SINGLE CRYSTAL X-RAY
STUDIES OF CRYPTO- AND MICRO-PERTHITES

By

W. S. MacKenzie and J. V. Smith

Geology Department, Manchester University, England
and Department of Geophysical Sciences, University of Chicago, U.S.A.

Abstract

A study has been made of the single crystal X-ray diffraction patterns of about 150 micro- and crypto-perthitic feldspars from a variety of geological localities. These patterns are divided into five types, each type corresponding to a different stage of exsolution. The single crystal X-ray technique appears to have considerable petrological application in the study of a layered complex such as the Kûngnât syenites (Upton (1960)) in which significant differences are found in the X-ray diffraction patterns of crystals from different units of the complex.

Introduction

A considerable amount of single crystal X-ray data has already been published on the separate phases of perthitic feldspars and these data, together with many new measurements on the reciprocal lattice angles α^* (010$\wedge$001) and γ^* (010$\wedge$100) of micro- and crypto-perthitic feldspars are the basis for the present review. This review has two primary objectives. Firstly there is the purely mineralogical aspect which is to consider what information can be obtained about the nature of the sodium-rich phase and the potassium-rich phase [1] in naturally occurring perthitic feldspars, and secondly an attempt is made to relate the nature of both phases to the geological environment in which the feldspar is found.

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[1] These terms will be abbreviated into sodium phase and potassium phase although it is understood that they are not necessarily pure $NaAlSi_3O_8$ and $KAlSi_3O_8$ respectively.

The history of the X-ray study of perthitic feldspars goes back to the work of Kôzu and Endô (1921). These authors found that the two phases of perthitic feldspar, visible as separate reflections on X-ray diffraction patterns, could be homogenized and partially unmixed again by suitable heat treatment. Chao, Smare and Taylor (1939) found that the separate phases in many microperthites had lattice parameters which corresponded with nearly pure potassium and sodium feldspar but in 1940 Chao and Taylor found that some of the specimens they examined had lattice angles which did not correspond with those of low-temperature albite although the majority of the specimens they studied had lattice angles close to those of low-temperature albite. In 1951 Taylor (personal communication, 1951) and Laves (1951) both concluded that the sodium phase of sanidine-cryptoperthites had lattice angles close to those of high-temperature albite.

Adopting Tuttle's classification of alkali feldspars (Tuttle (1952)) based on the value of the optic axial angle for a given composition, the present authors (MacKenzie and Smith (1955)), (Smith and MacKenzie (1955)), and MacKenzie and Smith (1956)) found that almost all orthoclase-microperthites had a sodium phase with lattice angles similar to low-temperature albite and almost all sanidine-cryptoperthites had a sodium phase with lattice angles corresponding to an anorthoclase. Tuttle and Keith (1954) found that specimens of alkali feldspar from the Beinn an Dubhaich granite in Skye were intermediate between orthoclase-microperthites and sanidine-cryptoperthites on the basis of optic axial angle measurements; these specimens had two sodium phases, one corresponding to a low-temperature plagioclase in lattice parameters and the other corresponding to anorthoclase (Tuttle and Keith (1954)). The validity of this simple classification has recently been questioned by Mukherjee (1961) but this will be discussed below.

The separate phases of perthites

Smith and MacKenzie (1955) developed a single crystal X-ray method for studying the separate phases of unmixed alkali feldspars, and for measuring the reciprocal lattice angles α^* and γ^* of twinned triclinic phases. These angles may be measured with an accuracy of

3′–10′ of arc and the method is ideally suited for studying a large number of crystals because of the simplicity of obtaining the X-ray photograph. The authors also adopted a procedure of plotting the values of α^* against γ^* for single phase feldspars and, by using this plot, the values of α^* and γ^* of the unmixed phases in perthites indicate the type and sometimes also the composition of these phases.

Figure 1 shows a plot of α^* against γ^* for the following feldspars: high-temperature albite $\alpha^* = 85°58'$, $\gamma^* = 87°54'$; low-temperature albite $\alpha^* = 86°24'$, $\gamma^* = 90°29'$ (Smith (1956)); maximum microcline $\alpha^* = 90°25'$, $\gamma^* = 92°16'$ (Laves (1952)); all monoclinic feldspars are represented by the point $\alpha^* = \gamma^* = 90°$. The four points are joined to form a figure fairly close to a parallelogram in shape. Approximately 180 points, each one representing a measurement of α^* and γ^* of an unmixed phase of a perthitic feldspar, are plotted in this diagram. All the measurements were made by the method mentioned above and, with the exception of seven points, are measurements made by the present writers. Some of the points represent more than one measurement where two different materials gave identical values of α^* and γ^*. Measurements made from albite twinned pairs are distinguished from those made from pericline twinned pairs and from those made from the individuals in diagonal association. The term "diagonal association" was proposed by the present authors (Smith and MacKenzie (1954), (1959)) to describe the relation between two crystallographic units which are not albite twinned or pericline twinned but their X-ray reflections, on *b*-axis oscillation photographs, lie intermediate between the positions for albite and pericline twinning. This relationship has so far only been found in the potassium phase of perthitic feldspars.

The most noticeable feature of figure 1 is that the points congregate fairly closely to three sides of the parallelogram and, with a few trivial exceptions, are within the parallellogram: there is a large area in which no points lie and this is hardly surprising since no single phase feldspar plots within the parallelogram. Many of the points represent one member of a coexisting pair of phases in a single perthitic crystal.

In the following sections an attempt is made to analyse the distribution of points within this diagram, particularly the points representing sodium phases, to find the cause of the variation in α^* and γ^* in different crystals. This can best be done by considering separately feldspars from differing geological environments, and each

