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Half a million years of magmatic history recorded in a K-feldspar megacryst of the Tuolumne Intrusive Complex, California, USA

Melissa Chambers[1], Valbone Memeti[1], Michael P. Eddy[2] and Blair Schoene[3]
[1]Department of Geological Sciences, California State University Fullerton, Fullerton, California 92831, USA
[2]Earth, Atmospheric, and Planetary Sciences Department, Purdue University, West Lafayette, Indiana 47907, USA
[3]Department of Geosciences, Princeton University, Princeton, New Jersey 08544, USA

ABSTRACT

K-feldspars reach megacrystic size (>3 cm) relative to their groundmass in many granitoid plutons and some volcanic rocks. However, the nature of the growth environment and the time scales for megacrystic growth remain poorly constrained. Chemical abrasion–isotope dilution–thermal ionization mass spectrometry with trace-element analysis (CA-ID-TIMS-TEA) U-Pb geochronology was carried out on zircon inclusions from the core and rim of one K-feldspar megacryst sampled from the interior of the Tuolumne Intrusive Complex (TIC), California, USA. Combined with new zircon ages from the groundmass, these data can test if K-feldspar megacrysts are igneous and capable of recycling and transport in the magmatic system or whether they formed by textural coarsening in low-melt-fraction or subsolidus conditions. The zircon ages reveal that the megacryst core is 0.5 m.y. older than the rim, which itself is older than the groundmass. Core ages match zircon dates from the TIC's porphyritic Half Dome unit, and rim and groundmass ages overlap with the younger Cathedral Peak unit. Trace elements of the zircons from the megacryst core and rim are similar and less evolved than the groundmass zircons. The core-to-rim age progression of zircon inclusions is inconsistent with subsolidus K-feldspar coarsening, but instead indicates that megacrysts in the TIC grew in an igneous environment over at least 0.5 m.y., and that growth likely occurred spanning two or more intrusive episodes. This supports models of an increasingly maturing magmatic system, where crystal recycling from older into younger magma batches is common.

INTRODUCTION

Megacrystic K-feldspars are commonly found in granitoid plutons and more rarely in volcanic rocks (Clavero et al., 2004; Słaby et al., 2007a; Moore and Sisson, 2008; Landi et al., 2019). Their euhedral shape, crystallographically aligned mineral inclusions, oscillatory geochemical zoning, mineral alignment in magmatic fabrics, and typical igneous microstructures all suggest that they are magmatic in origin (Moore and Sisson, 2008; Vernon and Paterson, 2008; Holness et al., 2018). However, phase equilibria experiments indicate that K-feldspar saturates late in the crystallization sequence of calc-alkaline, felsic magma (e.g., Clemens and Wall, 1981; Whitney, 1988; Johnson and Rutherford, 1989), leaving little space (<50% melt) to grow large, euhedral megacrysts (Johnson and Glazner, 2010; Glazner and Johnson, 2013). This apparent paradox has led to the debate about the factors that lead to K-feldspar megacryst growth. Several hypotheses, based on experimental, textural, and geochemical observations, have been proposed to explain the origin of K-feldspar megacrysts: (1) their large size reflects high crystal growth rates combined with low nucleation rates (Fenn, 1977; Swanson, 1977); (2) they grew to large sizes due to prolonged growth (Memeti et al., 2014; Holness et al., 2018) via crystal transfer or mixing into different magma batches (Hobden et al., 1999; Gagnevin et al., 2005a, 2005b; Davidson et al., 2008; Paterson et al., 2016); (3) they texturally coarsened during late-stage crystallization at low melt percentages due to thermal cycling (Higgins, 1999, 2011; Johnson and Glazner, 2010; Glazner and Johnson, 2013); and/or (4) they represent metasomatically coarsened megacrysts that formed as low as 400 °C due to fluid fluxing during incremental pluton growth (Glazner and Johnson, 2013; Glazner et al., 2017).

