Observations on the rhombic section of a zoned plagioclase crystal.

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Summary. A zoned plagioclase crystal from a magmatic quartz-diorite shows two generations of pericline twinning: one growth twinning, the other glide twinning. Plotting the angle of the rhombic section against composition for each set of twins gives curves indicative of an intermediate structural state with respect to the theoretical curves determined by Smith (1958). The curve for the growth twins is closer to the high structural state than that for the glide twins and supports the primary origin of the former. This curve is believed to fix approximately the lowest structural state at which primary pericline twinning can develop in magmatic rocks. The lack of coincidence of the curves for the two generations of twinning indicates partial inversion prior to formation of the glide lamellae, while the position of the curve for these secondary lamellae suggests a genetic relation to inversion. Both rhombic sections are probably relict with respect to the present structural state. The form of the curves confirms the general accuracy of Smith's curves for the maximum high and low structural states.

MÜGGE (1930) and Mügge and Heide (1931) showed that the crystallographic angles and the position of the rhombic section (σ) in plagioclase are dependent not only upon composition, but on temperature. This early work directly anticipated much of the current thought on the relation of plagioclase structure to temperature.

Smith (1958) has developed this theme in an important recent paper. He shows that plagioclase structure, rather than temperature *per se*, is the decisive control of σ and gives quantitative expression to the variation of σ with structure and composition. Smith points out that, because the rhombic section is determined by the structural state at the time of twinning, the rhombic section relict from this stage may provide a record of earlier plagioclase structure. A single zoned plagioclase crystal showing two generations of pericline twinning affords a unique opportunity to coordinate this principle with the study of twin genesis as well as to test the general accuracy of Smith's theoretical curves for the variation of σ with composition in the maximum high and low structural states.

Zoning and composition of the crystal.

The crystal described is from the Squire Creek stock, a Tertiary quartz-diorite intrusion situated in the Cascade Mountains near Darrington, Washington. The crystal is 3·5 mm wide and shows the complex zoning typical of most plagioclase in this magmatic body (fig. 1). The core of the crystal exhibits oscillatory zoning extending through

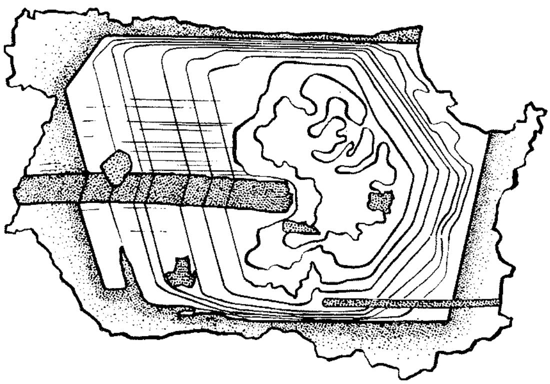

FIG. 1. Generalized sketch of plagioclase (An_{53}–An_{18}) showing oscillatory zoned calcic core and normally zoned sodic rim. Large primary pericline lamella and numerous hairlike secondary pericline lamellae. Section subparallel to (010). The base is oriented horizontally.

the andesine compositional range. Irregular anhedral zoning in the centre of the crystal gives way to euhedral zoning in the outer part of the core. The core is succeeded by a narrow mantle or rim of calcic oligoclase that shows normal zoning and entirely lacks oscillations. The boundary of the core and rim is for the most part euhedral, but the external form of the crystal is wholly anhedral. Several small inclusions of a plagioclase having the same composition as the rim are present in the interior of the crystal.

The section is oriented nearly parallel to (010) permitting determination of composition by measurement of extinction angles with respect to the (001) cleavage. The results indicate a composition ranging from An_{53} to An_{28} (average about An_{45}) for the core and a composition of from An_{28} to An_{18} for the rim. Determination of the composition of similar zoned grains in the same thin section by other methods (using the standard curves for low-temperature plagioclase) gave generally concordant results. The average of 4 determinations gave a compositional range of

An_{50} to An_{30} for the core and An_{30} to An_{20} for the rim. The accuracy of these determinations is believed to be within 5 % An.

Primary twinning.