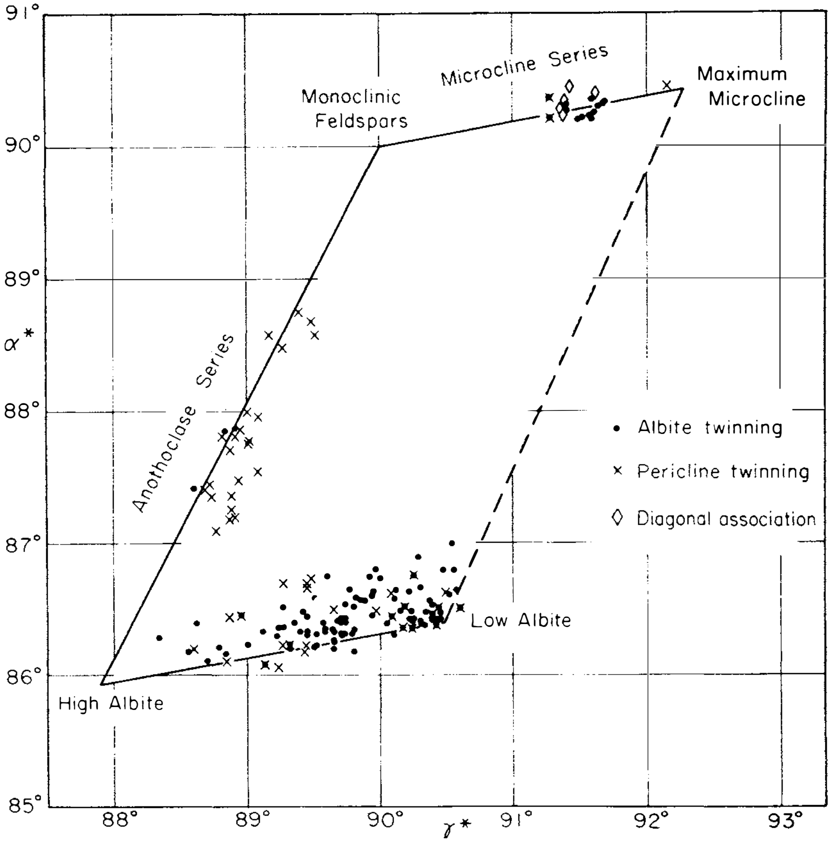

Figure 1. Plot of α^* against γ^* for 180 separate phases of unmixed alkali feldspars. Measurements made from an albite twinned phase are represented by a filled circle, those made from a pericline twinned phase are represented by a cross and those made from a diagonal association are represented by diamonds. The lines joining low albite to high albite, high albite to orthoclase and orthoclase to maximum microcline represent known variations in α^* with γ^* for alkali feldspars and the plotted points concentrate fairly close to these three lines.

area from which feldpars have been studied in this way is dealt with in turn.

Slieve Gullion ring dykes, Northern Ireland.

Emeleus and Smith (1959) have studied the feldspars from a porphyritic felsite ring dyke and a granophyre ring dyke from this area and a brief summary of their work is given here. The object of

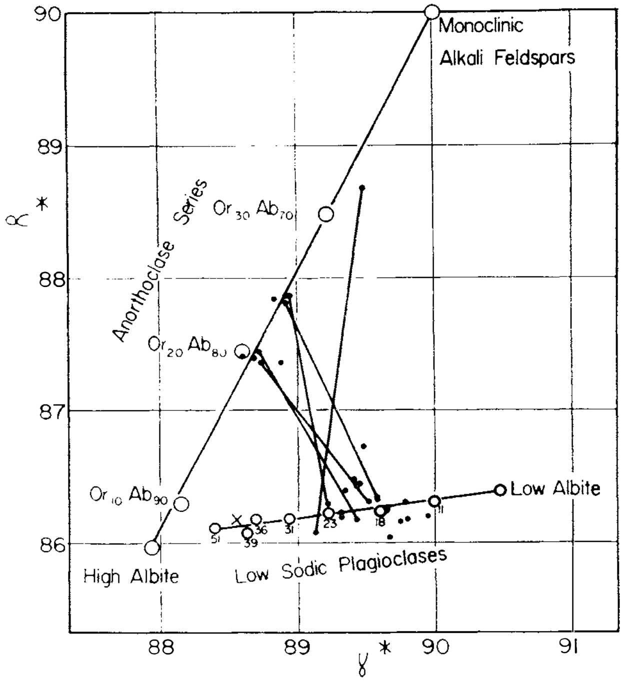

Figure 2. Plot of α^* against γ^* of the sodium phases of the perthitic feldspars from the Slieve Gullion felsite and granophyre. The open circles give reference values for homogeneous feldspars of known composition. The numbers 11, 18, 23, 31, 36, 39 and 51 are the An-contents of reference specimens of plagioclase. Tie lines join values obtained for anorthoclase and plagioclase in the same specimen. The cross represents values of α^* and γ^* for an albite twinned plagioclase from the same rock as one of the alkali feldspars (after EMELEUS and SMITH (1959)).

this study was to extend the data on feldspars transitional between those of volcanic rocks and those of plutonic rocks to supplement the work of Tuttle and Keith (1954). Most of the feldspar phenocrysts from these two rocks fall between the sanidine-cryptoperthite series and the orthoclase-microperthite series, and consist of a monoclinic potassium phase together with two sodium phases, viz. an anorthoclase and a sodium-rich plagioclase. The bulk chemical compositions of the crystals studied lie in the range $Or_{44.5}$–$Or_{62.5}$.

Figure 2 is reproduced from the paper by Emeleus and Smith (1959) and shows the plot of α^* and γ^* for the sodium phases of the feldspars from the porphyritic felsite and the granophyre. In addition to the points for low albite, high albite, maximum microcline and monoclinic feldspars plotted in figure 1, ten single phase feldspars are plotted and are shown by open circles: these points specify the anorthoclase, low plagioclase and microcline series. They were omitted from figure 1 to avoid confusion in the diagram. Tie lines join the values obtained for anorthoclase and sodium-rich plagioclase on the same specimen. It is believed that the feldspar phenocrysts in these rocks were originally homogeneous sanidine and during cooling changed to their present assemblage through a sequence of unmixing and ordering reactions.

Two crystals from the granophyre consist of orthoclase, microcline and low-temperature plagioclase, an association of microcline and low-temperature plagioclase quite different from the other perthites described above. They represent xenocrysts picked up from the Newry granodiorite.

In the interpretation of the nature of the phases represented by points near the line joining low albite to high albite it should be remembered that increasing anorthite content has the same effect as a high-temperature structural state, and the indicated anorthite content is the maximum value and corresponds to a low structural state. Even if these specimens have a zero anorthite content, which is most unlikely, the structural state of these phases appears to be less than half way to the extreme high-temperature state and so they are described here as low-temperature plagioclases.

The Beinn an Dubhaich granite, Isle of Skye.

Tuttle and Keith (1954), in a study of the Beinn an Dubhaich granite, found that the quartz had properties similar to that of quartz from rhyolites, the primary plagioclase had optical properties of an intermediate structural state between high- and low-temperature forms, and the alkali feldspars lay between the sanidine-cryptoperthite and the orthoclase-microperthite series. We have studied in considerable detail samples of feldspar from three rock specimens from close to the margin of this granite, kindly supplied to us by Dr. O. F. Tuttle, and we have been able to further develop the conclusions reached by Tuttle and Keith: the data are given in table 1.

The optic axial angle of each crystal has been measured (±.5°) and an X-ray oscillation photograph taken of the crystal. The potassium phase was found to be monoclinic: in a number of crystals there

Table 1. Beinn an Dubhaich granite.

