Non-symmetric zoning and lack of correlation among neighboring K-feldspar megacrysts in granodiorite

Justine G. Grabiec[1], Allen F. Glazner[1], and Bryan S. Law[2], (1) Department of Geological Sciences, University of North Carolina at Chapel Hill, CB# 3315, Mitchell Hall, Chapel Hill, NC 27599-3315, (2) Sparks, NV 89441, jgrabiec@live.unc.edu

K-Feldspar Megacrysts in Granites Worldwide

Large, eye-catching K-feldspar megacrysts (crystals >5 cm in the longest dimension; Fig. 1) are common in granite but the details of their formation are unknown[1].

Common characteristics include: Chemical and mineral inclusion zones (Fig. 1, left), biotite crusts, and Carlsbad twins[2].

Conditions during megacryst formation bear on late-stage granite formation and related meta-igneous textures.

Figure 1. Left: K-feldspar megacryst cut parallel to c-axis and perpendicular to the Carlsbad twin plane with macroscopic chemical and mineral inclusion zoning. Right: K-feldspar megacryst mosaic in the Cathedral Peak Granodiorite.

Conflicting Hypotheses of Formation

1) The classic interpretation: megacrysts grow early in a magma's crystallization history in abundant melt. There are few crystals and plenty of room to grow. Magma recharge mobilizes and churns settled crystals and mixes consecutive melt replenishments. Eventually the melts are homogenized and the crystals settle[3].

2) Interpretation consistent with experimental data and phase equilibria: The onset of K-feldspar nucleation does not begin until the latter half of cooling in a rheologically immobile system. There is little room to grow in heterogeneous melt pockets in the static crystal framework, and crystal coarsening occurs via dissolution-reprecipitation[4].

These hypotheses can be tested by mapping mineralogical and chemical zones in megacrysts from the Cathedral Peak Granodiorite, Tuolumne Intrusive Suite (Fig. 2), California.