In thin section the plagioclase crystal is seen to exhibit two very different sets of pericline twinning. That this is pericline twinning, and not acline-A twinning, is indicated by the curvature of the lamellae, which for the calcic oligoclase of the rim depart from parallelism with the basal cleavage by as much as 2·5° in one set and 6° in the other (figs. 1, 2). In one set of pericline twins a single broad lamella traverses the crystal from the rim nearly to the core where it terminates abruptly. (A somewhat similar but much narrower lamella is present in the other side of the crystal; its genesis is unclear, however, and it will not be considered further.) Zoning within the coarse lamella exhibits an abrupt zigzag with respect to the adjacent zoning. The composition plane of the large lamella is not a smooth curve but shows step-like irregularities. Average measurements of the position of the rhombic section, taking into account irregularities in the composition plane, were made for different parts of the crystal and are believed to be accurate within 1°. In the core of the crystal, at an average composition of An_{45}, σ is approximately $-1°$. The rhombic section in the interior of the crystal is not perceptibly influenced by the oscillatory zoning, but adopts a compromise position. At the boundary between core and rim (composition approximately An_{30}) σ is about 1·5°. Near the rim (approximate composition An_{20}) it is about 2·5°.

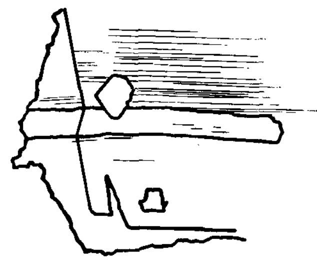

FIG. 2. Detail of the same plagioclase showing the relations of the two generations of twinning.

The coarse pericline twinning is believed to be growth twinning. The possibility that this is transformation twinning is ruled out by the deflection of the zoning as it crosses the large twin lamella. The blunt and abrupt termination and the absence of deformation in the area of termination of the twin indicate that it did not form by twin gliding. These characteristics, together with the thickness, irregularity, and paucity of lamellae, appear to be consonant only with a primary origin of the twinning (Vance, 1961).

Secondary twinning.

A second set of very different lamellae is abundantly developed in several parts of the crystal. These lamellae are of almost hairlike thinness and taper out regularly and generally in unison, terminating in exceedingly fine points. These lamellae are quite regularly spaced and of nearly uniform width. They are not strictly parallel with one another in the interior of the crystal, but diverge very slightly. The average position of the rhombic section of these lamellae is sensibly 0° in the core of the crystal where it departs clearly by about 1° from that of the primary twinning. Like the primary twinning the rhombic section of these fine lamellae does not fluctuate with the oscillatory zoning, but occupies an average position. Near the outer portion of the oscillatory zoned core (at a composition of approximately An_{34}), σ increases rapidly to about 2·5°. There is a further increase to a maximum angle of about 6° at the margin of the crystal (about An_{20}).

These fine pericline lamellae show the typical characteristics of glide twinning, including: uniformity in width and spacing, abundance, and termination in unison to finely tapering points (Vance, 1961). If the interpretation of the coarser lamellae as primary is correct, then the finer lamellae with their wholly different morphology and different rhombic section must be younger. This conclusion is supported by the position of the rhombic section which indicates a higher structural state at the time of formation of the coarse twinning than for the fine lamellae (*vide infra*).

Interpretation of the variation in the rhombic section.

Both generations of pericline lamellae are distinctly curved. This curvature, however, is not to be confused with bending, for neither the basal (001) cleavage nor the zoning is bent. The curvature must thus be explained as a change in σ in response to zonal compositional variations within the crystal.

The problem, rather, is the variation in σ for the two sets of twins within individual compositional zones of the crystal. In fig. 3 the general variation of σ with plagioclase composition is shown for each set of lamellae. The curve for each was established on the basis of 3 points for which the average composition and the average value of σ could be most accurately estimated. It is again emphasized that in the centre of the crystal neither the curves nor the twin lamellae, for that matter, reflect the detailed zonal variations in composition.

Smith (1958) has shown that plagioclase composition and crystal structure are the two dominant controls of the position of the rhombic section. To cause the observed variation, therefore, either composition or structural state must have changed after formation of the primary twinning, but prior to development of the secondary twinning. That the composition of the crystal has changed is doubtful, for it is improbable that the delicate primary zonal features could survive wholesale