Specimen Number	Crystal	$2V$	Potassium phase	Sodium phase			
				Albite twinning		Pericline twinning	
				α^*	γ^*	α^*	γ^*
F2–229	1	45°	Monoclinic	86°24′	89°44′	87°46′	89°01′
				no fine structure		some fine structure	
	2	54°	Monoclinic	86°20′	89°39′	87°15′	88°53′
				no fine structure		some fine structure	
	3	54°	Monoclinic with slight diffuse streaking parallel to the *b* axis	86°26′	89°44′	87°12′	88°55′
				no fine structure		no fine structure	
	4	56.5°	Monoclinic	86°32′	89°44′	87°33′	89°05′
				very diffuse		some fine structure	
	5	54.5°	Monoclinic	86°24′	89°34′	87°29′	88°56′
				rather diffuse		slight fine structure	
	6	51.8°	Monoclinic with slight diffuse streaking parallel to the *b* axis	86°25′	89°40′	87°11′	88°52′
				no fine structure		faint fine structure	
	9	57.6°	Monoclinic	86°12′	89°39′	87°49′	88°49′
				rather diffuse		considerable fine structure	
	10	54.7°	Monoclinic	89°19′	89°31′	87°06′	88°46′
				no fine structure		no fine structure	
	11	58°	Monoclinic	86°25′	89°44′	87°43′	88°52′
				no fine structure		slight fine structure	

	12	49°	Monoclinic	86°14′	89°31′	87°47′	89°01′
				rather diffuse		considerable fine structure	
	13	45°	Monoclinic	86°27′	89°56′	88°00′	89°00′
				no fine structure		faint fine structure	
F2–193	1	55.3°	Monoclinic	86°31′	89°48′	88°35′	89°10′
				slight diffuseness		mainly monoclinic with short tails corresponding to above angles	
	5	58.1°	Monoclinic, faint streaking parallel to the *b* axis	86°38′	89°57′	not measured	
				some fine structure		no fine structure	
	6	59.9°	Monoclinic, faint streaking parallel to the *b* axis	86°30′	89°45′	86°32′	89°34′
	7	58.9°	Monoclinic, faint streaking parallel to the *b* axis	86°31′	89°32′	Strong spot in the position for monoclinic symmetry which shows faint streaking along the layer lines	
F2–164	1	61.5°	Monoclinic	Largely complex superstructure, small amount of simple twinning		Very weak pericline twinning	
				Faint diagonal streaks connecting albite and pericline components			
	2	61.5°	Monoclinic	86°34′	89°51′	86°30′	89°39′
				Some superstructure			
				Albite and pericline components connected by diagonal streaks. There is a strong spot in the position for monoclinic symmetry.			

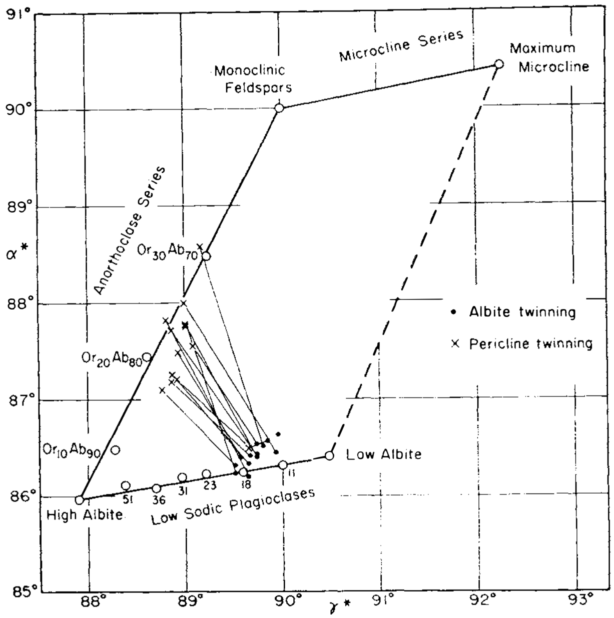

Figure 3. Values of α^* and γ^* for the sodium phases of perthites from the Beinn an Dubhaich granite. As in figure 1 the type of twinning in the phase is indicated by symbols.

was slight diffuse streaking parallel to the b^* axis of the crystal. (This is not the type of diffuse streaking found in intermediate microcline) (Smith and MacKenzie (1959)). The reciprocal lattice angles α^* and γ^* were measured from the albite and pericline twinning in the sodium phase and these data are plotted in figure 3. In almost all cases there are two sodium phases with quite distinct values of α^* and γ^* and where both have been measured the two sets of values are joined in the diagram.

If the lattice angles α^* and γ^* of the anorthoclase phases can be used as a measure of the potassium feldspar content of these phases, the anorthoclase ranges from about Or_{18} to Or_{37}. As in the case of the Slieve Gullion specimens the low-temperature plagioclase plots at some distance from low albite and the duality between the anorthite content and the structural state should be kept in mind in interpreting tha nature of the plagioclase.

The three specimens from which these crystals were separated were collected from the margins of this granite mass and are not representative of the bulk of the granite which may contain orthoclase-microperthites with no anorthoclase phase. The results obtained from these specimens indicate that they cooled under somewhat similar conditions to those of the Slieve Gullion ring dykes although the outcrops of the latter vary from a few feet to over a mile in width.

The Arran and Mourne granites

These two granites have been grouped together since the data obtained are limited and the results are very similar. They are both Tertiary in age, as is the Beinn an Dubhaich granite, but the feldspars differ from those studied from the Beinn an Dubhaich granite. Table 2 gives the data obtained from a few crystals from each mass and in each case the potassium phase is monoclinic in symmetry; the positions of the sodium phases are plotted in figure 4. There is no sign of an anorthoclase phase, the pericline twinned reflections giving values of α^* and γ^* not dissimilar from those of the albite twinned reflections: the pericline twinned reflections where present are all of very low intensity and the measurements from these are not as reliable as those obtained from the albite twinned reflections, even although the latter show superstructure. The low-temperature sodium phases do not plot close to the point representing low albite and presumably are partly transitional to high-temperature plagioclase or contain calcium.

Because of the absence of an anorthoclase phase it is deduced that these specimens represent the next stage in the sequence of unmixing in the alkali feldspars.

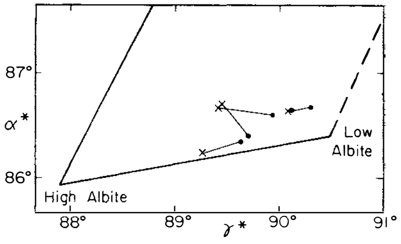

Figure 4. Values of α^* and γ^* for the sodium phases of the feldspars from the granites from Arran and Mourne.

Table 2. Mourne and Arran granites.

Specimen Number	Crystal	2*V*	Potassium phase	Sodium phase			
				Albite twinning		Pericline twinning	
				α^*	γ^*	α^*	γ^*
Mourne 90 [1]	2	65.9°	Monoclinic	86°40′ slightly diffuse Weak monoclinic reflections.	90°18′	86°38′ very weak; no fine structure The albite and pericline components are connected by diagonal streaks.	90°05′
	3	58.3°	Monoclinic	86°39′ rather diffuse	90°07′	short streak of low intensity	
	4	58.6°	Monoclinic	Regular superstructure		very weak pericline component	
Mourne 212 [1]	7	41.4°	Monoclinic	very weak albite twinning		not present	
	9	42.0°	Monoclinic	very weak albite twinning		not present	
	10	41.8°	Monoclinic	very weak albite twinning		not present	
Arran AR8	1	61.4°	Monoclinic	86°36′	89°56′	86°40′ wery weak pericline twinning	89°27′
	2	60.5°	Monoclinic	86°24′	89°42′	86°42′ very weak pericline twinning	89°27′
Arran AR9	1	61.0°	Monoclinic	86°21′	89°38′	86°14′ one reflection very weak	89°16′

[1] The specimens of the Mourne granite were received through the courtesy of Dr. P. E. Brown: the approximate compositions of these specimens are No. 90 – $Or_{70}Ab_{30}$; No. 212 – $Or_{85}Ab_{15}$ (Brown (1956)).