A Novel Approach to Imaging Megacryst Interiors

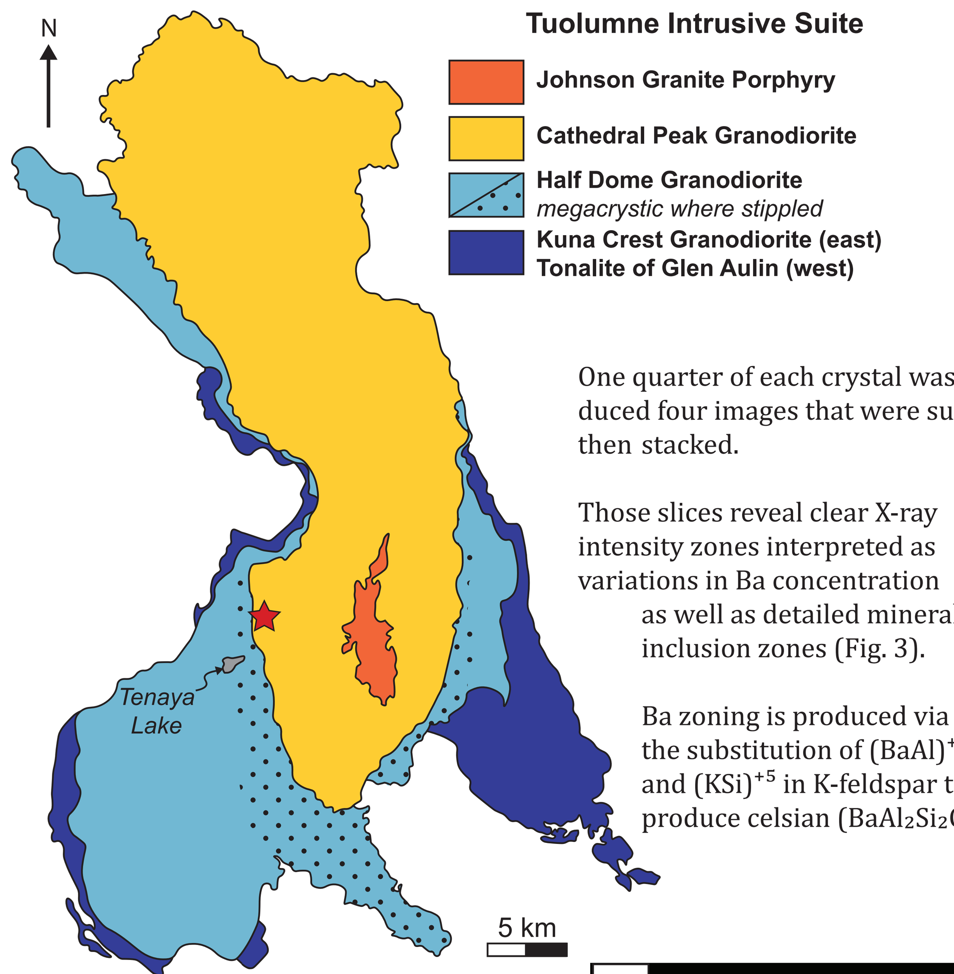


Figure 2. Geologic map of Tuolumne Intrusive Suite[5,6]. Few contacts are gradational. The surrounding rocks are older, and the units shown were emplaced between ~95 and 85 Ma[6]. The red star indicates the sample location of the analyzed megacrysts.

Ten whole-crystal samples from Cathedral Peak Granodiorite (Fig. 2) were analyzed via Micro CT[7] at Duke University.

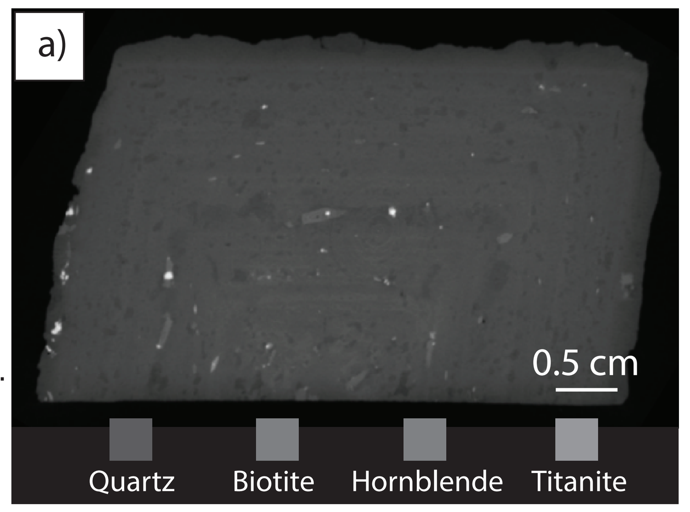
CT scans provide high resolution (~20 μm) 3D maps of the internal structure of the megacrysts and reveal clear X-ray intensity zones indicating variations in Ba concentration (Fig. 3).

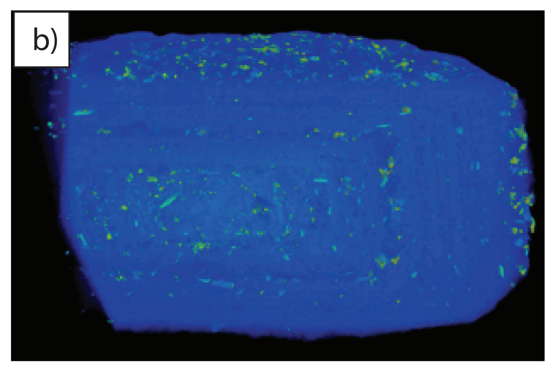
The scans provide detailed 3D maps of the megacrysts' internal structure and zoning at a resolution of ~20 μm.

One quarter of each crystal was scanned during a series of 2,500 rotations, each of which produced four images that were subsequently averaged to create a single slice (Fig. 3a) which were then stacked.

Those slices reveal clear X-ray intensity zones interpreted as variations in Ba concentration as well as detailed mineral inclusion zones (Fig. 3).

Ba zoning is produced via the substitution of (BaAl)$^{+5}$ and (KSi)$^{+5}$ in K-feldspar to produce celsian ($BaAl_2Si_2O_8$).





