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On the Relationship of Pericline and Albite Twinning to the Composition and Structural State of Plagioclase Feldspars

By John Starkey (London, Ont., Canada)*)

With 3 figures and 2 tables in the text

Abstract

Published crystallographic data from X-ray analyses of 105 plagioclase feld-spars have been collected and, where possible, the complete lattice angles have been calculated. From these data the orientation of the rhombic section and the obliquity of albite twins have been determined and the dependence of these parameters on both composition and structural state is demonstrated.

It is shown how information concerning the history of a plagicelase crystal may be obtained by measuring the orientation of the composition planes of secondary pericline twins. The possible influence of the obliquity on twinning is also discussed.

It is suggested that the ease of development of glide twins in the plagioclase feldspars is related to the crystal structure.

INTRODUCTION

The secondary origin of polysynthetic albite and pericline twins in plagioclase feldspars was first recognised independently by Judd (1885), Lehman (1884) and Van Werveke (1883) and more recently by Alling (1936) and Emmons and Gates (1943) among others. The secondary origin of the twinning in chess-board albite has been demonstrated by Starkey (1959). Polysynthetic twins have been produced experimentally in feldspars by Förstner (1884), Mügge and Heide (1931), Borg, Handin and Higgs (1959) and Starkey and Brown (1964). There is no

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compelling evidence that polysynthetic albite and pericline twins in plagioclase feldspars can be of primary origin (i. e. growth twins). This view is opposed to that expressed by Vance (1961).

The study of secondary twinning in feldspars is of interest not only for its own sake but also because of the information which can be gained about the history of the crystals and therefore of the host rock. Earlier studies along these lines have centered on the variations in the attitude of the twin elements relative to the crystal lattice as a function of both chemical composition and structural state. Unfortunately the earlier conclusions were based on very meagre data and it seems opportune at the present time to attempt to remedy this deficiency.

THE DATA

Published crystallographic data for a large number of plagioclase feldspars have been collected and, where possible, the direct and reciprocal lattice angles have been calculated. The results of this compilation are presented in Tables 1 and 2. The calculations were made with the I.B.M. 7040 Computer at the University of Western Ontario. The sources of the data recorded in Tables 1 and 2 are annotated below.

Table 1: Values for α , γ , α^* and γ^* have been taken from Laves and Chaisson (1950, Table 1); the data are all from albites. Specimen number 1¹) is a natural low albite and specimens 2 and 3 are the same material after heat treatment. Specimens 4 and 5 are synthetic.

Table 2: Reference 1²), GOLDSMITH and LAVES (1955, Table 1). Values of α^* , γ^* and β are given for a synthetic anorthite. The remaining lattice angles have been calculated from the following expressions:

$$\cos \beta^* = \left(\frac{\cos \alpha^* \cos \gamma^*}{\sin \gamma^* \sin \alpha^*} - \cos \beta\right) \sin \alpha^* \sin \gamma^*, \tag{1}$$

$$\cos \alpha = \frac{\cos \gamma^* \cos \beta^* - \cos \alpha^*}{\sin \gamma^* \sin \beta^*}, \tag{2}$$

$$\cos \gamma = \frac{\cos \alpha^* \cos \beta^* - \cos \gamma^*}{\sin \alpha^* \sin \beta^*}.$$
 (3)

Reference 2, Brown (1960, Tables 2 and 3). Brown measured α^* , γ^* and β for forty-five natural plagicalse feldspars selected from probable

¹) The specimen numbers used throughout are those listed in the first columns of Tables 1 and 2 under Js. No.

²⁾ The reference numbers are listed in Table 2, column 2.

low temperature environments; he excluded specimens which showed peristerite unmixing. Brown measured the same parameters for fifteen of the specimens after heating. The compositions of the feldspars were determined optically except for five specimens for which chemical analyses were available (Brown, op. cit. Table 1), these are specimens 15, 46, 65, 76 and 87. Values for β^* , α and γ have been computed from the expressions given under Reference 1.

