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EVIDENCE FOR CONSTANT HABIT DEVELOPMENT OF PLAGIOCLASE CRYSTALS FROM IGNEOUS ROCKS

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ABSTRACT

A new approach to the study of morphological development of crystals produced under natural conditions allows for the discrimination between constant and non-constant habit growth. In cases of non-constant habit growth, the method shows whether the changing habit is due to a variation in the ratio of the growth rates of the faces involved or to the particular growth rates in conjunction with the interfacial geometrical relationship. A brief application of the method reveals that constant habit growth is a common feature of plagioclase crystals in porphyritic extrusive and intrusive granitic rocks.

SOMMAIRE

Une nouvelle façon d'étudier le développement morphologique des cristaux de plagioclase formés dans la nature permet de distinguer si la croissance a été accompagnée ou non de modification de facies. De plus, pour les cas de facies variable, la méthode indique si le changement est dû à une variation du rapport des vitesses de croissance des faces impliquées ou à la combinaison particulière des vitesses de croissance et de la relation géométrique de ces même faces. Une brève application de cette méthode révèle qu'une croissance à facies constant est un phénomène courant parmi les cristaux de plagioclase des roches intrusives et extrusives porphyritiques à composition granitique.

INTRODUCTION

Surprisingly little information is available on the development of the habit of crystals grown under natural conditions. In the past, descriptions of crystal habit have followed a comparative or deductive trend; few studies of habit development have been carried out. Thus, crystal habits produced under various conditions have been catalogued and attempts have been made at inferring the degree of undercooling from the resulting habit (Kostov 1966; Bryan 1972; Leung 1974). Also reported are the effects of crystal shape and its development on other phenomena, such as synneusis (Vance 1969) or twinning (Ross 1957; Senechal 1976).

Experimental studies of the development of crystal habit during growth (Koptsik 1956; Pokrovsky 1956; Sheftal 1956; Hartman 1973; Lofgren 1974a,b) suggest that habit development is non-constant for many substances. Uncertainty as to the cause of this is indicated in the remark: "We can only conclude that relative growth rates, and therefore, crystal shapes, do change during growth . . . But it is not clear that the results may not have been related to the particular conditions of the experimentation" (Schneer 1970).

The object of this study is to demonstrate that one can obtain information on the development of the habit of crystals grown under natural conditions.

DESCRIPTION OF THE STUDY

In order to analyze the development of crystal habit, the faces must be located at different times during growth. Under experimental conditions, time-lapse photography can be used for this purpose. For crystals grown under natural conditions, several characteristics can indicate the positions of the faces during growth: compositional zoning, zones of inclusions or impurities, and the hourglass and Maltese cross structures.

Only those characteristics that influence as little as possible the natural development of a crystal's habit should be selected. Thus, the hourglass and Maltese cross structures commonly displayed by crystals of chloritoid and andalusite should be avoided, as they may be due to crystallographically controlled adsorption of impurities (Spry 1969), whose effects on growth rates of the faces involved have not yet been fully evaluated. The same argument applies to crystals showing zones of inclusions or impurities even though the structural control or anisotropy is less apparent than in the hourglass and Maltese cross structures.

The most suitable characteristic is compositional zoning, a common feature of plagioclase crystals that has been extensively studied (Ross 1957; Vance 1962, 1969; Bottinga *et al.* 1966;

Hoffer 1966; Wiebe 1968). Most zoned plagioclase crystals display compositional variations of a magnitude that has little or no influence on the final crystal morphology (Deer *et al.* 1967; Woensdregt 1975). Assuming that the zones indicate the positions of the faces at different times during growth, adequately selected crystals can provide the information necessary to analyze the development of their habit.

