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Philip E. Long and W. C. Luth

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PETROGENESIS OF MICROCLINE MEGACRYSTS FROM PRECAMBRIAN GRANITIC ROCKS OF THE DIXON-PENASCO AREA, NORTHERN NEW MEXICO

PHILIP E. LONG*

and

WILLIAM C. LUTH**

Department of Geology
Stanford University
Stanford, California 94305

INTRODUCTION

The origin of potassium feldspar megacrysts in granitic rocks has been a long-standing problem in petrology. Interpretations of their origin largely fall into two groups: (1) the megacrysts are porphyroblasts which grew after the bulk of the rock solidified (e.g., Dickson, 1968; Emmermann, 1968, 1969; Mehnert, 1969), or (2) the megacrysts are phenocrysts which crystallized directly from a melt as a primary phase (e.g., Kerrick, 1969; Nemeč, 1975). Unfortunately, the petrographic criteria that have been employed to distinguish these two possibilities are largely inconclusive. It has been argued, for example, that the presence of megacrysts in the country rock adjacent to a granitic intrusive body is evidence that the megacrysts in the granite itself did not grow from a melt because those in the country rock apparently did not. Such observations, however, are only permissive since they do not demand that the megacrysts in the granite be porphyroblasts. An alternative explanation might be that the megacrysts in the country rock grew from a vapor phase that coexisted with a crystallizing magma. On the other hand, the sub-parallel orientation of tabular megacrysts has been given as evidence of a magmatic origin, the alignment supposedly caused by flow in the magma. An alternative explanation here might be deformation of the granite during subsolidus growth of the megacrysts. Other field and petrographic criteria suffer from similar uncertainties.

In view of this situation, some investigators have examined the chemistry of potassium feldspar megacrysts in hopes of finding a definitive answer to their mode of origin. Most of these studies have emphasized the distribution of Ba. For example, Dickson (1968) studied megacrysts from the Papoose Flat pluton, Inyo Mountains, California by staining for Ba; Kerrick (1969) and Kuryvial (1976) used microprobe analyses for Ba; and Emmermann (1968, 1969) and Nemeč (1975) used bulk analysis for Ba. Emmermann (1968, 1969) and Dickson (1968) concluded that the megacrysts they studied formed as porphyroblasts, whereas Kerrick (1969), Nemeč (1975) and Kuryvial (1976) concluded that the megacrysts they examined were phenocrysts.

This disagreement has prompted us to conduct a detailed study of Ba zoning in megacrysts from two Precambrian granitic bodies in northern New Mexico, and to perform preliminary experiments producing Ba-zoned alkali-feldspar crystals

from a synthetic granitic melt at high temperatures and pressures.

In this study, megacrysts from the Puntiaquado granite porphyry and the Periasco quartz monzonite in the Dixon-Periasco area, northern New Mexico, were analyzed for Ba by continuous microprobe traverses from center to edge. This study was done as part of a larger study of the granitic and pegmatitic rocks of the Dixon-Penasco area (Long, 1974, 1976) in which particular attention was paid to late-stage and metamorphic processes in these rocks. Distinguishing between an igneous and a metasomatic origin for these megacrysts is important because it has a significant effect on our estimate of the relative importance of metasomatic processes in the area.

GENERAL GEOLOGY OF THE DIXON-PEICIASCO AREA

The geology of the Dixon-Periasco area has been described by Just (1937), Long (1974, 1976) and Montgomery (1953). It is a complex Precambrian terrane of metasedimentary and metavolcanic rocks that have been intruded over an extended period of time by a sequence of granitic rocks which include the Puntiaquado granite porphyry and the Penasco quartz monzonite. The oldest metasedimentary rocks comprise the Ortega group which consists of metaquartzites and schist, and which is overlain by quartzites, phyllitic schist, and metavolcanic rocks of the Vadito group. All of these rocks have been metamorphosed to lower- to middle-amphibolite grade. Holdaway (1975) indicates 527°C and 3.7 kb as the temperature and pressure of metamorphism of the Ortega group.

The metamorphic rocks have been intruded by four major granitic units as well as numerous pegmatite dikes. Granitic plutonism in the area began with the emplacement of the Cerro Alto metadacite as a stock-like body and as widespread dikes and sills. This was followed by the intrusion of the Puntiaquado granite porphyry which itself apparently was intruded by the Rana quartz monzonite, a large body of foliated biotite quartz monzonite. Subsequently, the last major granitic unit was emplaced (a sphene-bearing biotite quartz monzonite), the Penasco quartz monzonite. The major granitic units then were intruded by numerous pegmatite dikes, probably in more than one generation, and possibly some of them preceeded the Periasco quartz monzonite, although there is no direct field evidence for this. Field and petrographic characteristics of the granitic rocks and available radiometric ages have been construed by Long (1974, 1976) to indicate a progressive increase in the depth of intrusion of these granitic magmas over a time-span of about 300 million years. Specifically, the Puntiaquado granite porphyry was intruded at shallow depths (2 to 4 km)

*Present address: Department of Geology; Central Washington University; Ellensburg, Washington 98926.

**Present address: Organization 5541; Sandia Corporation; Albuquerque, New Mexico 87115.

sometime before 1675 m.y., whereas the Peñasco quartz monzonite was intruded at 8 to 13 km about 1400 m.y. ago.

THE PUNTIAGUDO GRANITE PORPHYRY

The Puntiaquedo granite porphyry occurs as a massive body of irregular shape that is in very sharp discordant contact with the country rock. Along the contact, there is usually a thin border zone (0 to 30 m) of finer-grained rhyolitic rock that appears to reflect marginal chilling. Aside from the border and marginal rhyolitic dikes, the body as a whole is mineralogically homogeneous. There are, however, textural variations such as differences in abundance of megacrysts and phenocrysts, and particularly, differences in degree of rock deformation associated with regional metamorphism.

