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Crystal Boundaries in Igneous Rocks: Genetic Classification and Geometric Features

Youngdo Park

Department of Earth and Environmental Sciences,
Korea University, Anam-dong, Sungbuk-ku, Seoul 136-701, KOREA

ABSTRACT : Crystal boundaries in igneous rocks are genetically classified in order to predict the geometric patterns of the boundaries which may aid deciphering the textural code in igneous rocks. Crystal boundaries may be formed by two end-member processes; (1) mechanical and (2) chemical removal of interstitial melt. Mechanical removal of the melt will form displacement impingement boundaries, while chemical removal of the melt will form growth impingement boundaries. The positions of boundaries relative to the material points may be affected by secondary processes such as (1) migration and (2) dissolution. The geometric features of crystal boundaries, suggested in this study, may be useful when studying igneous textures and processes, although it may be impossible to determine the suggested features with the analytical techniques currently available.

Key words : crystal boundaries, genetic classification, impingement, migration, dissolution.

INTRODUCTION

Crystal boundaries in igneous rocks may hold a key to understanding the processes or the history of the processes in magma chambers. These textural features of crystal boundaries, however, have been somewhat overlooked compared to other textural features such as crystal size distribution (e.g., Cashman and Marsh, 1988). This may be due to the weak link so far established between the processes at grain-scale and resulting properties of crystal boundaries.

To strengthen the link between grain-scale processes and geometric patterns of crystal boundaries, there are at least two approaches. First, one can study crystal boundaries from natural rocks in detail and infer the operative processes. Second, one can consider the possible processes that form or modify the crystal boundaries, and then predict the geometric patterns resulting from the considered processes. Probably the final step of the second approach is examination of the grain-scale textures in natural igneous rocks.

The latter approach is attempted in this study, although the last step of checking the idea in natural rocks is not carried out because of difficulties in *detailed* chemical mapping of crystals that are not currently unavailable (discussed later). In spite of these difficulties, it is hoped that this type of approach can initiate further research on the geometries of crystal boundaries as a potential tool for textural analysis of igneous rocks.

Most of the discussion on the geometry of crystal boundaries is made for two dimensions. However, caution is necessary when examining geometric features in thin sections and making interpretations, since some three dimensional features are not well represented in two dimensions.

Definitions

A *crystal boundary* is the region between two lattice domains of identical or different chem-

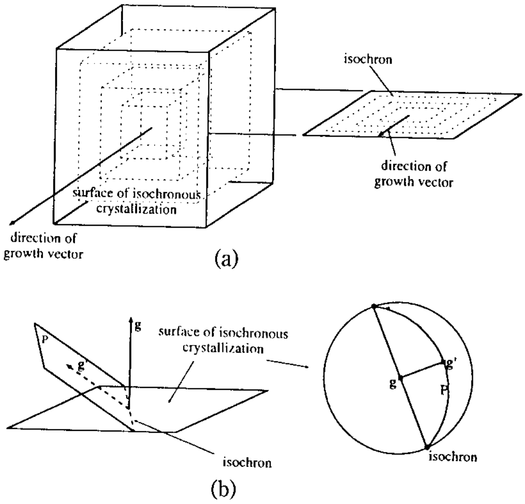


Fig. 1. Isochron and growth vector. (a) Surface of isochronous crystallization (surfaces of rectangular boxes) and direction of growth vector which is normal to the surface of isochronous crystallization. (b) Relationship between an isochron (trace of isochronous crystallization surface) and a projected growth vector on a two dimensional cutting plane. The projected growth vector is always normal to isochron (g: growth vector, g': orthogonally projected growth vector, P: arbitrary plane).

istry. A *grain boundary* is defined as the boundary between two crystals of the same phase (therefore a lattice domain boundary), and a *phase boundary* is defined as the boundary between two crystals of different phases (therefore a phase domain boundary).

The *material age* at a point in a crystal is defined as the time elapsed since crystallization. The crystallization event may be either crystallization from melt or recrystallization by migration of crystal boundaries. When material points of the same material age are connected within a crystal, a *surface of isochronous crystallization* can be constructed. An *isochron* in this study is defined as the trace of a three dimensional isochronous crystallization surface (Fig. 1a). Isochrons may be recorded as chemical zonation in crystals which change their composition during growth.

