Igneous phenocrystic origin of K-feldspar megacrysts in granitic rocks from the Sierra Nevada batholith

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ABSTRACT

Study of four K-feldspar megacrystic granitic plutons and related dikes in the Sierra Nevada composite batholith indicates that the megacrysts are phenocrysts that grew in contact with granitic melt. Growth to megacrystic sizes was due to repeated replenishment of the magma bodies by fresh granitic melt that maintained temperatures above the solidus for extended time periods and that provided components necessary for K-feldspar growth. These intrusions cooled 89–83 Ma, are the youngest in the range, and represent the culminating magmatic phase of the Sierra Nevada batholith. They are the granodiorite of Topaz Lake, the Cathedral Peak Granodiorite, the Mono Creek Granite, the Whitney Granodiorite, the Johnson Granite Porphyry, and the Golden Bear Dike.

Megacrysts in these igneous bodies attain 4–10 cm in length. All have sawtooth oscillatory zoning marked by varying concentration of BaO ranging generally from 3.5 to 0.5 wt%. Some of the more pronounced zones begin with resorption and channeling of the underlying zone.

Layers of mineral inclusions, principally plagioclase, but also biotite, quartz, hornblende, titanite, and accessory minerals, are parallel to the BaO-delineated zones, are sorted by size along the boundaries, and have their long axes preferentially aligned parallel to the boundaries. These features indicate that the K-feldspar megacrysts grew while surrounded by melt, allowing the inclusion minerals to periodically attach themselves to the faces of the growing crystals.

The temperature of growth of titanite included within the K-feldspar megacrysts is estimated by use of a Zr-in-titanite geothermometer. Megacryst-hosted titanite grains all yield temperatures typical of felsic magmas, mainly 735–760 °C. Titanite grains in the granodiorite hosts marginal to the megacrysts range to lower growth temperatures, in some instances into the subsolidus. The limited range and igneous values of growth temperatures for megacryst-hosted titanite grains support the interpretation that the megacrysts formed as igneous sanidine phenocrysts, that intrusion temperatures varied by only small amounts while the megacrysts grew, and that megacryst growth ceased before the intrusions cooled below the solidus. Individual Ba-enriched zones were apparently formed by repeated surges of new, hotter granitic melt that replenished these large magma chambers. Each recharge of hot magma offset cooling, maintained the partially molten or mushy character of the chamber, stirred up crystals, and induced convective currents that lofted, settling megacrysts back up into the chamber. Because of repeated reheating of the magma chamber and prolonged maintenance of the melt, this process apparently continued long enough to provide the ideal environment for the growth of these extraordinarily large K-feldspar phenocrysts.

Keywords: Sierra Nevada, megacryst, barium zoning, K-feldspar.

INTRODUCTION

Large, conspicuous crystals of potassium feldspar typify many granitic intrusions in the Sierra Nevada batholith complex, California, and giant crystals attaining 4–10 cm in length occur in a few major intrusions. The origin of these megacrysts has long been a subject of debate and study. They have been attributed to early phenocrystic growth by crystallization from the melt phase of magma (Kerrick, 1969; Vernon, 1986; Bateman, 1992; Cox et al., 1996), or to late porphyroblastic growth from a water-rich fluid phase under subsolidus conditions (Dickson and Sabine, 1967; Johnson et al., 2006a, 2006b). In this study we focus primarily on the texture and composition of megacrysts in four major intrusions spanning 300 km of the eastern, central part of the range to investigate the nature and origin of the megacrysts. The genesis of the megacrysts bears on another problem of Sierran geology, that of the nature of emplacement of the large granitic intrusions that contain them. A phenocrystic origin of the megacrysts is compatible with the host pluton having formed as a spatially extensive crystallizing reservoir of magma, a so-called “big tank” (Glazner et al., 2004). A porphyroblastic (post solidification) origin is necessary to account for the even distribution of megacrysts if the host plutons are aggregates of numerous dikes and sills that solidified shortly after their injection (Coleman et al., 2004; Glazner et al., 2004).

GEOLOGIC SETTING

Many of the intrusive granitic rock masses (here referred to as intrusions or plutons) mapped in the Sierra Nevada batholith contain conspicuous K-feldspar crystals (Fig. 1). In these mapped plutons (commonly called porphyritic), the feldspars are described as variable in abundance and size, and the host plutons as faintly, partly, or strongly porphyritic. Commonly the K-feldspar crystals are 1–2 cm in length.

However, a series of large intrusions in the eastern Sierra Nevada is characterized by giant K-feldspar crystals (Figs. 1 and 2). These megacrysts commonly attain 4 cm in length and rarely approach 10 cm. The host intrusions are each the central and youngest member within a sequence of nested intrusions that are nonporphyritic or have comparatively small phenocrysts. Generally the central megacryst-bearing intrusion is displaced east of the center of the overall intrusion sequence of related plutons. The rock of these megacrystic plutons

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is of restricted composition, generally close to the granodiorite-granite boundary in the modal classification of Streckheisen (1973). Volcanic analogs to these granitoids would be evolved dacite or rhyodacite.