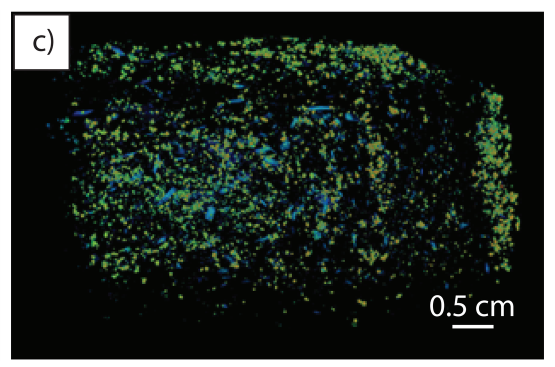


Figure 3. Processed CT data. a) CT slice perpendicular to c-axis and cut-plane; brighter areas indicate denser minerals. b) Rendered data; blue represents K-feldspar and quartz and warmer colors represent mineral inclusions. c) Inclusions in the same 3D model and orientation as (b) with feldspar and quartz removed.

Results: Non-Symmetric and Non-Correlated Zones

Images of megacryst interiors perpendicular to {010} were mapped by distinguishing zone boundaries, inferring zone boundary patterns, and color-coding zones qualitatively based on their greyscale value (Figs. 4, 5). Transects starting at the core and ending at the closest part of the rim on either side were used for analysis.

