K-FELDSPAR STRUCTURAL STATES AS PETROGENETIC INDICATORS

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Abstract

Structural states, based on $\Delta = 12.5[d_{1\bar{3}1} - d_{131}]$, are reported for approximately 200 K-feldspar specimens from rocks of several different known origins. Represented are volcanics, phenocrysts of diverse crystal habits and sizes, two instrusive sequences, pegmatitic generations and zones, pegmatites of diverse ages and localities, pegmatites of the same region but within country rocks of diverse metamorphic grades, authigenesis, different parts of a large porphyroblast, porphyroblasts from parts of a single metamorphic unit, rocks of a metasedimentary terrane which exhibit different grades of metamorphism, and miscellaneous, less commonly recognized kinds of rocks.

Several tentative conclusions are listed. In general, no Δ-value has been found to be restricted to K-feldspars within rocks of but one origin. If, however, obliquity fixation occurs under essentially equilibrium conditions and depends chiefly on temperature, Δ-values constitute additional, though quite provisional, evidence to aid petrogenetic interpretations.

Introduction

There have been several attempts to correlate structural states of K-feldspars, as defined by $\Delta = 12.5[d_{1\bar{3}1} - d_{131}]$ [1], to the petrogeneses of their containing rocks. Most attempts, however, have been

[1] This Δ-value has been designated *obliquity*, *triclinicity*, and even *degree of disorder*. In this paper, *Δ-value* or *obliquity* are used; *triclinicity* is considered inappropriate and *degree of disorder* is believed to have too broad connotations.

related to special problems and are thus of rather limited petrogenetic implication.

Perhaps the dearth of attempts to investigate the possible utility of the value as a general petrogenetic indicator reflects a reluctance dependent upon the fact that it is well known that more than one factor may control the measured parameter. There appears to be little doubt that K-feldspars with all Δ-values except theoretical 0.0 and 1.0 may have innumerable atomic arrangements because both Al–Si and K–Na relative quantities and arrangements may control the measured angle. Further, establishment of Δ-values [2] must be controlled by both static and dynamic conditions of temperature, pressure, and bulk composition (including both volatile and nonvolatile constituents) and even duration of time under each set of conditions.

The present investigation was undertaken despite cognizance of these contigencies. It was still believed that preliminary study of K-feldspars from several rocks of diverse known, *i.e.* generally agreed-upon, origins should be made to determine if their Δ-values might serve to aid general petrogenetic considerations.

Data are presented for K-feldspars with the following occurrences:

1. volcanic rocks of different ages and compositions,
2. phenocrysts from a single igneous mass but with diverse crystal habits and sizes
3. members of two intrusive sequences,
4. different generations and zones of individual pegmatite masses,
5. pegmatites of different ages and from several localities,
6. pegmatites of the same district but within country rocks of diverse metamorphic grades,
7. authigenic,
8. several parts of a porphyroblast,
9. porphyroblasts from relatively widespread parts of a single metamorphic unit,
10. rocks of a metasedimentary terrane which exhibit different grades of metamorphism,
11. miscellaneous, relatively uncommonly recognized occurrences.

[2] This establishment of Δ-values, with implication of all the controls will be termed fixation in this paper. *i.e. fixation* = conditions under which atomic migration that effects Δ-values ceases.

Acknowledgments

This investigation was initiated at the Mineralogical Museum in Oslo in 1960 and continued at the Virginia Polytechnic Institute at Blacksburg. All except the initial part of the study was sponsored by the National Science Foundation under Research Grant NSF-G 16022. Messrs. F. T. Lee and R. S. Dietrich assisted in the separation and X-ray laboratories. The names of the geologists who kindly supplied the specimens are given in the appropriate places on Table 1. Drs. W. S. MacKenzie and J. A. Redden read and criticized the original manuscript. Several scientists who attended the NATO-sponsored Advanced Study Institute of Feldspars made suggestions incorporated in the final manuscript. Each of these contributions is gratefully acknowledged.

Procedures

The K-feldpsars were hand-picked and/or separated from their associated minerals by using heavy liquids. Obliquities of all specimens were measured on graphs obtained from a General Electric XRD 5 spectrogoniometer X-ray diffraction unit with CuKα radiation and Ni filter (a scanning speed of 1°/5 mins. was used). Obliquities of some specimens were also measured on films taken with a 114.6 mm. Philips camera setup with CuKα radiation and Ni filter. With the former setup, 1°/5 mins. scanning speed, *and* narrow slits two reflections may be distinguished for some feldspars that yield essentially single lines on films and on spectrogoniometer graphs obtained by using wider slits and/or faster scanning speeds (*e.g.*, 2°/Min.).

The 2Θ or d values used to calculate the Δ-values were measured as indicated on Figure 1. The measurement procedures were established after many procedures were evaluated and after the writer had contacted and obtained opinions from several workers who had previously published data relating to K-feldspar obliquities.