Perpendicular to the surface of isochronous crystallization, a *growth vector* is defined as a vector, with magnitude equal to the growth distance per unit time. Growth vectors that are normal to the surfaces of isochronous crystallization in three dimensions are also normal to the isochrons in the plane of observation (Fig. 1b).

GENETIC CLASSIFICATION OF CRYSTAL BOUNDARIES

Grain or phase boundaries can be divided into two types based on their origin; primary boundaries and secondary boundaries. Primary boundaries are the boundaries formed by removal of melt. Secondary boundaries are the boundaries which changed their orientation or position by modification processes.

Two end-member processes by which interstitial melt is removed, are chemical and mechanical removal of melt. Primary boundaries formed by chemical removal of melt (or chemical transformation from liquid to solid) will be referred to as *growth impingement boundaries,* while the other kind formed by mechanical removal of melt will be referred to as *displacement impingement boundaries.*

Secondary boundaries are modified pre-existing primary or secondary boundaries. The modification processes considered in this study are *migration* of a boundary and *dissolution* of crystals along a boundary. Although these processes are normally considered as subsolidus processes, they may also occur at the supersolidus conditions, as observed in the analog crystal-melt system or in the natural systems (Means and Park, 1994; Hunter, 1988). For this reason, both supersolidus and subsolidus conditions are considered for the modification processes. Although there may be other processes which modify the boundaries, the discussion is restricted to the two aforementioned processes that are relatively familiar.

Growth Impingement Boundaries

In general, a growth impingement boundary has a younging direction, since crystals grow over a period of time. The younging direction of the boundary is the same as that of the material age along the boundary (Fig. 2a). For the special case of impingement of parallel faces, there will be no younging directions within the boundary.

In order to form growth impingement boundaries, growth of at least one crystal is necessary, while the other crystal can grow, stay at zero growth rate or even dissolve. The material ages across a growth impingement boundary are equal only when the boundary is formed by two growing crystals as indicated by o and x symbols in Fig. 2a. Otherwise, material ages across the boundary are unrelated.

Displacement Impingement Boundaries

A displacement impingement boundary is a boundary formed by displacement of crystals with mechanical expulsion of interstitial melt (Fig. 2b). There is no younging direction in a displacement impingement boundary, since formation of the boundary by displacement of crystals is an instantaneous process.

The relationship between the material ages across a displacement boundary will be dependent on the pre-displacement crystallization history. If two crystals were growing immediately prior to the formation of a displacement impingement boundary, the material ages across the boundary will be the same. If one crystal ceased to grow while the other was growing before the formation of the boundary, the material ages across the boundary are unrelated.