The procedure commonly used in the study of morphological development is to measure the distances from the crystal centre to the faces at different stages of growth, and to express these measurements graphically as plots of time *vs.* distance. This method has the advantage of simultaneously displaying information on habit development and relative growth rates of the faces present. An alternative method is used in the present study: the apparent lengths of the faces (the lengths of the lines resulting from the intersection of the zones and the plane of the thin section) are measured and expressed graphically as plots of zone intercept-lengths *vs.* corresponding zone intercept-lengths (Fig. 1). The use of zone-intercept-length measurements, rather than distances to the crystal centre, do

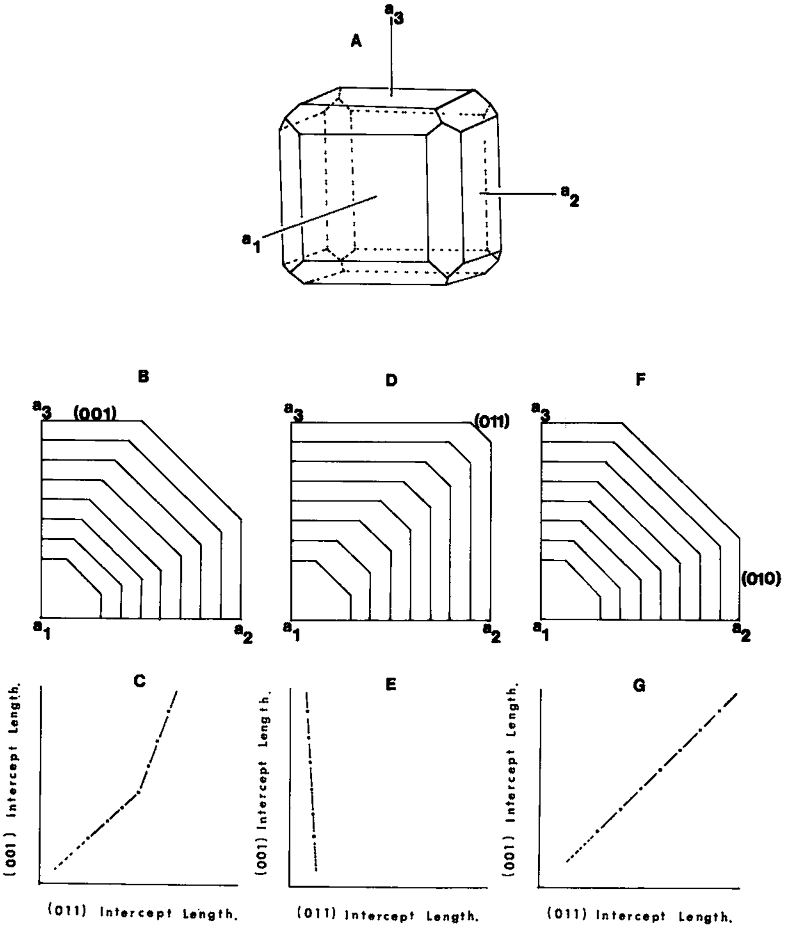

FIG. 1. A: theoretical isometric crystal of habit composed of the cube {001} and the rhombic dodecahedron {011} forms. B, D and F: Subset of the a$_2$–a$_3$ plane bound by the +a$_3$ and +$_2$ axes and the (001), (011) and (010) faces. The facial development depends on the relative growth rates of the forms present and on the geometrical relationships of the forms. C, E and G: Plots of the corresponding zone intercept-length *vs.* zone intercept-length illustrating the three possible types of habit development. Plots not passing through the origin (Fig. 1E) indicate a change in crystal habit during the early stages of growth.

not illustrate growth rates; however, as little can be deduced about the absolute timing of the formation of the zones, this is not a disadvantage. In fact, for the study of habit development, this method is superior in that the degree of linearity of the plots illustrating the observations (Figs. 1C,E,G, 2C, 3C and 4C), a quantity that can be measured statistically, is proportional to the absence of variation in the ratio of growth rates of the faces involved. Furthermore, this method removes the necessity of orienting the crystals in order to locate precisely the position of the crystallographic axes and the crystal centre. This is a considerable advantage as it allows direct measurements from suitably selected thin sections. It is probable that the use of a universal stage to orient especially poorly set crystals may increase the precision and reproducibility of the results.