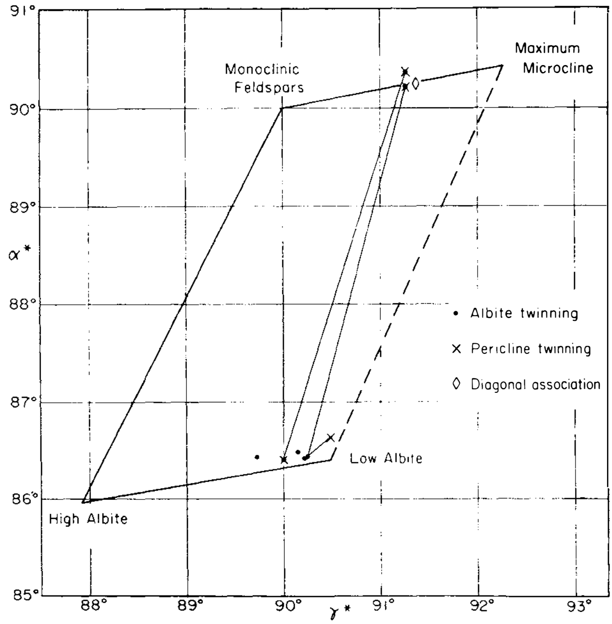

Figure 5. Plot af α^* against γ^* for the separate phases of some feldspars from the Dartmoor granite.

The Dartmoor granite

The specimens of the Dartmoor granite were collected by Dr. O. F. Tuttle and we are grateful to him for supplying us with them. This granite is of Caledonian age and undoubtedly represents a much larger mass emplaced at greater depth than any of the three previously mentioned. Thus it might be expected to have cooled at a much slower rate so that the feldspars would have attained a lower structural state.

The data obtained for the crystals of this granite are given in table 3 and the values af α^* and γ^* are plotted in figure 5. The presence of diffuse reflections indicating a triclinic potassium phase is characteristic of these specimens although the monoclinic potassium phase is dominant. The value of γ^* of the sodium phase is less than 90° in only one of the crystals and so the low-temperature sodium phase falls closer to low albite than in the granites described above. Only one specimen (F4–211) is from near the granite contact and this also has diffuse microcline reflections.

Table 3. Dartmoor granite.

Specimen Number	Potassium phase	Sodium phase			
		Albite twinning		Pericline twinning	
		α^*	γ^*	α^*	γ^*
F4–211	Mostly monoclinic with diffuse albite twinned reflections	86°24′	90°00′	present Difficult to measure accurately due to diffuse present streaking	
F4–213	Sharp monoclinic phase with diffuse albite & pericline twinning *A* $\alpha^* = 90°22'$ $\gamma^* = 91°16'$	Not measured			
F4–214	Diagonal association microcline *D* $\alpha^* = 90°14'$ $\gamma^* = 91°22'$ no monoclinic phase	86°26′	89°44′		
F4–215 Crystal 1	Monoclinic phase with strong diffuse albite twinned microcline *A* $\alpha^* = 90°13'$ $\gamma^* = 91°16'$	86°26′	90°15′	Weak pericline twinning not measured	
Crystal 2	Monoclinic with weak diffuse albite twinned microcline	86°25′	90°13′	86°38′	90°29′
F4–217	Monoclinic with strong diffuse albite twinned microcline	86°29′	90°09′	Weak pericline twinning not measured	

Note: *A* indicates albite twinning
D indicates diagonal association.

Table 4. Kûngnât syenites, S.W. Greenland.

Specimen Number	Composition (mol. %) and location	Potassium phase		Sodium phase			
				Albite twinning		Pericline twinning	
		α^*	γ^*	α^*	γ^*	α^*	γ^*
K 105	$Or_{32\cdot5}Ab_{60}An_{7}Cn_{0\cdot5}$ from base of Western lower layered series	Monoclinic and albite twinned microcline		86°26′	90°26′	not present	
		90°19′	91°40′				
K 55	about $Or_{41}Ab_{54}An_{5}$ from middle of Western lower layered series	Monoclinic and albite twinned microcline		86°22′	90°14′	weak pericline twinning	
		90°13′	91°31′				
K 50	about $Or_{41}Ab_{54}An_{5}$ from top of Western lower layered series	Monoclinic and albite twinned microcline		86°31′	90°26′	weak pericline twinning	
		90°18′	91°38′				
K 491B	about Or_{34} from bottom of Western upper layered series	Monoclinic and sharp diagonal microcline (not measured)		86°37′	90°31′	not present	
K 31	$Or_{37\cdot5}Ab_{59}An_{3\cdot5}$ from top of Western upper layered series	Monoclinic and albite twinned microcline					
		Crystal 1					
		90°14′	91°34′	86°25′	90°23′		
		Crystal 2				weak pericline	
		90°16′	91°37′	86°25′	90°25′	twinning	
K 218	$Or_{33}Ab_{58}An_{8}Cn_{1}$ from Eastern border group	Monoclinic and very weak albite twinned microcline		86°35′	90°06′	86°04′	89°14′
				albite twinned and pericline twinned reflections not connected by streaks			
K 235	about $Or_{33}Ab_{58}An_{8}Cn_{1}$ from Eastern border group	Monoclinic phase only		86°14′	89°00′	86°42′	89°16′
K 496A	$Or_{29}Ab_{59}An_{10\cdot5}Cn_{1\cdot5}$ from high in Eastern layered series	Monoclinic phase only with diffuse streak going to Na-phase		86°35′	89°49′	86°22′	89°14′

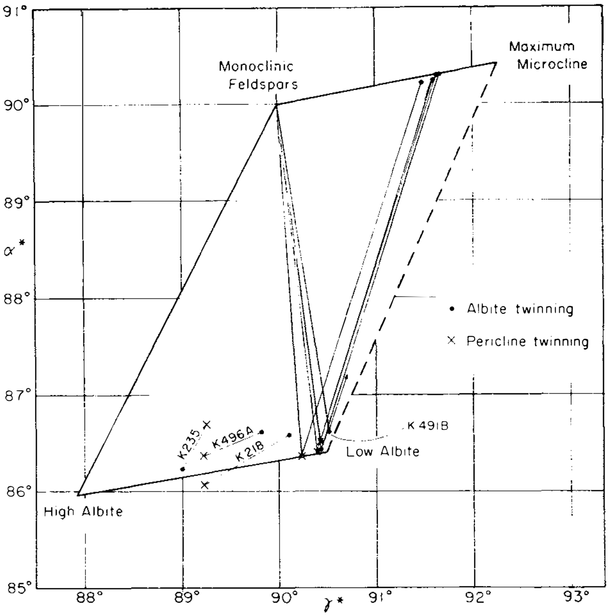

Figure 6. Plot of α^* against γ^* for the separate phases of feldspars from the syenites from Kûngnât, S.W. Greenland. In specimen K 491 B no measurements were made of the lattice angles of the potassium phase but comparison with the other specimens indicates similar values.