Reference 3, Brown (1960, Table 4). Brown measured α^* and γ^* and calculated β^* for two feldspars after successive heat treatments. The compositions were determined optically. Values for α and γ have been derived from expressions 2 and 3. Values for β have been calculated from the following expression:

$$\cos \beta = \frac{\cos \alpha^* \cos \gamma^* - \cos \beta^*}{\sin \alpha^* \sin \gamma^*}.$$
 (4)

Reference 4, Cole, Sörum and Taylor (1951, Table 4). Complete lattice parameters are given for three natural feldspars, an albite, a labradorite and an anorthite. The albite has been analysed chemically by Spencer (1935—1937, Table 1, Specimen T); it occurs in micapegmatites and is probably of low temperature origin. The composition of the labradorite has been determined by Emmons as An_{56.1} from

Table 1

Data from Laves and Chaisson (1950), see text. In column 1 are listed the specimen numbers allocated in the present study; the specimen numbers in column 2 are from the original reference.

Js. No.	No.	$\mathbf{A}\mathbf{n}$	Type	Alpha	Gamma	Alpha Star	Gamma Star	Sigma	Phi
1	1	0.00	1	94.333	87.650	86.333	90.500	32.686	4.362
$\bar{2}$	$\overline{2}$	0.00	$\bar{3}$	93,733	89.600	86,000	88.583	5.716	3.993
3	3	0.00	3	93.500	90.150	86.000	88.083	-2.149	3.990
4	5	0.00	4	93.433	90.033	86.133	88.250	-0.489	3.853
5	6	0.00	4	93.433	90.067	86.167	88.267	-1.002	3.845

Table 2

The references from which the data have been obtained are numbered in column 2; see text for details. The specimen numbers in column 1 have been assigned in order of increasing anorthite content. Column 3 lists the specimen numbers recorded in the original literature, a 0 indicates that no specimen number was given. Under AN are listed the compositions in Weight % Anorthite. Under Type are listed the nature of the specimen and its probable structural state, 1 = natural, probably ordered; 2 = natural, probably disordered; 3 = heat treated natural material, disordered; 4 = synthetic feldspar, disordered.

	Phi	444844444469006844944466969868989494946968888888889899999999
Table 2	Sigma	33.3.3.3.3.3.4.4.1.1.2.5.5.5.1.2.5.5.5.5.5.5.5.5.5.5.5.5
	Gamma Star	99.0.433 99.0.433 99.0.433 99.0.4417 99.
	Beta Star	663.44833 663.4586 663.4560 663.4560 663.660
	Alpha Star	86.433 86.433 86.334 86.334 86.333
	Gamma	847.741 877.741 877.741 877.741 877.789 877.789 877.700 877
	Beta	116.500 116.517 116.567 116.5500 116.447 116.447 116.357 116.357 116.3500 116.3500 116.3500 116.3500 116.3500 116.3500 116.440 116.3500 116.4500 116.4500 116.4500 116.4500 116.4500 116.4600 11
	Alpha	94.199 94.1199 94.2233 94.5617 94.5607 94.5607 94.5607 94.0009 95.6607 95.6609
	$_{\mathrm{Type}}$	
	$\mathbf{A}\mathbf{n}$	0.00 0.00
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Pericline and Alb	oite Twinning to	the Com	position and	Structural State
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3.403 3.909 3.924 3.957	3.950 3.950 3.957 8.935		3.335 3.935 3.962 3.962 3.740	3.9.878 3.9814 3.9828 3.954 4468		6.00 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	4.127 4.097 4.139 4.139 4.289 4.293
-2.502 15.010 -3.506 12.341 12.28	10.651 9.144 8.235 -4.223	4.1288 -4.288 -4.429 -3.183	-6.028 8.329 -3.156 6.314 6.953 -3.520	6.856 7.135 3.889 -3.220 5.937 7.004	4.03 4.03 4.03 4.03 7.59 7.59 7.59 7.59 7.69	-6.207 -6.207 -6.207 -1.625 -1.625 -2.7725 -2.7725 -4.018	-6.622 -7.014 -8.995 -9.397 -10.423 -10.523 -15.508 -16.478
88.367 89.220 88.040 89.033	88.933 88.817 88.000 88.000	888.020 888.020 888.161 888.161 88.161	88.217 88.083 88.650 88.683 88.133	888.700 888.417 888.0883 88.683 88.617	88.500 88.500 88.500 87.990 88.630 88.6417 88.667	88.267 88.280 88.267 88.500 88.500 88.117 88.117	87.750 87.750 87.583 87.583 87.567 87.150 87.100
63.803 63.560 63.570 63.663 63.579	63.489 63.432 63.612 63.660	63.545 63.576 63.345 63.941 63.560	63.679 63.696 63.603 63.471 63.640	63.557 63.4725 63.669 63.586 63.586	63.640 63.650 63.653 63.650 63.640 63.640 63.656	63.674 63.674 63.687 63.697 63.867 63.867 63.771	63.548 63.665 63.665 63.622 63.738 63.798 64.033
86.230 86.230 86.080 86.100 86.133	86.167 86.100 86.083 86.070	86.130 86.133 86.433 86.250 86.250	86.683 86.100 86.117 86.117 86.067 86.267	86.150 86.117 86.067 86.067 86.067 86.090	86.020 86.020 86.0117 86.030 86.030 86.200 86.200	86.060 86.060 86.120 86.1117 86.1133 86.050 86.050	85.900 85.900 85.933 85.917 85.917 86.001 85.867 85.883
90.149 88.990 90.240 89.147 89.158	89.280 89.373 89.434 90.290 80.950	99.290 90.290 89.433 90.208 89.467	90.350 89.429 90.214 89.571 89.521 90.230	889.537 890.514 890.518 890.591	990.230 89.245 90.745 90.255 90.280 89.590 89.836 89.836	90.426 890.400 89.890 89.783 89.783 90.155	90.476 90.500 90.654 90.675 90.750 91.146 91.217
116.150 116.450 116.360 116.33 116.417	116.500 116.550 116.367 116.270	116.300 116.367 116.633 116.000	116.267 116.283 116.333 116.500 116.333	116.417 116.250 116.483 116.267 116.383	116.290 116.400 116.300 116.290 116.290 116.300 115.300	116.250 116.250 116.250 116.250 116.350 116.350 116.360	116.257 116.253 116.253 116.283 116.283 116.267 116.083 115.850
92.986 93.830 93.400 93.873 93.873	93.752 93.769 93.390 93.750	93.340 93.072 93.755 93.279 93.745	92.819 93.749 93.385 93.667 93.738	93.654 93.697 93.3697 993.385	93.5460 93.5591 93.5591 93.5690 93.5688 93.5688	9933324 933560 935520 935567 935777 93477	93.461 93.455 93.417 93.361 93.326 93.261 93.167
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chemical analysis and as An₅₁ from the refractive index (see Cole et al., op. cit., Table 1). The composition of the anorthite has been given as approximately An₁₀₀ on the basis of refractive index and extinction (Gay, 1953—1955, Table 1) and as An₉₅₋₁₀₀ on the basis of universal stage measurements (Kempster, Megaw and Radaslovich, 1962, p. 1007). Gay (op. cit., p. 175) points out that the anorthite is of low temperature origin.