Samples were examined from the four major Cretaceous megacrystic intrusions near the crest of the range along a span of more than 300 km (Fig. 1). The intrusions are the granodiorite of Topaz Lake (~1030 km²; John, 1983; John et al., 1994; previously the Sonora pluton of Schweickert, 1976), well exposed on Sonora Pass; the Cathedral Peak Granodiorite (~620 km²; Bateman and Chappell, 1979; in Yosemite National Park); the Mono Creek Granite (~380 km²; Bateman, 1992; renamed from the quartz monzonite of Mono Recesses; Lockwood and Lydon, 1975), 30 km west of Bishop; and the Whitney Granodiorite (~590 km²; du Bray and Moore, 1985; Moore, 1981; Moore and Sisson, 1985; Stone et al., 2000), partly in Sequoia National Park. In addition, two late-stage hypabyssal intrusions were examined, the Johnson Granite Porphyry cutting the Cathedral Peak Granodiorite, and the Golden Bear dike, apparently fed from the Whitney Granodiorite. Modified from Kistler and Fleck (1994).

Figure 1. Map of Sierra Nevada batholith naming the four Cretaceous intrusive masses (plutons) that contain giant K-feldspar crystals (block pattern), and other less porphyritic plutons (cross-hatch pattern). In addition, two late porphyry intrusions are shown: the Johnson Granite Porphyry, cutting the Cathedral Peak Granodiorite, and the Golden Bear dike. These megacrystic intrusions are the youngest in the range, having cooled 89–83 Ma. They represent the culminating magmatic event in the evolution of the Sierra Nevada batholith. The concept that the four large megacrystic plutons are interconnected at depth and the whole was hot and molten concurrently might be termed the “giant tank” model.

METHODS

The nature of K-feldspar megacrysts in the granodiorite of Topaz Lake, Cathedral Peak Granodiorite, Mono Creek Granite, Whitney Granodiorite, Johnson Granite Porphyry, and the Golden Bear dike was examined in the field and laboratory. Collections were made containing megacrysts from outcrops, and at two localities extensive collections were made of crystals partly weathered out in glacial moraines. Samples were cut, stained, examined microscopically, and photographed in thin section. Scanning electron microscope backscatter images (commonly with dozens of images assembled in mosaics) were made with a LEO 982 field emission digital instrument with an accelerating voltage of 15 kV.

Electron microprobe analyses were performed with the 5-spectrometer JEOL 8900R instrument at the U.S. Geological Survey, Menlo Park, California. Feldspars were analyzed for Si, Al, Fe, Mg, Ca, Na, K, Ba, and Sr with wavelength-dispersive methods at an accelerating potential of 15 kV, a beam current of 10 nA, and a spot defocused to 2 μm. Standards were Si, Al: Tiburon albite; K: orthoclase OR1A; Ca: synthetic anorthite; Fe, Mg: synthetic glass RGSC (Corning #N201); Ba: natural barite; and Sr: natural strontianite. Titanite grains were analyzed for Zr, Nb, Ce, and Y at an accelerating potential of 20 kV, a beam current of 200 nA, and a focused spot. Each titanite point was analyzed for a total of 5 min consisting of 5 cycles of counting 30 s on peak and 15 s each of high and low backgrounds (total of 2.5 min on peak). Standards were Zr: natural zircon; Ce: synthetic Ce-phosphate; Y: synthetic Y-phosphate; and Nb: Nb metal. Background positions were selected to avoid interfering peaks and were sufficiently close to the peak of interest to apply a linearly interpolated background value at the peak position. Background-corrected count rates were converted to concentrations with the JEOL proprietary version of the CITZAF reduction program, using concentrations for CaO, TiO₂, and SiO₂ fixed to those of ideal titanite. These instrument conditions give a 20 ppm limit of detection for Zr, based on counting statistics, and we take 60 ppm (three times the limit of detection) as the limit of quantification. These rims were converted to concentrations with the JEOL proprietary version of the CITZAF reduction program, using concentrations for CaO, TiO₂, and SiO₂ fixed to those of ideal titanite. These instrument conditions give a 20 ppm limit of detection for Zr, based on counting statistics, and we take 60 ppm (three times the limit of detection) as the limit of quantification. This method was verified by repeated analysis of a titanite working standard BLR-1 employed by the U.S. Geological Survey–Stanford Ion-Microprobe facility, yielding 1310 ± 30 ppm Zr (n = 61). Zr concentrations for two titanite rims are below the limit of quantification, and one is at the limit of quantification, from host-granitoid sample LPL-7. These rims were
K-feldspar megacrysts in Sierra Nevada batholith

analyzed in triplicate to verify their low Zr concentrations.

X-ray maps of K, Na, Si, Ca, and Ba were made over features of interest in megacrysts in areas of ~1 cm² using the JEOL instrument with a 20 nA focused beam, a 10 µm point spacing, and a dwell time of 120 µs requiring ~1.5 days per map.

K-FELDSPAR MEGACRYST

Most of the K-feldspar megacrysts are microcline with perthite structure and Carlsbad twinning. Precise quantitative information on their size distribution is limited because they are embedded in the granitic matrix with commonly only a part of each crystal exposed on a fractured or glacially planed surface.

The easiest repeatable measure of megacryst size is the apparent length of all crystals above a specific size on a suitable flat surface. Megacrysts exposed on artificially cut and polished surfaces totaling 2.01 m² in area were examined on two monoliths from the granodiorite of Topaz Lake. (These blocks can be observed on the grounds of the U.S. Geological Survey in Menlo Park, California.) Of 638 measured and tabulated K-feldspar crystals >1 cm in length (Fig. 3), the largest crystal is 9.8 cm long, the median length is nearly 2 cm, and 5% of the crystals are >4 cm. Their abundance (~300/m²) is typical for megacrystic Sierran plutons. The largest crystal found on glaciated outcrops of the Cathedral Peak Granodiorite on the shore of Cathedral Lake is 7.4 cm in length. Hirt (1989) and Moore (1981) both reported Whitney Granodiorite megacrysts to 8 cm in length. The maximum size of all crystals would be somewhat larger because the length of the exposed part of any crystal is generally shorter than the true length.

