

# New experimental approach to understanding igneous texture

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## ABSTRACT

Thin sections containing a magma-like mixture of three crystalline ammonium compounds and intercrystalline melt can be prepared and observed microscopically during crystallization, melting, and deformation. The aim of such observations is to establish links between active processes in the crystal-melt mixture and the textural signatures of the processes. The hope is to improve the basis for process interpretation of textures in rocks, although the value of the experimental system in this regard is still unknown. Three unexpected processes are seen: creation of growth centers for later blocky grains by isothermal decomposition of early dendritic grains; migration of grain boundaries early in the crystallization history; and growth of porphyroblast-like grains by phase-boundary migration, with abundant melt nearby. Textural metamorphism begins in this material well before its melt-present history is complete.

## INTRODUCTION

For decades igneous petrologists have focused attention on the chemistry and mineralogy of magmatic rocks, and have paid less attention to textures. This has followed naturally from the relative ease of chemical and mineralogical analysis, and from the availability of a successful theoretical and experimental framework for interpretation provided by equilibrium physical chemistry (Bowen, 1928; Yoder, 1979). Recent developments have, however, renewed interest in texture. Across petrology in general, there is a higher proportion of *process* studies; this raises interest in texture because textural features are process sensitive. For example, the grain sizes of igneous rocks depend on the relative rates of nucleation and crystal growth processes, so that something can be learned of these processes by the study of grain sizes (Cashman and Marsh, 1988). Other process problems in igneous petrogenesis, such as the mechanism of melt separation from its source regions and the origin of magmatic layering, also call out for augmented textural study and for fundamental improvement in the basis for textural interpretation. Interest in texture has also been promoted by textural experiments on silicate crystal-melt systems (Lofgren, 1980, and references therein; Jurewicz and Watson, 1985) and by deformation experiments on partially melted rocks (e.g., Dell'Angelo and Tullis, 1988). In addition, there is new interest among mapping geologists in the textures of plutons, for what they reveal about the relative timing of pluton emplacement and tectonic deformation (Hibbard, 1987; Paterson et al., 1989).

The principal obstacle to textural interpretation, in all kinds of rocks, is a lack of thorough understanding of the links between various processes of rock transformation and the textural or microstructural "signatures" that the processes leave. In plutonic igneous rocks, for example, it is not even entirely clear which textural features were produced during magmatic crystallization and which represent later, solid-state adjustments (McBirney, 1984, p. 140). In this paper we describe a new approach to the problem of establishing links between the textures of igneous rocks and texture-controlling processes. Nongeologic samples of crystals and melt are prepared in *thin section* and are observed optically while subjected to various thermal and deformational histories. The technique is an extension of experiments in transmitted-light cells on entirely solid samples, explored by a few structural

geologists over the past 15 years (reviewed in Means, 1989).

## SAMPLE MATERIAL

The sample material consists of three crystalline phases and melt (Fig. 1). The crystalline phases are ammonium thiocyanate ( $\text{NH}_4\text{SCN}$ ), ammonium chloride ( $\text{NH}_4\text{Cl}$ ), and diammonia tetrathiocyanato cobaltate ( $(\text{NH}_4)_2[\text{Co}(\text{SCN})_4] \cdot n\text{H}_2\text{O}$ , referred to respectively as the white phase, the cube phase, and the blue phase. The white phase forms colorless, monoclinic crystals of blocky to bladed form. The cube phase is colorless and isometric, and it typically appears as small, more or less rounded, cubic grains. The blue phase is generally acicular to bladed and is probably tetragonal, judging from its parallel extinction and occasional isotropic and square cross sections. The melt is a hydrous fluid with ions such as