The Kûngnât and Tugtutôq complexes, S. W. Greenland

Through the kindness of Dr. B. G. J. Upton we have been supplied with a number of feldspars from these two masses in south Greenland. We are grateful to the Director of the Geological Survey of Greenland for permission to publish the results we have obtained on these specimens.

The Kûngnât igneous complex has been described in detail by Upton (1960) and the specimens obtained from him were from the syenites: table 4 gives the specimen locations and chemical compositions supplied by Dr. Upton together with the data obtained from the single crystal X-ray photographs by the present writers. The values of α^* and γ^* are plotted in figure 6 where it can be seen that the five specimens from the Western lower layered series and from the Western upper layered series are all very similar in having three phases: a monoclinic potassium phase, a triclinic potassium phase and a sodium

Table 5. Tuqtudôq complex, S.W. Greenland.

Specimen Number	Rock type	Approx. composition	Potassium phase			Sodium phase		
						Albite twinning		Pericline twinning
				α^*	γ^*	α^*	γ^*	
T 31	Nepheline syenite dyke	Or_{26}	Microcline in diagonal association—crystals deformed and difficult to measure			Crystal 1 86°25′ Crystal 2 86°29′	90°15′ 90°27′	None None
T 140	Nepheline syenite dyke	—	Microcline in diagonal association No monoclinic phase	90°20′	91°23′	86°18′	90°06′	No pericline twinning but streaking on constant θ
T 203	Nepheline syenite dyke	Or_{26}	Albite twinned microcline slightly diagonal No monoclinic phase	90°17′	91°21′	86°24′	90°18′	None
T 261	Phenocrysts from alkali quartz porphyry dyke	—	Albite twinned microcline No monoclinic phase	90°20′	91°41′	86°26′	90°13′	Spots near position for pericline twinning
T 64	Quartz fayalite syenite	—	Monoclinic phase and microcline in diagonal association	97°27′	91°25′	86°31′	90°36′	Very weak
T 212	Quartz fayalite syenite Central Tuqtudôq	—	Weak monoclinic phase and albite twinned microcline	90°20′	91°41′	86°23′	90°25′	Very weak
T 278	Quartz fayalite syenite Central Tuqtudôq	—	Monoclinic phase and diffuse albite twinned microcline	90°12′	91°29′	86°28′	90°23′	Very weak
T 74	Pegmatite in quartz fayalite syenite	Or_{34}	Monoclinic phase and diffuse albite twinned microcline	90°12′	91°35′	86°26′	90°26′	None
T 116	Soda granite pegmatite	Or_{40}	Microcline in diagonal association No monoclinic phase	90°24′	91°37′	86°23′	90°20′	None

phase which plots fairly close to low-temperature albite. Specimen 105 plots fairly close to low albite and yet the anorthite content of the specimen is given as 7 mol. %. We have noted above that the α^* and γ^* values may be used to indicate the maximum anorthite content of a sodium phase lying close to the join low albite—high albite and it may be concluded therefore that the crystal of specimen 105 used for this X-ray study is not representative of the sample which was analysed chemically but this is discussed below.

The two specimens from the Eastern border group and the one specimen from high in the Eastern layered series are quite distinct in that they have two sodium phases, each giving reciprocal cell angles quite far removed from those of low albite. Two of these carry only a monoclinic K-phase. The third one, K218, has a K-phase that is dominantly monoclinic but has a very small amount of albite-twinned microcline. These three specimens have higher anorthite contents than the other specimens but it is unlikely that the difference in anorthite content is responsible for the difference in the plotted positions of the sodium phases.

Table 5 gives the specimen numbers and types of rock from which the samples of the Tugtudôq complex were obtained, together with the data obtained from single crystal X-ray photographs, which are plotted in figure 7. In this suite of specimens all the values of γ^* of the sodium phase are greater than 90°06′ and so the points representing the sodium phase plot fairly close to low albite. Some of the specimens have a monoclinic potassium phase but all of them have intermediate microcline and in four of them the microcline reflections are in the diagonal association.

No simple relationship between the rock type and the appearence of the single crystal X-ray patterns can be seen from the data in table 5. It may be noted, however, that the three nepheline syenite dykes may be grouped together with the soda granite pegmatite in having no monoclinic potassium phase whereas the three specimens from the quartz fayalite syenite and the pegmatite in the quartz fayalite syenite each have a monoclinic potassium phase in addition to the microcline.

The tie lines joining the sodium phase to the potassium phase in figure 7 are all roughly parallel and these are very similar to the tie lines in figure 6 for the Kûngnât syenites. It is for this reason and

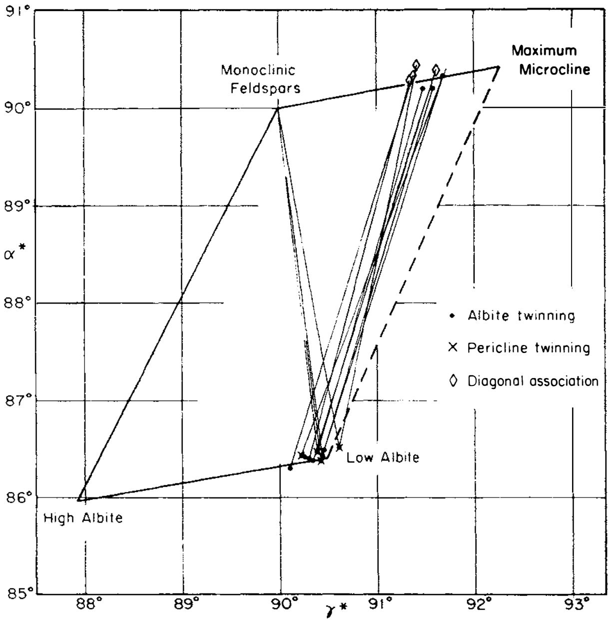

Figure 7. Plot of α* against γ* for the separate phases of the feldspars from rocks of the Tuqtudôq Complex, S.W. Greenland.

because the specimens have approximately the same range of sodium feldspar content in their bulk composition that the two complexes are discussed together.

The Finnemarka complex, Oslo region

Through the kindness of Dr. G. K. Czamanske we have obtained a number of specimens of feldspar from a small granitic complex in the Oslo region, which he has studied in detail (Czamanske (1962)). The data are set out in table 6 and the values of α* and γ* measured for the present study are plotted in figure 8. In all these specimens the potassium phase is dominantly monoclinic but there are weak diffuse streaks indicating some transition to microcline. The sodium phases plot fairly close to low albite with the exception of specimen 1–61 which Czamanske considered to be a separate phase of the granite on the basis of differences in texture and in weathering from the type represented by specimens 39 and 4–61. The chemical compositions of all these specimens are roughly similar.

Table 6. Finnemarka Complex, Oslo Region.