Although each of the powder methods leaves much to be desired, all are more useful than single crystal methods for studies such as this one, particularly since a larger sample is used, thus permitting easier determination of the homogeneity of specimens. (Time was, of course, another consideration because approximately 800 patterns were made.) In general, essentially identical values were obtained on

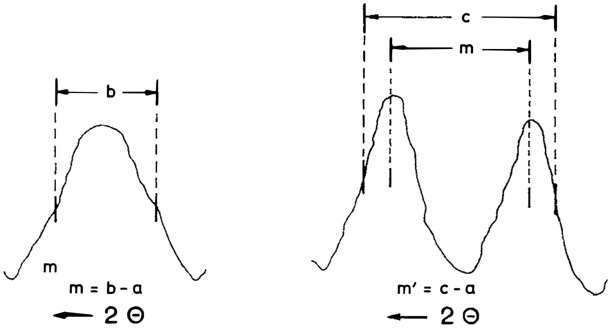

Figure 1. Schematic representation of patterns obtained from spectrogoniometer setup used in this study with a scanning speed of 1°/5 mins. Measuring procedures are indicated with m being the value used in the calculations, *i.e.* $m=2\theta_{1\bar{3}1}-2\theta_{131}$ with $Cu/K\alpha$ radiation. The figure a is the half-height width of the 022 (plus 041, $\bar{2}22$, $02\bar{2}$, and $04\bar{1}$ — see Goldsmith and Laves, 1952, p. 4) reflection for the measured specimen. The Δ-value is, therefore, 0.0 when 131 and 022 (*etc.*) $20\bar{1}$ reflection for a given specimen have equal half-height widths. For consistency, one might use $m=c-a$ for patterns with two distinct peaks; this was not done in this study. With a spectrogoniometer setup as used but run at a scanning speed of 2°/min. and with camera setups, single reflections, albeit not sharp, appear for most K-feldspars reported as less than ca. .25 in this paper. With narrow slits and the slow scanning speed Δ-values as low as .17 may commonly be based on measurements of two distinct peaks. It is interesting that for the right hand diagram if c were used as equal to m that, for example, a ca. 1.15 Δ-value would supplant a .80 Δ-value.

at least three "runs" with the X-ray beam centered on different parts of the specimens in each "run". The exceptions are those for which ranges are reported. Reported Δ-values have relative reliabilities of less than ± 0.01 deviation. Δ-values reported as less than ca. .20 would be equivalent to those reported as, for example, 0.0–.15, by some workers.

Optical observations (see Table 1) were made on fragments in oils and/or grains in thin sections with a polarizing microscope equipped with a Universal Stage.

Chemical and X-ray quantitative Ab-content determinations are incomplete at present but will be made available later.

Results

Volcanics and associated aphanophyres.—Ages represented include "older Precambrian", late Precambrian or early Cambrian, Carboni-

Table 1

Specimen numbers	Occurrence [1]		Δ-Values	Opt. class [2]	Per. [4]	Source of material	Reference
1	Peg.	Landsverk I, Evje, Norway (G–2)	.90–.94	Mi	P	T. L. Sverdrup	Taylor, *et al.*, 1960
2, 6, 7	Peg.	Landsverk I, Evje, Norway (G–3)	.81–.85	Mi		T. L. Sverdrup	Taylor, *et al.*, 1960
3	Auth.	John Day Fm., Mitchell, Ore., U.S.A.	.11	Or		R. L. Hay	Hay, 1960
5, 162–167	Meta.	Augen gn., Feda, Norway	.11–.13	Or	P	T. F. W. Barth	Barth, 1956
8, 9	Peg.	Landsverk I, Evje, Norway (G–1)	.93–.98	Mi	P	T. L. Sverdrup	Taylor, *et al.*, 1960
10, 11	Int.	Kjelsåsite, Søkeldalen, Norway	.17–.21	Or	P	Oslo Museum	Barth, 1945
12	Int.	Lardalite, Larvik, Norway	.44	Mi	P	Oslo Museum	Barth, 1945
13	Int.	Larvikite (*lgt*), Tvedalen, Norway	.35	Mi	P	Oslo Museum	Barth, 1945
14	Int.	Lavikite (*dk*), Tjølling, Norway	.55	Mi	P	Oslo Museum	Barth, 1945
15	Int.	Nordmarkite, Sognsvandet, Norway	.74	Mi	P	Oslo Museum	Barth, 1945
16	Int.	Ekerite, Hamre, Norway	.94	Mi	P	Oslo Museum	Barth, 1945
21	Vol.	"Cinder Tuff", Brohl Mtn., Germany	.07	San		Oslo Museum	Dorn, 1951
22	Meta.	Xenolith in hyperite, Hökås, Sweden	.07	Or	P	P. Ljunggren	Ljunggren, 1959
23–35	Int.	"Felsic Porphyry", Beartooth Mtns., Montana, U.S.A.	.08–.13	Or		W. D. Lowry	Eckelmann & Poldervaart, 1957
36	Peg.	Rutherford Mine, Amelia, Va., U.S.A.	.97	Mi	P	VPI Museum	Lemke, *et al.*, 1952
37, 38	Peg.	Delaware Co., Pa., U.S.A.	.93–.96	Mi	P	VPI Museum	Sterrett, 1923
39	Peg.	Villeneuve, Quebec, Canada	.95	Mi	P	VPI Museum	Spence, 1932
40	Peg.	Pikes Peak, Colo., U.S.A.	.95	Mi	P	VPI Museum	Hutchinson, 1960
41–59, 158–160	Meta.	Banded gneiss, Randesund, Norway	.88–.96	Mi		R. V. Dietrich	Dietrich, 1959
62	Peg.	Etta Mn., Keystone, N.D., U.S.A.	.93	Mi	P	VPI Museum	Page, *et al.*, 1953
64	Peg.	Branchville, Conn., U.S.A.	.90	Mi	P	VPI Museum	Shainin, 1946
65	Peg.	Parry Sound, Ont., Canada	.86	Mi	P	VPI Museum	Satterly, 1943
66	Peg.	Graham Mn., Ashe Co., N.C., U.S.A.	.93	Mi	P	VPI Museum	Sterrett, 1923
67	Peg.	Bathurst, Ont., Canada	.88	Mi	P	VPI Museum	Hewitt, 1952
68, 69, 91–93	Vol.	(Meta.) Mt. Rogers, Va., U.S.A.	.78–.87	Mi	P	R. V. Dietrich	Stose & Stose, 1957