To avoid this exposure factor, separate K-feldspar megacrysts were collected where weathered out of moraine deposits. From a moraine near Cathedral Lake, the largest Cathedral Peak Granodiorite crystal of 30 collected is 7.2 cm in length, and from a moraine near Lone Pine Lake in a collection of about the same size, the largest Whitney Granodiorite megacryst is 6.0 cm in length. The largest of a suite of ~12 weathered-out phenocrysts from the Golden Bear dike is 5.1 cm in length. These separate crystals are useful in determining the geometric center for sectioning.

The available data suggest that while megacrysts are abundant at 3–4 cm in length, a small proportion attain 5–7 cm, but only rarely do the largest ones approach 10 cm. No megacrysts were found that exceed 10 cm in length in the Sierra Nevada, but rare ones no doubt exist.

The largest megacrysts we have examined are from the Triassic quartz monzonite megaporphyr of Twentynine Palms south of the Sierra Nevada in the Pinto Mountains. Hopson (1996, p. 28) described megacrysts from the Joshua Mountains exposure of the megaporphyr up to 16 cm in length. Brett Cox collected one K-feldspar Carlsbad twin megacryst weathered out from its matrix in this unit that had a length of 15.3 cm, a density of 2.57 g/cm³, and a weight of 1.1 kg. Others have reported megacrysts elsewhere up to 18–20 cm in size (Vernon, 1986).

TEXTURAL AND COMPOSITIONAL ZONING

Zoning is ubiquitous in the K-feldspar megacrysts (Fig. 2). Many of the features defining
the zones are repeated in all of the four granitic intrusions examined, although considerable variation is found between megacrysts in the same outcrop and between megacrysts from different plutons.

Dark inclusions of biotite, hornblende, titanite, and iron oxide are arranged in internal zones parallel to the outer margins of megacrysts, and also commonly near the outer margin (Fig. 2). In some settings, particularly on weathered surfaces, inclusions of small plagioclase crystals are visible aligned along zone boundaries. They can be seen to advantage if the megacryst is sectioned, etched with HF, and stained for plagioclase with amaranth solution (Fig. 2).

Microscopically, small mineral inclusions in the K-feldspar megacrysts are seen to be abundant in some zones and rare or missing from others (Fig. 4). Plagioclase is the most abundant inclusion mineral. The other minerals, in common order of abundance, are hornblende, biotite, quartz, titanite, iron oxide, apatite, and zircon. The inclusion crystals (commonly euhedral to subhedral) are concentrated in layers along zone boundaries. Quartz is the only inclusion that rarely shows crystal form; it generally forms rounded blebs, or elongate stringers. The inclusions are usually sorted by size so that along one zonal layer the plagioclase crystals may average ~1 mm in length whereas in other layers they may average 0.1–0.5 mm (Figs. 5 and 6). Commonly zones up to 0.5 mm wide between the inclusion layers have virtually no mineral inclusions. In some plutons outside the Sierra Nevada batholith, mineral inclusions are preferentially concentrated in certain megacryst growth sectors (Vaniman, 1978), but this feature has not been found in the examined Sierran localities.

The mineral inclusions generally show a marked alignment of their long axes parallel to the zones in which they occur (Figs. 5, 6, and 7). This is especially so for plagioclase, hornblende, and titanite. The more equidimensional habit of biotite, quartz, and iron oxide inclusions does not lend itself to such alignment.

Scanning electron microscope and electron microprobe backscattered electron images reveal coarse oscillatory zoning in all megacrysts. The zoning is highlighted by the variation in Ba concentration (Figs. 5 and 6) because Ba readily replaces K in the feldspar lattice (in coupled substitution of Al for Si) and ranges from 0.5 to 3.5 wt% BaO. The high atomic weight of Ba and its ready acceptance in the feldspar makes it ideal to illustrate zoning in the megacrysts.

All examined megacrysts from the six studied intrusions are oscillatory zoned. Generally 10–16 discrete zones are present in the megacrysts (Fig. 8). The smaller K-feldspar phenocrysts in older marginal plutons (such as the Paradise Granodiorite, which surrounds the Whitney Granodiorite; Moore, 1981), have fewer, less-well-defined zones, and interstitial K-feldspar in the host granitoids generally lacks oscillatory zoning observable by the methods employed in this study.

The zones defined by Ba concentration range from 0.05 to several millimeters in thickness (Figs. 5 and 7), and are, of course, affected in thickness by the crystallographic face that they parallel. Backscattered electron beam images show that zonal layers enriched in Ba are almost invariably asymmetrical. They begin sharply and end more gradually (assuming they grow outward from core to rim in the crystal; Figs. 9, 10, 11, and 12). Prominent zone boundaries show an abrupt increase in BaO content of ~1 wt%, with the BaO content commonly doubling from 1% to 2% (representative results in Table 1). The abrupt increase in Ba content occurs within ~0.02 mm whereas it returns to an ambient value in 0.1–0.2 mm (Fig. 9), and thus produces a sawtooth concentration profile.

While most of the zone boundaries reflect growth of the megacryst, some indicate resorption, solution, or erosion of the outer edge of the megacryst before renewed growth and crystallization (Figs. 10 and 13). Such
resorption boundaries are particularly abrupt and may be wavy and channelized. It is not uncommon for one or more of the inclusion crystals to appear displaced from the orderly alignment for its particular zone of similar crystals. On close inspection the errant crystal proves to be lodged in a depression or channel cut in the zone older than the one containing it.

