SYMMETRY RELATIONS IN ALKALI FELDSPARS OF SOME AMPHIBOLITE-FACIES ROCKS FROM THE SOUTHERN NORWEGIAN PRECAMBRIAN

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Abstract

320 alkali feldspars from Precambrian granites and gneisses were examined for obliquity (Δ) by means of the X-ray powder method. The gneisses that surround the granites belong to the middle amphibolite facies, and the level of exposure is catazonal. K-feldspars from the granites and pegmatites exhibit maximum obliquity, those from ordinary gneisses generally have maximum obliquity or variable obliquity, and those from augen gneisses show lower and variable obliquity. The obliquities of K-feldspar crystals from a single hand specimen of augen gneiss may be highly variable. These augen gneisses exhibit apparent replacement features. Because microcline appears to be the stable K-feldspar phase throughout the entire area, the writer suggests that the K-feldspars of intermediate and variable obliquity are metastable phases caused by the interplay of bulk composition changes, growth rate, deformation, and temperature.

Introduction

General

In the course of studying the genesis of the Precambrian Flå granite, an investigation of the symmetry relations (obliquity) of the alkali feldspars was carried out as a possible indicator of the geologic history of the granite and the country rocks. Rao (1960) has applied obliquity values to the study of thermal metamorphic effects, Emerson (1960) investigated obliquity relations within a granite, and Heier (1957) and Guitard and others (1960) have studied the distribution of alkali-feldspar obliquities within regional metamorphic terrains. Almost all the obliquity values in the Flå granite were similar; however, unusual values which did occur in some gneisses, particularly augen gneisses, were surprising and led to a further investigation of these rocks.

A total of 320 specimens of alkali feldspars was X-rayed. Most of the samples studied were from the upland region between the valleys of Hallingdal and Ådal-Begndal about 100 km NNW of Oslo. Once the pattern of peculiar obliquities in augen gneisses became apparent, specimens from the Telemark and Bamble rocks along the southeast coast (Sörlandet) of Norway were also included in order to determine whether the same peculiarities occurred there.

Geology

The Flå granite is a group name that has been given to two elliptical granite bodies, the larger Hedal granite and the smaller Ådal granite (Figure 2). The general geology, gravity interpretation, and feldspar studies of these granites will be described in a later publication (Smithson, (1963)). The Flå granite is composed of two principal facies, a porphyric granite and a fine-grained granite. The porphyric variety is universally present at the border of the granite. The contact of the granite is marked by a breccia zone that can best be described as a large scale migmatite to agmatite. Gravity measurements over the granites reveal that the vertical thickness (1–3 km.) is much less than the width of the granites so that the granites would appear as thin plates in cross section. In places, these two late-kinematic granites are foliated, and they have deformed the country rocks. The Hedal granite is cut by a N–S trending Permian rhomb porphyry dike that varies from 10 to 30 m. in width. The granites are surrounded by zones of migmatites and augen gneisses of variable extent. These zones contain most of the alkali feldspars of unusual triclinicity.

The rocks samples along the southeast coast of Norway were augen gneisses and migmatites. These rocks occur interlayered with the supracrustal rocks of the Bamble area SE of the "great friction breccia" and in the granitized gneisses of the Telemark rocks NW of the breccia (Barth (1960)). The breccia zone marks a major fault separating the two areas. The Herefoss, Grimstad, and Levang granites are several of the syn- and post-kinematic granites which are emplaced within the Telemark and Bamble rocks.

The rocks of the Flå area are placed in the middle amphibolite facies. Although the characteristic pelitic mineral assemblage is missing, these rocks are probably in the kyanite-muscovite-quartz subfacies (Fyfe and others (1958)). The rocks sampled in the Bamble-Telemark area are also in the upper amphibolite facies, kyanite-muscovite-quartz to sillimanite-almandine subfacies. Both areas are classed as catazonal.

Method

X-ray technique: All X-ray films were taken using the powder method on a Guinier-Nonuis quadruple camera. The films were measured by enlarging them on a screen by means of a 35-mm.-slide projector. The precision of the method is ± 0.003 Å.