70–76	Auth.	Galena Fm., Fillmore Co., Minn., U.S.A.	.07–.15	Or		M. P. Weiss	Weiss, 1954
78	Int.	Adamellite, Boulder Bathylith, Mont., U.S.A.	.40–.45	Mi	P	A. Knopf	Knopf, 1957
79	Int.	Unionville gd., Boulder Bathylith, Mont., U.S.A.	.05–.07	Or	P	A. Knopf	Knopf, 1957
80	Int.	Clancy gd., Boulder Bathylith, Mont., U.S.A.	.08–.10	Or (+minor Mi)	P	A. Knopf	Knopf, 1957
81	Int.	Musc.-bio.gr., Boulder Bathylith, Mont., U.S.A.	.44–.50	Mi	P	A. Knopf	Knopf, 1957
83	Int.	Porphyritic gd., Boulder Bathylith, Mont., U.S.A.	.12–.13	Or	P	A. Knopf	Knopf, 1957
84, 170, 174–176	Auth.	Soil, Blacksburg, Va., U.S.A.	.78–.81	Mi [3]		C. E. Sears & R. V. Dietrich	none
85, 102 151–152, 154	Int.	Unakite, Vesuvius, Va., U.S.A.	.12–.29	Or	P	VPI Museum	Dietrich, 1962
86, 89, 101, 150, 153, 155	Meta.	Unakite, Vesuvius, Va., U.S.A.	.78–.91	Mi		VPI Museum	Dietrich, 1962
96	Peg.	Helen Beryl, So. Blk. Hills, S.D., U.S.A. (1 Int.)	.86	Mi	P	J. C. Ratté	Page, *et al.*, 1953
97	Peg.	Helen Beryl, So. Blk. Hills, S.D., U.S.A. (2 Int.)	.96	Mi	P	J. C. Ratté	Page, *et al.*, 1953
100	Peg.	Helen Beryl, So. Blk. Hills, S.D., U.S.A. (Fract.)	.92	Mi	P	J. C. Ratté	Page, *et al.*, 1953
103	Vol.	Trachyte, St. Leonards, Dunedin, New Zealand	.07	"An"		Otago Univ.	Marshall, 1909
104	Vol.	Trachyte, Otago North Head, New Zealand	.10	San		Otago Univ.	Marshall, 1914
105	Vol.	Trachyte, Omili, Otago Peninsula, New Zealand	.10	San		Otago Univ.	Marshall, 1909
106	Vol.	Ulrichite (dike), Portobello Peninsula, N. Zealand	.10	San		Otago Univ.	Benson, 1938
107–130	Meta.	Augen gneiss, Floyd Co., Va., U.S.A.	.88–.96	Mi	P	R. V. Dietrich	Dietrich, 1959
134	Vol.	Mt. Livermore, Jeff Davis Co., Texas, U.S.A.	.12	San		J. L. Snyder	Snyder, ms.
135–143	Vol.	Crowsnest vols., Alta., Canada	.06–.14	San		R. E. Folinsbee	Baadsgaard, *et al.*, 1961; Beveridge & Folinsbee, 1956
148–149	Vol.	Red Rock rhyolite, Tonto Basin, Arizona, U.S.A.	.05–.18	Or		E. D. Wilson	Wilson, 1939
156–157	Peg.	Mitchell #2, Bedford Co., Va., U.S.A.	.92–.98	Mi	P	R. V. Dietrich	none
169		Amygdules in Unicoi basalt, Damascus, Va., U.S.A.	.84	Mi [3]		A. J. Stose	Dietrich, 1956

Table 1 (*cont.*)