Under the microscope the perthitic nature of the K-feldspar megacrysts is apparent (Figs. 7, 10, and 11). Veins of perthitic albite formed by exsolution upon slow cooling of K-feldspar attain widths of 1–40 µm that are commonly parallel to one another and to 001. The perthite veins are often at a high angle to zone boundaries. In addition, irregular masses of patch perthite are common.

In some megacrysts zonal boundaries (apparently previous crystal faces) are visible as thin straight dusty lines that parallel other zonal boundaries. Under highest power magnification, some of the lines are seen to be the locus of tiny minerals generally of the same kind as those appearing as larger inclusions. Other lines prove to be narrow veins of perthitic albite that has apparently migrated to form a seam coincident with a previous crystal face (Figs. 7 and 11).

Without electron beam images showing Ba abundance, the details of oscillatory zoning are not readily apparent. Under the petrographic microscope varying abundances of perthitic albite from one zone to the next may highlight some zones as subtle differences in extinction angle when viewed in polarized light (Fig. 12). These varying abundances of perthite apparently reflect differences in the sodium content of the original K-feldspar zone before exsolution of albite.

Aside from the four K-feldspar megacryst–bearing large intrusions that have been examined that range from 380 to 1030 km² in area, K-feldspar megacrysts have been examined in two much smaller fine-grained intrusions. The Johnson Granite Porphyry intricately intrudes the south-central part of the Cathedral Peak Granodiorite (Bateman, 1992). The Golden Bear dike, apparently fed by the Whitney Granodiorite (yet beginning 0.5 km north of the exposed Whitney pluton), extends 15 km north-east across the Sierra crest and range front to the eastern foothills (Moore, 1963, 1981). The dike ranges from 5 to 30 m in thickness and contains zoned K-feldspar megacrysts similar to those in the main megacrystic masses. The 83 Ma dike has been correlated with another set of dikes to the southeast in the Coso Mountains, and the offset of the two suggests a 65 km post-dike, right-lateral displacement on faults along the alignment of Owens Valley; the combined length of the two dike sets exceeds 50 km (Kylander-Clark et al., 2005).

These granite porphyry intrusions are clearly magmatic in origin. They have sharp chilled margins and euhedral Carlsbad-twinned, K-feldspar phenocrysts (Fig. 3) set in a fine-grained groundmass. Scanning electron microscope images show BaO-enriched oscillatory zones similar to those of the main porphyritic plutons (Fig. 13). The abundant inclusions in the K-feldspar are the same mineral species as those previously described and some zonal boundaries show distinct evidence of resorption. Elongate inclusions

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**Figure 5.** False color mosaic of microprobe electron backscatter images of small parts of Whitney K-feldspar megacryst showing major Ba-rich zone boundaries (blue) along which plagioclase inclusions (red, yellow) as well as biotite, hornblende, and titanite (dark purple) are concentrated. Bottom image shows inner zone that curves around crystal corner on left, and dark purple 0.2 mm rhombic titanite crystals in top right. Top image shows the long axes of elongate plagioclase inclusions that are preferentially aligned parallel to a zone boundary. Megacryst rim and growth direction is to top. Note how Ba-rich bands start abruptly and fade gradually.

**Figure 6.** Mosaic of electron backscatter images of half of a megacryst in Whitney Granodiorite showing subtle BaO oscillatory zoning. Dark plagioclase inclusions are concentrated and aligned along zone boundaries. Inclusions of biotite, hornblende, and accessory minerals (white) are concentrated near outer margin. Irregular outermost rind of the megacryst indicates its continued enlargement during growth of groundmass minerals.
are preferentially aligned parallel to zone boundaries within the megacrysts (Fig. 13). Some megacrysts in the Johnson Granite porphyry are partly encased by medium-grained granitic rock similar to the Cathedral Peak granodiorite. Those megacrysts may be xenocrysts incorporated from that earlier intrusion, but megacrysts from the Golden Bear dike lack such xenolithic material. We conclude that the Golden Bear dike was fed from the Whitney pluton when a part of it was largely molten, yet contained suspended previously zoned megacrysts. The megacrysts survived with their delicate oscillatory zoning during dike intrusion and quenching of the fine-grained groundmass.

Ba oscillatory zoning in K-feldspar megacrysts has been identified at other plutonic localities (Vernon, 1986). K-feldspar megacrysts in the Shap granite in northern England show particularly fine oscillatory zones, defined by Ba concentration, that have been attributed to igneous crystallization (Cox et al., 1996). Ba oscillatory zoning also occurs in K-feldspar megacrysts in volcanic settings. Multiple Ba-defined sawtooth oscillatory zones are present in sanidine phenocrysts from the Fish Canyon Tuff that forms a vast ash-flow sheet in the San Juan Volcanic Field, Colorado (Lipman et al., 1997; Bachmann et al., 2002). We have observed about a dozen such zones in K-feldspar megacrysts from the South Mountain volcanic dacite dome in the San Juan volcanic field, Colorado (Steven and Ratte, 1960). The outstanding electron backscatter images of Ba oscillatory zoning in sanidine megacrysts from the Taapaca rhyodacite, Chile (Wegner et al., 2005), were an inspiration for our efforts with electron microscopy.