Zircon inclusions within megacrysts and their host granodiorite can be useful for reconstructing the megacryst growth history because they are excellent U-Pb chronometers, their magmatic growth ceases once they are enclosed and armored by K-feldspar crystals (Barboni and Schoene, 2014), and they can record geochemical information about the liquid from which they crystallized. The magmatic origin models listed above predict younger zircon ages from megacryst core to rim over either short durations (hypothesis 1) or longer, more protracted durations (hypotheses 2 and 3). Zircon trace elements from the megacryst core and rim and the host granodiorite could help to differentiate if magma mixing and moderate melt percentages were involved (hypothesis 2), or if zircons grew in a rigid, highly evolved mush at very low melt percentages (hypothesis 3). A subsolidus origin (hypothesis 4), on the other hand, predicts no relationship between zircon age and position within the megacryst, unless the zircons are also metasomatic. To explore these possibilities, we obtained 36 zircon dates and associated geochemical compositions using chemical abrasion–isotope dilution–thermal ionization mass spectrometry and trace-element analysis (CA-ID-TIMS-TEA) from the core, rim, and surrounding groundmass of one K-feldspar megacryst from the Tuolumne Intrusive Complex (TIC) in the Sierra Nevada, California (United States). Our results suggest a magmatic growth history over 0.5 m.y. related to recycling of K-feldspar from different magmatic units.

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GEOLOGIC SETTING

The Cretaceous TIC is a compositionally zoned, 1100 km^2 pluton (Bateman and Chappell, 1979) in the central Sierra Nevada batholith (Fig. 1A). It was incrementally constructed between 95 and 84.5 Ma (Kistler and Fleck, 1994; Coleman et al., 2004; Memeti et al., 2010, 2014; Paterson et al., 2016). The units are nested and become younger and more felsic toward the TIC's interior. Contacts vary from sharp to gradational, with hybrid zones up to >300 m wide that are inferred to represent magma mixing (Fig. 1B; Memeti et al., 2014; Paterson et al., 2016).

The 92.8–88.8 Ma Half Dome granodiorite (Paterson et al., 2016) is subdivided into the outer, equigranular Half Dome (eHD) and the inner, porphyritic Half Dome (pHD) granodiorites (Bateman and Chappell, 1979). While the eHD contains sub- to euhedral K-feldspar crystals <1 cm, the pHD contains characteristic euhedral K-feldspar up to 3 cm long. These phenocrysts commonly contain abundant, several millimeter or smaller inclusions of euhedral plagioclase, hornblende, biotite, titanite, apatite, Fe-oxides, and zircon (Fig. 1C; Burgess and Miller, 2008; Moore and Sisson, 2008), which are typically crystallographically aligned along growth zones (Vernon and Paterson, 2008; Memeti et al., 2014). The 88.8–85.1 Ma Cathedral Peak granodiorite (CP; Paterson et al., 2016) contains megacrystic K-feldspars up to 15 cm long, particularly along the pHD contact (Fig. 1C; Bateman and Chappell, 1979). Some of these CP megacrysts, including the 7 cm megacryst (sample LFO-74) analyzed in this study, exhibit mineral inclusion–rich cores (just like those found in the pHD) and mineral inclusion–poor rims (Fig. 2). LFO-74 was collected from a pHD-CP hybrid unit in the southeastern TIC, where all units grade into each other over tens to hundreds of meters (Fig. 1B).