Specimen numbers	Occurrence [1]		Δ-Values	Opt. class [2]	Per. [4]	Source of material	Reference
171, 173	Sed.	detritus (?), Elbrook Fm., Blacksburg,Va.,U.S.A.	.10–.15	Or		C. E. Sears	none
177, 179	Sed.	detritus (?), Elbrook Fm., Blacksburg,Va.,U.S.A.	.10–.15	Or		C. E. Sears	none
172,178,180	Auth.	Veins in #171 *etc.*, Blacksburg, Va., U.S.A.	.78–.82	Mi		C. E. Sears	none
181	Vol.	Carboniferous Qtz. Porphyry, Donnersberg, Germany	.12	Or	P	VPI Museum	Dorn, 1951
182	Vol.	Variscan Qtz. keratophyre, Wurdinghausen, Westfalia	.14	Or		VPI Museum	Dorn, 1951
183	Vol.	Tertiary trachyte, Mt. Dove, Auvergne, France	.07	San		VPI Museum	Dorn, 1951
184	Vol.	Variscan keratophyre, Hartz Mts., Germany	.10	Or	P	VPI Museum	Dorn, 1951
187	Meta.	Lynchburg Gneiss (staurolite-sillimanite zone boundary), Altavista District, Va., U.S.A.	1.06	Mi	P	J. A. Redden	Redden, ms. in prep.
188	Meta.	as 187 (high sillimanite zone)	.13			J. A. Redden	Redden ms. in prep.
189	Meta.	Archer Creek Fm. (low sillimanite zone) Altavista Dist., Va., U.S.A.	.50	Mi		J. A. Redden	Redden, ms. in prep.
190	Meta.	Archer Creek Fm (low sillimanite zone) Altavista Dist., Va., U.S.A.	1.0	Mi		J. A. Redden	Redden, ms. in prep.
191	Peg.	Sillimanite zone (high) Altavista Dist., Va., U.S.A.	.15	Or		J. A. Redden	Redden, ms. in prep.
192	Peg.	Sillimanite zone (low) Altavista Dist., Va., U.S.A.	.80	Mi	P	J. A. Redden	Redden, ms. in prep.
193	Peg.	Sillimanite zone (low) Altavista Dist., Va., U.S.A.	.91	Mi	P	J. A. Redden	Redden, ms. in prep.

[1] Peg.—pegmatite; Auth.—authigenic; Meta.—metamorphic; Int.—intrusive; Vol.—volcanic.
[2] Mi—microcline; Or—orthoclase; San—sanidine; "An"—anorthoclase.
[3] —after microcline signifies lack of "grid" twinning.
[4] P—mega- or micro-scopically perthitic.

ferous, Permian, Cretaceous, and Tertiary. Rock types include keratophyre, trachyte, rhyolite, and ulrichite (Olivine-bearing tinguaite porphyry). Four of the samples were derived from different units of the Late Tertiary of Otago, New Zealand and four other samples came from the Mesozoic Crowsnest Volcanics from different localities in Alberta, Canada.

It is very likely that the K-feldspars in each of these rocks were originally sanidine. The K-feldspars from most of them still are essentially monoclinic with either sanidine or orthoclase optics and with Δ-values of less than .14. Somewhat surprisingly, feldspars identified optically as sanidine had Δ-values ranging up to .14. Those identified as orthoclase ranged from .05 to .18. Of the K-feldspars that occur with high temperature (optically) plagioclase those studied from the Oligocene of the Davis Mountains in Texas, U.S.A. yielded the highest Δ-value, .12. There is no regular variation of Δ-value with rock type in the studied volcanic series. The volcanics from the Mt. Rogers volcanics of Virginia, U.S.A. contain phenocrysts (not xenocrysts) that are now microcline. These volcanics have undergone notable tectonism but only low grade metamorphism. Two relatively large K-feldspar phenocrysts from the Crowsnest Volcanics were selectively sampled and found to have higher Δ-values in their interiors than nearer their exteriors.

Injected mass–Phenocrysts.—Large and small phenocrysts of three crystallographic habits are intimately associated in a Laramide porphyry in the Beartooth Mountains, approximately two miles north of the Wyoming-Montana border, U.S.A. The crystallographic habits represented are: (1) simple crystals with basal and side pinacoids plus prism faces, (2) penetration Carlsbad twinned crystals, and (3) Manebach twinned crystals. The twinned individuals are like the simple crystals described in (1). Typically the *a* crystallographic axes are much longer than the *c* axes in crystals of types (1) and (3) whereas the reverse relationship prevails for the Carlsbad twinned phenocrysts. Central, intermediate, and marginal parts of both large and small phenocrysts of each habit yielded Δ-values between .08 and .13. No consistent relationship was found to exist between Δ-values and size of, habit of, or position within the phenocrysts.

Intrusive sequences.—K-feldspars from representative specimens of the Cretaceous composite Boulder Bathylith gave the results shown

Table 2. Parameters of the composite Boulder Bathylith phanerites: data, except for obliquity (Δ-value) and differentiation index (D.I.), are from Knopf (1957, p. 100); rocks are listed in order of intrusion, top to bottom, in left column.

Rock type	SiO_2 *content*	*Density*	*D.I.*	An *in plag.*	Color *Index*	Δ-*value*
Unionville granodiorite	61.14	2.78	58.1	47	21.6	.05–.07
Clancy granodiorite	65.49	2.71	67.3	44	15.0	.08–.10
Porphyritic granodiorite	66.14	2.70	71.9	40–20	10.4	.12–.13
Adamellite	71.28	2.65	79.7	40	5.8	.40–.45
Two mica granite	not anal.	2.61		30		.44–.50

on Table 2. The range of values given for some of these samples indicates inhomogeneity of Δ-values within the feldspars in these rocks.