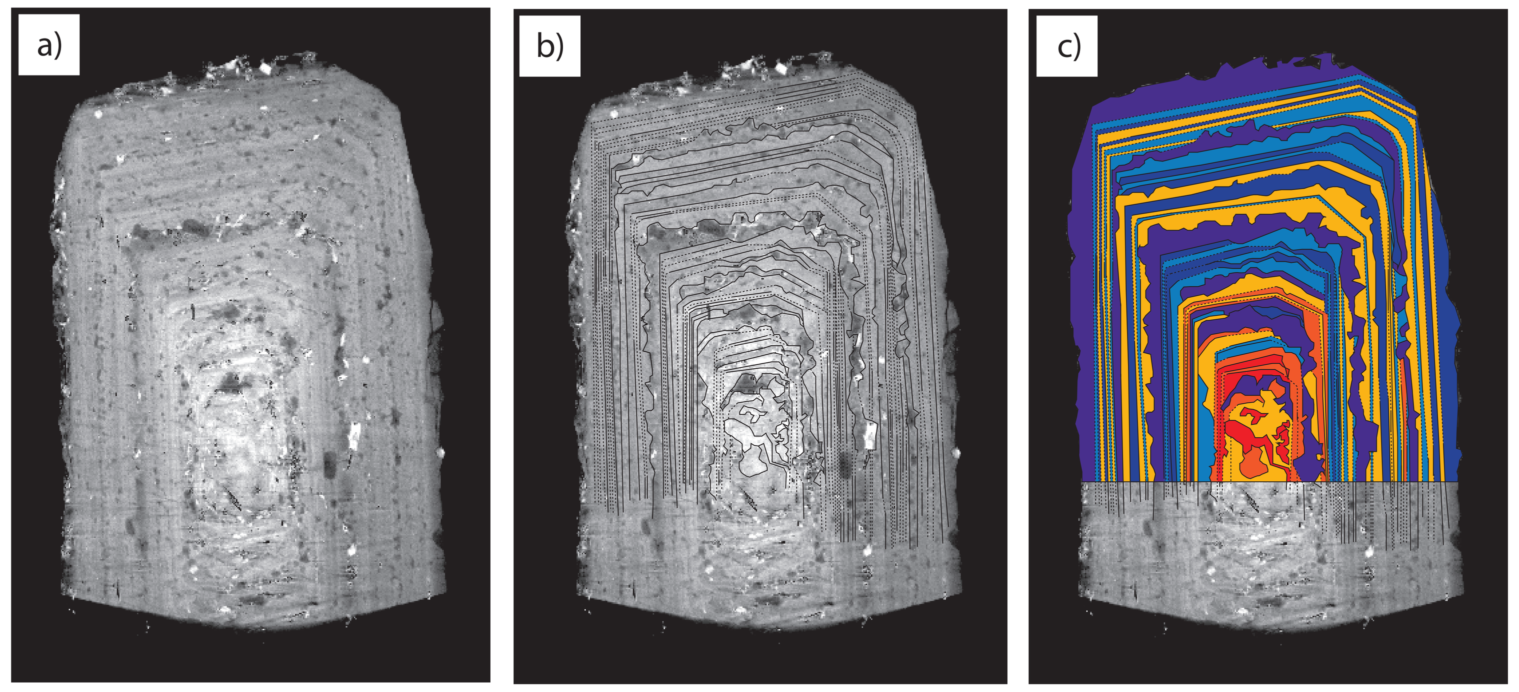


Figure 4. a) Original CT scan of sample LP4. b): Map of zone boundaries; solid lines represent observed boundaries, and dashed lines represent inferred boundaries. c): Color map of (b); warm colors represent more dense (high-Ba) zones and cool colors represent less dense (low-Ba) zones.