The validity of this method is based on two assumptions: firstly, that facial development is reflected directly by a corresponding zonal development, and secondly that measurements performed on semi-randomly oriented intersecting planes are valid representations of the extent of facial development. The first can be accepted intuitively; however, the second might lead to some uncertainty, depending on the relative orientation of the crystal with respect to the plane of the section. For this reason, sections were selected normal to one of the crystallographic axes of the observed euhedral crystals. In these, faces are as close as possible to perpendicular to the plane of the section, and complete faces can be followed throughout crystal growth.

One hundred and fifty photographic negatives were taken of zoned plagioclase crystals from a variety of rock types, including diorite, granodiorite, porphyritic rhyolite, porphyritic andesite, granite, gabbro and basalts. On the basis of absence of alteration and physical deformation, sharpness, concentration of the zones and completeness and number of faces normal to the plane of the section, the ten most suitable crystals were selected; only the zones that could be followed over several crystallographic directions were traced and their intercept lengths were measured from the reconstructed diagrams (Figs. 2B, 3B and 4B). The selection was performed according to the criteria described above rather than merely because of a certain type of habit development.

From these ten crystals, 55 unique zone-length vs. zone-length relationships were established, the number of relationships being related to the number of faces N for each crystal by: $N!/2(N-2)!$. For example, if a crystal showed zones accounting for the development of four faces, the following relationships were established: 1 *vs.* 2, 1 *vs.* 3, 1 *vs.* 4, 2 *vs.* 3, 2 *vs.* 4 and 3 *vs.* 4.

The best linear equations that could express each of these 55 relationships were determined by least-squares regression; the degree of association of the variables for each relationship was measured by a correlation coefficient (Neville & Kennedy 1964). An equal-tail t test was then used to determine the level of significance of the degree of association measured by the correlation coefficient, taking into account the number of variables (N) and the number of degrees of freedom (ν or N-2).

It can be appreciated that for a crystal to grow without changing its habit, the ratio of the growth rates of the forms or faces present must not only be constant but the magnitude of the growth rates must be within a range determined by the geometrical relationship of the forms or faces. Growth rates whose values fall outside this range cause a crystal to experience a change in habit during growth, even if the ratio of growth rates remains constant. With these facts in mind, it is possible to propose *a priori* that the relationships obtained by the analysis described above can belong to any one or more of the following theoretical types.

Type 1: A non-linear relationship (Fig. 1C). This type of relationship arises when the ratios of the growth rates of the forms or faces present change during growth. Figure 1B illustrates this possibility. During the first three growth increments, the ratio of the growth rates of the forms {001} and {011} is constant (1.0). After the third growth increment, the ratio changes in magnitude (0.8) and remains constant during the last four increments. Figure 1C is a graph of the (001) zone intercept-length *vs.* the (011) zone intercept-length for the crystal described in Figure 1B. The changing slope is a reflection of the changing ratio of the growth rates and implies a change in the crystal morphology.

Type 2: A linear relationship with negative slope (Fig. 1E). The linearity displayed by relationships of this type indicates that the ratio of growth rates of the faces involved remained constant during growth. The negative slope indicates that the magnitude of the difference between the growth rates or the geometrical relationship of the faces involved, or both, causes one of the forms to disappear. Figure 1D illustrates this type of relationship. The ratio of the growth rates of the {001} and {011} forms is constant (.7) but the growth rates and geometrical relationship of the faces cause the {001} form to become dominant. Figure 1E is a graph of the (001) zone intercept-length *vs.* the (011) zone intercept-length for such a crystal.

Type 3: A linear relationship with positive slope (Fig. 1G). As in the preceding type, the linearity displayed by these relationships indicates that the ratio of growth rates of the faces involved remained constant during growth. In this case, however, the positive slope indicates that the individual growth rates or the geometrical arrangement of the faces involved, or both, are such that the faces are able to expand externally and laterally without either one becoming dominant or recessive. In Figure 1F, the ratio of the growth rates of the {011} and {001} forms is 1.0 and the growth rates and geometrical relationship present allow the crystal to grow with a constant habit. Figure 1G is a graph of the (001) zone intercept-length *vs.* the (011) zone intercept-length for such a crystal.

