

ALKALI-FELDSPARS FROM THE CROWSNEST VOLCANICS, ALBERTA

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ABSTRACT

Alkali-feldspar occurs in the Crownsnest Volcanics as phenocrysts and as free euhedra in the pyroclastics and their re-worked derivatives. Composition varies from 60% to 95% Or-molecule and $2V$ from $50^\circ[\sim \perp (010)]$ to $35^\circ[|| (010)]$. Individual crystals show a range of $2V$ values, but only rarely contain more than one K-rich phase. Optics indicate that most of the K-feldspar is intermediate between high and low sanidine. A little is intermediate between low sanidine and orthoclase.

The more Na-rich K-feldspars contain flecks to large areas of pink cloudy albite with chess-board twinning whose optical and x-ray properties indicate a structural state intermediate between high and low albite. This is thought to be a replacement which has inherited the Al-distribution of the K-feldspar, thus producing the intermediate optics. As both original and replaced material coexist in many instances, this material may be suitable for testing the ionic theory of feldspar formation proposed by Ferguson and co-workers.

INTRODUCTION

The Crownsnest Volcanics of southern Alberta, are of Cretaceous (either upper Albian or lower Cenomanian) age (MacKenzie, 1956) and occur only in the foothills in the Crownsnest Pass region. The unit consists of pyroclastics and reworked pyroclastics with a greater or lesser admixture of allochthonous material. In addition, occasional flows and also a pene-contemporaneous sill are present in the section on Highway 3 west of Coleman (S. 7, Tp. 8, R. 4, W5M). The petrology and other characteristics of the unit have been discussed by J. D. MacKenzie (1914) and H. N. S. MacKenzie (1956).

DESCRIPTION OF ALKALI-FELDSPARS

The flows, many of the volcanic blocks in the pyroclastics, and the gravels and sands derived therefrom, contain abundant alkali feldspar. In some cases the feldspar grains, although free of matrix, have suffered little abrasion, and are more or less euhedral. Examples have been described (as orthoclase) by Rutherford (1938).

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Macroscopically four types of alkali feldspar can be recognised using colour as a criterion. Colour designations are after Goddard (1951).

- I. Yellowish brown (10YR5/2)—large well formed crystals of translucent appearance.
- II. light brownish gray (5YR6/1)—medium to small perfect euhedra. Opaque.
- III. Reddish brown (10R4/4)—medium to small subhedral crystals, often with cream to white core; occasionally with cream outer zones.
- IV. Yellowish gray (5Y8/1) to colourless subhedra; transparent to translucent. May be white or cream in some cases.

Type I appears to be restricted to the upper portions of the Type Section. It typically occurs as phenocrysts in a dusky yellow green (5GY4/2) trachyte, and in derivatives therefrom. Type II has only been encountered on Lynx Creek, below George Creek (S. 12, Tp. 6, R. 4, W5M) in the Carbondale River area (Clow and Crockford, 1951, p. 31); the matrix is tuffaceous. Specimens examined were collected by Crockford. Types III and IV are widespread, occurring throughout most of the Type Section, and also in the section on Mill Creek (S. 25, Tp. 5, R. 2, W5M), although the crystal form is not generally preserved in examples from the latter locality.

In thin section Types I and IV are clear and colourless. Type II is almost opaque, due to a dense white "alteration" which may consist of minute bubbles, since no trace of a clay mineral appears on *x*-ray powder patterns. Where it is unaltered the feldspar is colourless. Type III is pink and clouded, or colourless and more or less clear with irregular pink clouded areas.

The crystal forms present have been described by Rutherford (1938) using material of Type III. Faces with the following Dana letters are recorded: *b*, *c*, *m*, *y*, and *z*. Other similar crystals bear form *a* and those of Type II exhibit *b*, *c*, *m*, *y*, and *o*.

Although MacKenzie (1914, p. 17) records Carlsbad twinning in phenocrysts of the volcanics this has not been encountered in the feldspar crystals examined in this study. Some individuals are twinned, always on the Baveno law, often with a quite irregular composition face.