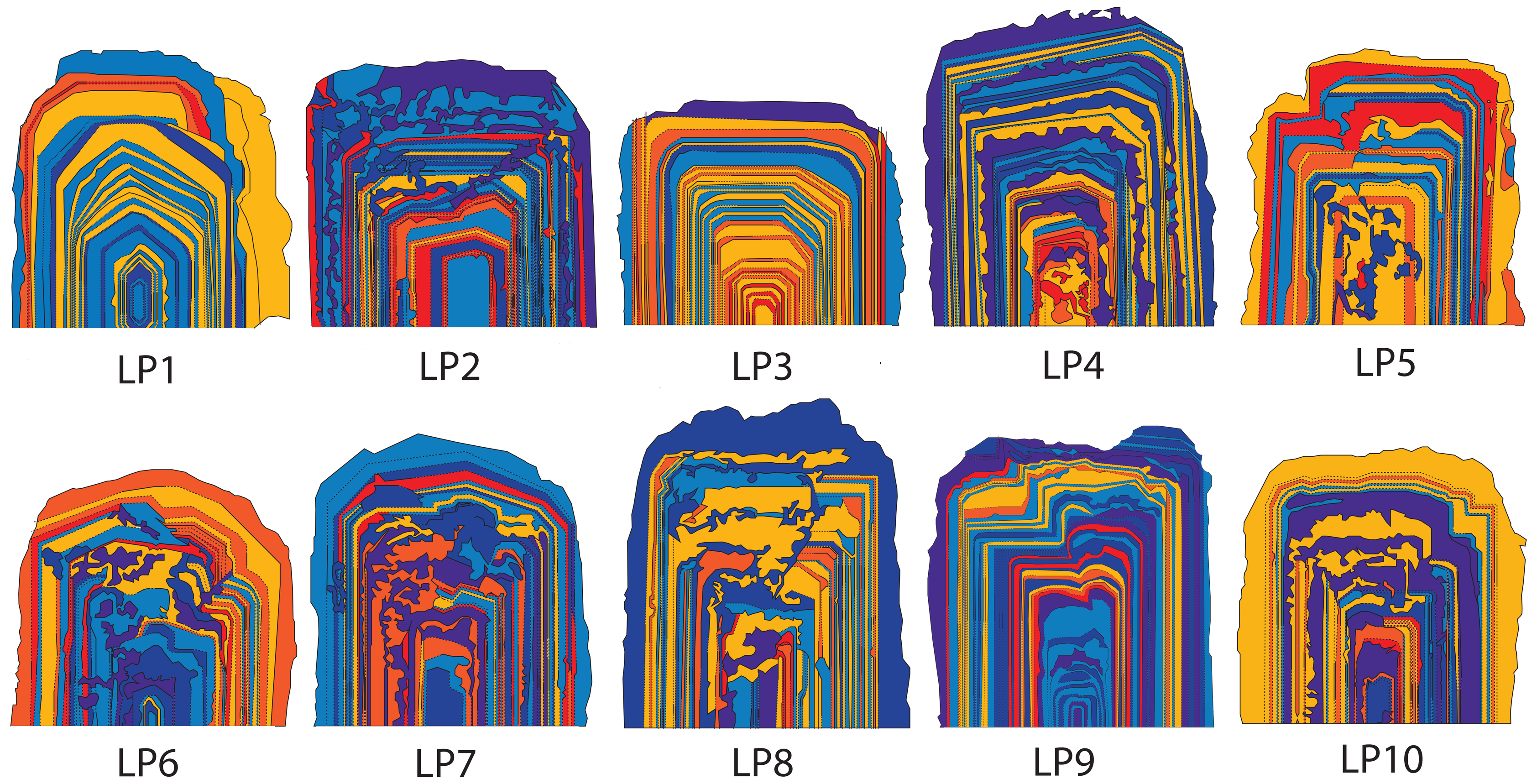


Figure 5. Scaled color maps of the megacrysts. Solid lines and dashed lines represent distinguishable and inferred zone boundaries, respectively. Truncations in the zones (LP2, LP5, LP6, LP9, LP10) reflect the intersection of the {110} and {010} planes caused by Carlsbad twinning. Note the interbedded nature and the truncations (resorption features) of some zones.

If megacrysts are mobile and crystallize from mixed and homogeneous melt, chemical zones would be similar from megacryst to megacryst; if they form in a static crystal framework, each megacryst would be exposed to individual, heterogeneous melt pockets and would crystallize via dissolution-reprecipitation to form zones unique to each megacryst.

Correlation Test 1

1) Each zone color assigned a number (dark purple = 0, red =5).
2) Transects divided into 100 equidistant points where the zone color number was recorded.
→ Correlation coefficients for different megacrysts: ≤ 0.54 (majority are much lower)
→ Correlation coefficients for the same megacryst: ≤ 0.49

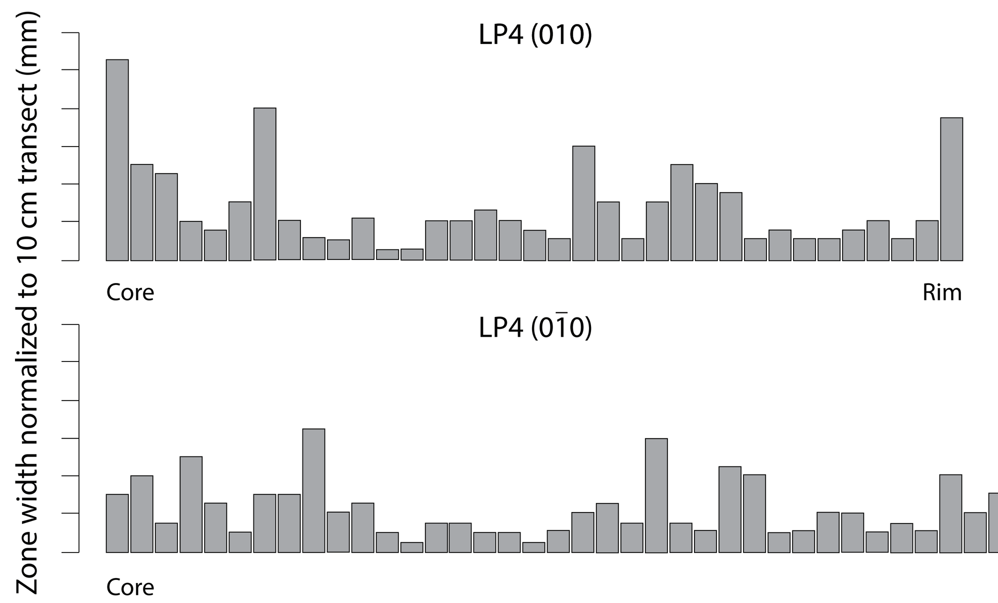


Figure 6. Skeleton plots for sample LP4.

Correlation Test 2

Skeleton plots[8] record thickness as a function of distance from the core (Fig. 6).
→ No obvious patterns couldbe matched between transects.
→ The number of zones on either side of a megacryst's core can vary and is inconsistent.