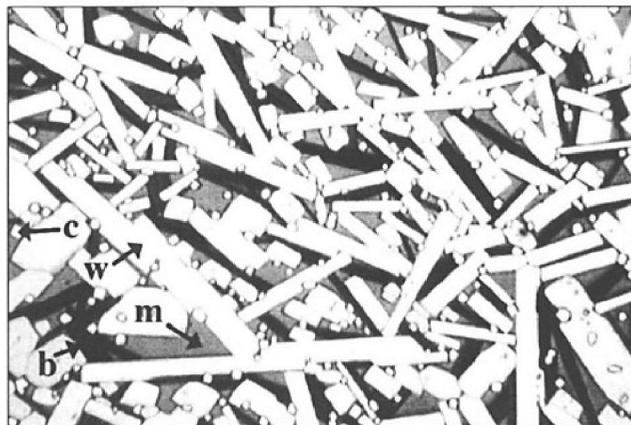
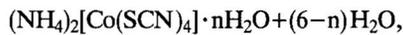
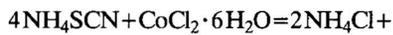


Figure 1. Sample material, consisting of main white phase (w), cube phase (c), blue phase (b), and melt (m), at room temperature. Field width is 1.5 mm. Plane-polarized light.

$\text{NH}_4^+$ ,  $\text{Cl}^-$ ,  $\text{SCN}^-$ , and  $[\text{Co}(\text{SCN})_4]^{2-}$  in solution. The melt color varies from pale blue to a deeper blue in plain light, depending on the concentration of the blue phase in solution and on the thickness of the section. Typical samples are about the thickness of an ordinary petrographic thin section of rock.

Samples can be made as follows. Saturated aqueous solutions are prepared of  $\text{NH}_4\text{SCN}$  (clear solution) and  $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$  (red-wine-colored solution). Five parts by weight of the clear solution are mixed with one part of the wine-colored solution. This yields a blue solution instantly, by the following reaction:



which in turn yields the blue cobaltothiocyanate ion (Young, 1948, p. 159). A drop of this blue solution is put on a glass slide on a hot plate at 80 °C for about 10 min. This dehydrates the fluid and produces a thick, felted mass of crystals. This material is remelted on a hot plate at about 150 °C. The melt puddle is covered with a second slide heated to the same temperature, and the melt film between the slides is thinned as desired, by pressing with some convenient implement (e.g., the eraser on a pencil) while the liquid layer is still entirely molten. The sandwich of two slides and a melt layer is then removed to room temperature. Rapid dendritic crystallization of the white and cube phases follows, and eventually the blue phase appears. After at least 10 min (to ensure appearance of the blue phase), the sample is moved to a hot plate set to about 50 °C and left overnight, or longer, to coarsen and acquire a blocky texture. Coarser grain sizes are obtained by longer holding at 50 °C. The eventual melt fraction at room temperature is controlled primarily by the severity of dehydration at the 80 °C heating step described earlier. A sample like that in Figure 1 can be obtained by dehydration for about 10 min. Samples intended for holding at room temperature for hours or more must be sealed around the edges (e.g., with epoxy cement); otherwise, atmospheric moisture infiltrates and causes isothermal melting. Although we are not aware of any particularly dangerous toxic properties of this material, all preparation steps are carried out in a hood and with gloves.

Samples prepared as above can be used for a wide variety of experiments, including melting or crystallization experiments, isothermal experiments to study time-dependent transformations, and deformation experiments. Here we describe three processes

that are seen without deformation. Each is geologically somewhat unfamiliar, yet could be geologically important. Preliminary accounts of deformation effects were given in Means (1991), Park and Means (1992), and Means and Park (1993).