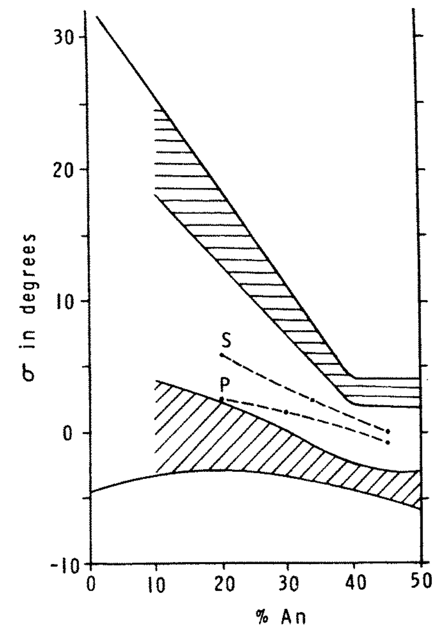

Fig. 3. Variation of σ with plagioclase composition and structural state (modified from Smith, 1958). Values for the 'maximum' high and low structural states are shown by the lower and upper solid lines respectively. Fields of the high (diagonal lines), low (horizontal lines), and intermediate (no pattern) structural states are designated arbitrarily at σ values 25 % and 75 % of the distance between the maximum values. *P* and *S* curves for primary and secondary twinning respectively in the Squire Creek plagioclase.

compositional reworking of the crystal. Structural changes, on the other hand, are not only possible, but probable in a plutonic plagioclase that has undergone slow cooling after initial crystallization in a relatively higher structural state. Smith has calculated the theoretical variation of σ with composition for plagioclase in the maximum high and maximum low structural states from the lattice angles. These variations for plagioclase from An_0 to An_{50} are shown in fig. 3 (more calcic compositions are not reproduced here because of uncertain control data and because it does not seem possible to reconcile the curves with the data of Mügge and Heide (1931) for anorthite). Smith emphasizes that because σ is controlled by the structure at the time of twinning, the relict σ is indicative of this earlier structural state and may thus provide useful data on the thermal history of the plagioclase.

As already indicated, the coarse pericline twinning of the present material is believed to be growth twinning and to have developed at magmatic temperatures. The fine pericline twinning is thought to be secondary, to have formed after crystallization of the plagioclase, and presumably at a lower temperature. If this interpretation is correct, then the position of the relict rhombic section for the primary twinning should lie nearer to the curve for the maximum high structural state than does the rhombic section for the secondary twinning. Inspection of fig. 3 shows that this is, indeed, the case. Although both curves lie within the field of the intermediate structural state (as arbitrarily designated here) the curve for the primary twinning is much closer to the curve for the high state. This bears out the higher temperature origin of the primary lamellae and indicates partial inversion of the plagioclase prior to formation of the secondary lamellae.

Since the curve for the primary twinning is, in terms of the rhombic section, essentially a magmatic crystallization curve, it may serve, qualitatively at least, as a geologic thermometer. Under plutonic conditions the temperature interval of crystallization of the quartz-diorite was probably in the range 700° to 950° C (Turner and Verhoogen, 1960, p. 55). Inasmuch as crystallization of similar plagioclase in a volcanic environment would presumably proceed at higher temperature, the curve for primary twinning probably approaches the lowest structural state at which magmatic crystallization of this plagioclase could take place. For magmatic plagioclase, points above the curve would thus generally indicate secondary twinning.

The curve for the secondary twinning lies near the middle of the field of the intermediate structural state indicating that the glide twinning occurred after partial inversion from the higher form. As the Squire Creek quartz-diorite crystallized under plutonic conditions, it is probable that the plagioclase is now in a structural state lower still than that indicated by the curve for the secondary twinning. The curves for both sets of twinning are thus probably relict with respect to the present structure. These relations suggest that the secondary twinning formed at temperatures intermediate between those of magmatic crystallization and final cooling, and that the twinning is genetically related to the cooling history of the intrusion. Differential internal stress associated with partial inversion is probably the cause of the glide twinning. The possibility that the glide twinning formed as a result of externally imposed deformation is incompatible with the general absence of bent crystals or other evidence of such deformation in the quartz-diorite.

Smith (1958, p. 923) has plotted the variation of σ with composition for a large number of natural plagioclases. In the oligoclase–andesine range most of these points fall in the field of the intermediate structural state and lie very near the curve for the secondary twinning in the Squire Creek material. The reason for this is not entirely clear, but one may speculate that much of this twinning is also secondary and perhaps related to inversion from a higher structural state. Such an origin would imply that a maximum value of differential change in volume is commonly attained upon inversion across this particular structural state. The data presently available on the environment, thermal history, and genesis of twinning of these plagioclases as well as on volume changes with heating and cooling are too scanty, however, to permit a definite conclusion.

The curve showing the variation of σ with composition for the primary twinning fixes approximately the structural state at the time of initial plagioclase crystallization. At the same time, the curve for the secondary twinning gives the structural state after inversion. The separation of the curves thus serves as a rough measure of the degree of inversion between the formation of the two generations of twinning. The form of the curves for the Squire Creek material appears to be concordant with and supports the general accuracy of Smith's calculated curves for the maximum high and maximum low structural states.

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