**ORIGIN OF ZONING**

The K-feldspar megacrysts show oscillatory zoning patterns that record the size and shape of previous boundaries of the crystals during growth. The zones are characterized by multiple, fine, asymmetric, Ba-enriched layers, channelized and resorbed zone boundaries, and zonally concentrated inclusions that are sorted...
K-feldspar megacrysts in Sierra Nevada batholith

Figure 9. Electron microprobe BaO and Na$_2$O concentration profiles across BaO-enriched zones in each of five megacrysts from several intrusive masses. Growth direction of the crystal (toward the rim) is to the right. Arrow shows beginning of zone boundary as defined by BaO content. BaO buildup takes place in 0.015–0.025 mm and returns to the ambient level in ~0.2 mm. Na$_2$O content shows little relationship to BaO, but reflects the presence of perthitic albite stringers.

Figure 10. Two major Ba-enriched (lighter colored) zone boundaries (A-A and B-B) in a Cathedral Peak K-feldspar megacryst. Growth direction (and crystal rim) is to the right. These prominent irregular boundaries apparently signal recharge of the magma chamber with fresh, hotter Ba-rich granitic melt that has partly dissolved the megacryst, producing an irregular and channelized boundary. Plagioclase inclusions (dark) are aligned parallel to zone boundaries, but some are nestled in depressions eroded and/or dissolved in the older Ba-poor zone. Backscattered electron image is 4.5 mm wide.

The K-feldspar zoning is apparently produced by an abrupt increase in the Ba concentration of the nourishing melt, coupled in some instances by partial solution of K-feldspar. This increase is then followed by a more gradual growth of the K-feldspar during which the Ba concentration is depleted back to its previous concentration. This cycle is likely caused by replenishment of the cooling intrusion by repeated injections of fresh, hot, relatively Ba-rich granitic magma, followed by size and aligned by shape parallel to zone boundaries. The similarity of these patterns in the four studied plutons, as well as in the dikes related to these plutons, supports the notion that the crystals grew surrounded by melt. These features are most compatible with crystal growth in a melt (Kerrick, 1969; Long and Luth, 1986; Vernon, 1986; Cox et al., 1996), rather than with subsolidus crystallization (Dickson and Sabine, 1967; Johnson et al., 2006a, 2006b) engulfing and replacing other mineral grains.
by a period when crystallizing K-feldspar quickly extracted Ba from the melt, causing its concentration to return to a lower level. Replenishment may have been accompanied by cycling of megacrysts between crystal-rich mushy, and melt-rich portions of the magma bodies. With replenishment, the higher concentration of Ba in the new magma relative to the host melt, caused the growing K-feldspars to rapidly incorporate Ba into their crystal lattices because of the particularly strong affinity of Ba for K-feldspar. This accounts for the sharp beginning of Ba enrichment at each zone boundary. Continued growth of the new zone then depleted the liquid in Ba, leading to the progressive decrease in Ba concentration moving outward through each sawtooth oscillatory zone.

In some cases megacrysts were apparently close to the region where a large and hot batch of new magma entered the chamber. This entry heated and shifted the local melt composition so that it was temporarily undersaturated in K-feldspar components, causing partial dissolution and resultant irregular wavy zone boundaries.

Introduction of each batch of fresh magma into the chamber, presumably through its lower portions, would have reheated the magma, offset its conductive cooling, and prolonged the life of the chamber as a viable reservoir of granitic magma. Intermittent recharge would also have accelerated stirring and mixing of the magma bodies, thereby lofting settling crystals back up into the interior of the chamber. It is clear that all of the minerals of the final granodiorite rock were periodically suspended in the melt during K-feldspar megacrystic growth because they are all found as inclusions in the megacrysts.

**MEGACRYST GROWTH TEMPERATURES**

The concentration of Zr in titanite depends primarily on temperature in zircon-saturated magmas (Hayden et al., 2007). Since Zr diffuses slowly, Zr-in-titanite geothermometry can preserve details of thermal histories that are lost by mineral phases that continue to react at subsolidus temperatures, such as feldspars and FeTi oxides. All of the examined K-feldspar megacrysts contain zonally arranged idiomorphic titanite inclusions, and idiomorphic titanite is also a widespread accessory mineral in the surrounding host granitoids. We use electron microprobe analyses of Zr in the titanite grains to estimate the temperatures of megacryst growth and to investigate the thermal histories of the intrusions.

Concentrations of Zr, Nb, Ce, and Y were measured in the cores and rims of numerous titanite grains (generally 0.1–0.2 mm in size) along traverses across megacrysts, and in the contiguous host granitoid for selected samples (see Table 2 for representative results). Anhedral granules of titanite included in locally chloritized biotite were not analyzed. Zr-in-titanite temperature (T) is a weak function of pressure (~+12 °C/100 MPa) and also of the activities (a) of SiO2 and TiO2, and is given by (Hayden et al., 2007): 

$$ T(°C) = \frac{7708 + 960P(GPa)}{10.52 - \log_{10}(a_{TiO_2}) - \log_{10}(a_{SiO_2}) - \log_{10}(ppm \text{ Zr, titanite})} - 273. $$

Temperatures presented here assume crystallization at 250 MPa, consistent with diverse estimates of intrusion depth in the central part of the Sierra Nevada batholith (Ague and Brimhall 1988; Sisson et al., 1996). Quartz inclusions show that the zSiO2 was 1 when the megacrysts grew. The aTiO2 is more difficult to assess, but in practice is not a serious limitation. Estimates

**Figure 11.** False color electron backscatter image of Cathedral Peak K-feldspar megacryst showing multiple curving Ba-rich zone boundaries (darker blue) near a previous lower right crystal corner. Growth direction (megacryst rim) is to the right. Plagioclase (red, yellow, green) occurs as inclusions and as small parallel perthitic albite stringers. These stringers aligned upward to the right generally cut zone boundaries. However, a perthitic albite stringer starting on lower left cuts other perthite stringers and is parallel to zone boundaries. It has apparently invaded a seam along a previous crystal face. This stringer will be visible under an optical microscope and will hint as to the extent of fine zoning. Image is 4 mm wide.