Specimen Number	Composition and type of rock	Potassium phase	Sodium phase			
			Albite twinning		Pericline twinning	
			α^*	γ^*	α^*	γ^*
39	$Or_{45\cdot3}Ab_{54\cdot2}An_{0\cdot5}$ Main mass of one feldspar biotite granite	Monoclinic mainly with weak diffuse streaks indicating some microcline	86°25′	90°24′	Very weak	
4–61	$Or_{42\cdot8}Ab_{56\cdot6}An_{0\cdot6}$ Main mass of the feldspar biotite granite	Monoclinic mainly with weak diffuse streaks indicating some microcline	86°26′	90°27′	Very weak	
1–61	$Or_{43\cdot0}Ab_{55\cdot4}An_{1\cdot6}$	Monoclinic mainly with weak diffuse streaks indicating some microcline	86°23′	90°12′	86°16′	89°27′
H–1	$Or_{43\cdot7}Ab_{56\cdot3}$ [1] Pyroxene-bearing granite from contact with sediments	Monoclinic mainly with weak albite twinned microcline—not measured	Crystal 1 86°31′	90°11′	86°31′	90°11′
			Crystal 2 86°22′	90°10′	Not measured	
B–5	$Or_{37\cdot6}Ab_{59\cdot1}An_{3\cdot4}$ granodiorite surrounding granites mass on northern margin	Monoclinic mainly with weak albite twinned microcline—not measured	86°29′	90°14′	86°27′	90°05′

[1] CaO not determined.

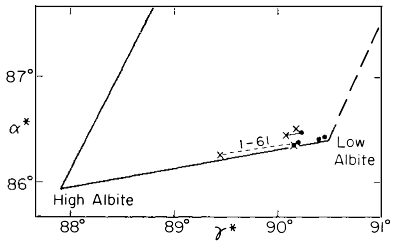

Figure 8. Plot of α^* against γ^* for the separate phases of the feldspars from the Finnemarka complex, Oslo Region.

The Tatoosh pluton, Mount Rainier National Park

Dr. T. L. Wright of the United States Geological Survey has kindly permitted us to quote the data he has obtained on a series of feldspars from a shallow pluton composed of hornblende biotite, quartz monzonite and granodiorite in Mount Rainier National Park. Dr. Wright has made a special study of these feldspars (Wright (1962)) and the results are being prepared for publication. Table 7 gives tha data provided for us by Dr. Wright and the values of α^* and γ^* are plotted in figure 9.

The compositions of these samples were determined from the position of the $\bar{2}01$ reflection in homogenized samples and these are rather potassium-rich feldspars, compared with those obtained from the Kûngnât, Tugtutôq and Finnemarka complexes. The sodium phase in these specimens plots at a considerable distance from low albite (figure 9) and the potassium phase is dominantly monoclinic with very faint streaking indicating some triclinic material. Wright (personal communication, 1962) has interpreted the sodium phase of these

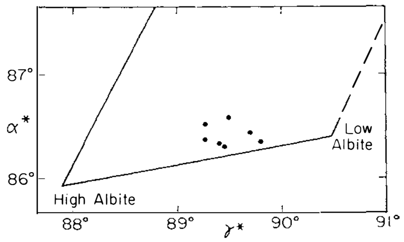

Figure 9. Plot of α^* against γ^* for separate phases of the feldspars from the Tatoosh pluton, Mount Rainier National Park, Washington, U.S.A.: these data are from Wright (1962).

Table 7. Tatoosh pluton, Mt. Rainier National Park.

Specimen Number	Approximate composition	Potassium phase	Sodium phase		
			Albite twinning		Pericline twinning
			α^*	γ^*	
32	$Or_{85\cdot4}$	Monoclinic only	86°31′	89°16′	None
72	$Or_{83\cdot0}$	Monoclinic only	86°35′	89°30$\frac{1}{2}$′	Very weak
102	$Or_{84\cdot6}$	Monoclinic with weak diffuse streaks parallel to *b* axis	86°21′	89°48′	Very weak
66	$Or_{84\cdot1}$	"	86°22′	89°16′	Very weak
201	$Or_{83\cdot8}$	"	86°18′	89°27′	Very weak
9a	$Or_{81\cdot0}$	"	86°26′	89°42′	None
246a	$Or_{85\cdot2}$	"	86°20′	89°24′	Very weak

Table 8. Miscellaneous specimens.

Specimen Number	Rock type		Sodium phase			
			Albite twinning		Pericline twinning	
			α^*	γ^*	α^*	γ^*
Cambridge University 77892	Rhomb porphyry, Norway	crystal 1	86°24′	88°37′		
		crystal 2	86°17′	88°20′		
Cambridge University 61647	Rhyolite, Tardree, Ireland		86°19′	89°31′	87°22′	88°44′
Geological Survey of Great Britain S9376	Quartz-porphyry, Scalpay, Scotland		86°24′	90°03′		
Cambridge University 56308	Granophyre, Skye, Scotland		86°20′	89°27′	86°26′	88°52′

specimens to be in an intermediate structural state on the basis of (*a*) the optical properties of the sodium phase and (*b*) the position of the points on the plot of α^* against γ^*.

The seven measurements made by Dr. Wright are the only values of α^* and γ^* plotted in figure 1 which were not obtained by the present writers.

Miscellaneous specimens

In addition to the α^* and γ^* values given in tables 1–7, all the data given by the present authors in a previous paper (Smith and MacKenzie (1959)) and the data of Muir and Smith (1956) and Emeleus and Smith (1959) are plotted in figure 1, together with the α^* and γ^* values of a number of miscellaneous specimens which are listed in table 8. It is noted here again that most of the points fall within the limits of three sides of the parallelogram and do not scatter far within the parallelogram.

In a paper on the relation between structure and optical properties of alkali feldspars, Marfunin (1961) gave twelve measurements of α^* and γ^* of the sodium phases of some perthitic feldspars from a variety of environments, together with optical and chemical data on these specimens: Marfunin's values of α^* and γ^* are plotted in figure 10. Two of the three specimens whose sodium phases have γ^* angles close to 89° are grouped by Marfunin under high orthoclases and microclines on the basis of 2V and extinction angle measurements. The third specimen with a γ^* value close to 89°, and all the remaining specimens, are classed as either intermediate orthoclases and microclines or low orthoclases and cryptotwinned microclines. The region outside

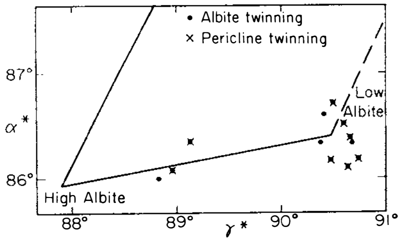

Figure 10. Plot of α^* against γ^* for the sodium phases of a number of alkali feldspars from a variety of localities in the U.S.S.R.: these data are from Marfunin (1961).

the parallelogram near to low albite and in which seven of Marfunin's specimens fall is virtually free from points in figure 1 which represent the data of the present authors: we find it difficult to reconcile these measurements of Marfunin with the belief that the maximum An content of a low-temperature sodium phase is indicated by the α^* and γ^* values (see section on the sodium phase below).

Mukherjee (1961) has recently given values of α^* and γ^* for the potassium and sodium phases of a series of feldspars from rhyolites from West Rajasthan, India, together with optical and chemical data on these feldspars. All except one of Mukherjee's points fall in a region of the parallelogram which is completely devoid of points in figure 1 and Mukherjee suggests that "these transitional forms necessitate a modification of the simple classification of perthites proposed by Tuttle (1952) and supported by MacKenzie and Smith (1956)."