The Puntiaquedo granite porphyry consists of moderate-sized, subequant Carlsbad and M-twinned megacrysts of microcline with muscovite and biotite as lesser constituents. In addition to the obvious megacrysts of microcline, there are less obvious oblate, polygonized quartz-grain aggregates which appear to be relict phenocrysts of quartz. Furthermore, there are elongate areas of thoroughly polygonized plagioclase that are distinguished from the matrix only by a slightly larger grain size and in some instances, by a greater amount of secondary muscovite. These areas are probably relict plagioclase phenocrysts that have been destroyed by a combination of chemical breakdown and mechanical granulation. Evidence that there were once intact, euhedral plagioclase grains in this rock is provided by rare grains in the matrix that have not been granulated so thoroughly and by large, partially included, intact grains of plagioclase within some of the microcline megacrysts. Some of these textural features of the Puntiaquedo granite porphyry are illustrated in Figure 1.

Figure 2 shows a detailed view of typical microcline megacrysts from the Puntiaquedo granite porphyry. Slightly asymmetrical shapes of the two halves of Carlsbad twins and the irregularity of twin planes are common features of the megacrysts. The presence of Carlsbad twinning, as well as the very existence of the M-twinning, indicates that the K-feldspar originally crystallized with monoclinic symmetry. While this does not distinguish between a magmatic or post-magmatic origin

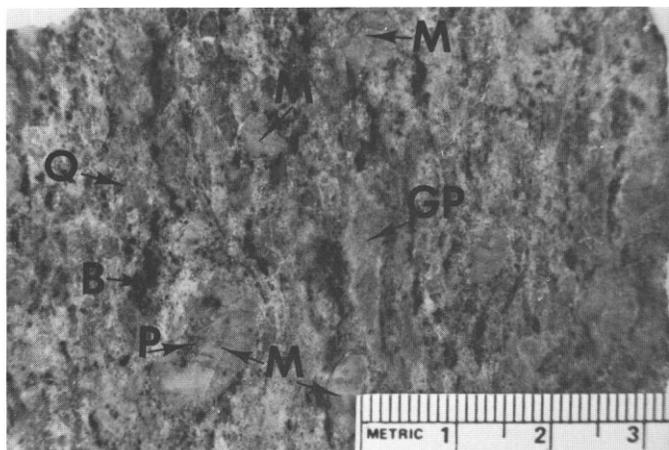


Figure 1. Stained slab of Puntiaquedo granite porphyry. Potassium feldspar has been stained yellow, here identified with an "M" for microcline. Other symbols are: P = plagioclase, GP = granulated plagioclase, Q = quartz, B = biotite + opaque Fe-oxides. Each division on the scale = 1 mm. PL73-681s.

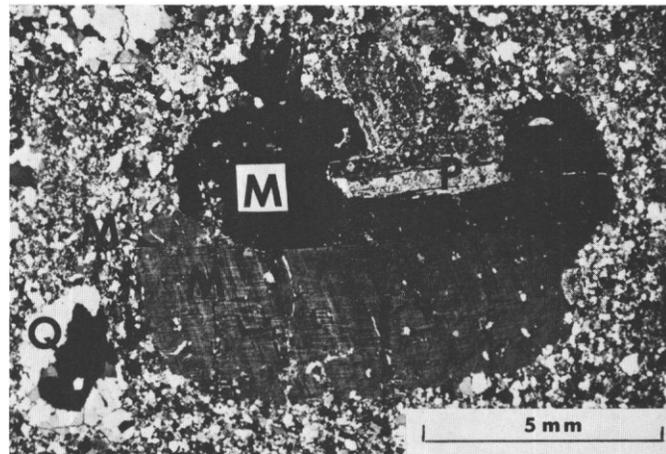


Figure 2. Photomicrograph of a Puntiaquedo granite porphyry megacryst. The megacryst is partly at extinction. Note plagioclase inclusion and polygonized quartz phenocryst. Symbols same as for Figure 1. Transmitted light, crossed polars. PL73-681s.

for the megacrysts, it does seem to preclude direct growth at low temperatures (below the monoclinic-triclinic inversion) in their present polymorphic modification.

The large plagioclase inclusion in the megacryst in Figure 2 is typical. Rarely, they are included completely, while in some instances they are simply adjacent to a megacryst. Smaller inclusions are, however, very common, and they show a slight suggestion of a concentric arrangement around the center of the megacrysts. Veinlets of albite occur in some megacrysts. The megacrysts appear resistant to deformation, but in some severely deformed rocks their margins are granulated.

Overall, the petrographic evidence that the microcline megacrysts in the Puntiaquedo granite porphyry are phenocrysts seems rather compelling. Still, such textural evidence does not provide substantive proof that the megacrysts did not grow in a post-magmatic environment. In the case of the Peñasco quartz monzonite, though, the textural evidence is even less clear-cut, and the need for additional criteria becomes obvious.

PENASCO QUARTZ MONZONITE

In contrast to the Puntiaquedo granite porphyry, the Peñasco quartz monzonite is largely concordant with the country rock and shows minor migmatization along its contacts. It is a sphene-bearing biotite quartz monzonite to granodiorite that shows fairly strong compositional variations, but which lacks a distinctive border zone or a strong orientation of platy minerals. The concentration of megacrysts varies markedly in the body from zero to about thirty per cent. No sharp, internal contacts have been observed, but the greatest concentration of megacrysts occurs in scattered local areas which seem to bear no obvious relation to the margins of the body.

Where the Peñasco quartz monzonite does contain megacrysts, they are usually large (<9 cm), tabular crystals set in a medium-grained matrix of plagioclase, quartz, microcline, biotite and sphene, plus numerous accessory minerals such as epidote, muscovite, zircon and allanite. The plagioclase grains are euhedral to subhedral and typically show undulatory normal zoning. The quartz grains, on the other hand, are distinctly an-

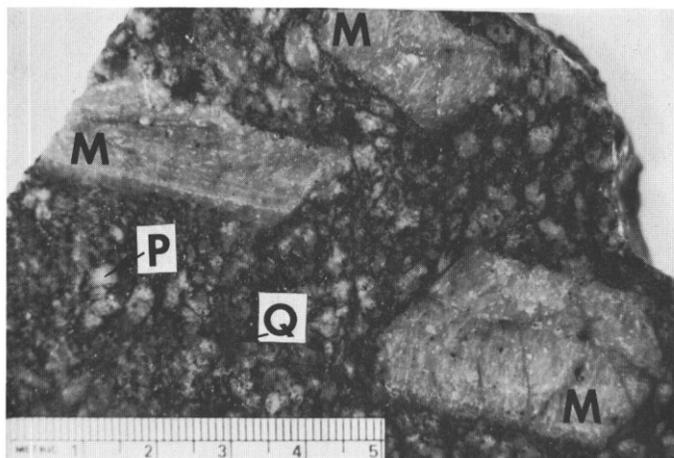


Figure 3. Stained slab of Peñasco quartz monzonite. Symbols same as in Figure 1. Each division on the scale = 1 mm.

hedral and show undulatory extinction. Biotite commonly is associated with quartz and occurs as clots or groups of grains that include the assemblage of mafic accessory minerals.