**Figure 12.** Three images of a zone boundary in a megacryst from the Whitney Granodiorite, all of the same area at the same scale with growth direction to the right. (Left) False color backscatter electron image of Ba-enriched zone boundary (dark blue). Plagioclase inclusions are blocky red and yellow crystals ~0.2–0.5 mm in size. Perthite is represented by nearly horizontal red and yellow stringers. (Middle) Optical microscope image with plane light showing faint lineation induced by perthite, with no hint of zone boundary except for alignment of plagioclase inclusions. (Right) Optical microscope image with crossed polars showing faint indication of zoning by subtle changes in character of perthite.
of $\alpha$TiO$_2$ in titanite-bearing dacites and rhyolites are in the range 0.7–0.95 (Hayden et al., 2007). Near 750 °C, an $\alpha$TiO$_2$ of 0.7 would lower estimated temperatures by 20 °C relative to an $\alpha$TiO$_2$ of 1. Two titanite-bearing dacites that were used to develop the geothermometer, and that have compositions and mineralogy similar to megacrystic Sierran granitoids (Lund and Fish Canyon Tuffs), have weighted-mean $\alpha$TiO$_2$ of 0.8 (Hayden and Watson, 2007), which would lower estimated temperatures by 13 °C relative to $\alpha$TiO$_2$ of 1. These differences are sufficiently small that we calculate temperatures with $\alpha$TiO$_2$ set to 1. The Zr-in-titanite temperature results are plotted against distance across their host megacryst (Fig. 14; negative values are distance into the host granitoid), and as curves of relative frequency (Fig. 15).

The analyses give the following results. (1) The megacryst-hosted titanite grains all yield igneous temperatures, mainly in the range 735–760 °C, similar to FeTi-oxide pre-eruption temperatures of rhyolites with phenocrysts of quartz, sanidine, plagioclase, and biotite (± pyroxene, amphibole) (Hildreth, 1981), and toward the low end of two-feldspar and FeTi-oxide temperatures of titanite-bearing dacites (Nakada, 1991; de Silva et al., 1994; Bachmann et al., 2002; Maughan et al., 2002). (2) Titanite grains in the granitoid host rocks have growth temperatures that overlap those of titanite grains included in the megacrysts, but also extend to lower temperatures—in some cases below solidus values. (3) With the possible exception of the Golden Bear dike sample, titanite growth temperatures do not define systematic heating or
cooling gradients from megacryst cores to rims. In the Golden Bear dike sample some titanite grains near the edges of the studied megacryst record higher growth temperatures than those in the megacryst interior, possibly revealing a gradual heating event prior to dike emplacement. (4) For the grains included in megacrysts, most titanite rims record growth temperatures close to or only slightly cooler than those of titanite cores (51 of 66 core-rim pairs have rim temperatures less than, to no more than five degrees above, associated cores). (5) For grains in the surrounding granitoid, titanite rim growth temperatures can be substantially cooler (to >100 °C) than those of respective cores.

The limited range and igneous values of growth temperatures for megacryst-hosted titanite grains support the interpretation that the megacrysts formed as igneous sanidine phenocrysts, and that intrusion temperatures varied by only small amounts while the megacrysts grew. Titanite growth temperatures from the host granitoids extend to much lower values, but such solidus and subsolidus temperatures are absent for titanite grains included within the K-feldspar megacrysts. Absence of titanite with subsolidus growth temperatures within the megacrysts is evidence that the intrusions never cooled below the solidus during megacryst growth. Combined with the observation of ubiquitous sawtooth Ba zoning in the megacrysts, the narrow igneous temperature range recorded by included titanite grains is consistent with episodic recharge of the magma bodies by granitic liquids that sustained the intrusions above their solidus temperatures and replenished the Ba concentrations in the melt.

Each idiomorphic megacryst is overgrown by a rind, ~0.5 mm thick, of amoeboid K-feldspar that extends interstitially between the plagioclase, quartz, and other minerals of the host rocks (Fig. 6). Oscillatory sawtooth Ba zoning is absent from these overgrowth rinds and in the anhedral interstitial K-feldspar of the host rocks. Barium concentrations are also generally lower in the interstitial K-feldspar than in the oscillatory-zoned megacrysts (Kerrick, 1969). The cessation of sawtooth Ba zoning and the decrease in K-feldspar Ba concentrations, accompanied by the appearance of titanite with near-solidus and subsolidus temperatures, indicate that the megacrysts ended their idiomorphic growth when they became isolated from replenishing hot granitic liquids. Idiomorphic growth may have ceased when the megacrysts settled into and were captured by solidifying mushy portions of the intrusions, or replenishment events may have stopped for that magma body, allowing it to finally cool and solidify.