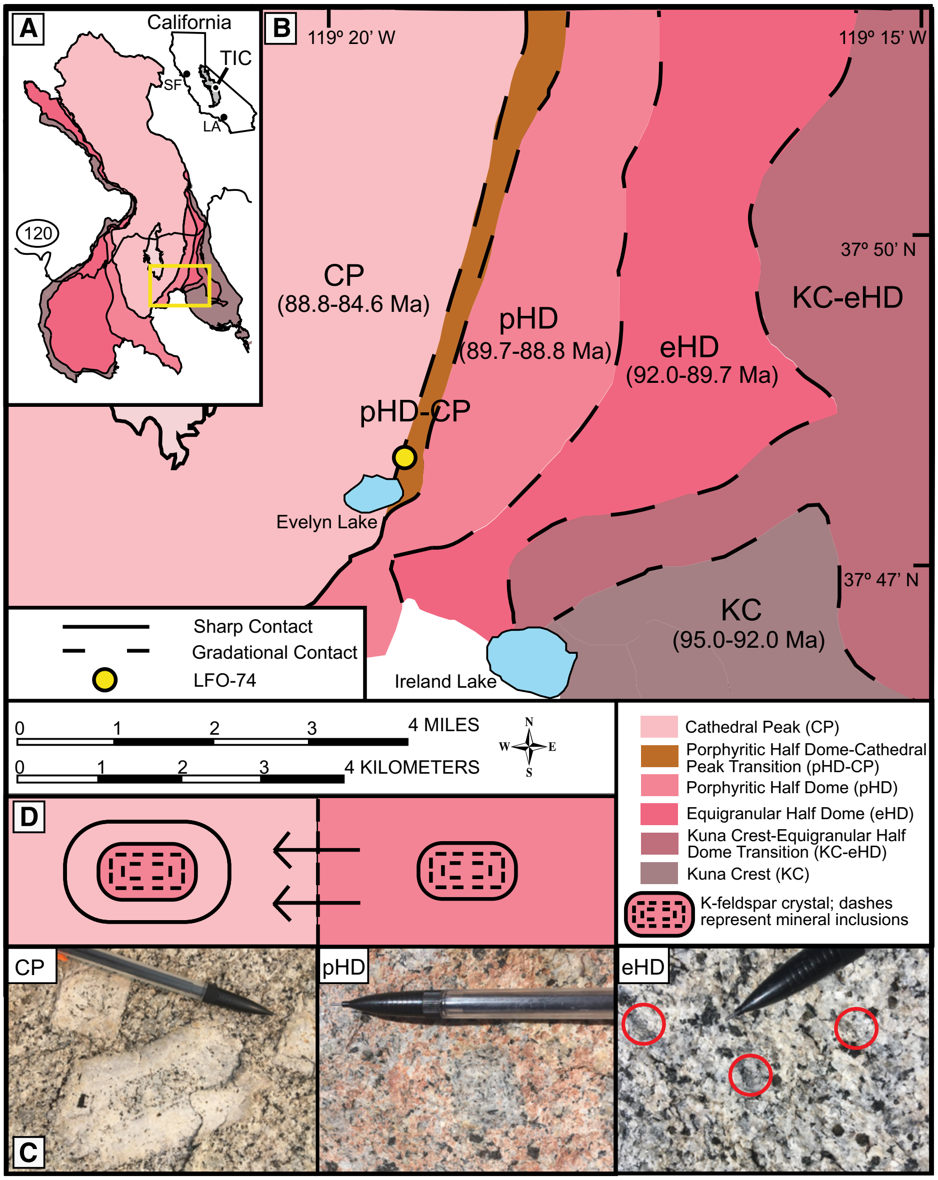

Figure 1. Sample location of megacryst LFO-74. (A) Inset map of the Tuolumne Intrusive Complex (TIC) and its location in California, USA. SF—San Francisco, LA—Los Angeles. (B) Location of LFO-74 in the southeast lobe of the TIC where contacts are gradational and hybrid units separate main TIC units. Map was adapted from Huber et al. (1989) by Louis Oppenheim (May 2019, personal commun.). (C) Increasing K-feldspar size and distribution of mafic mineral inclusions for Cathedral Peak granodiorite (CP), porphyritic Half Dome (pHD), and equigranular Half Dome (eHD) granodiorites. (D) Cartoon of the K-feldspar recycling hypothesis indicating inclusion-rich pHD K-feldspars are recycled into the CP unit, where they grow inclusion-poor rims.

METHODS

Zircon inclusions were separated from LFO-74, which was cut perpendicular to the crystallographic *b* axis. Both halves were cut into core, mantle, and rim sections defined by mineral inclusions (core) or lack thereof (rim; Fig. 2). The mantle (between the core and rim) was excluded from analyses to focus on retrieving the minimum duration of megacryst growth. Zircons were separated from the groundmass of the same sample with megacrysts removed. The euhedral, oscillatory-zoned zircons were dated using U-Pb CA-ID-TIMS geochronology following methods slightly modified from Mattinson (2005) and Barboni and Schoene (2014). The trace-element composition of each dated zircon was measured using inductively coupled plasma–mass spectrometry (ICP-MS) following the methods of Schoene et al. (2010). Analytical work was done at Princeton University (New Jersey, USA), and detailed methods, trace-element data, and concordia plots are presented in the GSA Data Repository[1]. All subsequent discussion uses $^{206}Pb/^{238}U$ dates, as this isotopic system provides the most precise dates for rocks of Cretaceous age.