The megacrysts (fig. 3) generally show a simple Carlsbad interpenetration twin plane and primarily consist of microperthitic M-twinned microcline with plagioclase inclusions, and rarely, albite veinlets. The inclusions are about 0.5 mm in length, roughly tabular in shape, and show a definite pattern of concentric arrangement which appears to indicate ghost crystal faces (fig. 4). That is, they mark the position of crystal growth faces at previous stages in the growth of megacrysts. The concentricity of these crystal growth faces allows the determination of the exact center (presumably also the nucleation point) of the megacryst. The inclusions usually are zoned, having a more anorthite-rich core that itself normally is zoned, and this core is rimmed by a discrete zone of albite-oligoclase composition. The more An-rich portion commonly is altered to very fine-grained epidote and muscovite.

BARIUM DISTRIBUTION—DESCRIPTION OF FEATURES

Methods and Techniques of Analysis

The variation of Ba typically observed in traverses of spot microprobe analyses suggested the possible value of continuous microprobe traverses. Such traverses were employed successfully in this study using the following analytical conditions: 10-micron beam diameter, 20-ky accelerating potential, 0.5-p-amps sample current on an ARL EMX microprobe. The sample was translated at a rate of 100 μ J./minute. Overall, about 50 traverses were done on megacrysts from both the Periasco quartz monzonite and the Puntigudo granite porphyry. In addition, numerous quantitative analyses of individual points were done under similar analytical conditions except that the beam diameter was reduced to about 2 microns and sample current to as low as 0.03 p amps depending on susceptibility of the sample to damage by the electron beam.

In general, the traverse technique proved to be invaluable not only for the immediate information that was provided, but it also turned out to be impractical to attempt quantitative analyses of the megacrysts without first doing a continuous

traverse, due to the heterogeneity of the megacrysts on a 5-to-10-micron scale.

During the traverses, Na and either K or Ca were monitored so that barium levels could be correlated with position in the megacrysts and with major phases present. The traverses produced two kinds of information: (1) the number and kinds of phases present within the megacrysts, and (2) the variation of barium as a function of position relative to the center of the megacrysts. There are four phases present in all of the megacrysts: maximum microcline (Or96); plagioclase solid-solution (An, to An12); "albite" (An5 to An2); and a minor high-Ba phase (Or81 Cn13 Ab6). The microcline is the dominant phase, acting as host to all the others. It has a barium concentration that varies from about 1,600 to about 10,000 ppm. Other cations, however, are rather constant; the Or content is about 96 mol percent, Ab approximately 3 mol percent, and Ca less than or equal to 50 ppm. Table 1 gives representative analyses of megacryst microcline from both the Puntigudo granite porphyry and the Periasco quartz monzonite.

General Barium Zoning

Table 1 shows that the microcline has a variable Ba composition, and it is this variation in Ba with position in the megacrysts that is documented particularly well by the continuous traverses. A portion of the results of a typical traverse is shown in Figure 5. Note that the traverse intersected some grains of high-Ba feldspar and numerous plagioclase inclusions and albite lamellae (low Ba concentration). If, however, these phases are ignored and only the general level of Ba concentration in the microcline is considered, it is possible to plot the Ba zoning across a megacryst. One such plot is shown in Figure 6. A series of such plots from megacrysts of varying size from a single hand specimen from the Periasco quartz monzonite is shown in Figure 7. This series of plots has the property that each zoning profile can be correlated with the others if one assumes that the smaller megacrysts began growing at an appropriate later time than the larger ones. For example, notice that each of the megacrysts, starting at the outer margins, shows a decrease in Ba toward the center. If a megacryst is large enough, then it shows an increase in Ba toward the center which is then followed by a decrease, until in the largest

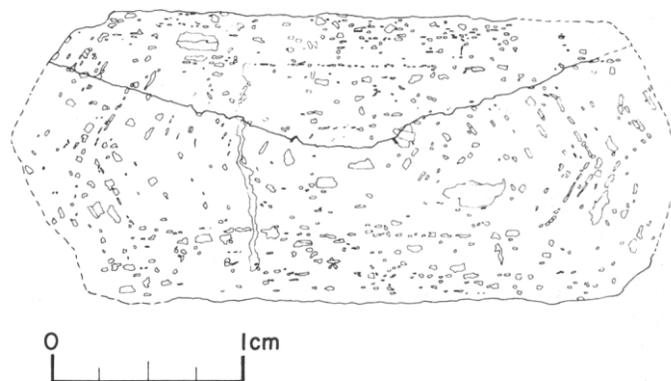


Figure 4. Line drawing of a Peñasco quartz monzonite megacryst. Note arrangement of plagioclase inclusions defining center of crystal and lack of any obvious sector zoning. Continuous line transecting the crystal marks the position of the Carlsbad interpenetration twin plane.

Table 1. Electron Microprobe Analyses of Microcline Megacrysts from the Púntiagudo Granite Porphyry and the Peñasco Quartz Monzonite.