If the measured samples are truly representative and if this sequence is representative of intrusive sequences, it may be said that there is a tendency for Δ-values of K-feldspars to increase with silica content. Therefore, it may also be inferred, with the same qualifications, that Δ-values commonly increase with "normal" magmatic evolution, lowering of temperature of consolidation, increase of volatile-content (?!!), *etc.*

K-feldspars from Permian Oslo Series rocks were also measured. These feldspars have been studied by several investigators (*e.g.*, Barth (1945), Oftedahl (1948), Muir and Smith (1956)) and each has used different nomenclature. This apparent disagreement stems chiefly from the fact that the feldspars are highly variable and even some individuals are difficult to name. The designations of the present writer (Table 1) need not compound this apparent confusion. They apply only to the triclinic K-rich phase with the highest obliquity found in each of the studied specimens (all specimens show ranges of Δ-values). These specimens were supplied as being representative of the listed rock types. The fact that the most oblique, K-rich feldspar constituents do yield mean Δ-values that "fit" into the sequence as

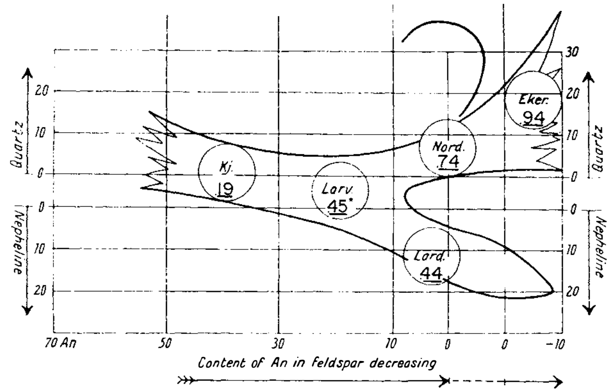

Figure 2. Family tree, showing the systematic positions and interrelationships of the principle Oslo Series rocks (after Barth, 1945) and mean Δ-values, underlined figures within circles, for the contained K-feldspars. * "dark" larvikite −.55 and "light" larvikite −.35.

shown (Figure 2) may corroborate the tentative conclusion based on the Boulder Bathylith rocks. This aspect of the study is being continued by checking to see what ranges of Δ-values exist within certain of the individual intrusive masses.

These apparent trends are interesting. The fact that all the Boulder Bathylith rocks crystallized originally with monoclinic K-feldspar (the microclines have "grid" twinning) and that only the K-feldspars of the late members of the sequence were transformed to microcline may have great bearing on questions such as those relating to whether Δ-values are fixed under essentially equilibrium conditions as well as metastably at lower temperatures.

Pegmatite generations and zones.—The Landsverk I Pegmatite of Evje, Norway, described by Taylor *etal.* (1960), has at least three generations of K-feldspars. These are: (1) massive pink microcline, (2) amazonite, and (3) reddish microcline which coats surfaces of the other feldspars. The feldspars of these generations have Δ-values as follows:

generation 1 – – – .93 to .98
generation 2 – – – .90 to .94
generation 3 – – – .81 to .85.

Feldspars were also checked from different zones of the Helen Beryl Pegmatite of South Dakota, U.S.A. Those from the first intermediate zone were found to have a Δ-value of .86. those from the second intermediate zone a Δ-value of .96, and those of late fracture fillings to have a Δ-value of .92.

Although these data do not appear to offer any consistent pattern, the generation 3 feldspar of the Landsverk I Pegmatite does appear possibly to fit into a picture mentioned in a subsequent section. Further, in a few specimens from this same mass which are composed of amazonite and a pink feldspar not readily identifiable as belonging to generation 1 versus generation 3, Δ-values appear possibly to offer a means of distinguishing between them.

Pegmatites from several localities.—K-feldpars from pegmatite masses of 15 widespread districts in North America yielded Δ-values ranging from .80 to .98 with all but five greater than .92 (exceptional is the metamorphosed, sillimanite-bearing one alluded to in the next section). These masses include Precambrian and Paleozoic pegmatites. The K-feldspars are white, pink, salmon colored, buff, taupe, light gray, and green. No correlation with color or any other known characteristic was recognized.

Pegmatites within country rocks of diverse metamorphic grades.—During the study, Dr. J. A. Redden suggested inclusion of K-feldspars from some of the pegmatites and enclosing country rocks of the Altavista District of the western Piedmont of Virginia, U.S.A. Dr. Redden collected the samples and gave the grade designations used in the next paragraph.

K-feldspar from three pegmatite masses of the sillimanite zone were checked: one in the "hottest" part of the zone, one in the "coolest" part, and the third in an only slightly warmer part. As might be expected, the Δ-values of the K-feldspars of these pegmatites – – .15, .91 and .80,, respectively – – vary inversely with the indicated degree of metamorphism of the country rocks. Probably more noteworthy, however, is the fact that the Δ-values of the pegmatitic K-feldspars from the "hottest" zone and of those of the surrounding country rocks are nearly the same, .15 and ca. .13.