RESULTS

Zircon dates become progressively younger from the megacryst core, where 8 of 11 zircons group around 89.0 Ma, to the rim, where 10 of 12 zircons group at 88.45 Ma (Figs. 2 and 3). The groundmass of the megacryst is younger than the rim, with 10 of 13 zircons clustering at ca. 88.25 Ma. The age difference between the youngest core zircon and youngest rim zircon, 88.86 ± 0.06 Ma and 88.29 ± 0.15 Ma, respectively, is ~0.5 m.y. The older zircon grains found in the core and rim are earlier-grown zircons likely remobilized and reincorporated from older TIC crystal mushes (antecrysts) or

[1]GSA Data Repository item 2020117, detailed CA-ID-TIMS-TEA methods, and Figure DR1–DR4, is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org.

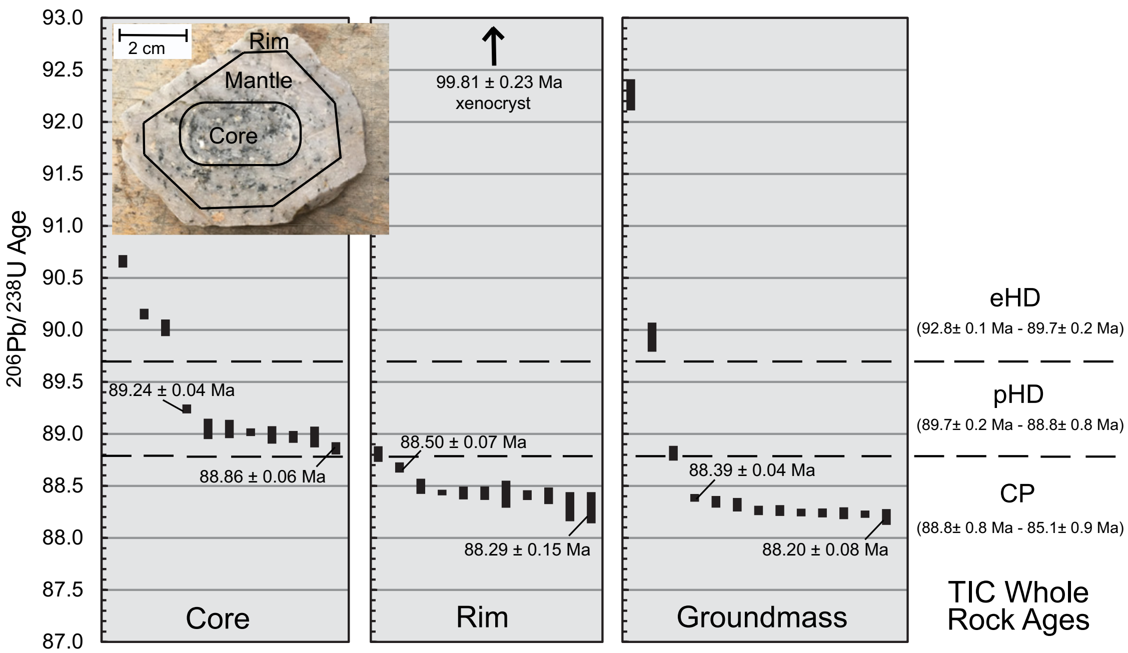

Figure 2. Chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) U-Pb zircon ages from core, rim, and groundmass of K-feldspar megacryst LFO-74 (from the southeastern Tuolumne Intrusive Complex, California, USA). Identification of K-feldspar core and rim based on mafic mineral density is shown in inset photo. Horizontal dashed lines represent single-zircon bulk sample age ranges from Paterson et al. (2016) used for comparison with K-feldspar megacryst zircon inclusion ages. One older zircon from the rim (99.8 ± 0.23 Ma) is not shown on plot. Uncertainties are 2σ. Abbreviations used are the same as in Figure 1.

the surrounding host rock (xenocrysts) during new magma intrusions (Miller et al., 2007; Paterson et al., 2016). A significantly older grain (99.81 ± 0.23 Ma) dated in the rim is outside the TIC age range and is interpreted to be a xenocryst (Fig. 2). Trace elements from the core and rim zircons show the same concentrations and variations, while groundmass zircons cluster at more evolved compositions (Fig. 3; Fig. DR3 in the Data Repository).