Oxide	68 Ksp1 Wt. %	68 Ksp2 Wt. %	68 Ksp3 Wt. %	68Ksp4 Wt. %	92 Ksp1 Wt. %	92 Ksp2 Wt. %	96 Ksp1-07 Wt. %	96 Ksp1-08 Wt. %
Na ₂ O	0.44	0.37	0.23	0.28	0.61	0.54	0.54	0.49
K ₂ O	15.95	15.91	16.43	16.43	15.43	15.67	15.97	16.11
CaO	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
BaO	0.67	1.09	0.25	0.18	1.16	0.90	0.44	0.51
Al ₂ O ₃	18.52	18.57	18.34	18.09	18.59	18.59	18.15	19.19
SiO ₂	63.62	63.65	64.25	64.17	64.18	64.29	65.38	65.62
Total	99.20	99.59	99.51	99.15	99.98	99.99	100.48	101.92
Ba	6030 ppm	9720 ppm	2230 ppm	1640 ppm	10430 ppm	8080 ppm	3960 ppm	4530 ppm
	Mol %	Mol %	Mol %	Mol %	Mol %	Mol %	Mol %	Mol %
Ab	3.94	3.33	2.11	2.50	5.53	4.86	4.86	4.40
Or	94.83	94.69	97.44	97.17	92.32	93.45	94.34	94.69
An	0.00	0.00	0.00	0.00	0.01	0.03	0.00	0.00
Cn	1.23	1.98	0.45	0.33	2.14	1.65	0.80	0.91

Oxide	96 Ksp1-09 Wt. %	96 Ksp1-10 Wt. %	96 Ksp2-05 Wt. %	96 Ksp2-06 Wt. %	96 Ksp2-08 Wt. %	96 Ksp2-10 Wt. %	96 Ksp3-02 Wt. %
Na ₂ O	0.84	0.54	0.57	0.64	0.74	1.93	0.30
K ₂ O	15.30	15.87	15.89	15.85	14.93	13.41	16.37
CaO	0.00	0.00	0.00	0.00	0.01	0.01	0.00
BaO	0.45	0.60	0.40	0.35	0.46	0.46	0.55
Al ₂ O ₃	18.15	18.90	18.82	19.39	19.19	19.10	18.83
SiO ₂	65.35	64.76	64.76	65.20	64.45	65.46	65.02
Total	100.10	100.68	100.44	101.42	99.78	100.36	101.07
Ba	4030 ppm	5350 ppm	3540 ppm	3130 ppm	4110 ppm	4110 ppm	4910 ppm
	Mol %						
Ab	7.68	4.87	5.15	5.72	6.94	17.79	2.67
Or	91.49	94.04	94.13	93.64	92.15	81.31	96.34
An	0.00	0.00	0.00	0.00	0.04	0.04	0.00
Cn	0.83	1.09	0.72	0.63	0.87	0.85	0.99

megacryst, the lowest Ba content is actually at its center. The smaller megacrysts do not show the "complete" zoning pattern because they apparently did not nucleate until the cores of the larger megacrysts already had grown. Thus, it is possible to correlate positions in the megacrysts that were exposed simultaneously to the medium from which they grew. Such a correlation is suggested by the lower-case letters on each traverse in Figure 7.

Problems in correlations arise from two facts: (1) it was not always possible to insure that the megacrysts were cut precisely through the centers, and (2) the correlation is based on general gradients in the crystals rather than on exact Ba concentration. Traverse 5 in Figure 7, for example, probably did not pass through the center of the megacryst, and as a result, much of the center part of the traverse was actually in a single zone or along a growth face instead of perpendicular to it. That the correlation must depend on general gradients and not on precise barium concentration is seen from the lack of exact correlation of marginal Ba, in spite of the fact that the marginal gradients (decreasing Ba toward the center) correlate very consistently.

Figure 8 is a similar series of traverses for megacrysts from a single hand specimen of Púntiagudo granite porphyry. The general notion of correlation of megacrysts still holds for this sample. There is, however, a marked asymmetry in the distribution which is itself fairly consistent from megacryst to megacryst. If the megacrysts are large enough, one-half typically will show a sharp peak in Ba while the other half will show a broad maximum. If both this asymmetry and the size

of the megacrysts are taken into account, then it is possible to make a megacryst-to-megacryst correlation in a fashion similar to that for the Peñasco quartz monzonite. There are several differences, however. First, there is no increase in Ba toward the margins. Instead, there is a steady decrease in Ba during the later stages of growth. Also, the grain-size distribution in the Púntiagudo granite porphyry is such that there is not a continuous gradation from megacrysts to groundmass-size grains, and the very small matrix microclines consistently have uniform Ba concentrations identical with that of the margins of nearby megacrysts.

Overall, though, there are some gross similarities between megacrysts from the two rock units. The average level of Ba concentration, although variable, is roughly the same. But more importantly, in both cases, the concentration gradients go through reversals (starting out positive, becoming negative, and in the case of the Peñasco quartz monzonite samples, switching back to positive in the final stages of growth). These reversals in Ba-concentration gradients occur consistently in megacrysts from rocks representing rather different magmatic and post-magmatic environments, and provide information pertinent to the origin of the megacrysts.

The interpretation of Ba-zoning patterns in megacrysts de-

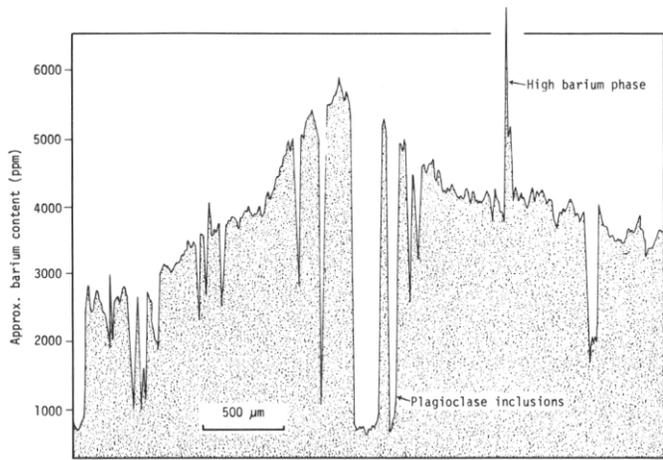


Figure 5. A continuous microprobe traverse for Ba across a portion of a microcline megacryst. In addition to showing the general variation of Ba across part of the specimen, the traverse reveals plagioclase inclusions (low Ba) and a high barium phase (K-Ba feldspar). PL73-681s.