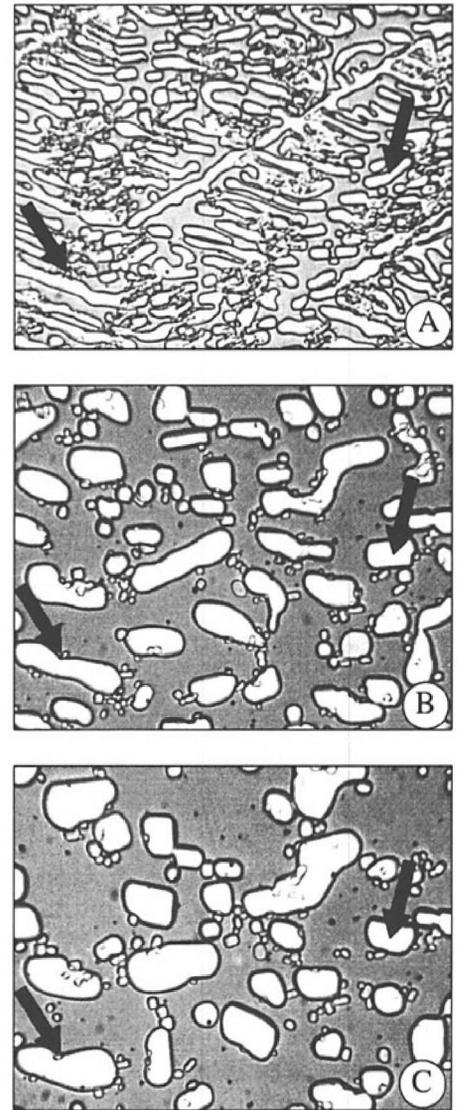
### DENDRITE SEGMENTATION

A surprising feature of the material of Figure 1 is that few if any of the white-phase crystals nucleated in the classical sense. That is, few of these crystals contain within their present boundaries a tiny region around which accretion began for that specific crystal. The present crystals grew, but the "growth centers" from which they grew originated by a process of geometrical decomposition or "segmentation" of formerly much larger, multiply branched, single-crystal dendrites. This is the usual *initial* growth habit of the white phase from melt, even at our lowest cooling rate (5 °C/h). The dendritic form is unstable, however, because of the high ratio of surface area to crystal volume. The dendrites spontaneously break down by the process shown in Figure 2.

In Figure 2A, the material of a single, white-phase dendrite is shown at 50 °C, just moments after it was cooled to this temperature. Segmentation has already begun, but the single crystal character of the dendrite can still be seen from the strong preferred orientations of the northeast-trending "stems" and southeast-trending "branches" (and from the uniform extinction of crystals like this when the nicols are crossed). In Figure 2A most of the branches have already melted through at their former junctions with the stems, and some of the branches have been subdivided by melting along their lengths. Subdivision of dendrites by melting is accompanied by complete melting of the smallest segments and by corresponding growth of the larger segments, such that the average segment size increases and the segment shapes become more equant. A classic igneous texture with more or less random orientations of grains, as in Figure 1, is produced by subsequent crystallization if the segmentation process is accompanied or followed by relative rotation of the segments, as in parts of Figure 2.

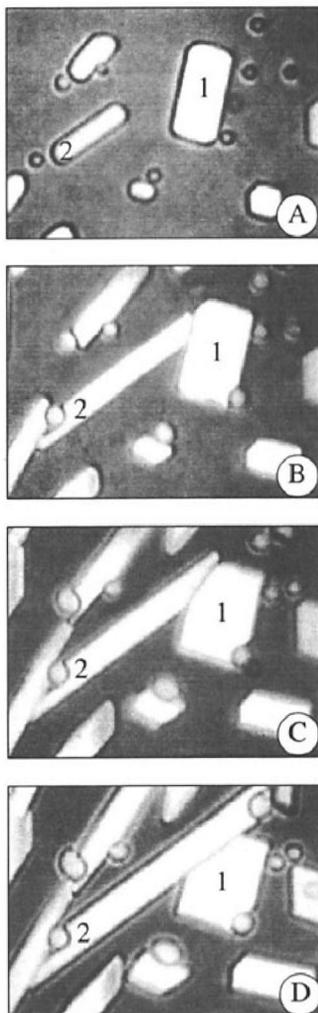
### GRAIN-BOUNDARY MIGRATION

Grain-boundary migration is a familiar metamorphic process, a well-known solid-state phenomenon operating during recrystallization or grain growth. It is not normally thought of as a process that operates in the "magmatic realm" (but see Hunter, 1988). In our samples, grain-boundary migration commonly occurs. It can make its first appearance at any melt fraction, without con-