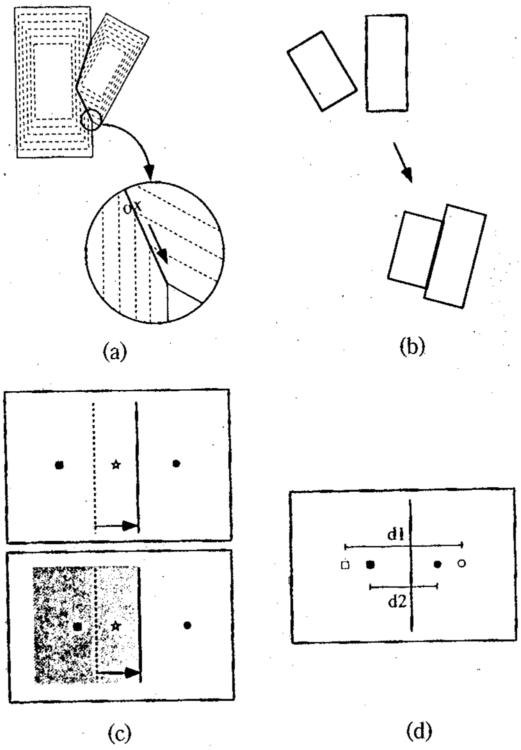


Fig. 2. Genetically classified crystal boundaries. (a) Growth impingement boundary. Arrow along the boundary indicates the younging direction of growth impingement boundary. (b) Displacement impingement boundary formed by rotation and translation of crystals. (c) Migrated grain boundaries (top) and phase boundaries (bottom). Boundary migrates through material point (star symbols). (d) Dissolution boundary formed by dissolution of crystal(s) along the boundary. Notice the change of distance (from d1 to d2) of material points. Empty symbols represent the position of material points before dissolution and filled symbols represent the position after dissolution. The diagram represents the special case when equal amounts of material are removed from both crystals.

Migrated Boundaries

Grain- or phase-boundary migration is the process by which a grain or phase boundary is moving through material points (Fig. 2c). Migration of boundaries can be caused by interfacial surface free energy (textural readjustment of boundaries), chemical free energy (chemical reaction along the boundary) or stored strain energy in crystals (strain induced boundary migration).

Grain-boundary migration can be a mass-conservative process, a process during which there is no loss or gain of material. In the absence of deformation, the distance between material points across the boundary will remain unchanged after grain-boundary migration (Fig. 2c). The material age will be reset for the newly grown part of one crystal during grain-boundary migration. Although resetting of the material age occurs, the chemical signature (e.g., trace element concentration) of the older crystal before migration may remain unchanged after migration, depending on the range of diffusion along the grain boundary.

Contrary to grain-boundary migration, phase-boundary migration in general (except for isochemical phase transformation) is a non-conservative process, involving influx and/or outflux of material along the boundary (Fig. 2c). The distance between material points across the boundary may change during phase-boundary migration, depending on the volume change. During phase-boundary migration (or reaction at the phase boundary), the material age of newly forming phase at the boundary is always younger than that of the pre-existing part of crystal. After phase-boundary migration, the material ages across the boundary will be discontinuous. Similar to grain-boundary migration, some chemical signature of the older crystal before boundary migration may be preserved in the newly formed crystal.

For a crystal that grew by migration of grain or phase boundaries, the material age of the crystal can be considered in two ways; (1) *lattice age* - time elapsed after incorporation of atoms in the current lattice and (2) *chemical age* - time elapsed after the present chemistry is established. As discussed earlier, lattice age and chemical ages may or may not reset, depending on the range of diffusion along a migrating boundary (i.e., short vs. long range diffusion) and types of boundary migration (i.e., grain- vs. phase-boundary migration), Both lattice age and age of bulk chemistry establishement will always be reset after phase boundary migration, but age after establishement of trace-element chemistry may or may not reset, depending on the range of tracer diffusion. Simialr types of age resetting can also occur during grain-boundary migration.

Dissolution Boundaries

When dissolution of crystals occurs at grain or phase boundary while the two crystals are still in contact, the position of the boundary changes with respect to material points in crystals (Fig. 2d). Since the crystal-to-crystal distance decreases during dissolution, local deformation is necessary in order to maintain the boundary (e.g., Fig. 4., Park and Means, in press). One of the geological processes that can produce a dissolution boundary is pressure solution.

A dissolution boundary is similar to a migrated phase boundary which involves a change in distance (i.e., length decrease) between material points across the boundary. However, the relationship of material ages across the boundary is somewhat different, although the difference may not help distinction of the two boundaries. For a migrated phase boundary, the material age of the newly-grown phase near the boundary is always younger than the material age of reactant phase near the boundary. On the other hand, for a dissolution boundary, this relation is not necessarily found. It can be expected in many cases, however, since dissolution at a boundary is unlikely to juxtapose isochrons of identical age in the two crystals separated by a dissolution boundary.

GEOMETRIC FEATURES OF BOUNDARIES

Growth Impingement Boundaries

The orientation and length of a newly forming segment of a growth impingement boundary can be determined if growth vectors of the two crystals are known. The newly forming segment can be constructed by drawing lines normal to the tip of each vector as shown in Fig. 3a and connecting the intersection point of these lines to the previous end of growth impingement boundary.