depends on application of crystal-growth theory and the knowledge of certain parameters involved in that theory, most notably the distribution coefficient for barium between alkali feldspar and the medium from which it has grown. This growth medium is, presumably, either a water-rich, low-viscosity fluid phase, or a high-viscosity, silicate-melt phase, depending on whether the megacrysts are porphyroblasts or phenocrysts. In order to simulate the growth of alkali feldspar phenocrysts from the melt, we have grown Or-rich alkali-feldspar crystals at high temperature and pressure from synthetic granite melts doped with Ba. In addition, we have used these experiments actually

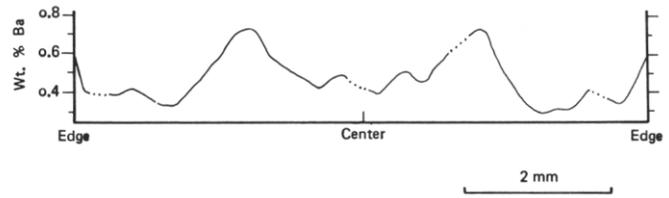


Figure 6. Plot of the variation of Ba across an entire megacryst. The plot is bilaterally symmetrical, an observation that is consistent with growth of the megacryst progressively from the center outward. Dotted portions of the plot are extrapolations across areas occupied by plagioclase inclusions. PL72-96.

to measure the distribution coefficient for Ba (D_{Ba}^{fild}). The results of these experiments are reported in the following section.

BA DISTRIBUTION BETWEEN SILICATE LIQUID AND OR-RICH ALKALI FELDSPAR

Three high-temperature-high-pressure, hydrothermal-type crystal-growth experiments were performed. These experiments were designed to provide a general notion of the magnitude of D_{Ba}^{fild} . Preliminary data on the effects of temperature and bulk composition on D_{Ba}^{fild} , and an idea of the effect of boundary-layer diffusion phenomena on zoning in synthetic crystals. The results have shown that the distribution coefficient is always strongly greater than 1, ranging from about 6 to as high as about 14 for petrologically relevant compositions. Further, the distribution coefficient appears to be strongly dependent on temperature and is sensitive to significant change in bulk composition, particularly the addition or subtraction of major components in the systems involved. Crystallization

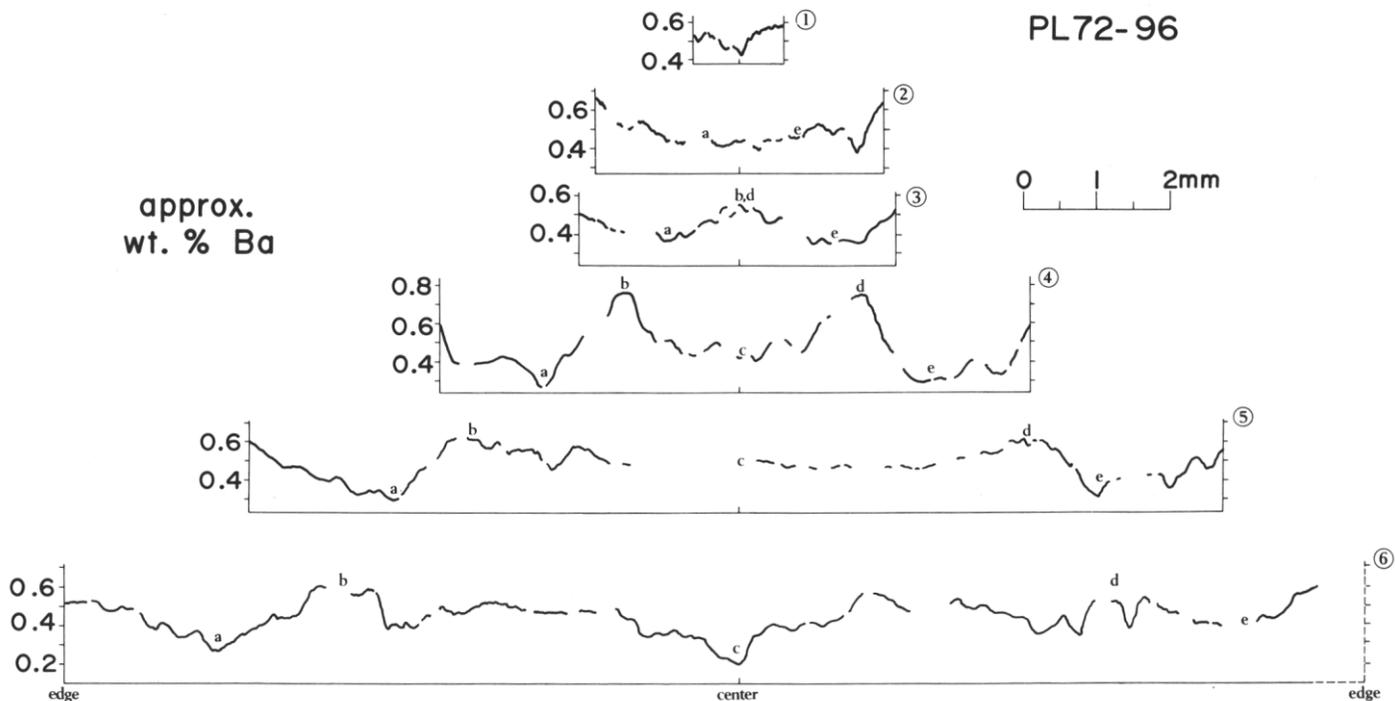


Figure 7. Correlation of Ba traverses for a series of megacrysts from a single hand specimen of Peñasco quartz monzonite. Lower case letters a, b, c, d and e denote approximately correlative points from one traverse to another. Progressively smaller megacrysts toward the top of the diagram apparently grew at later times than the larger megacrysts. Traverse #1 at the top of the figure is actually a groundmass-sized microcline crystal and its Ba zoning reflects its relatively late crystallization.