Sampling: A large number of rock samples was collected during the geological mapping of the area. These supplied the alkali feldspars that were X-rayed. Twenty-five specimens were pulverized and separated by means of heavy liquids. These, of course, represent an estimation of the obliquity of the K-feldspar from the entire rock. The remaining feldspars were hand picked. The sampling is therefore limited to crystals greater than *ca.* 1 mm.; most of the hand-picked specimens were of megacrysts and porphyroblasts. The sampling is thus essentially limited to larger feldspars.

Definitions: Goldsmith and Laves (1954a) have defined the separation of the 131 and the $1\bar{3}1$ reflections in X-ray powder patterns as a measure of triclinicity (obliquity). The spacing of these two reflections is called Δ, and Δ is defined so that $\Delta = 0.0$ is monoclinic feldspar and $\Delta = 1.0$ is microcline of maximum obliquity. Δ, which is a measure of Al–Si order-disorder (Barth (1959)) may assume any value between 0.0 and 1.0. Examples of maximum microcline ($\Delta = 1.0$) intermediate microcline ($\Delta = 0.5$), and monoclinic alkali-feldspar ($\Delta = 0.0$) appear in Figure 1*a,b,c*. In addition to Δ with a definite value, diffuse reflections which represent variable Δ-values within a crystal are encountered (Goldsmith and Laves (1954b); Christie (1962)). These may vary from reflections which are diffuse about a definite Δ-value (Figure 1*i*) to reflections that are evenly diffuse up to a certain

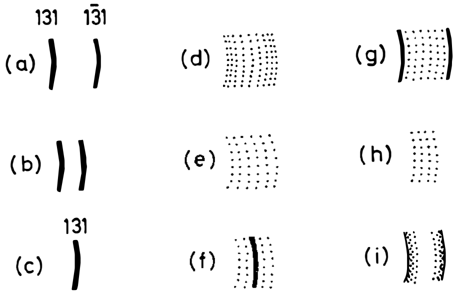

Figure 1. Appearance of 131 and 1$\bar{3}$1 reflections used to measure obliquity in X-ray powder patterns. (*a*) Maximum microcline, $\Delta = 1.0$. (*b*) Intermediate microcline, $\Delta = 0.5$. (*c*) Sanidine and orthoclase, $\Delta = 0.0$. (*d*) Microcline with Δ varying from 0.0 to 1.0, $\Delta = 1.0$ strongest. (*e*)*RD* microcline, maximum $\Delta = 1.0$. (*f*) Monoclinic alkali feldspar on a *RD* background. (*g*) Maximum microcline on an *RD* background. (*h*) *RD* intermediate microcline, $\Delta = 0.5$. (*i*) Somewhat disordered microcline, maximum $\Delta = 1.0$.

Δ-value (Figure 1*e*). The latter have been called randomly disordered (*RD*) by Christie (1962). The *RD* K-feldspar crystals are composed of small domains that have every possible Δ-value between 0 and a fixed maximum value. If the frequency of a certain Δ-value predominates, the corresponding reflections will be more intense and appear as darker lines superposed on a diffuse background (Figure 1*d,f,g*). Because these K-feldspars of variable obliquity obviously represent departures from equilibrium, they have received as much attention in this investigation as the K-feldspars of low to intermediate obliquity values.

Distribution of Obliquity among the Rock Types

Table 1 shows the numerical distribution of Δ-values of K-feldspars, which are usually perthitic, for the different rock types. The range of Δ from 0.0 to 1.0 has been arbitrarily divided into four intervals, and each interval has been subdivided into groups of uniform (sharp reflections) triclinicity and variable obliquity (diffuse reflections).