Results (cont.) & Discussion

Maps of individual megacrysts are clearly unique simply based on a visual comparison. The calculated correlation coefficients comparing zoning patterns of different megacrysts and those of the same megacryst indicate that they each crystallized in chemically different melts and coarsened via dissolution-reprecipitation.

Dissolution-reprecipitation occurs during temperature oscillations, and promotes coarsening of neighboring crystals via mass transfer[1,9,10] (Fig. 7).

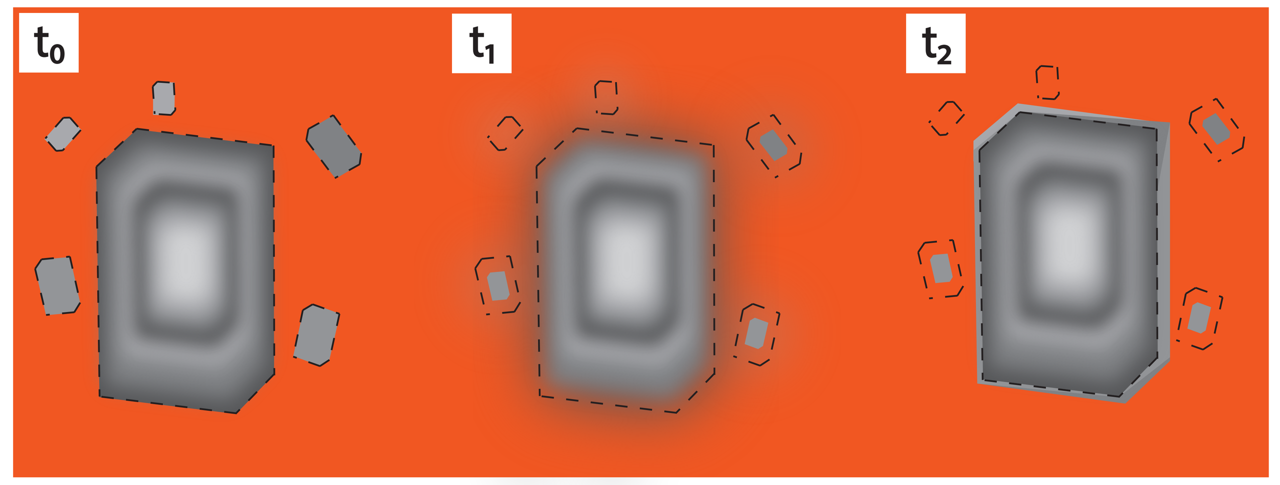


Figure 7. Simplified illustration of megacryst coasrsening due to temperature oscillations. t_0: Initial temperature with K-feldspar crystals of variable sizes and Ba concentration expressed as differences in grayscale value. t_1: Temperature increases, resulting in complete melting of small K-feldspar crystals and melting of the outer layer of the moderately-sized and large crystals. Nuclei for the partly melted crystals remain. t_2: Temperature decreases back to initial temperature. Chemical constituents bond with the crystals with the least amount of surface energy per unit volume (i.e., larger crystals[12]), resulting in the loss of the small crystals, reduction in size of the moderately sized crystals, and coarsening of the largest crystals locally.

The mineral inclusions do not accurately reflect the modal abundance of the granodiorite.
- Dacitic melt phase equilibria predict biotite and hornblende nucleation prior to that of K-feldspar[4].
- The Cathedral Peak Granodiorite contains significantly less hornblende (<3 modal percent) than biotite (3-5 modal percent)[11].
- Despite biotite's ubiquity in the host granodiorite and its presence as a crust surrounding the megacrysts, hornblende and titanite are the dominant minerals inclusions with few to no biotite inclusions.

The interbedded nature and asymmetry of zones in a single megacryst (Fig. 5) imply coarsening via dissolution-reprecipitation.
- Temperature oscillations occur during melt replenishments in a plutonic systems[6,15].
- Crystal coarsening via dissolution-reprecipitation can take place after a portion of a plutonic system is completely crystallized[15], making the crystals are meta-igneous.