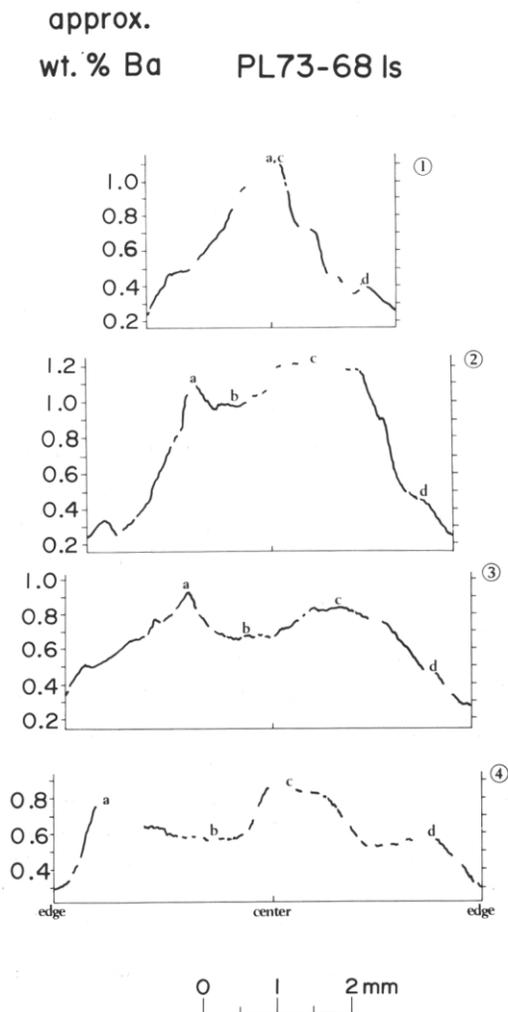


Figure 8. Correlation of Ba traverses for a series of megacrysts from a single hand specimen of Puntigado granite porphyry. Lower case letters a, b, c and d denote approximately correlative points from one traverse to another. Note the consistent asymmetry in the traverses.

at progressively decreasing temperatures of a single alkali-feldspar phase from a granitic melt doped with Ba results in progressive depletion of Ba in the melt, such that, in spite of an increase in distribution coefficient, the crystals are zoned normally with respect to Ba.

The procedures and techniques used in these experiments are those developed in the Jahns-Tuttle Laboratory for Experimental Petrology at Stanford. Most of the techniques used here are reported in Fenn (1973) and Swanson (1974). The basic approach is to homogenize a synthetic-rock-composition gel with added Ba and H₂O at conditions above its liquidus, and then to drop the temperature either in a single step or in multiple steps for a sufficient length of time for nucleation to occur (2 to 4 days per step). The resulting charges of crystals plus glass then are examined under the petrographic microscope, and appropriate areas are selected for polishing and microprobe analysis.

The first run was designed to test the feasibility of the method and involved two compositions: (1) Abs 001-5 + 2.4 wt. per cent Ba (as BaCO₂), and (2) Ab300r40Q30 + 3.05 wt.

per cent Ba (as BaCO₂) both with 3.5 wt. per cent H₂O. The run was homogenized at 1150°C, 2.5 kb for four days, then

the temperature was dropped (pressure held constant) to 925°C for two days, after which the run was quenched to room temperature. For both compositions, Ba was concentrated strongly in the crystals, but quantitative microprobe analyses show that there is a strong difference in DaBf/Iq for the two bulk compositions (see Table 2). Apparently, the excess quartz in the Ab300r40Q30 composition allows more Ba in the melt than does the alkali-feldspar composition. The general results, then, are that in these simple systems, Ba has a D-value much greater than one (7.8 to 95) and the addition of silica to the Ab-Or join has a pronounced effect on the distribution coefficient.

In subsequent runs, a quaternary granite similar to that studied by Whitney (1972, 1975) was doped with a 3-wt.-per cent-Ba-feldspar gel (equivalent to 1.09 wt. per cent Ba) (see Table 2). The material then was crystallized in two separate runs. The lower-water-content charges (3 to 6 wt. per cent) were homogenized at 1150°C, 8 kb and were crystallized in 100°C steps from 1050° to 650°C. The higher-water-content charges were homogenized at 1000°C, 8 kb and were crystallized in 25° steps from 825°C to 700°C.

The low-water-content charges typically consisted of 2 to 4 spherulitic, filamental rosettes (2 to 3 mm in diameter) of plagioclase, alkali feldspar and glass. These rosettes are mineralogically and chemically zoned, with the last stage of crystallization resulting in growth of a fringe of hopper-shaped alkali feldspar crystals. These crystals were of sufficient size to allow direct measurement of DaBf/Iq (see fig. 9 and Table 2).

The higher-water-content charges, however, were more successful in producing large single crystals of alkali feldspar, some of which are shown in Figure 10. Their longest dimensions are roughly parallel to the a crystallographic axis, their intermediate dimensions about parallel to b and their shortest dimensions about parallel to c. When sectioned perpendicularly to their long dimension, the crystals show both concentric and sector zoning (fig. 11). The crystals are commonly hollow, with the hollow portion tapered and parallel to the long dimension of the crystal. In Figure 11, the birefringence or degree of brightness of the crystal correlates well with Ba concentration, as can be seen in a Ba traverse of the same crystal (fig. 12). Ba is concentrated in the crystal relative to the glass, and with progressive crystallization, the Ba decreases steadily in each successive zone of the crystal.

Quantitative analyses are given in Table 2 and they make it possible to calculate directly the distribution coefficient for the last zone ($D_{Ba}^{Iq} = 13.9$); because the starting Ba concentration is known, it is possible to estimate the distribution coefficient of the first zone (6.1). It appears that as the temperature dropped from 800°C to 700°C, the distribution coefficient increased from 6.1 to 13.9*, behavior that is consistent with trends observed by Drake and Weill (1975). In spite of this increasing distribution coefficient, the depletion of Ba in the melt with crystallization was sufficient to result in the observed steady decrease in Ba with each successive growth zone.

*See Long (1978) for a more detailed study of the parameters affecting D_{Ba}^{Iq} , D_{Ba}^{Rb} and D_{Ba}^{Sr} in similar synthetic granite systems.