**Figure 2. Isothermal segmentation and coarsening of single-crystal dendrite of white phase. A: Immediately after cooling to 50 °C; formerly continuous crystal has already been subdivided extensively. B: Same field after 214 min. C: Same field after total of 589 min. Arrows mark corresponding parts of original crystal through history, as indicated by time-lapse video recording. Note shortening and thickening of segment indicated by left arrow, and rotation of segment indicated by right arrow. Smaller crystals of lower relief are cube phase, which is also coarsening. Background is melt. Field width is 0.4 mm. Plane-polarized light.**

current or prior deformation. All that is required is the existence of a grain boundary—an interface between two grains of the same phase. Figure 3 shows an example of grain-boundary migration in the white phase during cooling, with surprising geometric consequences. In Figure 3B a normal growth-impingement boundary has been established between growing grains 1 and 2, rational with respect to grain 1. By the stage shown in Figure 3D, however, the boundary

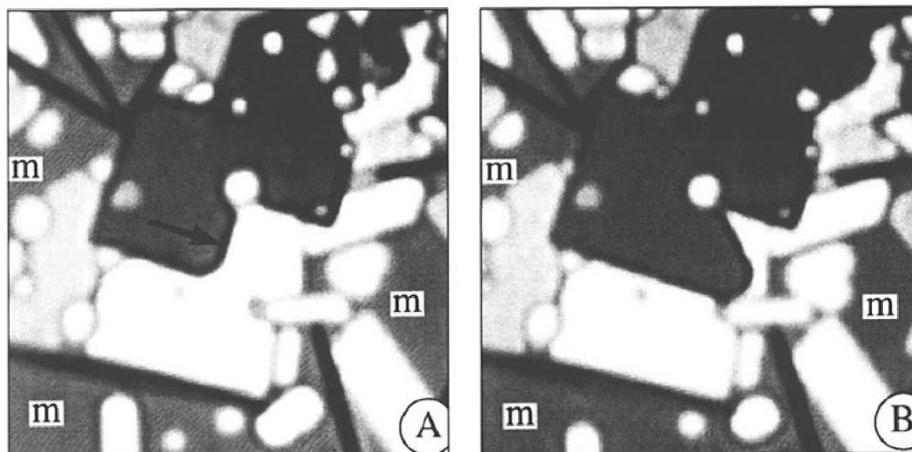


**Figure 3.** Grain-boundary migration between crystals 1 and 2 of white phase, during cooling from 83 °C to 61 °C. Smaller, more rounded grains are cube phase. Background is melt. Grain-boundary migration occurs between B and D. Total elapsed time = 191 min. Field width is 0.3 mm. Plane-polarized light.

is rational with respect to grain 2. It is no longer a simple growth-impingement boundary, although it looks like one. It is a migrated boundary, altered in position and orientation by transfer of atoms from grain 1 to grain 2. An intermediate step is shown in Figure 3C. As a result of this history, grain 2 is part “phenocryst” and part “porphyroblast.”

#### PHASE-BOUNDARY MIGRATION

Another familiar metamorphic process is the migration of a “phase boundary,” an interface between chemically or structurally dissimilar grains—e.g., the interface between a growing garnet porphyroblast and neighboring grains of quartz in a schist.



**Figure 4.** Isothermal phase-boundary migration between growing crystal of blue phase (under arrow) and white phase; m is melt. Tip of arrow marks most conspicuously mobile phase boundary. Internal boundaries between blue crystal and its cube-phase inclusions are also mobile, consuming inclusions. Elapsed time between A and B = 6 days; 50 °C. Field width is 0.1 mm. Plane-polarized light.

Phase-boundary migration between chemically different grains always requires diffusive or other transfer of atoms to and from the migration site, unlike the simplest kind of grain-boundary migration. Phase-boundary migration is less common in our material and typically less rapid than grain-boundary migration, but it does occur. Figure 4 shows migration of the phase boundary between a growing grain of the blue phase and a neighboring grain of the white phase that is being replaced, isothermally, with abundant melt nearby.

#### DISCUSSION

Processes such as the ones above are geologically interesting, but are they possible or ever important in natural magmatic systems? There are several ways to answer this question. First, and least rigorously, one can compare the textures in rocks with the final textures in the experiments and conclude, if they are similar, that geologically realistic processes may be acting in the experiments. This has been our main source of encouragement to date, but it is not fully satisfactory, because similarity of final textures is no guarantee of similarity of processes or of process history. Second, one can use the experimental result, not as a direct analog for natural behavior, but as a source of ideas for setting up experiments on silicate systems, and let the results of the silicate experiments confirm or deny the value of the model system. We have begun to pursue this approach (Park and Hanson, 1993). Third, one can build a theoretical model based on the experimental observations, in which quantitative description of texture (e.g., rate of crystal size change) is predicted, and see if such

textural development is reasonable in geological time. For some processes and their resulting textural development, even geological time may be too short because of slow kinetics; in such cases a process observed in the experiments can be rejected as a process in rocks.