The pegmatite in the "hottest" part of the zone contains much sillimanite and appears to have been modified since formation. The other two masses appear to have had simpler histories. Therefore, although the Δ-values of the K-feldspars of each of the pegmatites may reflect a reaching of equilibrium during the metamorphism, more likely only the sillimanite-bearing pegmatite reflects such. In fact, the other two pegmatites may have been formed after the chief period of metamorphism.

The sillimanite-bearing pegmatite is especially interesting not only because of its sillimanite content but also because it is the only pegmatite the writer has found to contain an essentially monoclinic K-feldspar (others have been reported by other workers, however).

Authigenic.—Δ-values have been measured for K-feldspars termed authigenic from the Upper and Lower Dubuque and Stewartsville members of the Ordovician Galena Formation in southeastern Minnesota, U.S.A. and from the Upper Oligocene John Day Formation near Mitchell, Oregon, U.S.A. and for K-feldspars, which probably would be designated by most geologists as authigenic, that occur in the Upper Cambrian Elbrook Dolomite, spatially associated veins, and overlying "residuum" in and near Blacksburg, Virginia, U.S.A.

Locally the bulk of some of the rocks of the Galena Formation is now K-feldspar and several specimens have been found in which even fossil fragments are now composed of K-feldspar (Weiss (1954)). Δ-values of these feldspars range between .07 and .15.

Hay (1960) reported K-feldspar in the John Day Formation to

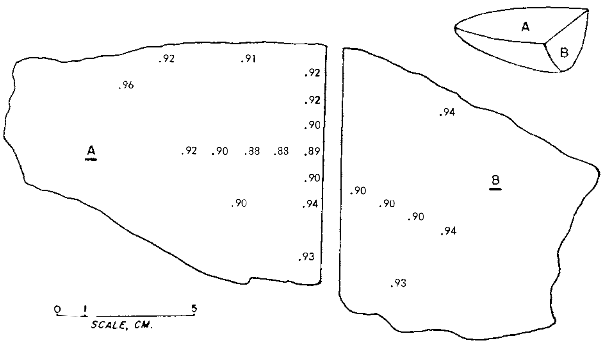

Figure 3. Tracings of sections, cut as indicated on the small diagram, of a porphyroblast from a banded gneiss of the Randesund Area of Norway with Δ-values indicated for the measured zones.

occur as pseudomorphs after plagioclase and interpreted certain data to support a low pressure and low temperature origin for the K-feldspar. The Δ-value of this K-feldspar is .11.

The K-feldspar of the Elbrook Formation dolomite and shale may be detrital rather than authigenic. However, both that within the veins, which are chiefly carbonate and comprise a reticulate network enclosing brecciated rock fragments, and that of the overlying "residuum" may be authigenic. The interrelationships among these are currently being studied more thoroughly and will be reported upon more fully in the near future. Of the K-feldspars studied, those within the rocks of the formation are optically monoclinic and have Δ-values of .10–.15, whereas those within the veins and "residuum" are optically triclinic and have Δ-values of .78 to .82.

These data appear to agree with those of Baskin (1956) who found both monoclinic and triclinic authigenic feldspars. The reader is referred to Baskin's conclusions (*op.cit.* p. 153–154).

In addition, it may be noteworthy that along with the Elbrook Formation microclines, microcline amygdule fillings and the generation 3 microclines of the Landsverk I Pegmatite have Δ-values of circa .80. Each of these very probably was formed at relatively low temperatures.

Porphyroblast parts.—A porphyroblast from one of the banded gneisses of the Randesund area of southern Norway, and interpreted by the writer (Dietrich (1960)) to have been formed by metasomatism, yielded the data given on Figure 3. There is a tendency toward lower Δ-values in the central part than nearer the margins of the porphyroblast but the slight differences may not be significant.

The K-feldspar augen gneiss specimen from Feda which has been described and pictured by Barth (1956) was similarly sampled. Seven samples yielded values ranging between .11 and .13 with no regular relationship between Δ-values and position of samples within the individual grains.

Porphyroblasts widespread within a unit.—Porphyroblasts, augen, were collected from four exposures of the Little River gneiss in Floyd County, Virginia, U.S.A. (Dietrich (1959)). This unit is a highly sheared biotitic gneiss with blue quartz flaser and K-feldspar augen. The K-feldspar augen are typically light gray to cream colored but are locally pinkish. Most are thumb-sized but a few are up to fist-sized.

The unit is interpreted to be a metamorphosed sedimentary rock. The exposures from which the measured samples were collected include at least three different horizons and the extreme exposures are approximately 11 miles apart along the strike. Six samples were run from each area so the inside and outside portions of two different augen and matrix feldspars were included from each locality. All of the feldspars were gray except for pink ones from one of the localities. All Δ-values ranged between .88 and .96. All but three ranged between .93 and .96. This would appear merely to reflect the establishment of approximately the same conditions throughout at least the sampled parts of this metamorphic unit. Such is also suggested by the petrography of the rocks.