TABLE 1. DATA OBTAINED FROM THE TEN SELECTED CRYSTALS

Crystal Number*	Number of faces	Number of zones	Correlation coefficient Level of significance
Ma-56-a	3	6	-0.98: <1% -0.82: >1%, <5% 0.91: >1%, <5%
Ma-56-k	3	7	0.98: <1% 0.99: <1% 0.99: <1%
Ma-56-c	4	6	0.98: <1% 0.99: <1% 0.98: <1% 0.98: <1% 0.99: <1% 0.98: <1%
Ma-56-g	4	6	0.88: >1%, <5% 0.98: <1% 0.89: >1%, <5% 0.96: <1% 0.92: >1%, <5% 0.93: <1%
A-92-a	4	5	-0.62: >5%, rejected 0.85: >5%, rejected -0.69: >5%, rejected -0.94: >1%, <5% 0.99: <1% -0.97: <1%
A-92-b	6	7	0.86: >1%, <5% 0.93: <1% -0.76: >1%, <5% 0.93: <1% -0.77: >1%, <5% 0.88: <1% -0.80: >1%, <5% 0.98: <1% -0.81: >1%, <5% -0.95: <1% 0.97: <1% -0.88: <1% -0.87: >1%, <5% 0.86: >1%, <5% -0.87: >1%, <5%
Q-164	4	7	0.99: <1% 0.99: <1% 0.99: <1% 0.99: <1% 0.99: <1% 0.99: <1%
Dksm-4	2	5	0.99: <1%
D-51	3	7	0.99: <1% 0.99: <1% 0.99: <1%
D-53-a	4	7	0.99: <1% 0.98: <1% 0.89: <1% 0.88: <1% 0.90: <1% 0.89: <1%

* Ma-56-a, Ma-56-k, Ma-56-c and Ma-56-g: porphyritic rhyolite, Disraeli, Qué; A-92-a and A-92-b: porphyritic andesite, Mont Pelée, Martinique; Q-164: quartz diorite, Noosa National Park, Queensland, Australia; Dksm-4: granodiorite, Southern California batholith; D-51: diorite porphyry, Abajo Mountains, Utah; D-53-a: granodiorite porphyry, Fraser River canyon, B.C.

In this study, the number of observations for each relationship varies between five and seven, and the number of relationships for each crystal varies between two and six.

RESULTS

Table 1 is a list of the crystal identity, number of faces, of zones, the correlation coefficients obtained for each of the relationships and their level of significance for the ten selected crystals. Figures 2, 3 and 4 illustrate the crystals, the zones measured and the plots of the zone intercept-length *vs.* zone intercept-length for three crystals that demonstrate constant-habit growth.

Of the 55 relationships established, three cases correspond to type 1. The correlation coefficients obtained for these cases are such that they fail to reject the null hypothesis that there is no association between the variables at the 5% level of significance. In oher words, the degree of linearity displayed by these three cases is such that identical results could have been obtained by chance alone in five or more cases out of 100. The 5% level of significance is an arbitrarily selected statistical threshold value marking the difference, in this case, between a valid and a non-valid example of a linear relationship.

Twelve cases are of type 2, *i.e.*, growth characterized by a constant ratio of growth rates of the faces involved but accompanied by a habit modification. Ten of these twelve type-2 cases together with the three of type 1 occur in crystals from the same thin section (A-92, a porphyritic andesite from Mont Pelée). Most of the type-2 relationships are also characterized by a good though not excellent degree of linearity. In these cases, the correlation coefficients generally fall in the range of the 1 to 5% level of significance, *i.e.*, they could have been produced by chance alone in one to five cases out of 100.

Finally, 40 cases are of type 3. All are characterized by correlation coefficients better than the corresponding value at the 1% level of significance. This result seems to indicate that constant habit growth is preferred in the plagioclase crystals studied. This becomes most apparent when the anomalous section mentioned above (A-92) is omitted; type-3 development then accounts for 32 out of the 34 observed cases in the five rock types studied.