It is notable that all three processes illustrated above are “metamorphic” in the literal sense; they involve a *change in form*. They modify the pristine “igneous” morphology. If this has any parallel in petrology, it is that metamorphism can begin in igneous systems well before the igneous (i.e., melt present) part of the history is over. This is not a novel idea in one respect; *chemical* metamorphism in the igneous environment is familiar (e.g., compositional changes of crystals in the continuous reaction series during magmatic cooling). However, *textural* metamorphism in the igneous realm (apart from crystal growth itself) is less familiar, though it has been emphasized recently by some workers (Hunter, 1988).

Dendrite formation is commonplace in cast metals and other nongeologic, melt-grown materials (Rostoker and Dvorak, 1977). It has also been observed in experimentally crystallized plagioclase and other silicates (Lofgren, 1980). Dendrite coarsening has been reported in metals (Kattamis et al., 1967) but has not to our knowledge been mentioned in the geological literature. Dendrite segmentation and coarsening may need to be considered as an additional “nucleation” mechanism in some igneous systems. Arguing against this are Lofgren’s (1980) experimental results that showed dendritic forms only in rapidly cooled or strongly undercooled samples. With slower cooling or

smaller undercooling, blocky or normal bladed forms were found in the samples upon quenching. Lofgren interpreted these as original growth forms, but the results are also consistent with dendritic growth in *all* the experiments, dendrite segmentation and coarsening giving the observed blocky or bladed forms in the samples held longer at high temperature. Perhaps experiments using the high-temperature transmitted-light technique of Sunagawa (1990) can resolve this question. If dendrite segmentation is a possible "nucleation" process in magmas, recent models for crystal-size distribution, which assume only classical nucleation, may need to be enlarged. Dendrite or other coarsening processes *eliminate* small crystals, as Marsh (1988) noted, so that there can be fewer growth centers as time passes, not more centers as in classical nucleation models. One can even speculate (Park and Hanson, 1993) that the coarse grain size of plutonic rocks is due mainly to coarsening during long residence time at high temperature, rather than due to a low nucleation rate relative to crystal growth rate, as classically understood.

If melt-present grain- and phase-boundary migration are important in the magmatic realm in nature, then new caution must be exercised when interpreting the order of crystallization from texture. Thus, the relations in Figures 3D and 4B interpreted classically (see Flood and Vernon, 1988) would indicate that grain 2 in Figure 3 and the large gray grain in Figure 4 are *older* than the grains they adjoin: both of these interpretations are known to be wrong.

Another complication associated with growth of grains by phase-boundary migration is that it may allow grains to grow in an "igneous" environment but without very good communication with the main melt, even at high melt fractions. There may be a thin melt film along the migrating boundary, but this could be chemically different from the main melt. Partial chemical isolation of growing grains from the main melt could presumably lead to departures from the mineral compositions expected under "global" equilibrium conditions, at least temporarily. Other possible consequences of grain- or phase-boundary migration in rocks are zoning patterns that would not arise in the absence of these processes. An example would be zones in an invader crystal parallel to crystal faces of its invaded neighbor, where diffusion associated with grain-boundary migration is sufficiently short range, so that

homogenization does not occur during migration.

Although our crystal-melt mixture looks quite geologic, there is no reason to suppose that it is a particularly good or instructive rock analog. We only accidentally discovered that magma-like materials could be made in this system (in the course of some failed attempts to use it to simulate porphyroblast growth by solid-state reaction). There must be numerous other chemical systems that can better serve to shed light on the behavior of particular natural magmatic systems and problems.

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#### Reviewer's Comment

May change forever the way in which we interpret textures in *all* crystalline rocks.

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