Rocks from a metasedimentary terrane exhibiting different metamorphic grades.—Some of the metasedimentary rocks of the western Piedmont of Virginia, U.S.A. exhibit various degrees of metamorphism (Redden, personal communication (1962)). K-feldspars from different parts of two metasedimentary units in different parts of the sillimanite zone were measured.

The highest grade rock was from a Lynchburg Formation, two-mica gneiss. The K-feldspar yielded a Δ-value of .13. The two intermediate grade rocks were from calc-silicate rocks of the Archer Creek Formation. The K-feldspars gave Δ-values of .50 and 1.0. The lowest grade rock was a Lynchburg Formation, two-mica gneiss which contains K-feldspar augen. The K-feldspars yielded Δ-values of 1.06, the greatest measured during this study.

This cursory examination of the K-feldspars of this metamorphic terrane is to be continued. The presently available data suggest that metamorphic zoning may be reflected by K-feldspar Δ-values. Perhaps rocks of certain high grade zones can even be subzoned on the basis of K-feldspar obliquities. However, those in diverse lithologies apparently may attain different Δ-values at essentially equal temperature(s) because of grain sizes, different compositions, including volatile contents, *etc.* of the rocks. Because absence of water apparently hinders ordering (Donnay, *et al.* (1960)), the volatile-content factor lends a most discouraging aspect to such studies.

Miscellaneous.—The feldspar reported by Ljunggren (1959, p. 88) as occurring within a gneissic xenolith in a hyperite dike at Hökås in southern Sweden was measured because it was reported to represent an original microcline changed to orthoclase as a result of heating consequent to incorporation within the hyperite magma. This feldspar yielded a Δ-value of .07.

Unakite from the "Blue Ridge complex" near Vesuvius, Virginia, U.S.A. commonly grades through partially unakitized, *i.e.* epidotized and K-feldspar enriched, rock to essentially unaltered original rock. The partially altered rock at this locality contains two megascopically and microscopically distinct K-feldspars as well as plagioclase feldspar. Numerous specimens of each of these distinct K-feldspar generations were measured. The "original" gray feldspars yielded Δ-values ranging from .12 to .29. The introduced pink feldspars yielded Δ-values of .78 to .91.

Conclusions

The main conclusion that can be drawn on the basis of this cursory study is that no Δ-value is restricted to rocks of any particular origin. Therefore, this parameter cannot be used as an absolute criterion for any paragenesis. Nonetheless, if obliquity values are fixed with temperature as the chief control so that Δ-value varies inversely with temperature of fixation, the obliquities of each of the measured feldspars can be correlated readily with the known geneses of the containing rocks (Figure 4). Because of this apparent agreement, obliquity values may, if nothing more, serve to focus attention on rocks the field relationships and/or petrography of which are misleading, *e.g.*, if Δ-values of some or all of the contained K-feldspars appear to be inconsistent with field relationships or general composition, preexisting disequilibrium or other commonly obscured conditions may be indicated.

Further, on the basis of the K-feldspars studied several conclusions, some of which are strictly tentative, may be made. Some of these have been suggested previously—see, for example, Eskola (1951) and Goldsmith & Laves (1954). These conclusions are:

> K-feldspars in volcanics and associated aphanophyres, all of which appear to have crystallized rather rapidly at relatively high temperatures, are monoclinic unless they have undergone subsequent deformation and/or metamorphism.

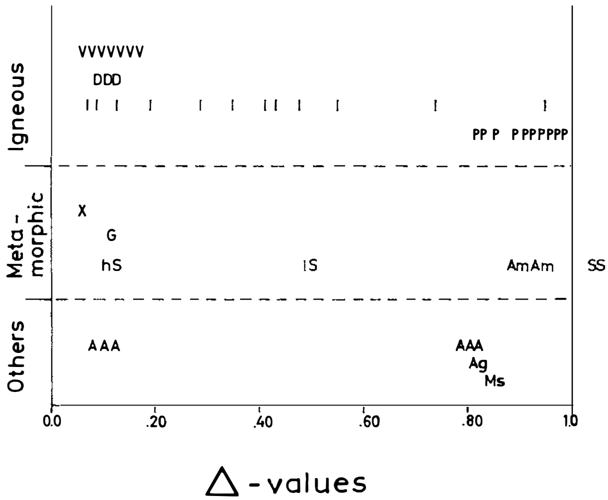

Figure 4. Distribution of Δ-values as to known rock types included in this study. Igneous rocks are indicated as follows: *V*—volcanics, *D*—minor intrusions, *I*—major intrusions, and *P*—pegmatite masses. Metamorphic rocks are indicated as follows: *X*—xenolith, *G*—granulite facies, *hS*—"hottest" sillimanite facies, *lS*—low sillimanite facies, *SS*—sillimanite-staurolite border, *Am*—amphibolite facies. "Others" are indicated as follows: *A*—authigenic, *Ms*—metasomatic (perhaps should be in previous general group), and *Ag*—amydule.

Deformation may, under some conditions, promote increase in Δ-values of K-feldspars.

Intimately associated phenocrysts within single igneous units, even though they have different crystal habits and sizes, may have essentially equal Δ-values.