The feldspars have been studied by a combination of optical and *x*-ray methods. Values of $2V$ have been determined on a 4-axis universal stage, orthoscopically, using the method of Fairbairn & Podolsky (1951). This method gives results reproduceable to $\pm 0.5^\circ$, but in the present case larger errors may be assumed for values $< 10^\circ$. Measurements were made on plates from selected crystals cut approximately parallel to (100). In all cases the position of the (001) cleavage was noted on the slides before grinding of the plates had commenced.

X-ray studies have been carried out by the smear-mount method,

using a lacquer-acetone solution, on a Norelco diffractometer equipped with a geiger counter and Brown recording equipment. Exploratory patterns of the range 20° – 37° in 2θ were run at $1^{\circ}/\text{min}$, and subsequently selected diagnostic portions in the region of 20° – 22° and 31° – 34° were run at $\frac{1}{4}^{\circ}/\text{min}$. In a few cases where the presence of a clay mineral alteration was suspected the region 3° – 20° was scanned at $1^{\circ}/\text{min}$. In all cases 1° slits were used, and the chart speed was $\frac{1}{2}''/\text{minute}$.

The Potash Feldspars

All the crystals examined contain a potassium-rich phase: in most it is the only or the most dominant phase present. $2V$ determinations indicate a range of values from close to 50° [with optic plane sensibly perpendicular to (010)] through zero to near 35° [with optic plane $\parallel(010)$] (Fig. 1). Three maxima occur in the frequency distribution, in the ranges 40° – 45° and 15° – 20° [optic plane $\sim \perp(010)$] and 20° – 25° [optic plane $\parallel(010)$].

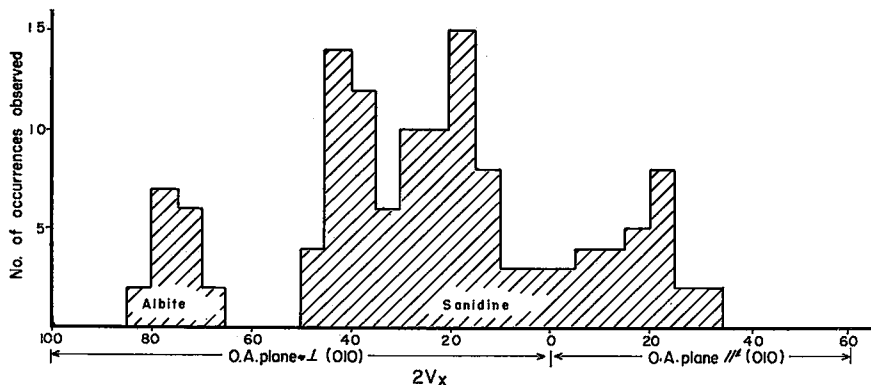


FIG. 1. Distribution of $2V$ values in alkali feldspars.

Individual crystals may show a range of values of $2V$ (Table 1). In almost every case where the range exceeds a few degrees, the crystal is zoned. Occasionally the values of $2V$ increase from core to margin, or decrease to zero and then increase in the same direction. More often, however, there is either no recognizable pattern, or much of the crystal is composed of two optically distinct phases, in a fine rhythmic alternation of zones. Some blotchiness in the extinction is often noticeable, particularly in unzoned areas, and usually the extinction is incomplete due to dispersion.

The composition of 23 selected crystals has been determined by the ($\bar{2}01$) method of Orville (1958), using KBrO_3 as an internal standard. The appropriate region was run, by oscillation, at least six times, and the

distances between peaks measured and averaged arithmetically. Unheated natural material was used in all cases. Results are tabulated in Table 1.