A growth impingement boundary is unlikely to be a rational crystal face if the boundary is formed by two growing crystals, since the

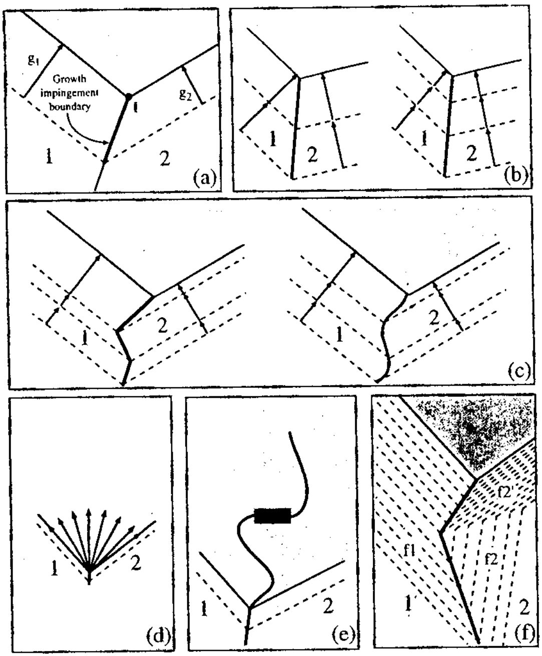


Fig. 3. Geometric features of growth impingement boundaries. (a) Construction of a new segment of a growth impingement boundary, using two growth vectors (g1 and g2). I: intersection of two isochrons. (b) Straight growth impingement boundaries formed when relative growth rate of two crystals is constant. (c) Kinked or curved growth impingement boundaries formed when relative growth rate of two crystals is changing over time. (d) Orientation limit of a growth impingement boundary when the growth impingement boundary is formed by growing crystals. Rays of arrows represent the possible orientations. (e) Example of geometrically impossible orientation of a growth impingement boundary (in the dark rectangular region). (f) Kink in a growth impingement boundary formed by the change in the impinging crystal faces. The older segment of the boundary is formed by f1-f2 face. Sudden orientation change occurs when the boundary is formed by f1-f2' face.

orientation of a growth impingement boundary is controlled by the two growth vectors, not by the growth habits or the forms of crystals. However, if the boundary is formed by only one growing crystal, the boundary can be a rational crystal face of the non-growing crystal.

So long as there is no change in growth rates of two crystals or no change in the relative growth rates, a growth impingement boundary is expected to be straight (Fig. 3b). When the relative growth rate changes over time, the growth impingement boundary is not straight. Such boundaries can have a kink (sudden changes in orientation) or smooth curvature, depending on how the relative growth rate is changing (Fig. 3c).

If a growth impingement boundary is formed by one or two growing crystals, two crystal faces are associated with the growth impingement boundary. If these two faces from two crystals are not changing and crystals are not dissolving during the formation of growth impingement boundary, there is a limit in orientation of a growth impingement boundary, as shown in Fig. 3d. In general, if two crystal faces intersect at an angle less than 180° facing the melt (Fig. 3d), the orientation of the growth impingement boundary should be in an orientation between that of the two growing crystal faces. Orientations other than those (illustrated in Fig. 3e) are not geometrically allowed, unless one crystal is dissolving while the other is growing, or there is a change in the growth faces that are impinging. Due to the discussed geometric limit in the orientation, for a curved growth impingement boundary, the tangential line to the boundary should be within the orientations of two impinging faces.

If one of the impinging crystal faces changes (face f2 to f2' in Fig. 3f), the growth impingement boundary will display a kink. When the angle between two crystal faces is becoming larger by the change in crystal face, the possible orientations of tangential lines will be wider. Therefore, an example such as Fig. 3e can be a possible growth impingement boundary, if there has been a change in two crystal faces which define the growth impingement boundary.

Displacement Impingement Boundaries

Although there is a possibility that two crystals of complicated shape can form an irregular displacement boundary, displacement impingement boundaries are most likely to be straight. An example of a displacement boundary and isochron relationship is shown in Fig. 4a. Although the material ages across the boundary may not match, the isochrons of both crystals tend to be parallel to the boundary. If there is further growth of both crystals, the displacement impingement boundary will propagate by development of growth impingement boundaries as shown in Fig. 4a.