Table 2. Summary of Experimentally Determined D Values

Run #	Charge #	Temperature	Pressure	Wt. % H ₂ O	Nominal anhydrous bulk composition	D ^{af/liq} _{Ba}
1	1	900°C	2.5 kbar	3.54	Ab ₃₀ Q ₃₀ Or ₄₀	7.8, 8.2
1	3	900	2.5	3.41	Ab ₅₀ Or ₅₀	95
2	22	650	8	4.98	R1+10% Or*	13.7, 12.3 (D ^{Pl/liq} _{Ba} = 0.68)
2	23	650	8	5.99	R1+10% Or	9.8
3	24	700	8	7.01	R1+10% Or	13.6
3	25	700	8	8.02	R1+10% Or	11.5, 11.3, 11.8

*Nominal anhydrous bulk composition of R1+10% Or is Ab₂₉Or₄₀Q₂₄An₇

DISCUSSION

The crystal growth and partitioning phenomena producing the growth zones in the synthetic alkali feldspar crystals are complex, and a mathematical treatment is beyond the scope of this paper. It is possible, however, to draw an important overall conclusion from these experiments, namely, that in a magmatic system where alkali feldspar alone is crystallizing, the crystals will be zoned normally with respect to Ba. This is true largely because of the continuous depletion of Ba in the liquid which outweighs any opposing changes in D^{af/liq}, and because diffusion phenomena at the growing crystal face do not affect zoning significantly (see Long, 1978). A corollary to this conclusion is that we expect no reversals in the gradient of Ba concentration across a crystal. It is clear, however, that such reversals do occur in the megacrysts here studied. This implies that the megacrysts, if they grew from a melt, did so simultaneously with other phases. Crystallization of significant amounts of plagioclase with DPB_q < 1 (see Drake and Weill,

1975, and Table 2) and/or quartz with qtaziliq → 0 will have a significant effect on the Ba concentration of the remaining liquid, and this will be reflected in the zoning pattern of the growing megacryst. Thus, it is necessary, in attempting to understand the Ba zoning in the megacrysts, to consider the liquid concentration of Ba as a variable dependent on the total crystallization behavior of the rock, not just on the behavior of one phase.

Unfortunately, to keep track of the liquid composition during crystallization requires knowledge of the proportions of phases at each infinitesimal step of crystallization. Such knowledge generally is not available for compositionally complex granite systems, nor is it ordinarily discernable in detail from interpretation of rock textures. It can be stated, however, that as a general case, subsolvus granites crystallize at least three phases simultaneously (quartz, plagioclase and K-feldspar) for significant portions of their cooling histories. In theory, by adjusting the timing and proportions of phases,

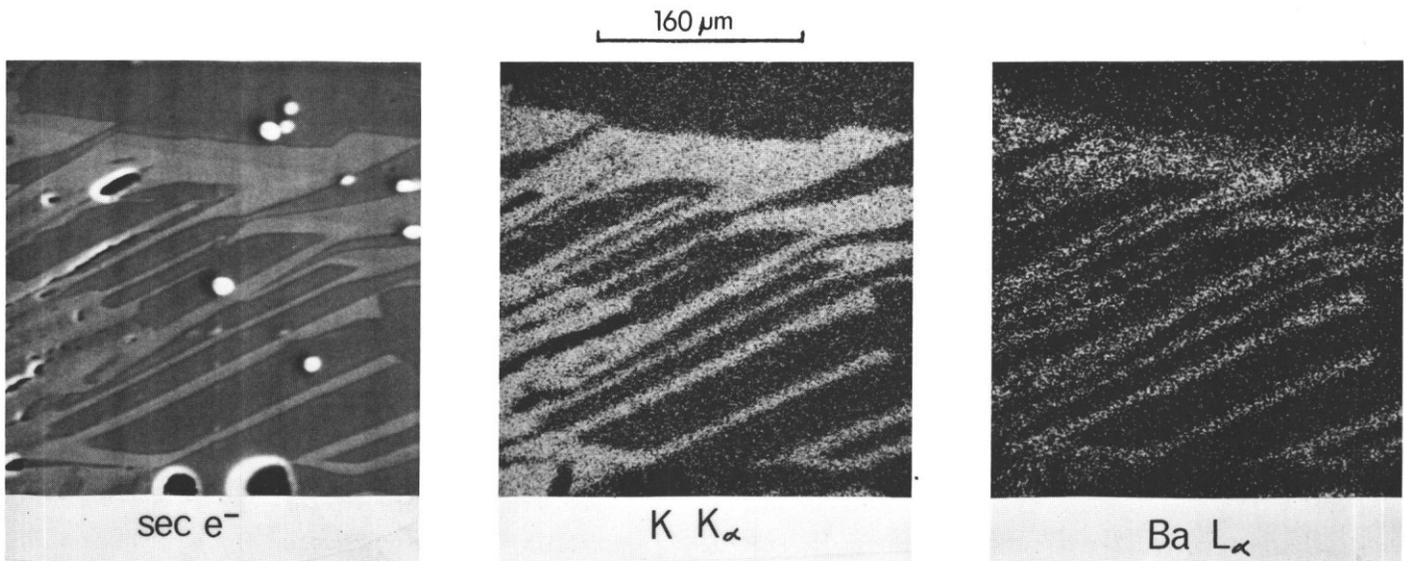


Figure 9. Electron microprobe scanning photographs of zoned, hopper-shaped crystals of synthetic alkali feldspar from run #2. The secondary electron image shows the crystal outlines and zoning which are reflected in the potassium and barium x-ray images. Note the concentration of barium in the crystals relative to the glass that surrounds them. See Table 2 for run conditions.

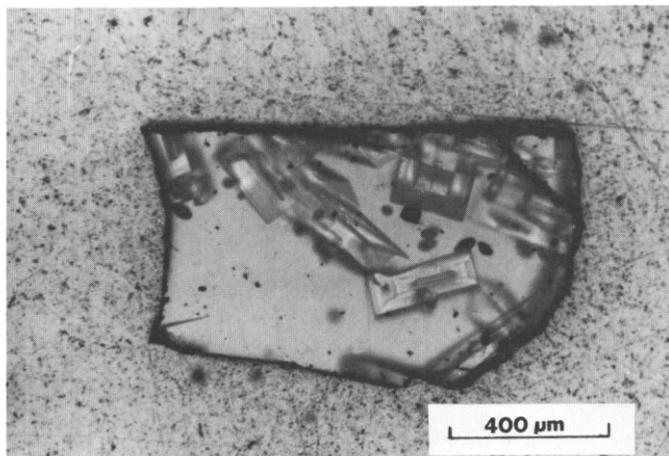


Figure 10. Photomicrograph of alkali-feldspar crystals typical of run #3. The crystals are surrounded by glass which represents the melt from which the crystals grew. Most of the crystals shown here are cut approximately perpendicularly to their longest dimension (approximately equal to the a crystallographic axis). See Table 2 for run conditions. Simultaneous transmitted and reflected light.