TABLE 1. COMPOSITION AND OPTICAL DATA OF SELECTED ALKALI FELDSPARS

Specimen number	$\Delta 2\theta^\circ$	Or%	$2V_X^\circ$	O.A. plane
5c(i)	0.973	76.6	29.9–44.6	$\sim \perp (010)$
8c	1.092	65.7	29.1–32.2	$\sim \perp (010)$
13(1)	0.909	82.6	6.1	$\sim \perp (010)$
13(7)	0.892	84.2	0	
13(8)	0.898	83.8	0–17.2	$\sim \perp (010)$
13(11)	0.886	84.6	18.5	$\sim \perp (010)$
13(15)	0.906	82.8	3.8–19.1	$\sim \perp (010)$
13(18)	0.933	80.4	0–24.8	$\sim \perp (010)$
13(19)	0.949	79.0	10.8	$\sim \perp (010)$
24b	1.125	62.5	43.8	$\sim \perp (010)$
	1.728	6.3	86.6	$\sim \perp (010)$
34c	0.745	97.5	—	—
	1.123	62.7	38.3–45.8	$\sim \perp (010)$
	1.812	0.0	77.2	$\sim \perp (010)$
34e(1)	1.011	73.2	12.1–38.2	$\sim \perp (010)$
35g	1.128	62.2	36.1–44.4	$\sim \perp (010)$
	1.773	2.2	76.4	$\sim \perp (010)$
42b	0.815	91.4	—	—
	1.156	59.8	40.5	$\sim \perp (010)$
	1.792	0.5	68.5	$\sim \perp (010)$
49g	0.779	94.5	16.2–24.7	$\parallel (010)$
71	0.821	90.7	24.1	$\parallel (010)$
	0.911	82.3	15.7	$\sim \perp (010)$
75	0.919	81.7	14.7–27.6	$\sim \perp (010)$ to $\parallel (010)$
83(i) ^a	0.972	76.8	19.9–20.9	$\sim \perp (010)$ to $\parallel (010)$
83(ii) ^a	0.926	81.1	17.1–24.4	$\sim \perp (010)$ to $\parallel (010)$
83(iii) ^a	0.887	84.5	13.5–21.0	$\sim \perp (010)$ to $\parallel (010)$
84(iii)	0.864	86.7	3.6–26.2	$\parallel (010)$
1355	1.017	72.5	12.5–32.2	$\sim \perp (010)$
	1.813	0.0	76.2	$\sim \perp (010)$
MC14 ^b	0.997	74.3	$\sim 0^\circ$	

^aCrystals from a sample from which sanidine used in K/Ar dating was selected. University of Alberta date No. AK-147.

^bFine sanidine from a bentonite; University of Alberta K/Ar date No. AK-98.

Exclusive of the phases near pure albite, which are discussed below, the range in orthoclase-content of the K-feldspar is from 60% to 95%. In most cases the presence of only one potassium-rich phase is indicated on the powder patterns. The possibility of slight exsolution, below the sensitivity range of the instrument, cannot be completely discounted in the absence of single crystal data, but is considered unlikely on petrogenetic grounds: the crystals plot above the solvus on Fig. 2.