Migrated Boundaries

Unlike primary boundaries, migrated boundaries have few predictable geometric characteristics. Instead, there seems to be a characteristic pattern of chemical zones (e.g., trace element) with respect to the boundary, namely zonation patterns which are truncated and terminate at boundary (Fig. 4b).

Depending on the range of diffusion during boundary migration, the chemical signature may be preserved locally after boundary migration. When diffusion range along the boundary is short during boundary migration, the chemical signature of the older crystal before migration will be preserved in the newly formed part of the crystal (Fig. 4b, top). When long range diffusion is possible, resetting of the chemical signatures may occur (Fig. 4b, bottom).

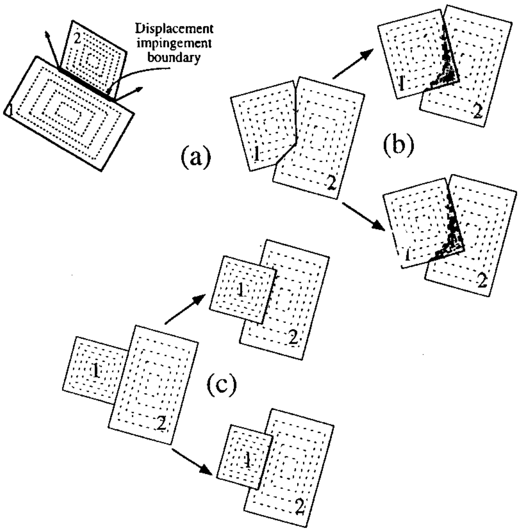


Fig. 4. Geometric features of displacement impingement boundaries, migrated boundaries, and dissolution boundaries. (a) displacement impingement boundary. (b) Migration of an initial growth impingement boundary (left). top: when resetting of chemical zoning does not occur, older chemical pattern of crystal 2 can be preserved in crystal 1. bottom: when resetting occurs, chemical pattern in the migrated part of crystal 1 will not have any relation to the original chemical patterns in crystals 1 and 2. (c) Dissolution at a displacement impingement boundary. Chemical zones truncated by the boundary are expected. top: for a situation where only one crystal is dissolving. bottom: for a situation where both crystals are dissolving.

Dissolution Boundaries

As with migrated boundaries, a characteristic feature of a dissolution boundary is isochrons or chemical zones truncated by a boundary. Fig. 4c illustrates two possible patterns of chemical zones after dissolution along the boundary. Although the truncation pattern of chemical zones for one crystal (crystal 2 in Fig. 4c) is similar to the truncation pattern by migration of boundary (crystal 2 in Fig. 4b), there is a difference in patterns of chemical zones in the other crystal (crystal 1 in Fig. 4 b and c). For a dissolution boundary formed by dissolution of only one crystal at the boundary (Fig. 4c, top), the chemical zones of the other crystal are preserved. When dissolution occurs on both crystals (Fig. 4c, bottom), chemical zones of both crystals are truncated. Contrary to these patterns for a dissolution boundary, no such relation is found in a migrated boundary (Fig. 4b). Therefore, a dissolution boundary can be distinguished from a migrated boundary by the patterns of isochrons or chemical signatures in the two crystals.

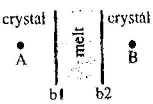
Although the zonation pattern of a dissolution boundary is quite different from that of a migrated boundary, the distinction between a dissolution boundary and a growth impingement boundary will often be very difficult. A diagram such as Fig. 4c (top) could also be interpreted as a growth impingement boundary formed by growth of only one crystal (crystal 2). Similarly, a diagram such as Fig. 2a could be also interpreted as simultaneous dissolution of two crystals. The presence of other deformation microstructures such as preferred orientation of dissolution boundaries indicating role of stress during formation of the boundaries, may help to distinguish dissolution boundaries from growth impingement boundaries. Detailed chemical mapping of isochrons, if crystals are zoned, will also help to distinguish dissolution boundaries from growth impingement boundaries, since isochrons across growth impingement boundaries will be continuous in contrast to the discontinuous isochron patterns across dissolution boundaries.