HISTORY OF CRYSTALLIZATION

Megacryst-bearing granitoids have an average composition near the granodiorite-granite boundary in the classification of Streckeisen (1973). Their average modal abundances are ~45 vol% plagioclase, 30 quartz, and 25 K-feldspar (normalized to 100%, Bateman, 1992, p. 32). Experimental studies and textural relations indicate that the order of initial crystallization of the salic minerals in the Cathedral Peak Granodiorite began with plagioclase, followed by quartz, and then by K-feldspar (Bateman, 1992). With cooling, crystallization drove the melt composition to the plagioclase-quartz-sanidine cotectic so that all three minerals crystallized from the ternary minimum of true granite composition where complete solidification took place.

Therefore, during much of the solidification of these megacrystic rocks, the three major phases, plagioclase, quartz, and K-feldspar, crystallized simultaneously, as demonstrated by the inclusion in the megacrysts of the other two minerals (as well as the mafic and accessory minerals). During this period of simultaneous major

Figure 13. Mosaic of electron backscatter images of part of a megacryst from the Golden Bear dike showing BaO oscillatory zoning nearly identical to that seen in pluton-hosted megacrysts. Crystal rim and direction of zone growth is to the top. The seven zone boundaries (numbers on left) begin abruptly with higher concentration of BaO (lighter shade) and fade gradually to lower concentration (darker shade). Boundaries 6 and 7 (toward top edge) show evidence of resorption with crystal inclusions in pits. Dark inclusions are plagioclase and light are biotite, hornblende, and accessory minerals. Small white 0.1–0.2 mm rhombic titanite crystals occur in upper part of the image. Width of mosaic is 6 mm.
<table>
<thead>
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<th>Grain number</th>
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<th>Y (ppm)</th>
<th>Nb (ppm)</th>
<th>Zr (ppm)</th>
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**Note:** Position is measured perpendicular to one edge of megacryst, positive values are in the megacryst, negative values are in host granitoid. T—temperature.

Temperatures close to 740 °C for the rims of megacryst-hosted titanites are a shared feature of all the studied intrusions and support the interpretation that sustained near-isothermal conditions were critical for the K-feldspar phenocrysts to grow to megacrystic dimensions. Large granitic magma reservoirs that are well mixed and semicontinuously replenished by new additions of felsic magma may be optimal for growth of megacrysts, consistent with the megacrystic intrusions in the Sierra Nevada being among the largest in the batholith (Fig. 1) with protracted intrusive histories (Coleman et al., 2004). Many large granitic intrusions in the Sierra Nevada batholith and elsewhere lack K-feldspar megacrysts, and instead are either equigranular or have inconspicuous to small (1–2 cm) K-feldspar phenocrysts. These intrusions may have cooled through the K-feldspar crystallization interval faster than the megacrystic bodies due to less frequent recharge events, or they may have attained high crystallinities before saturating with K-feldspar due to more mafic bulk compositions (e.g., Mount Givens Granodiorite; Bate- man and Nokleberg, 1978). Some megacrystic plutons do not have unusually large exposure areas (e.g., the granodiorite of White Mountain; du Bray and Dellinger [1981]; the “quartz monzonite” [granite] of Papoose Flat; Nelson et al. [1978]), seemingly inconsistent with protracted near-isothermal growth of megacrysts in a large, multiply replenished magma reservoir. However, these smaller megacrystic intrusions may be apophyses above larger plutons, or the megacrysts may have grown in larger magma.

**TABLE 2. TITANITE TRACE ELEMENT CONCENTRATIONS AND ZR-IN-TITANITE TEMPERATURES FOR MOUNT WHITNEY GRANODIORITE SAMPLE LPL-7 MEASURED BY ELECTRON MICROPROBE**

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<th>Y (ppm)</th>
<th>Nb (ppm)</th>
<th>Zr (ppm)</th>
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reservoirs at greater depths and were later carried to the site of emplacement.

Why do the K-feldspar megacrysts commonly become 10–100 times larger than plagioclase crystals, even though the rock contains many more discrete plagioclase than K-feldspar crystals? This fact has long been a puzzle, but most workers attribute it to low nucleation rates and high growth rates for K-feldspar crystals under certain conditions in melts of granitic composition (Vernon, 1986; Cox et al., 1996; Paterson et al., 2005) as verified by experimental studies (Swanson, 1977; Day and Fenn, 1982; Whitney, 1975).

We propose that K-feldspars can grow to megacrystic dimensions, whereas other granite-forming minerals do not, because K-feldspar is most similar in composition to the granitic liquid in terms of the major components that diffuse slowly in silicate melts. For a crystal to grow, essential components must diffuse through the melt to the crystal-melt interface, and excess or excluded components must diffuse away from the interface. Diffusivities in silicate melts generally decrease in the sequence Na ≥ K > Ca > Al >> Si (Hofmann, 1980), so the rate-limiting process for growth of feldspars and quartz is attainment of the appropriate proportions of Si:Al on the crystal-melt interface. Granodiorite-to-granite series liquids have Si/Al ratios in the range 4–5 (molar). Sanidines do not depart appreciably from the alkali-feldspar join and therefore have Si/Al ratios very close to 3. Since nearly all plagioclase grown in natural subalkaline magmas have significant anorthite components, their Si/Al ratios are appreciably <3 (An_{95} 0.1, An_{90} 1.7). Igneous quartz contains only trace Al and thus has a nearly infinite Si/Al ratio. Viewed in this light, K-feldspar is most similar in composition to the coexisting granitic melt and therefore has the least diffusive barrier to growth, followed by plagioclase, followed by quartz. Those minerals with greater diffusive barriers to growth are also expected to have higher nucleation rates because larger volumes of melt distant from established crystals can achieve the high supersaturation levels necessary for nucleation of new crystals. These arguments account for why crystal sizes in true granites are routinely K-feldspar ≥ plagioclase > quartz. In less evolved granitoid magmas this ordering of growth and nucleation rates due to relative “diffusive melt-similarity” is manifest by the common poikilitic habit of late interstitial K-feldspar that is practically unknown for late quartz. In contrast, growth from an aqueous metasomatic fluid provides no simple mechanism explanation for why the K-feldspars attain megacrystic dimensions.