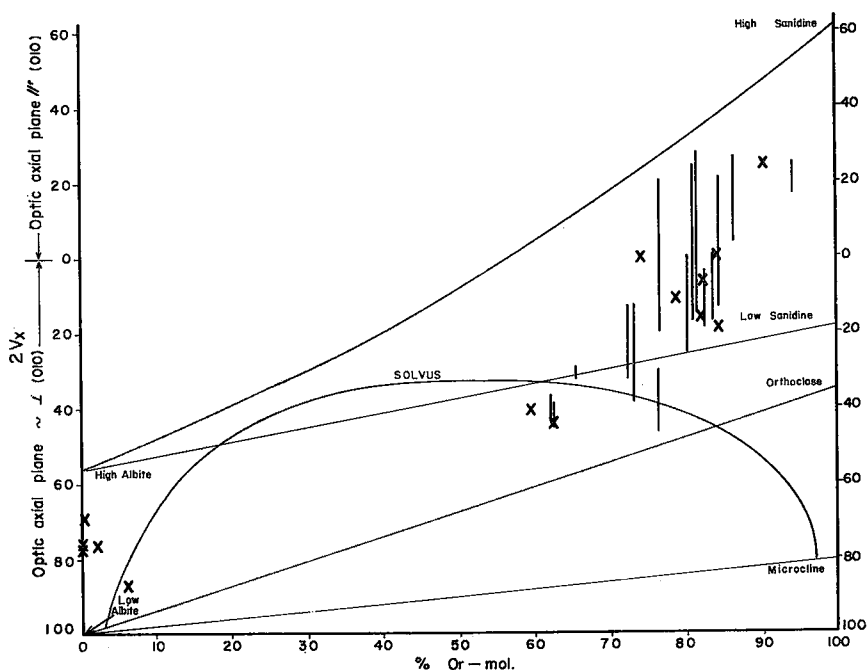


FIG. 2. Correlation of optical and compositional properties of feldspars. Lines parallel to abscissa represent variation of $2V$ in zoned feldspars showing a single potassic phase on x -ray examination. Diagram after Smith & Mackenzie (1959).

Two K-rich phases have been found in the following specimens:

Spec. No.	Or% in phases		
	I	II	III
34c	97.5	62.7	0.0
42b	91.4	59.8	0.5
71	90.7	82.3	—

In the case of Spec. 71 the two phases are thought to be represented by zones of different composition and optical properties. In specimens 34c and 42b the $Or_{60\pm}$ and $Ab_{100\pm}$ phases (II and III) are optically distinguishable. The remaining K-rich phase (I) may result from partial exsolution of crystals of phase (II) composition, in which case a corresponding sodic exsolved phase should also be present. Examination of the solvus (Fig. 2) shows that the sodic phase (III) in each specimen does not have the composition appropriate to an exsolved phase. No other sodic phase has been recognized. An exsolved sodic phase might however

pass unrecognized if it occurred in quantities below the sensitivity range of the instrument, or if its peaks were masked by those of the sodic phase (III) (which is thought to be of secondary origin). Petrogenetic considerations support the idea that exsolution has occurred: these two specimens plot below the solvus on Fig. 2, and their proximity to it suggests sluggish and incomplete exsolution should be expected (Smith & MacKenzie, 1959, p. 1175 and Fig. 5).

In Fig. 2 the feldspars studied have been plotted on the modified Tuttle diagram of Smith & MacKenzie (1959, p. 1172) (see also MacKenzie & Smith, 1955, p. 708). All may be termed sanidines: most are structurally intermediate between high and low sanidine, and the remainder are best termed low sanidines, although some of them are structurally intermediate between low sanidine and orthoclase.

There is a distinct trend towards a lower, and hence probably more ordered, structural state with decrease in orthoclase molecule content. The slope of the trend indicates that two factors contributed. In a series of feldspars formed at a constant temperature, decrease in K-content will be accompanied by a change in $2V$ which simulates the change resulting from increasing order on cooling. This effect is responsible for much of the slope of the trend on Fig. 2. The remainder of the slope apparently reflects the lower temperature of extrusion of the more Na-rich sanidines. Unfortunately little can be said about the temperature at which they initially crystallized.

As the sanidines plotted in Fig. 2 have been largely obtained from pyroclastic material, no inferences on variation of K:Na ratio in the magma during differentiation can be drawn. K-content is independent of the position of the samples in the stratigraphic sequence.

As far as can be determined from optical study and examination of powder patterns, all the potassium-rich feldspars are monoclinic. There is no appreciable doubling of the (130) and (131) peaks, which are sensitive to the development of a triclinic lattice (MacKenzie, 1954).

The Soda Feldspars

Several of the crystals examined contain a sodium-rich phase, albite. All belong to macroscopic types III and IV, most being of Type III. In all cases the sodic phase is pink, and clouded, and it is this which imparts the pink colour to crystals of Type III. In cases where it occurs in crystals of Type IV, the albite is present in insufficient quantity to influence the overall colour.