Reference 5, Laves (1952, Table 2). The complete lattice parameters of both a low and high temperature albite are given.

Reference 6, Donnay and Donnay (1952, Tables 5 and 10). The complete lattice parameters are listed for a synthetic albite.

Reference 7, SMITH (1956, Table 4). SMITH has calculated complete lattice parameters from powder data for nine natural plagioclase feld-spars (eight of low temperature origin and one of high temperature origin), for seven of these feldspars after heat treatment (one of them heated for two different periods of time) and for four synthetic plagioclase feldspars. The specimen numbers listed in column 3, Table 2 are consecutive numbers, 1 to 21, which have been allocated to SMITH's samples since his specimen numbers are unwieldy.

Reference 8, Ferguson, Traill and Taylor (1958, Table 3). Complete lattice parameters are given for a natural low temperature albite and for a natural albite after heat treatment. The compositions of both materials were determined chemically by Emmons (see Ferguson et al., op. cit., Table 1).

PERICLINE TWINNING

In pericline twins the twin axis is the b crystallographic axis and the twin plane and composition plane are the rhombic section. The rhombic section is an irrational plane, it can be defined as the plane which includes both the b axis and the normal to b in (010). The orientation of the rhombic section is specified by the angle σ , which is the angle between the trace of the rhombic section and the trace of (001) on (010), σ is considered positive if the trace of the rhombic section on (010) lies between +a and +c. The angle can be calculated from the relationship cot $\sigma = \cos \alpha^*/\cot \gamma$. Calculated values for σ are listed in Table 1, column 9 and Table 2, column 12. The values for σ are plotted against composition in Figure 1.