That the alkali feldspars from granites and pegmatites fall into a grouping characterized by maximum obliquity is immediately apparent. The Herefoss granite (Nilssen (1961)) also contains alkali feldspars that are mostly near maximum microcline. Also, alkali

Table 1. Numerical Distribution of Obliquity Values within each Rock Type

Δ	Pegmatite	Granite	Inclusions	Gneiss	Augen Gneiss
> 0.85	28	65	4	15 + 5*	8 + 1*
Diffuse			1	2 + 2*	1 + 4*
0.70–0.85	1	1		5	9 + 2*
Diffuse		1		6 + 2*	8 + 2*
0.35–0.70		1			
Diffuse				2	5 + 2*
> 0.35					1 + 1*
Diffuse				1	2 + 3*

* Specimens from Telemark-Bamble area.

feldspars of variable obliquity are almost completely lacking within the granites and pegmatites.

Most of the gneisses, which include migmatites in Table 1, contain maximum microcline. K-feldspars of low and intermediate obliquity occur, however, and alkali feldspars of variable obliquity are fairly common. These latter two types including an occurrence of orthoclase are found in migmatites in which the alkali feldspar becomes distinctly porphyroblastic.

The augen gneisses include most of the samples which had low to intermediate obliquity and which had variable obliquity. Orthoclase is found within the augen gneiss although it occurs rather sporadically. The mode of these rocks falls in the Δ range from 0.70–0.85 even though this is the smallest interval. Variable obliquity within one crystal is common. Obliquity measurements on alkali feldspars from the Telemark-Bamble area were undertaken in order to determine whether this peculiarity was confined to the Flå area. The Herefoss granite in the Telemark-Bamble area contains K-feldspars being predominantly near maximum microcline while the augen gneisses again exhibit K-feldspars of variable obliquity. The measurements indicate that low- to intermediate and variable K-feldspar obliquities are common in augen gneisses in the catazone rather than being confined to a specific area. These results are very similar to those reported by Guitard and others (1960) for the augen gneisses from the mesozone. The augen gneisses can then be regarded as a group of rocks possessing unusual K-feldspar obliquity.

These augen gneisses are characterized by the mineral assemblage, hornblende, alkali feldspar, quartz, plagioclase, and biotite. The alkali feldspar is blastic; the hornblende is highly corroded and seems to have been largely replaced by biotite. The plagioclase contains many small patches of hazy-appearing alkali feldspar along the twin lamellae. This mineral paragenesis is not found anywhere in the area except for these restricted zones. The texture indicates that the hornblende disappeared as alkali feldspar formed; therefore, the hornblende appears to be a relic. The variable obliquity reflects non-equilibrium conditions within the augen gneisses, the mineral assemblage seem to indicate the occurrence of replacement phenomena.

Obliquities of K-feldspars from inclusions in the granite are near maximum with the exception of those from one inclusion. This was a rather large (10–20 m) inclusion of augen gneiss that graded imperceptibly into porphyric granite. K-feldspars from this inclusion (Sp 482 in Figure 3) exhibit variable obliquity within some individuals, but typically attain a maximum value of about 0.90 which probably represents equilibrium. The obliquities of K-feldspar from this rock are more typical of augen gneisses than the enclosing granite.

An alkali feldspar from the Hedal granite right at the contact of the Permian rhomb porphyry dike was X-rayed. The 131 and $1\bar{3}1$ reflections were evenly diffuse, and a monoclinic reflection appeared similar to Figure 1*f*. Because K-feldspars from granite several hundred meters away from the dike showed maximum obliquity, this phenomenon must be ascribed to thermal metamorphism by the dike.

The feldspars from one 15-cm. alkali feldspar crystal fall in the upper intermediate obliquity class constitute somewhat unusual occurrences. The large crystal occurs in a granite dike which contains *RD* alkali feldspar. Another intermediate alkali feldspar is from within 1 cm. of the contact between the Ådal granite and the surrounding gneiss (Sp 509G in Figure 3).

In a hornblende gneiss, which occurs as a 20–30-m layer between granite gneiss and amphibolite, shadowy-appearing alkali feldspar is found as interstitial fillings and films between grains and as replacement patches in plagioclase (An_{35}). The K-feldspar is randomly disordered but has a maximum Δ of *ca.* 0.8. This *RD* K-feldspar is associated with antiperthite interpreted as incipient replacement of plagioclase.