The albite occurs as irregular flecks and patches, often tabular and lying in (001). It is enclosed by sanidine, and may be concentrated in certain areas, usually in the core of a crystal. The albite may also form

an outer "zone" to crystals of pure sanidine otherwise free of albite. In these cases sanidine is restricted to the interior zones and core, all of which are free of albite.

Albite occurs in all the more sodic sanidines ($<74\%$ Or) and in several of the more potassic sanidines which are close to low sanidine in structural state. In specimens 24b, 34c, and 42b it makes up the greater part of the crystal. In 1355 and 35g it is a dense peripheral phase simulating an outer zone, but with a gradational boundary with the enclosed sanidine. It is present as irregular flecks in 5c(1), 8c, 13(1), 13(11), 13(15), 13(19) and 34e(1). Other specimens are free of any albite phase.

Where there are patches sufficiently large to enable careful study, the albite is seen to be twinned. Twinning is multiple, on the albite law, but is imperfect, the lamellae failing to traverse the full width of the patch. This gives a "chess-board" pattern, a type of arrangement occasionally noted in albite (Starkey, 1959).

All the albite encountered is unusual in being optically negative, with $2V$ in the range 68.5° – 86.6° . A partial analysis of 1355 gave 2% CaO ($= \text{An}_{10}$), the analytical error due to the small sample-size, being $\pm 5\%$ An mol. Two refractive index determinations on 1355 gave $\alpha = 1.536 \pm 0.002$ ($= \text{An}_{15}$). Determinations of potassium content, made as before by the $(\bar{2}01)$ technique, indicate a range from 0–6.3% of orthoclase molecule (Table 1). A plot of these specimens on the modified Tuttle diagram (Fig. 2) indicates that they fall on positions structurally intermediate between high and low albite.

To check the structural state of the material the region 31° – 34.25° was scanned, and the angular distances between the (131) and $(\bar{1}32)$ peaks were measured. Due to poor resolution of peaks the results given below are subject to rather large errors.

<i>Specimen</i>	$2\theta^\circ$ (131) $\wedge$ ($\bar{1}32$)	<i>Or-content</i> (%)
24b	2.54 ± 0.05	6.3
34c	2.56 ± 0.10	0.0
35g	2.71 ± 0.10	2.2
42b	2.40 ± 0.10	0.5
1355	2.55 ± 0.05	0.0

Comparison of these data with the diagram of Smith (1956, Fig. 4) indicates that, with the possible exception of specimen 35g, the structural state is intermediate between high and low albite. The correlation between these data and the measured values of $2V$ (Table 1) is poor, however. It was not possible to make confirmatory checks in other regions due to interference from the sanidine peaks.

RELATION BETWEEN SANIDINE AND ALBITE

While the occurrence of sanidine and albite together in the same crystal might suggest exsolution from an originally homogeneous crystal, there are good reasons for believing that this is not the case in the present instance.

In certain cases, where the albite forms an outer "zone", or occupies part of the core, an exsolution origin is unlikely.² In other cases, the irregularity of shape of the patches of albite, and their parallelism to (001) rather than to the exsolution direction (100) suggest that exsolution is not operative.

Further evidence comes from the compositions of the co-existing sodic and potassic phases. These are not what one would expect on petrogenetic grounds: they cannot be related to tie-lines on any known solvus. Furthermore an albite phase is present in several sanidines which occupy positions remote from the solvus determined by Smith & MacKenzie (1959); and, assuming this solvus is real, exsolution in these feldspars would not be expected.

MacKenzie & Smith (1956, p. 408) point out the ease with which unmixed high-temperature feldspars can be homogenized: heating at 700° C for an hour or two is sufficient. Accordingly two specimens containing albite and sanidine phases, 35g and 8c, were heated for 30 hours at 800° C. Powder patterns indicated that the two phases were still present. Further heating of 35g for another 30 hours at 800° C induced homogenization, the orthoclase content of the potassic phase dropping from 62.2% to 53.0%, and the albite phase disappearing. The prolonged heating required for homogenization points to an origin other than exsolution for the phases present.

