, Fourth Edition, John Wiley and Sons, Inc. New York.