In Figure 1 the data points for albite-rich compositions are distributed in two groups, those representing ordered feldspars (i. e. of low tempera-

ture origin) lying above those for more disordered ones. The groups tend to merge towards more anorthite-rich compositions. Unfortunately there are no data for plagioclase feldspars of high temperature origin within the composition range $\rm An_{50}$ to $\rm An_{100}$. However it is probable that the trend indicated by the more sodic feldspars continues until at $\rm An_{100}$ the

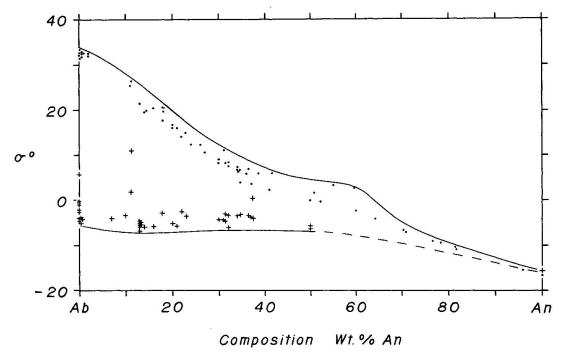


Fig. 1. The variation of σ with composition and structural state of plagioclase feldspars. The upper curve is for ordered feldspars and the lower one for disordered feldspars. The data are from Tables 1 and 2: dots represent ordered feldspars (Type 1) and crosses represent disordered feldspars (Types 2, 3 and 4). Brown's monablites, specimens 19 and 20, are not included since the calculated value for σ has no meaning in a monoclinic crystal.

distinction between feldspars of high and low temperature origin disappears as is indicated by the data points for specimens 104 and 105 in Figure 1. This must be the case since anorthite occurs only in a highly ordered structural state. Since it is not certain that any of the feldspars considered here are in a state of maximum order or disorder, curves indicating the variation of σ with composition for ordered and disordered feldspars have been drawn along the "outer" margins of the data. These two curves are in general agreement with those of SMITH (1958, Figures 1 and 5), although the present curve for disordered feldspars indicates slightly larger negative values of σ for compositions more sodic than An_{55} , and both curves indicate slightly smaller negative values for

anorthite-rich specimens. It should, however, be remembered that SMITH's curves are based on fewer data and, further, for compositions more calcic than An_{55} his curves are actually those for Γ and not σ !

ALBITE TWINNING

In albite twinning the twin plane and composition plane are (010) and the twin axis is [010]. The angular misfit between the two individuals on either side of the twin plane is termed the obliquity and this can be defined as the angle between the normal to the twin plane and the lattice row quasi-normal to it. In albite twinning this is the angle between [010] and the b crystallographic axis, it is designated ϕ . The value of ϕ can be calculated from the expression, $\cos \phi = \sin \alpha \sin \gamma$. The computed values for ϕ are listed in Table 1, column 10 and Table 2, column 13.

In Figure 2 ϕ is plotted against composition, again curves for maximum ordered and maximum disordered feldspars have been drawn along

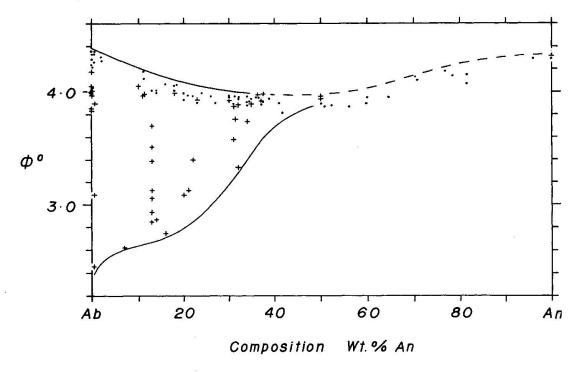


Fig. 2. The variation of ϕ with composition and structural state of plagioclase feldspars. The upper curve is for ordered feldspars and the lower one for disordered feldspars. The data are from Tables I and 2: dots represent ordered feldspars (Type 1) and crosses represent disordered feldspars (Types 2, 3 and 4). Brown's monabites, specimens 19 and 20, are not included, they would plot at $\phi = 0^{\circ}$.

the "outer" margins of the data. Figure 2 shows that for ordered plagioclase feldspars ϕ is at a minimum around An_{40} and increases towards An_0 and An_{100} . For the disordered feldspars the picture appears to be more complex, it is also, unfortunately, less complete. Data are lacking for compositions between An_{50} and An_{100} and it is therefore not possible to draw a curve with any certainty. However it is probable that the curves for ordered and disordered feldspars are sub-parallel and close together over this composition range, finally converging on anorthite (see the discussion under Pericline Twinning above). For disordered feldspars with compositions more sodic than An_{50} , ϕ decreases sharply and is 0° for Brown's monable (specimens 19 and 20) as is dictated by the monoclinic symmetry.