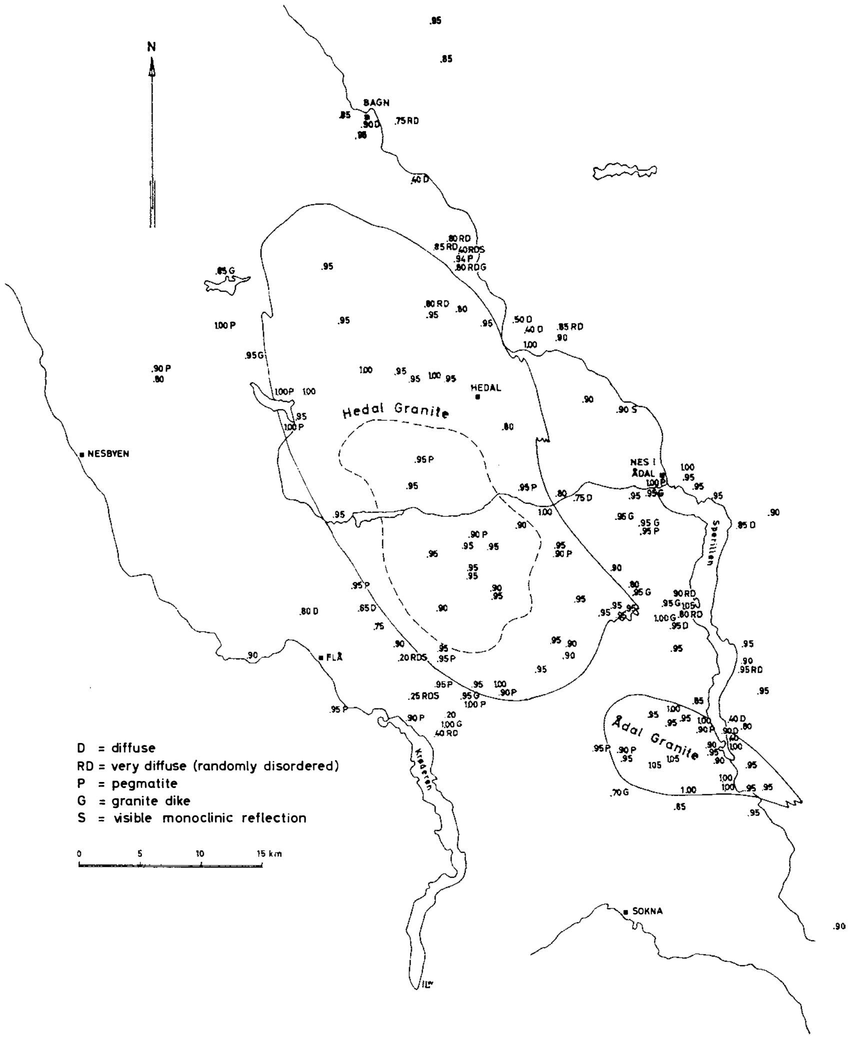

Figure 2. Map of the Flå granite area showing the areal distribution of K-feldspar obliquities. The lower Δ-values follow zones of augen gneiss and migmatite.

Distribution of Obliquity within Single Hand Specimens

An estimate of the distribution of obliquity within a single hand specimen was desired in order to obtain a better insight into the distribution of K-feldspar obliquity within a small volume. Ac-