The results of this study can be summarized as follows. Amongst the ten selected crystals, three show a non-constant habit development with growth. One of these shows a change in the ratio of the growth rates of some of its faces, whereas the other two are characterized by constant ratios of their facial growth rates; in the latter, habit modification led to the disappearance of some of their faces. The seven other crystals grew with a constant habit, *i.e.*, not only the forms and number of forms but also their exact degree of relative development remain constant during growth. The following conclusions can be drawn: (1) The proposed method succeeds in providing information on the habit development of naturally formed plagioclase crystals.

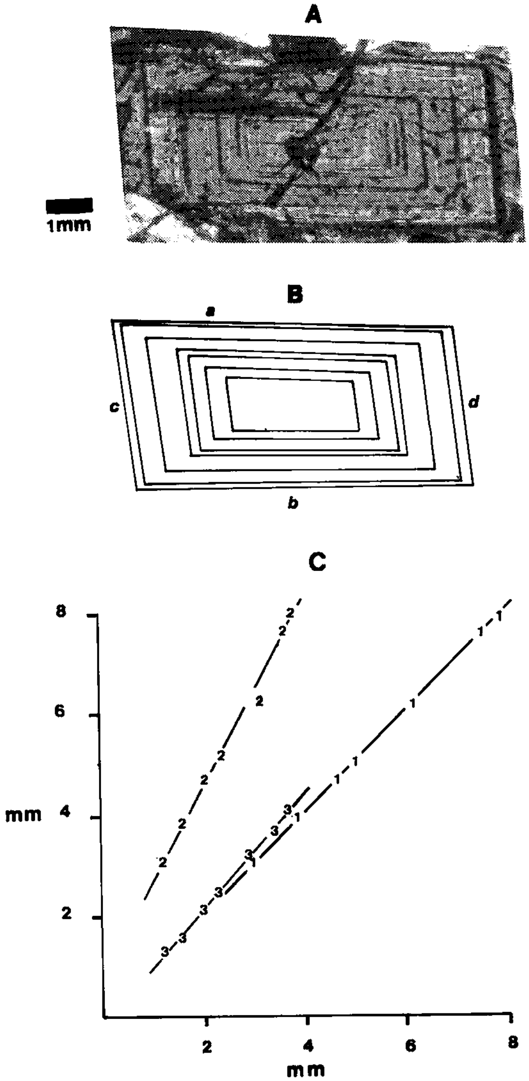

FIG. 2. A: Photograph of zoned plagioclase crystal Q-164. B: Reconstructed diagram of the selected and measured zone intercept-lengths. C. Plot of three of the six unique zone-intercept-length *vs.* zone-intercept-length relationships established. The correlation coefficients of the relationships plotted are: (1) *a vs. b* 0.99, (2) *a vs. c* 0.99, and (3) *c vs. d* 0.99; all are much better than the corresponding value at the 1% level of significance (.87) for the appropriate number of degrees of freedom (5). This crystal is from a quartz diorite from Noosa National Park, Queensland, Australia. The crystal length is 7.9mm.