Mukherjee states that "the examined feldspars have optic angles roughly intermediate between those of sanidine-cryptoperthites and orthoclase-microperthites within the same compositional range"; however, examination of Mukherjee's figure 2 shows that for only three of the fifteen specimens which he studied is this statement valid. One specimen has an optic axial angle of 48.4°, one has a range of 60.5–66.0° and the third has a range of 62.5–65.0°. The remaining specimens have optic angles falling in the range 74.5–84.3°, which are unusually high values for volcanic alkali feldspars of composition about Or_{40}–Or_{60}. The values of α^* and γ^* for the potassium phase of four specimens which Mukherjee studied are not discussed by him, but these plot well outside the parallelogram and they are very far removed from those of any single phase feldspar. It would appear that Mukherjee's specimens are fundamentally different from any investigaed by all other feldspar workers, and we feel that until other feldspars are found having both optical properties and lattice parameters similar to Mukherjee's specimens, no modification is necessary of the simple classification of feldspars proposed by Tuttle (1952) and adopted by many other workers.

Discussion of results

In view of the rather limited chemical and optical data on many of the specimens we have discussed, it would be unwise to draw too many conclusions from the observations we have made: those conclusions we have arrived at may require modification in the light of future work. It does seem appropriate, however, on the occasion of a feldspar symposium to present all the data available and try to explain it as far as possible. In this way other workers may decide for themselves whether they should undertake more detailed studies of the separate phases in unmixed feldspars.

The differences in the single crystal X-ray diffraction patterns are discussed first of all from a purely mineralogical viewpoint without reference to their petrological environment.

Potassium phase

The presence of a triclinic potassium phase is readily detected from single crystal X-ray diffraction patterns although it may not be apparent in powder patterns: (the powder method has the advantage, however, of being much faster and that a more representative sample of a large crystal can be studied in one pattern). The triclinic phase may show up in the single crystal patterns as diffuse streaks associated with the reflections of the monoclinic potassium phase and parallel to the b^* axis. When the intensity of these streaks is sufficiently high it is usually possible to detect distinct spots representing albite twinned triclinic material or in other cases both pericline and albite twinning. In such cases the values of α^* and γ^* can usually be measured. These angles may also be measured when the reflections from the triclinic potassium phase are in diagonal association.

The diagonal association, described by Smith and MacKenzie (1954) and Smith (this conference) has now been found in quite a number of specimens of perthites and it is noticeable that when it occurs it does so to the exclusion of albite and pericline twinning. This diagonal association has not yet been found in a homogeneous feldspar, except for its occurrence in an authigenic specimen (Smith, this conference). In the present study nothing in the geological occurrence of crystals having this diagonal association of the triclinic potassium phase has given us a clue to its significance, if any.

It is noticeable that, of the potassium phases in perthites described in this paper, not one has α^* and γ^* values corresponding to a maximum microcline despite the association with a sodium phase which plots close to low albite in the α^* and γ^* diagram and probably in many cases is indeed low albite. This matter will be discussed at the end of the section dealing with the sodium phases.

The presence or absence of a triclinic potassium phase is related to the nature of the sodium phase and this also is discussed below.

Sodium phase(s)

(*a*) Specimens with one sodium phase. The most important feature of the sodium phase to which attention has been previously directed is whether it is near to low albite or high albite. To be more precise we should differentiate between specimens whose sodium phase is an *anorthoclase* and those whose sodium phase lies close to the *line joining low albite to high albite* in the $\alpha^* \gamma^*$ plot. For ease of description points falling near this line will be referred to as *plagioclases* since this term includes both low-temperature plagioclases and specimens transitional to a high temperature structural state which may contain quite a small proportion of the An molecule.

We have previously given reasons (Smith and MacKenzie (1958)) for believing that the values of α^* and γ^* give an approximate value of the ratio of Or to (Ab + An) in the anorthoclase phase in sanidine-cryptoperthites. In addition we believe that the values of α^* and γ^* of the plagioclase phase in orthoclase-microperthites give an indication of the upper limit of the An content of this phase. The bulk of the calcium present in an unmixed ternary feldspar is likely to be held in the sodium phase rather than in the potassium phase because of the very limited solid solution of $CaAl_2Si_2O_8$ in $KAlSi_3O_8$, and it is therefore difficult to explain why so many points plot close to low albite from samples whose bulk composition contains approximately equal amounts of Or and Ab and about 5% of An. The sodium phase of such a specimen should be expected to plot near $Ab_{90}An_{10}$ with a γ^* value of about 90°.

Chemical analyses of low-temperature albites show that these characteristically have very low potassium contents and it may be that the low albite structure can accommodate only very little calcium also, certainly the existence of peristerites seems to indicate this. When the plagioclase phase reaches the structural state of low-temperature albite this phase has a composition which is fairly nearly pure $NaAlSi_3O_8$. It may be then that a separate calcium-rich phase is present but cannot always be detected by the method: indeed the reflections of several specimens were irregular and would be consistent with the presence of a small amount of another plagioclase. The advent of the electron-probe microanalyser may make it feasible in the near future to ensure that the crystals used for X-ray investigation have compositions which are representative of the bulk sample of feldspar. One of us (J.V.S.) will shortly test whether some of the calcium occurs as an alteration product.

(*b*) Specimens with two sodium phases. There are two types of association of two sodium phases. In one the phases are anorthoclase and plagioclase and in the other there are two plagioclases [2]: the plagioclase phases do not plot near to low albite in either case. When an anorthoclase phase coexists with a plagioclase phase the latter has a γ^* angle which is invariably less than 90° with an average value between 89°30′ and 89°40′ (figures 2 and 3). When two plagioclase phases are found at least one is well removed from the point representing low albite (figures 4 and 6).

Specimens having two sodium phases are characterized by a dominantly-monoclinic potassium phase and if any triclinic material is present in the potassium phase it is in very minor amounts (figures 4 and 6). On the other hand when the sodium phase plots close to low albite there is generally and appreciable amount of microcline present (figures 6 and 7). The specimens represented in figure 5 may represent the transitional stage between these two extremes since the sodium phase is only moderately close to low albite and the potassium phase is dominantly monoclinic but with diffuse streaks indicating the presence of some triclinic material.

The specimens from the Tatoosh pluton (figure 9) have a potassium phase which is dominantly monoclinic as also have the specimens from the Finnemarka complex (figure 8); however, the position of the sodium phases in the two groups of specimens differ appreciably. The average composition of the Tatoosh specimens is Or_{84} whereas the Finnemarka specimens have an average composition of Or_{42}. It would appear that the bulk composition of the specimens influences the nature of the sodium phase and this conclusion is supported by the results obtained in a previous study of perthites (Smith and MacKenzie (1959)) in which it was found that potassium-rich specimens sometimes

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[2] It must be recalled that in this context use of the term plagioclase means that the $\alpha^*\gamma^*$ values plot near the low albite—high albite line.

had an anorthoclase sodium phase coexisting with microcline and in other cases when the potassium phase was monoclinic the sodium phase was well displaced from the point representing low albite.