Each megacryst likely crystallized in chemically different melts.
- Each crystal face experienced local chemical differences, resulting from both anisotropic melt flow through the static crystal framework and the asymmetric nature of mass transfer during dissolution-reprecipitation.
- Small crystals providing material for only a portion of the megacryst creates interbedded zones (Figs. 5, 7).
- Resorption features (Fig. 5) point to mass loss during heating and are consistent with other observations[3].

These megacrysts with unique, asymmetric zones are meta-igneous.
- Garnet, a metamorphic mineral, can also form concentric, oscillatory zones[15].

Acknowledgements

This project was funded by the University of North Carolina at Chapel Hill Department of Geological Science's Martin Fund and GSA Grant 12049-18. Thank you to Drew Coleman and his first year seminar students for their assistance in the field, and to Justin Gladman at Duke Shared Materials Instrumentation Facility for his assistance during Micro CT data collection.

References

[1]Johnson, B.R., and Glazner, A.F., 2010 Formation of K-feldspar megacrysts in granodioritic plutons by thermal cycling and late-stage textural coarsening. Contributions to Mineralogy and Petrology, v. 159, p. 599-619. [2]Vernon, R.H., 1986, K-feldspar Megacrysts in Granites – Phenocrysts, not Porphyroblasts: Earth-Science Reviews, v. 23, p. 1-63. [3]Moore, J.G., and Sisson, T.W., 2008, Igneous phenocrystic origin of K-feldspar megacrysts in granitic rocks from the Sierra Nevada batholith: Geosphere, v. 4, p. 387-400. [4]Glazner, A.F., and Johnson, B.R., 2013, Late crystallization of K-feldspar and the paradox of megacrystic granite: Contributions to Mineralogy and Petrology, v. 166, p. 777-799. [5]Bateman, P.C., 1992, Plutonism in the Central Part of the Sierra Nevada Batholith, California: United States Geological Survey Professional Paper, v. 1483, 194 p. [6]Coleman, D.S., Gray, W., and Glazner, A.F., 2004, Rethinking the emplacement and evolution of zoned plutons: Geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California: Geology, v.32, p. 433-436. [7]Ketcham, R.A. and Carlson, W.D., 2001, Acquisition, optimization and interpretation of X-ray computed tomographic imagery: applications to the geosciences: Computers & Geosciences, v. 27, p. 381-400. [8]Phipps, R.L., 1985, Collecting, preparing, crossdating, and measuring tree increment cores: Water-Resources Investigations Report 85-4148 – U.S. Geological Survey, 48 pp. [9]Mills, R.D., Ratner, J.J., and Glazner, A.F., 2011, Experimental evidence for crystal coarsening and fabric development during temperature cycling: Geology, v. 39, p. 1139-1142. [10]Wickland, T.D. (2016) Experimental effects of thermal cycling on titanite morphology and growth [Master's thesis]: University of North Carolina at Chapel Hill, 45 p. [11]Burgess, S.D. and Miller, J.S., 2008, Construction, solidification, and internal differentiation of a large felsic pluton: Cathedral Peak granodiorite, Sierra Nevada Batholith: The Geological Society of London Special Publications, v. 304, p. 203-233. [12]Higgins, M.D., 1999, Origin of megacrysts in granitoids by textural coarsening: a crystal size distribution (CSD) study of microcline in the Cathedral Peak Granodiorite, Sierra Nevada, California: The Geological Society of London Special Publications, v. 168, p. 207-219. [13]Boudreau, A., 2011, The evolution of texture and layering in layered intrusions: International Geology Review, v. 53, p. 330-353. [14]Coleman, D.S., Glazner, A.F., and Bartley, J.M., 2017, Meltamorphism. Geological Society of America Abstracts with Programs, v. 49, p. 6. [15]Clechenko, C.C. and Valley, J.W., 2003, Oscillatory zoning in garnet from the Willsboro Wollastonite Skarn, Adirondack Mts, New York: a record of shallow hydrothermal processes preserved in granulite facies terrane: Journal of Metamorphic Petrology, v. 21,p. 771-784.