Several features suggest that the albite is a late-stage replacement of the sanidine. The occurrence of an exterior "zone" of albite in some cases suggests late stage replacement, and the irregular occurrence of the albite and its parallelism to the (001) cleavage are also suggestive of a replacement origin.

It is interesting, therefore, to note that Starkey (1959) in his discussion of the origin of chess-board twinned albite, concludes that replacement of potash feldspar is essential to the development of the chess-board structure. He considers that there is some genetic relation between the chess-board twinning and the polysynthetic twinning of the microcline which the albite is often thought to have replaced; but this would not

²Tuttle (1952) has interpreted sodic plagioclase rims to feldspars in certain granites as the result of exsolution. The occurrence of rims of this type in rapidly cooled extrusives would, however, not be expected.

apply in the present instance. The derivation of the triclinic albite structure from the monoclinic orthoclase or triclinic microcline structure involves significant changes in the values of the angles of the reciprocal lattice. One might expect this to be accommodated by repeated complex twinning, and it is not impossible that the chess-board pattern is the result. Detailed examination of the relationships between the twins in suitable material, and the correlation of this data with theoretical studies of the structural changes which could be expected to occur in a K-feldspar lattice on albitization, should lead to the elucidation of this problem.

A further interesting point is the structural state of the albite phase. Intermediate albites have been infrequently recorded in nature (Tuttle & Bowen, 1950): usually the high temperature form inverted to the low on cooling, or albite has crystallized directly in the low-temperature form. While the present case may be an exception to the usual behaviour, it may equally be due to the relation between the albite and its host.

Ferguson *et al.* (1958) maintain that the structural state of alkali-feldspars is dependent on the relative distribution of Si and Al atoms between the four possible tetrahedral positions. Now it is known that at relatively low temperatures (below 500° C) the alkali ions in feldspar are quite mobile (Wyart & Sabatier, 1956). Further, it seems probable that Si-Al mobility is very limited below 600° C (McConnell & McKie, 1960). Thus, if the albite in the feldspars examined in this study were a replacement of the sanidine, it could have developed at a fairly late stage when temperatures were low enough to prevent interchange between the Si and Al in the tetrahedral positions. It would then inherit the structural arrangement of the pre-existing sanidine.

In the case of K-feldspar, during cooling, the distribution of Al in the four tetrahedral positions $T_1(0)$, $T_1(m)$, $T_2(0)$, $T_2(m)$ is thought to change from 25% in each position (for high sanidine) towards 36% in each T_1 position and 14% in each T_2 position (for orthoclase) (Ferguson, 1960). The corresponding values for the ordinary high to low albite series are: 25% in each position for high albite, and for low albite 75% in $T_1(0)$ and 8% in each of the other positions.

In the present case, the allegedly replaced material was intermediate-to low-temperature sanidine. The Al distribution in this lattice would thus be somewhere between the values given above. With the substitution of Na^+ for K^+ the lattice would become triclinic, but would retain the Al-distribution as before. The resultant albite would necessarily have an Al-distribution characteristic of intermediate albite, and give congruent optics.

Ferguson (1960) has suggested the possible existence of a second series of low temperature albites slightly different from ordinary low albite. The

least ordered of these he terms "maximum albite". It has the Al-distribution of orthoclase, and would be expected to occur as an exsolution in perthite derived from a K-rich feldspar. If such a series exists, and the above origin of the albite in the Crowsnest feldspars is correct, this albite can be considered as a member of such a series—for the characteristic of the series is that their Al-distribution is characteristic of a potassic, rather than a sodic, feldspar. Furthermore the Crowsnest material offers a possibility of checking the ionic theory of feldspar formation proposed by Ferguson *et al.* (1958), for the unaltered host sanidine presumably preserves the K:Na ratio and Al-distribution originally present in the areas which are now replaced by albite.

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