The influence of the bulk composition of a micro- or crypto-perthite on the structural state of the sodium phase seems not unreasonable since all the available evidence indicates that the degree of ordering of Al and Si of sodium and potassium feldspars is not the same for a given temperature (MacKenzie and Smith (1961)). If it is assumed that at a certain temperature, sodium feldspar is more ordered than potassium feldspar, and that the dominant component of an unmixed pair controls the structural state of the component present in minor amount, in a potassium-rich feldspar, the sodium phase will have a much lower degree of order for a given temperature when it occurs in micro- or crypto-perthitic intergrowth than it would have if it existed in isolation. Because of the larger contact area a perthitic intergrowth has a higher free energy than that of two discrete phases so that the above conclusion should not be unexpected.

Perthitic structure in relation to geological environment

From the foregoing descriptions of the different types of X-ray diffraction patterns in perthites it is possible to arrange these in what may be loosely called a cooling sequence. Although temperature is doubtless the most important factor it is probable that rate of cooling through a temperature range is of more significance and this may depend on a number of factors which are extremely difficult to evaluate.

The types of X-ray diffraction patterns might be arranged in the following cooling sequence:

a)	K phase—monoclinic	Na phase—anorthoclase
b)	K phase—monoclinic	Na phases—anorthoclase + plagioclase
c)	K phase—monoclinic	Na phases—2 plagioclases
d)	K phase—monoclinic	Na phase —1 plagioclase
e)	K phases—monoclinic + triclinic	Na phase —1 plagioclase

Type (*a*) is represented by the feldspars from volcanic rocks which belong to the sanidine-cryptoperthite series (MacKenzie and Smith (1956)).

Type (*b*) is represented by specimens from the ring dykes of Slieve Gullion and the marginal specimens of the Beinn an Dubhaich granite. Heating experiments at 900 °C on crystals of this type reveal that the anorthoclase phase mixes readily with the potassium phase but the plagioclase phase remains unmixed unless the heating is carried out at much higher temperature. This indicates a difference in the Si/Al ordering between the two sodium phases which could be explained in two different ways. Either the exsolution is accomplished in two distinct stages with the anorthoclase appearing at the highest temperature and the plagioclase later, or that the two phases are exsolved simultaneously at one temperature but the anorthoclase does not achieve significant order at this temperature because of its potassium content whereas the plagioclase phase orders readily because of its relatively high calcium content and low potassium content.

Type (*c*): The first specimen of this type was described by Laves (1952) and subsequently MacKenzie and Smith (1955) found a similar specimen. In these examples the sodium phases were correlated with the peristerite-type structure; however, in both these cases and in the three examples of this type of structure found in the Kûngnât syenites (figure 6) the potassium phase is monoclinic. Peristerites are, however, generally associated with microcline in pegmatites, the microcline occurring as separate crystals from the peristerite. Furthermore the reciprocal lattice angles of the two plagioclases do not fit with those to be expected for a peristerite (measurements of peristerites give angles that correspond fairly well with compositions of An_3 and An_{25}: see papers by W. L. Brown and P. Ribbe, this conference). Since our knowledge of the temperature range over which the peristerite structure is stable is very incomplete, it is unwise to pursue this problem further here. It may be noted, however, that specimens of this type are always fairly sodium-rich and therefore might be expected to have a relatively high calcium content. This may be the reason for the presence of two plagioclase phases whether these can be correlated with the peristerite structure or not.[3]

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[3] In the specimens which contain two plagioclase phases, viz. those from the Arran and Mourne granites and three specimens from the Kûngnât syenites, the pericline twinned phase invariably plots further from low albite than the albite

Type (*d*) is represented by some of the specimens of the Dartmoor granite (figure 5), the Finnemarka complex (figure 8) and the Tatoosh pluton (figure 9), in which there is only one sodium phase coexisting with a potassium phase which is dominantly monoclinic (small amounts of a triclinic potassium phase are present in addition to the monoclinic phase in some specimens). The specimens from the Finnemarka complex and those from the Tatoosh pluton have been grouped together since the difference in the positions of the sodium phase in the $\alpha^* \gamma^*$ plots for these two groups of feldspars has been attributed to the difference in bulk chemical composition of the specimens.

Type (*e*) is represented by some of the specimens of the Dartmoor granite in which a triclinic potassium phase is present in addition to a monoclinic phase (figure 5), five of the specimens from the Kûngnât syenites (figure 6) and most of the specimens of the Tuqtudôq complex in which a monoclinic and triclinic potassium phase coexist. In these specimens the triclinic potassium phase is quite distinct and its lattice parameters can be measured.

An additional group of specimens which have no monoclinic potassium phase could be described as type (*f*): four of the feldspars from the Tuqtudôq complex come in this category. Insufficient data is yet available on specimens of this type, however, to be certain that these represent a distinctly slower rate of cooling or cooling to a lower temperature than specimens of type (*e*).

The mechanism whereby these five groups of feldspars attain their present structure type is of considerable interest. If this is accomplished through the successive stages listed above then what is the intermediate stage in the derivation of, for example, the type (*c*) pattern from a type (*b*) pattern? Presumably some of the potassium in the anorthoclase phase must exsolve and be added to the monoclinic potassium phase permitting the formation of the additional plagioclase phase seen in type (*c*) specimens. The very faint streaks associated with many of the spots on the X-ray diffraction patterns could account for this change but there is no reason to expect sharp reflections between the anorthoclase line and the plagioclase line (figure 3)

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twinned phase. In the Slieve Gullion and Beinn an Dubhaich feldspars the anorthoclase phase is pericline twinned and the low-temperature plagioclase phase is albite twinned. It appears that the pericline twin arrangement is favoured by the higher temperature structural state.

since no known single phase feldspar plots in this region. The alternative explanation for the formation of these different types of pattern is that each type represents *a specific temperature range in which the feldspar existed for a considerable time.* (It should be noted that the bulk composition may have an effect on the cell angles of the sodium phase.) In other words the type (*c*) pattern may be formed because the rock mass existed for a time at the temperature for which the type (*c*) pattern is characteristic and then cooled fairly rapidly and it need not have been derived from a pre-existing type (*b*) pattern. The conditions under which the feldspar exsolved, viz. cooling rate, temperature, pressure and concentration of volatiles, may all be important factors in determining the type of pattern produced but since these are not independent variables it may be best to equate the type of pattern simply with a temperature at which atomic migration effectively ceases.

In comparison of granites such as the Arran and Mourne with the apparently much larger mass of the Dartmoor granite, the conclusions as to cooling rate are, of course, so obvious as not to require stating but the significance of the differences in the single crystal X-ray patterns, may become of considerable geological importance in the study of a complex such as Kûngnât where the feldspars from different units show distinctly different types of diffraction patterns.

It is not improbable that the question of the evolution of these different X-ray diffraction patterns is amenable to experimental study under controlled conditions using natural crystals although the runs might have to be of fairly long duration. Such an approach would be required before any temperature values could be equated with a given type of pattern.

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