In addition to the evidence from the zoning of the megacrysts recounted above, field evidence indicates that the large K-feldspar crystals grew as phenocrysts in a melt. Telling evidence is the concentration of megacrysts in swarms, their presence in dikes, the orientation of their long axes parallel to flow sorting and dike walls (Vernon, 1986; Bateman, 1992; Paterson et al., 2005), and their association in ladder dikes and schlieren with swarms of mafic enclaves. Some orbicular granitic rocks (as within the mapped
K-feldspar megacrysts in Sierra Nevada batholith

Recharge brought fresh hot magma into the chamber, which renewed or accelerated convection and mobilized existing crystals on the floor and walls. It enriched the melt in Ba, much of which had previously been depleted because of its strong affinity to the growing K-feldspar phenocrysts. The re-entrained small earlier crystals then adhered to the surface of the suspended, growing K-feldspar crystals and formed layers of crystal inclusions. At a particularly vigorous and hot recharge event, some material was dissolved from K-feldspar crystals before crystal growth began anew.

The repeated recharge of a large magma chamber over a period measured in millions of years provides a mechanism to maintain it in a hot and partially molten state, a condition that would not be possible if the intrusion were emplaced at a single event as envisaged in simplified thermal models (Glazner et al., 2004). This extension of the life of a large magma chamber by repeated injections of hot melt could maintain a relatively stable composition and temperature for a long time, an environment in which crystallizing K-feldspar would be stable. Apparently such an environment is required to generate these extraordinarily large crystals.

CONCLUSIONS

Megacrysts of K-feldspar from all four of the granitic plutons containing the largest megacrysts (4–10 cm in length) in the Sierra Nevada composite batholith, and from megacryst-bearing dikes associated with these plutons, all show sawtooth oscillatory zoning marked by varying concentration of BaO. Generally each of about a dozen rather evenly spaced zones in the megacrysts begins rimward with a sharp increase in Ba concentration over a distance of 10–25 µm and declines over a much greater distance. Some of the more pronounced zones begin with resorption and channeling of the underlying zone.

Parallel to the BaO delineated zones are zonal arrangements of small mineral inclusions, principally plagioclase, but also biotite, quartz, hornblende, titanite, opaques, and other accessory minerals. These inclusions are concentrated along zone boundaries, sorted by size along the boundaries with their long axes preferentially aligned parallel to the boundaries. These features indicate that the K-feldspar megacrysts grew while suspended in melt, allowing the inclusion minerals periodically to attach themselves to all the faces of the growing crystals.

The temperature of growth of titanite inclusions in K-feldspar megacrysts has been estimated by use of a zirconium-in-titanite geothermometer. Microprobe analyses of zirconium in titanite inclusions indicate that the megacryst-hosted titanite grains all yield igneous temperatures, mainly in the range 735–760 °C. The growth temperatures of titanite grains in the granodiorite hosts marginal to the megacrysts overlap, but are commonly cooler than those of titanite grains in the megacrysts. The limited range and igneous values of growth temperatures for megacryst-hosted titanite grains support the interpretation that the megacrysts formed as igneous sanidine phenocrysts, and that intrusion temperatures varied by only small amounts while the megacrysts grew. Subsolidus temperatures are only recorded by titanite grains in the host, indicating that megacrysts ceased growing before the magmas cooled below the solidus.

The oscillatory zoning and temperature data demonstrate that the megacrysts are igneous phenocrysts that grew in melt. The individual Ba-enhanced zones are believed to signal discrete surges of new, hotter felsic melt injected from beneath the magma chamber, and maintained the partially molten or mushy chamber for an extended period until the next recharge surge. Each recharge of magma would have stirred up crystals on the floor and walls of the chamber, and induced convective currents that lofted the settling megacrysts back up into the chamber, where suspended small crystals would stick onto their outer faces, producing the zonal arrangements of inclusions. Because of the extended period of maintenance of the magma chamber, this process continued long enough to provide the ideal environment for the growth of these extraordinarily large megaphenocrysts.

ACKNOWLEDGMENTS

Mike Diggles aided in the field with photography and collecting; Allen Glazner championed fresh investigations of Sierra problems; Leslie Hayden generously provided her titanite geothermometer prior to publication and also advised us on its use; William Hirt supplied samples of the Whitney granodiorite; Forrest Hopson made available information on the Twentynine Palms locality and Brett Cox produced samples from it; Keith Howard provided information on the K-feldspar porphyritic plutons in the Mojave Desert; Peter Lipman supplied samples from the South Mountain dacite dome on the margin of the Platoro Caldera, Colorado; Jacob Lowenstern helped with microphotography; Muriel Myers tabulated crystal size information; Robert Oscarson facilitated electron microscopic and electron probe investigations; Karen Sundback helped with backcountry collecting; and Gerhard Wörner supplied information on backscatter electron images. Charles Bacon, Michael Clynne, Peter Lipman, Sheila Seaman, and Ronald Vernon reviewed the manuscript and all offered valuable advice. We are grateful for this help.

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Moore and Sisson