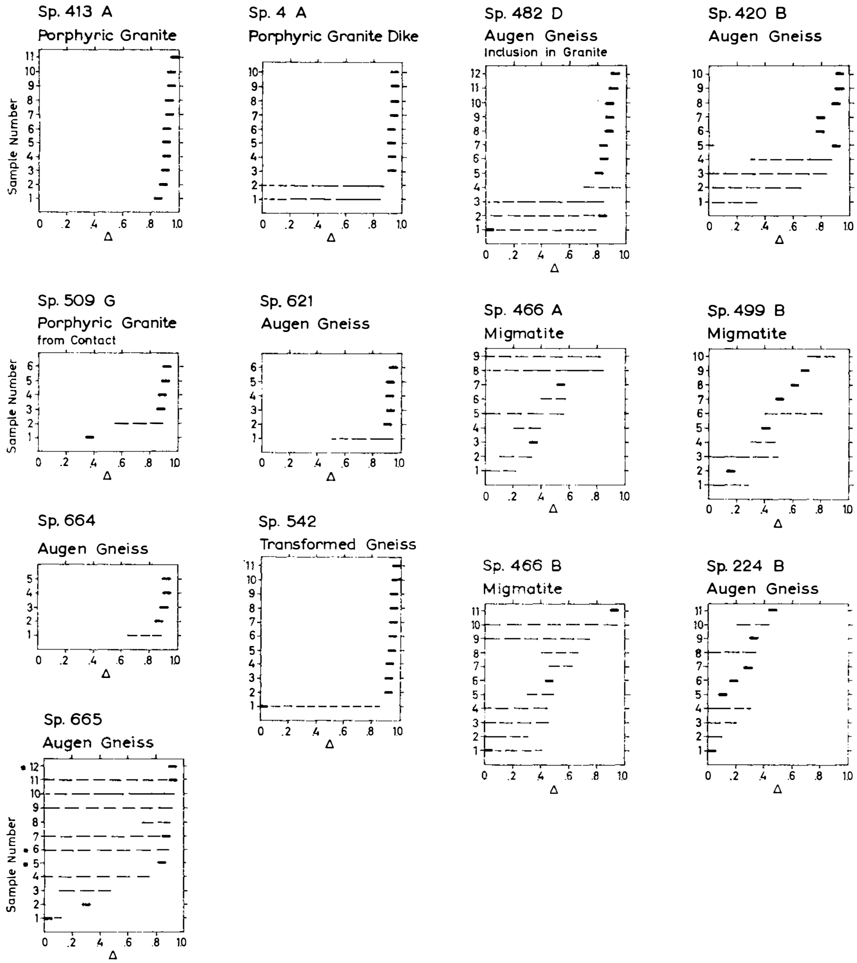

Figure 3. Graphs showing the distribution of Δ in crystals picked from a single hand specimen. ■ Sample with uniform obliquity (sharp reflection).
— — — — — Sample with variable obliquity increasing toward 1.0.
— — — — — Sample with variable obliquity decreasing toward 1.0.
— — — — — *RD* sample.
■— — — — Sample with dominantly uniform obliquity and some *RD* domains.
*) Samples from the same feldspar augen.

cordingly, approximately 10 alkali feldspar crystals were picked from each one of selected specimens. The rather surprising results are displayed in Figure 3.

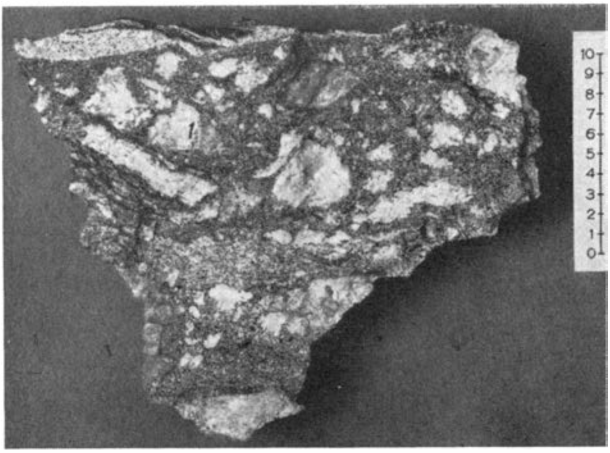

Figure 4. Feldspar porphyroblasts in a transformed gneiss (Sp. 542). The one RD orthoclase (see Figure 3) is marked by the number 1. The other prophyroblasts are microcline and a few plagioclases, scale in cm.