The curves of Figure 2 differ considerably from those previously published (Donnay 1940, Gay 1956—1958, Smith 1958), the difference is particularly noticeable in the curve for disordered feldspars. In view of the well documented trend towards monoclinic symmetry exhibited by sodic plagioclase feldspars on heating it is thought that the trend of the curve for disordered feldspars proposed here is at least in the right direction.

CONCLUSION

The significance of the variation of σ and ϕ with composition and structural state have been discussed at length by SMITH (1958, 1962) so that detailed reiteration is not necessary here.

In the case of pericline twins the argument, briefly, is that, since the composition plane of the twins at the time of their formation was parallel to the rhombic section at that time, measurement of the composition plane and the determination of the present attitude of the rhombic section can give information on the thermal history of the feldspar and hence of the host rock.

In the case of secondary pericline twins which may result from deformation at different times during the cooling, and consequent ordering, of the plagioclase crystals, the values of σ for successively younger twins will decrease. The maximum value of σ will give an indication of the structural state in which the feldspar originally crystallized, remembering that it may have crystallized in a still more disordered state but that no twins developed at that time. The structural state in which the crystal originally grew can only be ascertained with certainty from the orientation of growth twins after the pericline law.

Rocks undergoing heating and in which the plagioclase feldspars are becoming increasingly disordered might preserve evidence of this so that the earlier formed pericline twins would yield smaller values for σ . Further cooling could of course be accompanied by further generations of twins.

It has been thought that the ease of formation of albite twins reflects variations in the obliquity, ϕ (Donnay 1940, Gay 1956—1958, Smith 1958). The less the obliquity the easier the development of twins. In support of this idea Smith (op. cit.) correlates his predictions with the observations of Turner (1951) and Gorai (1951). However where the twinning results from deformation the problem is almost certainly more complex. Since glide twinning of an ordered plagioclase feldspar produces a markedly different structure in the twinned individual (Starkey 1963), one can expect that where this structure is sufficiently unstable the crystal will resist twinning. On the basis of this Figure 3 has been prepared to show, in a purely qualitative way, how the ease of twinning can be expected to vary with composition and structural state. In deformation twinning the structural control will probably be more significant

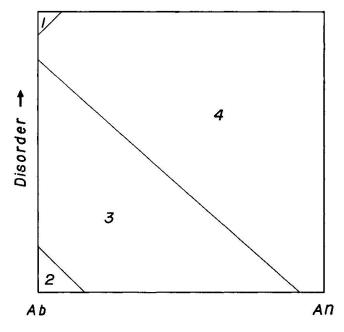


Fig. 3. The postulated effect of composition and structural state of plagioclase feldspars on the ease of formation of pericline and albite twins by gliding. Area 1 represents the possible field of monalbite, twinning is precluded by the monoclinic symmetry. Twinning is precluded on structural grounds in feldspars in area 2. In feldspars occurring in area 3 twinning is possible but not easy. Twinning is easy in feldspars occurring in area 4.

than variations in obliquity. The obliquity may exercise a control over the development of growth twins (see Vance 1961).

Figure 3 is in general accord with the observations of Turner (1951) and Gorai (1951). With increasing grade of metamorphism the plagioclase feldspars become more calcic and are in a structural state more favourable to twinning. Therefore frequency of twinning should increase with metamorphic grade. Secondary twinning should also be common on hornfelses and igneous rocks where temperatures are still higher and the structural state of the feldspars consequently more disordered.

Since the data which have been used to prepare Figures 1 and 2 were obtained at room temperature it might be supposed that the conclusions based on them apply only to feldspars which twin at room temperature. However Smith (1958, p. 919) has pointed out that the orientation of the rhombic section is probably independent of temperature, this is perhaps also true in the case of the obliquity. As far as the boundaries indicated on Figure 3 are concerned, elevated temperatures and the accompanying increase in thermal vibration would tend to reduce the effect of the degree of structural order present so that the boundaries should shift towards the abscissus: the effects of this are not likely to be present in nature since prolonged heating would change the structural state. It is therefore felt that the conclusions presented above can be extended to natural environments.

Acknowledgements

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