DISCUSSION

Igneous Origin for Megacrystic K-Feldspar

The U-Pb zircon age results from this study show a younging trend from the core to the rim of the megacryst. The zircons from the groundmass of the megacryst are even younger (Figs. 2 and 3), favoring igneous growth. Euhedral, oscillatory-zoned zircon morphology (Fig. DR4) and the coexistence with other magmatic mineral inclusions (Moore and Sisson, 2008; Vernon and Paterson, 2008) support the interpretation that the zircons are of magmatic origin. These results are incompatible with a subsolidus, metasomatic textural-coarsening origin (hypothesis 4; Johnson and Glazner, 2010; Glazner et al., 2017).

This result is consistent with petrographic, physical, and chemical evidence that supports a magmatic origin for K-feldspar megacrysts: Igneous megacrysts are euhedral and display Carlsbad twinning; they show oscillatory zoning of slow-diffusing trace elements; and they contain crystallographically aligned, euhedral mineral inclusions with hypersolidus temperatures of crystallization (Moore and Sisson, 2008; Vernon and Paterson, 2008; Vernon, 2010; Memeti et al., 2014). They are also locally aligned parallel to magmatic foliations and lineations, accumulate in clusters, or become entrained into enclaves and magmatic structures formed by flow sorting (Zák et al., 2007; Vernon and Paterson, 2008; Paterson, 2009; Paterson et al., 2018), all of which argue for K-feldspar growth in a melt-present environment. Holness et al. (2018) showed that, although K-feldspar is one of the last phases to saturate, as predicted by experiments, the magma may still contain 50%–60% melt at this stage, leaving enough space for megacrystic growth. A magmatic environment has also been suggested based on megacrystic growth in a melt with changing isotopic composition (Hobden et al., 1999; Gagnevin et al., 2005a; Davidson et al., 2008). Erupted volcanic K-feldspar megacrysts (<5 cm) with glass inclusions also favor growth in a melt-rich environment (Clavero et al., 2004). Thus, evidence from these other studies and our new U-Pb zircon ages provide ample evidence that sample LFO-74 and many other investigated plutonic and volcanic megacrysts are not only of igneous origin, but they grew in crystal mushes capable of movement and sometimes eruption.

K-Feldspar Megacryst Size

One important question remains: How did this K-feldspar attain its megacrystic size? Possible origins are (1) short-duration, fast growth driven by repressed nucleation leading to growth of fewer, but larger crystals (hypothesis 1; Swanson, 1977); (2) slow, prolonged (either continuous or episodic) growth (Memeti et al., 2014; Holness et al., 2018) while undergoing crystal transfer by advective processes such as magma mixing/mingling, and/or mechanical plucking from partially solidified magmas (hypothesis 2; Paterson et al., 2016); or (3) *in situ* growth via coarsening at low melt percentages (hypothesis 3).

The 0.5 m.y. age difference between the megacryst core and rim zircons supports the idea of continuous, prolonged growth in a long-lived magma body, or pulsed, rapid growth in multiple magma bodies, and/or a combination of these two end members, rather than fast, short-lived growth of the whole crystal (hypothesis 1). The K-feldspar core ages match the pHD bulk sample zircon ages, and the K-feldspar rim and groundmass zircon ages agree with the CP bulk sample zircon ages from previous studies (Memeti et al., 2010; Paterson et al., 2016). The megacryst-groundmass bulk-rock zircon age comparisons suggest the megacryst started growth in the pHD magma and was transferred into the CP magma by magma mixing or mechanical plucking, where continued growth resulted in the final size (Fig. 1C). This interpretation is consistent with the significantly higher mineral inclusion density in the K-feldspar cores, typical of pHD K-feldspars, compared to the inclusion-poor rims, typical of CP K-feldspars (Figs. 1C and 1D). The gradational contacts and hybrid units in this area of the TIC (Fig. 1B) also support the idea of interaction between adjacent units, and they make megacryst growth in different magma batches likely (Fig. 1D). Our interpretations of megacryst growth due to crystal recycling are supported by isotope data and mineral trace-element analyses from other studies that show that K-feldspars crystallized in different magma compositions over time (Troll and Schmincke, 2002; Słaby and Götze, 2004; Ginibre et al., 2004, 2007; Gagnevin et al., 2005a, 2005b; Zellmer and Clavero, 2006; Słaby et al., 2007a, 2007b, 2017).