The granite (Sp 413A) from the Hedal granite contains maximum microcline (Figure 3). More unusual is Sp 4A of a porphyric granite dike. Two of the 10 alkali feldspars showed obliquities that vary from 0 to 0.85. Sp 509G from the contact (within 0–5 cm. of the contact) of the Ådal granite contains some K-feldspars of unusual obliquity (Figure 3).

The K-Feldspars from augen gneisses and certain migmatites are highly variable, both among and within hand specimens. Some K-feldspars from augen gneisses (Sp 621 and Sp 664) exhibit a mode which has an obliquity equal to granite feldspars, but they both contain alkali feldspars with variable obliquity. Alkali feldspars from the other augen gneisses and migmatites range from monoclinic to almost maximum triclinic within the same hand specimen. They also commonly contain crystals with variable obliquity in which Δ ranges from 0.0 to 0.9. Although both orthoclase and maximum microcline are not rare in these specimens, feldspars of variable obliquity are most common. Both monoclinic domains and domains of variable obliquity may be found in the same crystal, or domains of variable obliquity and domains of uniform maximum obliquity may occur in the same crystal.

Three specimens from one large (5 cm.) alkali feldspar eye in Sp 665 were X-rayed. The Δ-value was different in each of these, and one was an *RD* K-feldspar (Figure 3). At least this *RD* crystal and probably many more are characterized by comparatively large (1–2 mm.) volumes that differ in obliquity from each other, a not uncommon phenomenon described previously by Goldsmith and Laves (1954b) and Guitard and others (1960).

Two specimens, Sp 542 and Sp 665 (Figure 3), show extreme ranges of obliquity. Of the 11 samples X-rayed from porphyroblasts of Sp 542, 10 of them were maximum microcline and the other was mainly orthoclase that was randomly disordered. The orthoclase porphyroblast looked exactly like the triclinic porphyroblast (Figure 4) in hand specimen. Sp 665 also contains crystals of both monoclinic and maximum microcline, but the variability is great in this hand specimen; *i.e.*, 10 out of 12 samples produced X-ray patterns with diffuse $131/1\bar{3}1$ reflections. It seems reasonable that near-maximum microcline, which is the usual K-feldspar throughout the area, is the stable K-feldspar phase in both these specimens which are typified by metastable phases.

Conclusions

This investigation shows the following trends for an area composed of gneisses in the upper amphibolite facies and of granites: 1) K-feldspars from granite and pegmatite have maximum obliquity. 2) K-feldspars from gneisses may have either maximum or variable obliquity. 3) K-feldspars from augen gneisses and migmatites are often randomly disordered over the whole range of Δ values and include all *RD* scale numbers (Christie, this volume pp. 383). 4) Obliquity of K-feldspars in single hand specimens of augen gneisses and migmatites is highly variable from crystal to crystal as well as in single crystals and ranges continuously from $\Delta = 0$ to $\Delta = 1$. 5) The characteristic feature of the peculiar K-feldspar symmetry is blastesis and replacement associated with a rock that appears to undergo a change in bulk composition.

How can the petrogenic history of these rocks be interpreted in light of the symmetry relations of these alkali feldspars? It is generally recognized that monoclinic alkali feldspar may form in two ways: 1) Within the stability field of monoclinic feldspar over *ca.* 500°C. (Goldsmith and Laves, 1954a) or 2) metastably within the stability field of microcline at less than *ca.* 500°C; *e.g.*, authigneic K-feldspars (Baskin (1956)).

If the monoclinic alkali feldspars crystallized in the granulite facies above *ca.* 500 °C. where orthoclase is common (Heier (1957)), they were either formed in extremely restricted "hot spots" or represent the frozen relicts of an earlier regional crystallization within the monoclinic stability field. Both of the above possibilities seem unlikely in view of the restricted occurrence of the gneisses that show replacement features and amphibolite-facies mineral assemblages. The only monoclinic alkali feldspar that can reasonably be ascribed to high temperature conditions is the one from the contact of the rhomb porphyry dike. Both the field occurrence and the textural features suggest that these augen gneisses are the product of at least a local metasomatism.