DISCUSSION

New Type of Boundary Classification

So far geometric features of the boundaries have been discussed for end-member processes. Other possibilities, when the boundaries are formed by combination of the two end-member processes, will be discussed briefly.

During the formation of primary boundaries, motions of two structures and two material points inside crystals are involved (Fig. 5a). They can be represented as velocities, ${}_{A}V_{B}$ (velocity of A with respect to B), ${}_{B}V_{b2}$ (velocity of B with respect to b2), ${}_{b2}V_{b1}$ (velocity of b2 with respect to b1) , and ${}_{b1}V_{A}$ (velocity of b1 with respect to A). Among these four velocities, only three are independent because of the constraint, ${}_{A}V_{B}+{}_{B}V_{b2}+{}_{b2}V_{b1}+{}_{b1}V_{A}=0$. All the possible combinations of the signs of the three independent velocities (${}_{A}V_{B}$, ${}_{b2}V_{B}$ or negative ${}_{B}V_{b2}$ and ${}_{b1}V_{A}$), including zero velocity, are given in Fig. 5a. It is found that the end-member processes for the formation of boundaries are still growth impingement and displacement impingement.



${}_{A}V_{B}$ \ ${}_{b1}V_{A}$: ${}_{b2}V_{B}$	+,+	+,-	-,-	+,0	-,0	0,0
+	o	o	x	o	x	x
0	# o	# o	x	# o	x	x
-	o	o	o	o	o	* o

A and B : material points inside crystals. b1 and b2 : crystal-melt interface (or boundary)

${}_{B}V_{A}$: velocity of B with respect to A (positive and negative signs represent distance increase and decrease by motion of two crystals, respectively. Zero velocity represents no motion between two crystals.)

${}_{b1}V_{A}$: velocity of a crystal melt-interface (b1) with respect to a material point inside a crystal (positive and negative signs represent growth and dissolution, respectively).

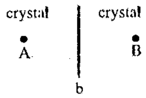
${}_{b2}V_{B}$: velocity of a crystal melt-interface (b2) with respect to a material point inside a crystal

O: conditions for the formation of crystal boundaries. x: conditions when crystal boundaries do not form

#: boundaries formed by the end-member process - growth impingement

*: boundary formed by the end-member process - displacement impingement

(a)



${}_{b}V_{A}$ \ ${}_{b}V_{B}$	+	0	-
+	Δ ⊕	Δ ⊕	(+,-,0)
0		% ⓪	⊖
-			⊖

(b)

${}_{b}V_{A}$: velocity of a crystal melt-interface (b2) with respect to a material point inside a crystal

${}_{b}V_{B}$: velocity of a crystal melt-interface (b2) with respect to a material point inside a crystal

Signs in the circle represent the sign of ${}_{B}V_{A}$ (velocity of B with respect to A).

%: no modification

Δ: newly recognized classes

Fig. 5. Classification of boundaries based on velocities of material points and boundaries. (a) for primary boundaries. (b) for secondary boundaries.

A similar attempt was made for secondary boundaries using the two independent velocities among the possible three. The two independent velocities are the velocities of the boundary with respect to two material points in crystals (Fig. 5b). A new class of boundary modification process, a process similar to veining, is found (marked with triagle symbols in Fig. 5b). Classes other than the newly found class still belong to the group of dissolution and impingement boundaries.