both of which are sensitive to water content and pressure among other variables, it would be possible to produce almost any continuous zoning pattern. We suggest that this readily explains the Ba zoning in the megacrysts. That is, they grew from a melt, and during the course of their growth, quartz and/or plagioclase crystallized in sufficient quantity to produce the reversed portions of the Ba zoning, while depletion caused by Or-rich feldspar crystallization was more important during crystallization of normally zoned parts of the megacrysts. Changing distribution coefficients and variations in growth rate also exert an effect on the zoning pattern, but our experiments suggest that, taken together, these variables are not sufficient to cause reverse zoning.

Given the nonunique character of the zoning patterns that theoretically may be produced in a crystallizing granite, would seem that no zoning pattern actually observed in a rock could provide useful information about the origin of megacrysts. Two observations need to be emphasized in this regard (1) in spite of probable differences in exact conditions of crystallization, megacrysts from both the Periasco quartz monzonite and the Puntigudo granite porphyry have similar Ba-zoning patterns, and (2) the crystallization of quartz and plagioclase provides a mechanism which consistently can produce reverse zoning during part of a megacryst's crystallization. These two points are particularly pertinent if a subsolidus origin for the megacrysts is suggested. It is not at all obvious why distinctly different megacrysts from very different rocks should end up with similar zoning patterns if they formed from aqueous fluid phases. This would require a relatively consistent change in the Ba concentration in a fluid phase during megacryst growth, and there is no obvious mechanism for such behavior. Furthermore, there are local areas in the Puntigudo granite porphyry that show superimposed epidote alteration and in most of these areas, the megacrysts retain their characteristic zoning pattern. In the most severely altered areas, however, the relict megacrysts have a constant, relatively high Ba content. Apparently, under certain conditions, a fluid phase is

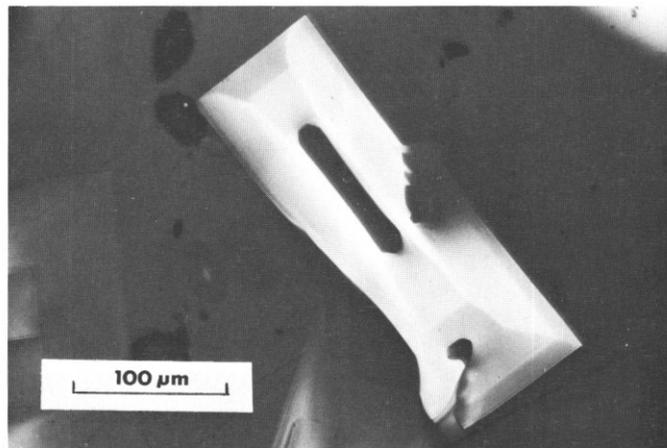


Figure 11. Detail of a hollow, synthetic alkali-feldspar crystal shown in Figure 10. Note its glass-filled core, concentric zoning (temperature induced) and sector zoning. The zoning reflects differences in Ba concentration with the highest Ba contents associated with the lightest (most highly birefringent) areas of the crystal. Those areas are also the areas of the crystal which grew earliest. Simultaneous transmitted and reflected light. Polars partially crossed.

capable of homogenizing Ba in the megacrysts, and we interpret this to mean that if the megacrysts had actually grown from a fluid phase, they would have tended to lack Ba zoning. Taken together, the absence of a mechanism for consistently changing the Ba content of a fluid phase and the tendency for a fluid phase to homogenize feldspars make it difficult to envision a way in which such a fluid phase could produce the Ba zoning patterns we have reported here.

CONCLUSIONS

Ba zoning in microcline megacrysts from the Periasco quartz monzonite and the Puntigudo granite porphyry suggests that they crystallized from granitic melts, in large part simultaneously with quartz and/or plagioclase. The growth of mega-

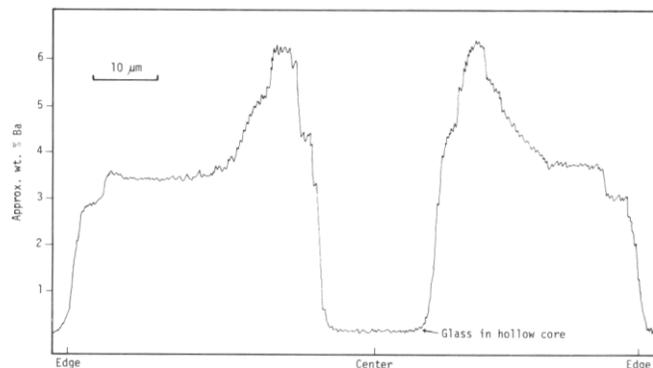


Figure 12. A microprobe traverse for Ba taken across the crystal shown in Figure 11. The traverse approximately bisected the crystal along its shortest dimension. The parts of the crystal that are highest in Ba grew at the highest temperature during the first stage of growth. Subsequent growth zones all have lower Ba concentration, and thus, there are no reversals in Ba concentration gradient as measured outward from the points of initial growth.

crysts from a granitic melt provides a mechanism that can explain readily the Ba zoning observed in megacrysts from both the Puntiaquado granite porphyry and the Periasco quartz monzonite. No such mechanism is provided by the growth of the megacrysts from a water-rich fluid phase.

Crystallization of alkali-feldspar megacrysts from a granitic melt theoretically can result in a wide variety of zoning patterns, some of which may be indistinguishable from zoning resulting from subsolidus growth of megacrysts. Megacrysts formed from melts, however, will show zoning patterns that are consistent within a single locality if the relative sizes of the megacrysts are taken into account. Furthermore, many igneous megacrysts will show Ba-zoning reversals that reflect concomitant crystallization of quartz and plagioclase. We suggest that further investigation of Ba-zoning profiles in megacrysts will shed considerable light on the general crystallization histories of the granitic rocks that enclose them.

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