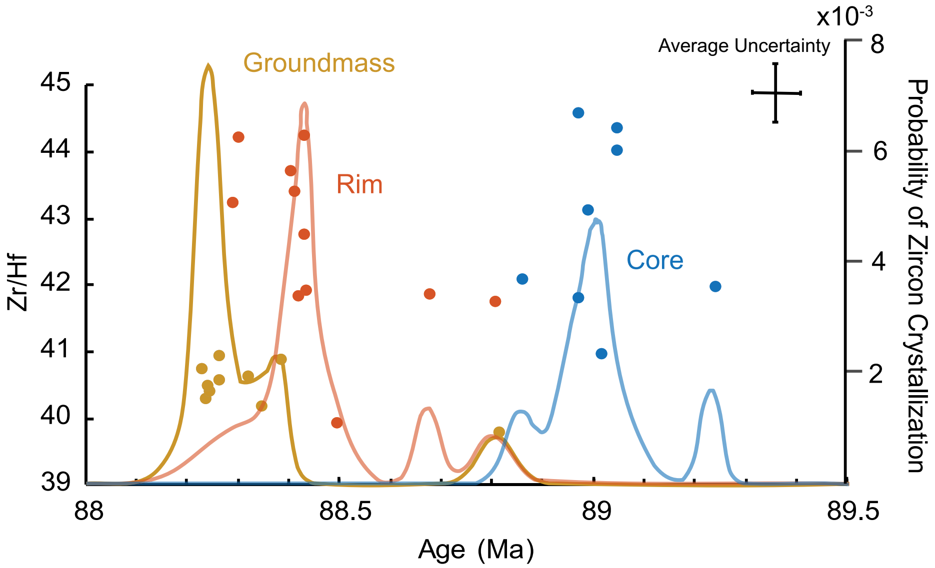

Figure 3. U-Pb age probability density plot and Zr/Hf ratios for zircons from core, rim, and groundmass of megacryst LFO-74 (collected from the southeastern Tuolumne Intrusive Complex, California, USA). Only zircons with ages between 88.2 Ma and 89.4 Ma are shown. Zr/Hf values of core and rim zircons show overlapping concentrations. Groundmass values group separately from core and rim values at more-evolved compositions, suggesting growth from a more-evolved, zircon-fractionated composition during final crystallization. Probability density plot shows distinct age differences between three zircon separates.

The trace-element data from the analyzed zircons act as geochemical recorders of magma composition from which the zircons, and thus the K-feldspar grew. Trace elements from the core and rim zircon populations display similar means and large variances, even though these zircons are distinctly different in age. This is consistent with observations made using whole-rock isotopes and geochemistry showing that the interior units of the TIC become increasingly more similar in their compositions (Memeti et al., 2014). This trend is, in part, due to widespread mixing/mingling and recycling processes (Paterson et al., 2008, 2016). Furthermore, although the similar pHD and CP magma compositions do not allow for the distinction between pHD- and CP-derived zircons based on chemistry alone, the core-to-rim age difference, the similarities with pHD and CP whole-rock zircon dates, and the characteristic pHD and CP mineral inclusion patterns are significant and consistent with pHD K-feldspar phenocryst transfer into the CP. The slightly younger groundmass zircons have more evolved (low Zr/Hf) and homogeneous trace-element compositions (Fig. 3) that record the crystallization of melt that had previously crystallized a significant volume of zircon (Claiborne et al., 2006). The groundmass zircons are collectively compositionally more evolved than the chemically heterogeneous zircons from the megacryst. This suggests that the megacrysts could not have grown at low melt percentages as suggested by hypothesis 3. Furthermore, time scales of textural coarsening in igneous systems are unrealistically large to grow even millimeter-size minerals (Gualda, 2019).