Δ-values of K feldspars within different phases of intrusive sequences apparently increase with silica contents, *etc.*, although the control is believed possibly to be one involving chiefly volatile-content and/or rate of cooling.

Pegmatite generations and zones may be identified on the basis of Δ-values although the values may or may not show any consistent variation with the apparent chronological overall evolution of the pegmatite-forming solution(s).

Δ-values of K-feldspars in metamorphosed pegmatites may reflect the metamorphic grades of the surrounding country rocks.

Authigenic feldspars may be either monoclinic or triclinic. At least the former may have been formed metastably at low temperatures. (Triclinic ones measured have Δ-values of ca. .80.)

Parts of individual porphyroblasts may have different Δ-values, generally within relatively small ranges.

Ranges of Δ-values within single porphyroblasts are commonly as great as those for spatially associated porphyroblasts within individual units.

Augen may attain equilibrium (may be formed??) with either low or high Δ-values.

Porphyroblasts may have essentially identical Δ-values within different parts of single metamorphic units so long as the parts are of the same metamorphic grade.

Rocks containing two generations of K-feldspars, typically recognizable petrographically, may have both high and low obliquity K-feldspars with no accompanying intermediate-value ones.

Metamorphic zoning may be reflected by K-feldspar Δ-values. Perhaps rocks of certain lithologies in given high grade zones may even be subzoned on the basis of Δ-values.

Essentially simultaneous Δ-value fixation of spatially associated K-feldspars may take place under diverse conditions (*e.g.*, surrounded by volatile- versus nonvolatile-bearing minerals) and thus result in attainment by those K-feldspars of different Δ-values.

Natural feldspars that have transformed from sanidine to microcline as well as in the opposite direction have no unique Δ-values.

Ranges of Δ-values within phenocrysts and porphyroblasts appear to be similar.

There appears to be no correlation between Δ-values and color of K-feldspar.

Most Ab-content must be exsolved before Δ-values of greater than ca. .85 can be fixed (of the approximately 80 checked, the Ab-content in solid solution is less than six per cent in microclines with Δ-values of greater than .85).

The feldspars of different occurrences that are reported in this paper plus others that have been reported in the literature since July 1960 have been added to those plotted previously by the writer (1961)

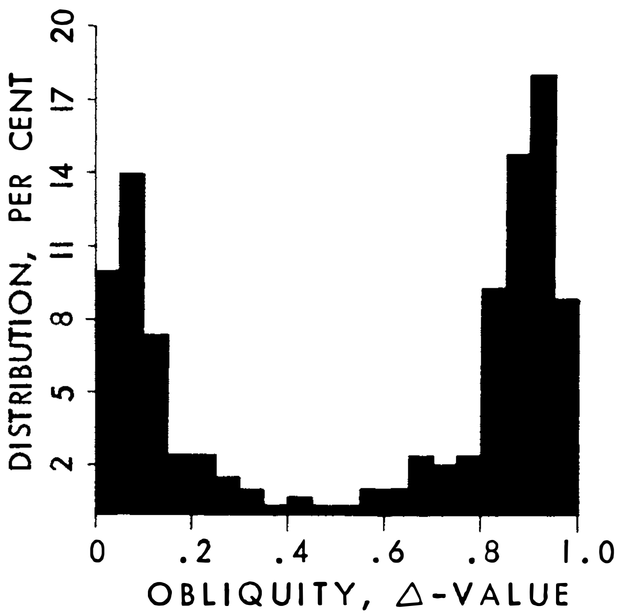

Figure 5. Distribution of obliquity (Δ-values) for 500 K-feldspars.

to compile Figure 5. There still is a definite dearth of studied feldspars with intermediate Δ-values. Therefore, two previously posed questions (Dietrich, *op.cit.*) are raised again: 1. is the lack of K-feldspars with intermediate obliquity values real (?) and 2. if so, what is the explanation (?).

The first question has been answered in the affirmative by Laves (Disc. of Dietrich, *op.cit.*) and he also has made suggestions as to how to explain it. The present writer is less convinced of the reality of the "gap". Among other things, the results of this study would appear to indicate that numerous K-feldspars with intermediate Δ-values might be found in the socalled intermediate quartz-bearing igneous rocks formed from magmas intruded into the epizone and not subsequently metamorphosed.

Until many such samples are checked it would appear superfluous to discuss possible explanations for the only possibly existent "gap". Only two points will be mentioned: 1) a curve with nearly the same form as those presented by Heier (1960, Figure 36b) and by Goldsmith and Laves (1961, Figure 7) results when population of Δ-values is plotted on a curve, the .50–1.0 portion is inverted, and temperature is considered to be the perpendicular variable; and 2) it appears advisable to call attention again to the fact that many of the data from this study appear to support stepwise changes from monoclinic to triclinic, probably along an equilibrium path, for microclines with "grid" twinning.

Δ-values of K-feldspars may become valuable petrogenetic indicators when conditions of their fixation become known. Even then, however, the petrologist will have to remain ever aware of the fact that the conditions of latest Δ-value fixation, and *not* necessarily the conditions under which the containing rock was formed or gained even most of its features, will be those reflected. It is only hoped that "memory values", heretofore not recognized, may be preserved and decipherable.

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