Crystallization of K-feldspar under laboratory conditions always results in the formation of the monoclinic phase. Goldsmith and Laves (1954b) stated that, although grid twinning in microcline indicates inversion from an original monoclinic phase, the monoclinic phase was not necessarily formed above 500 °C. The structural relations of the alkali feldspars from augen gneisses are suggestive of the variable structure of adularia. Laves (1950) and Chaisson (1950) have noted the extremely variable structural character of adularia which may be either monoclinic or triclinic. More recently, Bambauer and Laves (1960) have shown that adularia is composed of volumes that vary in optical properties and that these volumes are caused by structural rather than chemical differences. They propose that adularia crystallizes as a monoclinic feldspar and then inverts to microcline by going through intermediate stages.

The occurrence of authigenic orthoclase and low-obliquity microcline within sedimentary rocks is well known (Baskin (1956)). These feldspars and the adularias from alpine veins have probably formed metastably within the stability field of maximum microcline. The metastable structural state of authigenic feldspar and of adularia must have been determined by the conditions of growth. The alkali feldspars from these augen gneisses and migmatites may have formed in a similar manner, although probably at a higher temperature.

The augen gneisses and the migmatites are commonly sheared as are the border facies of the Flå granite. This deformation can hardly be responsible for the unusual obliquities in K-feldspar of the augen gneisses. On the contrary, Eskola (1951) and Karamata (1960) believe that deformation catalyzes the ordering process in alkali feldspar. Deformation may have hastened the ordering process, and, in fact, some of most highly sheared augen gneisses have the higher Δ-values.

The plagioclase content of the alkali feldspars has been determined by an X-ray powder method (Orville (1960)). The composition of these feldspars ranges from Or_{78} to Or_{92}. If anything, the alkali feldspars from the augen gneisses tend to be richer in the K-feldspar molecule; therefore, a greater plagioclase content cannot cause the peculiar obliquities.

Since megacrysts of ordered K-feldspar occur in the granite, growth cannot be the only prerequisite for the retention of low- and variable-obliquity feldspars. Goldsmith (1953) has stated a simplexity principle by which minerals will always tend to crystallize in the disordered state, especially when crystallization is rapid. Bambauer and Laves (1960) have noted that in adularia the crystals grow more slowly as they become larger so that the outer part is more ordered than the center, and ordering progresses from the border to the center. Water is a most effective catalyst for the ordering process (Donnay and others (1960)). The obliquities of K-feldspars may depend on the amount of volatiles present, or, more likely, obliquities may depend on a delicate balance between growth rate, temperature, deformation, and available volatiles. If the growth occurs at a relatively low temperature, thermal energy may be too low to initiate ordering of the crystal lattice. The conditions must be quite variable from crystal to crystal for hand specimens to exhibit highly variable Δ-values.

The water may be present as a variable adsorbed film that facilitates metasomatic transport, crystal growth, and ordering processes. Finitely spaced shear planes may further add to the heterogeniety of the rock. Obviously, these factors might tend to counteract each other somewhat; *i.e.*, greatest shearing, and most rapid chemical transport and crystal growth would probably occur where water was most abundant. The effect of locally varying water content on K-feldspar obliquity has been stressed by several authors (Emeleus and Smith (1959); Guitard and others (1960)).

As a result of this study, the author makes the following proposals: 1) In areas where different Δ-values are found, more than one sample is necessary from each hand specimen in order to determine a representative Δ-value. 2) *RD* K-feldspars are characteristic of metasomatic gneisses which exhibit replacement fatures. 3) *RD* K-feldspars form by a delicate interplay of growth rate, shear, temperature, and volatiles present, of which volatiles may be the most important. 4) Amphibolite-facies gneisses are characterized by alkali feldspar with a wide range of obliquities (see also Guitard and others (1960)). 5) As already noted by Goldsmith and Laves (1954a), alkali feldspars often form metastably so that care must be exercised in interpreting low Δ-values as a function of high temperature.

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