CONCLUSIONS

CA-ID-TIMS-TEA U-Pb zircon ages from the core and rim of a K-feldspar megacryst and its surrounding groundmass from the pHD-CP hybrid unit in the Tuolumne Intrusive Complex, California, show younging trends from core to rim, which, along with field, petrographic, and geochemical evidence, support a magmatic origin for TIC K-feldspar megacrysts. The 0.5 m.y. age difference between megacryst core and rim zircon ages suggests that K-feldspar megacrysts had the capability to grow over at least that long—either continuously or during punctuated intervals—in a magmatic system undergoing magma mixing and crystal recycling. The 0.5 m.y. age difference and the similarities with whole-rock zircon ages from the pHD and CP units as well as the trace-element characteristics compared to those in the groundmass zircons indicate growth of the K-feldspar into its megacrystic size by growth in different, interacting magma bodies, rather than through fast growth or *in situ* textural coarsening in a crystal-rich, closed-system magma body.

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REFERENCES CITED

Barboni, M., and Schoene, B., 2014, Short eruption window revealed by absolute crystal growth rates in a granitic magma: Nature Geoscience, v. 7, p. 524–528, https://doi.org/10.1038/ngeo2185.

Bateman, P.C., and Chappell, B.W., 1979, Crystallization, fractionation, and solidification of the Tuolumne Intrusive Series, Yosemite National Park, California: Geological Society of America Bulletin, v. 90, p. 465–482, https://doi.org/10.1130/0016-7606(1979)90<465:CFASOT>2.0.CO;2.

Burgess, S.D., and Miller, J.S., 2008, Construction, solidification and internal differentiation of a large felsic arc pluton: Cathedral Peak granodiorite, Sierra Nevada batholith, *in* Annen, C., and Zellmer, G.F., eds., Dynamics of Crustal Magma Transfer, Storage and Differentiation: Geological Society [London] Special Publication 304, p. 203–233, https://doi.org/10.1144/SP304.11.

Claiborne, L.L., Miller, C.F., Walker, B.A., Wooden, J.L., Mazdab, F.K., and Bea, F., 2006, Tracking magmatic processes through Zr/Hf ratios in rocks and Hf and Ti zoning in zircons: An example from the Spirit Mountain batholith, Nevada: Mineralogical Magazine, v. 70, p. 517–543, https://doi.org/10.1180/0026461067050348.

Clavero, J.E., Sparks, R.S.J., Pringle, M.S., Polanco, E., and Gardeweg, M.C., 2004, Evolution and volcanic hazards of Taapaca volcanic complex, Central Andes of northern Chile: Journal of the Geological Society [London], v. 161, p. 603–618, https://doi.org/10.1144/0016-764902-065.

Clemens, J.D., and Wall, V.J., 1981, Origin and crystallization of some peraluminous (S-type) granitic magmas: Canadian Mineralogist, v. 19, p. 111–131.

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, https://doi.org/10.1130/G20220.1.

Davidson, J.P., Font, L., Charlier, B.L.A., and Tepley, F.J., 2008, Mineral-scale Sr isotope variation in plutonic rocks—A tool for unravelling the evolution of magma systems: Transactions of the Royal Society of Edinburgh–Earth Sciences, v. 97, p. 357–367, https://doi.org/10.1017/S0263593300001504.

Fenn, P.M., 1977, The nucleation and growth of alkali feldspars from hydrous melts: Canadian Mineralogist, v. 15, p. 135–161.

Gagnevin, D., Daly, J.S., Poli, G., and Morgan, D., 2005a, Microchemical and Sr isotopic investigation of zoned K-feldspar megacrysts: Insights into the petrogenesis of a granitic system and disequilibrium crystal growth: Journal of Petrology, v. 46, p. 1689–1724, https://doi.org/10.1093/petrology/egi031.

Gagnevin, D., Daly, J.S., Waight, T.E., Morgan, D., and Poli, G., 2005b, Pb isotopic zoning of K-feldspar megacrysts determined by laser ablation multi-collector ICP-MS: Insights into granite petrogenesis: Geochimica et Cosmochimica Acta, v. 69, p. 1899–1915, https://doi.org/10.1016/j.gca.2004.10.007.

Ginibre, C., Wörner, G., and Kronz, A., 2004, Structure and dynamics of the Laacher See magma chamber (Eifel, Germany) from major and trace element zoning in sanidine: A cathodoluminescence and electron microprobe study: Journal of Petrology, v. 45, p. 2197–2223, https://doi.org/10.1093/petrology/egh053.