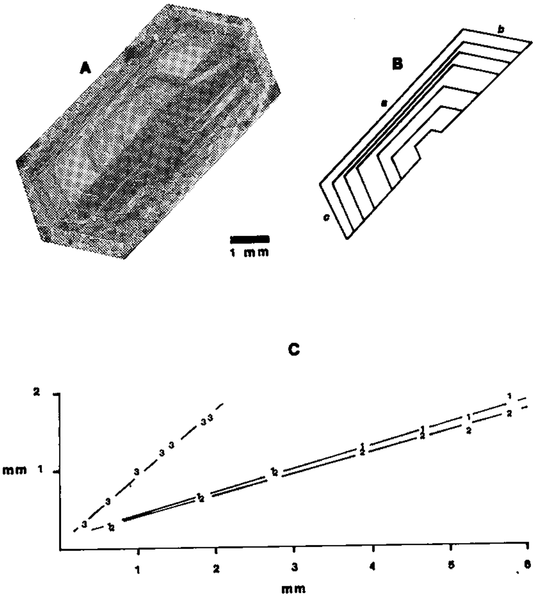

FIG. 3. A: Photograph of zoned plagioclase crystal Ma-56-k. B. Reconstructed diagram of the selected and measured zone intercept-lengths. C: Plot of three unique zone-intercept-length *vs.* zone-intercept-length relationships established. The correlation coefficients of the linear relationships plotted are: (1) *b vs. a* 0.99, (2) *c vs. a* 0.98, and (3) *c vs. b* 0.99; all are much better than the corresponding value at the 1% level of significance (.87) for the appropriate number of degrees of freedom (5). This crystal occurs in a porphyritic rhyolite from Disraeli, Québec. The longest dimension is 7.4mm.

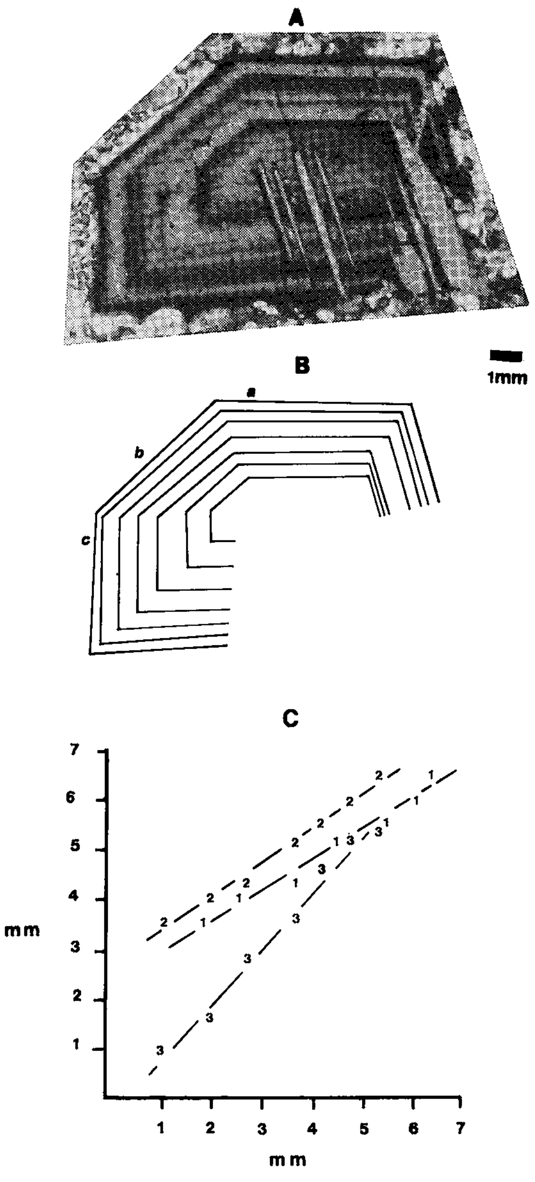

FIG. 4. A: Photograph of zoned plagioclase crystal D-51. B: Reconstructed diagram of the selected and measured zone intercept-lengths. C: Plot of the three unique zone-intercept-length *vs.* zone-intercept-length relationships established. The correlation coefficients of the relationships plotted are: (1) *a vs. b* 0.99, (2) *a vs. c* 0.99, and (3) *b vs. c* 0.99; all are much better than the corresponding value at the 1% level of significance (.87) for the appropriate number of degree of freedom (5). This crystal occurs in a diorite porphyry from Abajo Mountains, Utah. The external zone of the series labelled *a* in Fig. 4B measures 6.5mm.

(2) A change in habit during growth can result from a variation in the ratio of the growth rates of some faces, or from the relative growth rates and/or the geometrical relationship of the faces or forms present on the crystal. The proposed method allows one to distinguish between these two possibilities. (3) Constant habit growth, as defined above, is common in porphyritic extrusive and granitic intrusive rocks. This confirms the vectorial nature of crystal growth and seems to indicate that growth may have occurred in a relatively free environment, devoid of obstacles.

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