Cut Effect

Two dimensional geometric features of various types of boundaries have been discussed so far, as if the plane of observation were perpendicular to the boundaries and to surfaces of isochronous crystallization. To see the effect of orientations of cutting plane, two isochronous crystallization surfaces and a growth impingement boundary are considered (Fig. 6a). If the cutting plane includes both growth vectors (a fold profile-like cutting plane, great circle x in Fig. 6a), each planar feature (i.e., the two isochronous crystallization surfaces and the growth impingement boundary) has a vertical dip relative to the cutting plane and the observed younging direction of the growth impingement boundary on the cutting plane is the true younging direction (i.e., the direction of maximum gradient in the age of the impingement boundary). If the cutting plane is in the orientation such that the measured in-

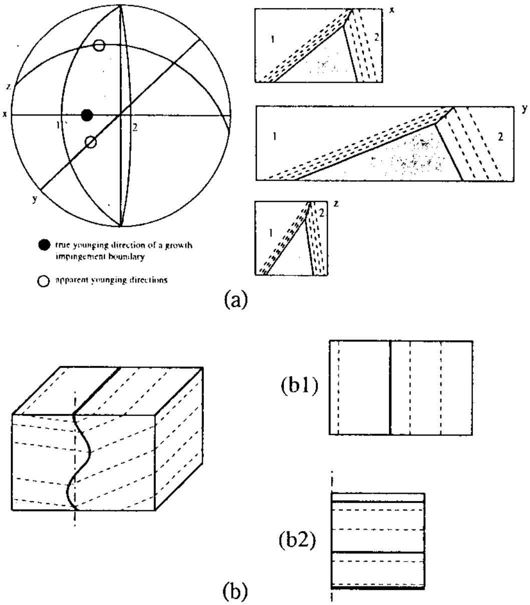


Fig. 6. Effect of cutting on apparent orientation of the younging direction in a growth impingement boundary. (a) Stereographic projection (low hemisphere) of isochronous crystallization surfaces (1 and 2) and cutting planes (x, y and z). When a cutting plane (x) includes two growth vectors, the younging direction observed on the plane is the true younging direction. Apparent younging direction appears when the cutting plane (y and z) is in a more general orientation with respect to the two growth vectors. (b) Depending on the orientation of a cutting plane, younging directions can be hidden, and isochrons appear parallel to the boundary, resulting in similar patterns to a displacement impingement boundary. (b1) cuts boundary parallel to the top of the block diagram. (b2) cuts parallel to the right vertical face of block diagram.

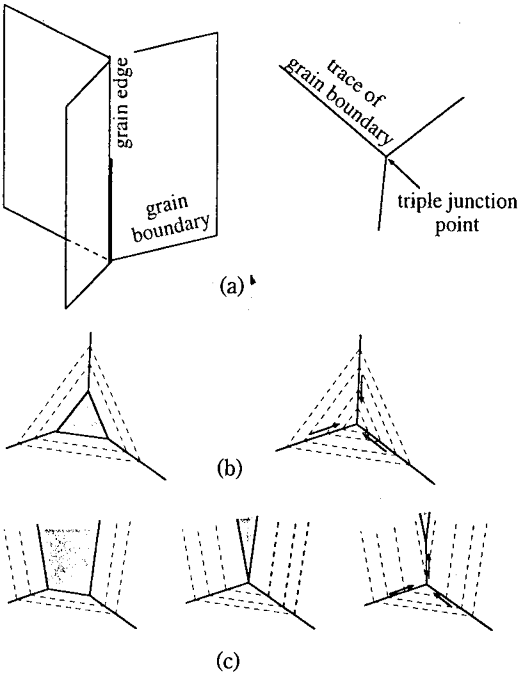


Fig. 7. Patterns of younging directions at triple junctions of growth impingement boundaries. (a) Schematic three dimensional illustration of grain boundaries, a grain edge and a triple junction point. (b) and (c) Patterns of possible younging directions at a triple junction. (b) Pattern with three converging younging directions; last melt consumption by crystallization occurs at the triple junction. (c) Pattern with two converging younging directions and one diverging direction. The diverging younging direction indicates the direction of local melt consumption by crystallization.

ter-isochron angle is larger (great circle y) or smaller (great circle z) in Fig. 6a, at least one of the three planar features is not vertically dipping, and the constructed younging direction on the cutting plane is an apparent younging direction (younging direction on the cutting plane). When a cutting plane is in the orientation which includes the intersection line of two isochrons (Fig. 6b), younging direction along the growth impingement boundary is hidden, resulting in a similar pattern to that of a displacement impingement boundary (isochrons parallel to the boundary).

Similar problems may exist for other types of boundaries, and petrographic studies using serial sections or U-stage will help to avoid these pitfalls caused by projection of three dimensional features into two dimensions.

Crystal Boundaries as a Tool to Understand Magma Processes: Example- Construction of Paleo-isotherms in Magma

When three grain boundaries meet, a grain edge is formed. A grain edge, on a two dimensional cutting plane, will appear as a triple junction point defined by intersection of the traces of three boundaries (Fig. 7a). For the triple junction point defined by three growth impingement boundaries, the pattern of three younging directions from the three boundaries

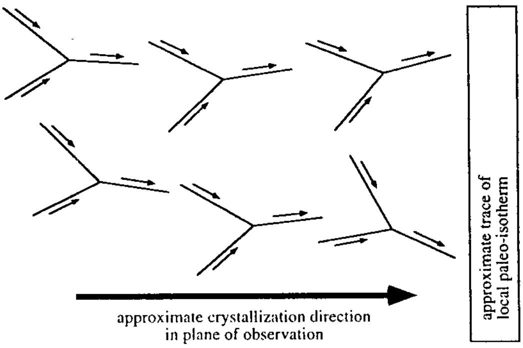


Fig. 8. Hypothetical illustration of preferred orientation of local melt consumption directions which could be interpreted as approximate two-dimensional crystallization direction of magma. Drawn perpendicular to the crystallization direction is the trace of paleo-isotherm.

may provide a clue for understanding the local crystallization process, as follows.

Two patterns of younging directions at triple junctions are physically possible on a two dimensional plane. All the younging directions can converge toward a triple junction (Fig. 7b). This represents consumption of the last melt at the triple junction by crystallization. Alternatively, two of the younging directions can converge toward a triple junction and one diverge (Fig. 7c). This represents convergence of two impingement boundaries and subsequent formation of a new boundary between the two of three original crystals. The divergent younging direction points away from the triple junction in the direction of local melt consumption by crystallization. A hypothetical situation in which there is a preferred orientation of local melt consumption direction, is shown in Fig. 8. Such preferred orientation, if found in rocks, can be used to interpret the direction of crystallization. If such patterns are consistent over a volume of rock, the surface normal to the direction of crystallization can be considered as an isothermal surface in the crystallizing magma.

CONCLUDING REMARKS

A detailed map showing isochrons or perhaps quite subtle chemical differences within crystals is essential for identifying the types of boundaries discussed here and inferring past processes. Geometric features of the boundaries themselves are usually not sufficient to determine the origin of crystal boundaries. It is not clear whether the precision of the currently available techniques for chemical analysis is good enough to detect isochrons for major igneous minerals and to apply the suggested features of crystal boundaries to igneous rocks. However, it is hoped that the present discussion provides a new incentive for analyses of this kind, and that eventually crystal boundaries in igneous rocks will be realized as a potential textural tool.

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(책임편집 : 안중호)

화성암에서의 결정경계: 성인적 분류와 기하학적 특성

박영도

서울시 성북구 안암동 고려대학교 지구환경과학과

요 약 : 이 연구에서 시도된 화성암에서의 결정경계에 대한 성인적 분류는 각 성인 별로 기하학적 특성이 어떠한 양상으로 결정경계의 조직에 반영되는가를 연구하는 데에 목적을 두고 있다. 결정경계는 기계적 또는 화학적 방법에의해 결정간의 액상이 제거되는 두 가지 작용에 의해 형성될 수 있다. 결정경계가 형성된 후, 결정경계의 결정내의 어느 한 점에 대한 상대적 위치의 변화는, 결정경계 이동 작용 및 결정경계에서의 결정 용해 작용과 같은 작용에 의해 이루어진다. 이 연구에서 고려된 결정경계의 기하학적 특성은 화성암의 미구조 해석에 중요할 것으로 생각되지만, 현재 이용 가능한 분석 기술로 직접 암석을 대상으로 응용하는데 어려움이 많다.

핵심어 : 결정경계, 성인적 분류, 합치, 경계 이동, 경계에서의 용해