Ginibre, C., Wörner, G., and Kronz, A., 2007, Crystal zoning as an archive for magma evolution: Elements, v. 3, p. 261–266, https://doi.org/10.2113/gselements.3.4.261.

Glazner, A.F., and Johnson, B.R., 2013, Late crystallization of K-feldspar and the paradox of megacrystic granites: Contributions to Mineralogy and Petrology, v. 166, p. 777–799, https://doi.org/10.1007/s00410-013-0914-1.

Glazner, A.F., Coleman, D.S., and Bartley, J.M., 2017, What is a pluton? What is a magma?, *in* Vearncombe, J., ed., Granites: Australian Institute of Geoscientists Bulletin 65, p. 53–55.

Gualda, G.A.R., 2019, On the origin of alkali feldspar megacrysts in granitoids: The case against textural coarsening: Contributions to Mineralogy and Petrology, v. 174, p. 88, https://doi.org/10.1007/s00410-019-1621-3.

Higgins, M.D., 1999, Origin of megacrysts in granitoids by textural coarsening: A crystal size distribution (CSD) study of microcline in the central Cathedral Peak Granodiorite, Sierra Nevada, California, *in* Castro, A., et al., eds., Understanding Granites: Integrating New and Classical Techniques: Geological Society [London] Special Publication 168, p. 207–219, https://doi.org/10.1144/GSL.SP.1999.168.01.14.

Higgins, M.D., 2011, Quantitative petrological evidence for the origin of K-feldspar megacrysts in dacites from Taapaca volcano, Chile: Contributions to Mineralogy and Petrology, v. 162, p. 709–723, https://doi.org/10.1007/s00410-011-0620-9.

Hobden, B.J., Houghton, B.F., Davidson, J.P., and Weaver, S.D., 1999, Small and short-lived magma batches at composite volcanoes: Time windows at Tongariro volcano, New Zealand: Journal of the Geological Society [London], v. 156, p. 865–868, https://doi.org/10.1144/gsjgs.156.5.0865.

Holness, M.B., Clemens, J.D., and Vernon, R.H., 2018, How deceptive are microstructures in granitic rocks? Answers from integrated physical theory, phase equilibrium, and direct observations: Contributions to Mineralogy and Petrology, v. 173, p. 62, https://doi.org/10.1007/s00410-018-1488-8.

Huber, N.K., Bateman, P.C., and Wahrhaftig, C., 1989, Geologic Map of Yosemite National Park and Vicinity, California: U.S. Geological Survey, scale 1:125,000.

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, https://doi.org/10.1007/s00410-009-0444-z.

Johnson, M.C., and Rutherford, M.J., 1989, Experimentally determined conditions in the Fish Canyon Tuff, Colorado, magma chamber: Journal of Petrology, v. 30, p. 711–737, https://doi.org/10.1093/petrology/30.3.711.

Kistler, R.W., and Fleck, R.J., 1994, Field Guide for a Transect of the Central Sierra Nevada, California: Geochronology and Isotope Geology: U.S. Geological Survey Open-File Report 94–267, 50 p.

Landi, P., La Felice, S., Petrelli, M., Vezzoli, L.M., and Principe, C., 2019, Deciphering textural and chemical zoning of K-feldspar megacrysts from Mt. Amiata Volcano (southern Tuscany, Italy): Insights into the petrogenesis and abnormal crystal growth: Lithos, v. 324–325, p. 569–583, https://doi.org/10.1016/j.lithos.2018.11.032.

Mattinson, J.M., 2005, Zircon U-Pb chemical abrasion (“CA-TIMS”) method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages: Chemical Geology, v. 220, p. 47–66, https://doi.org/10.1016/j.chemgeo.2005.03.011.

Memeti, V., Paterson, S., Matzel, J., Mundil, R., and Okaya, D., 2010, Magmatic lobes as “snapshots” of magma chamber growth and evolution in large, composite batholiths: An example from the Tuolumne intrusion, Sierra Nevada, California: Geological Society of America Bulletin, v. 122, p. 1912–1931, https://doi.org/10.1130/B30004.1.

Memeti, V., Paterson, S., and Mundil, R., 2014, Day 4: Magmatic evolution of the Tuolumne Intrusive Complex, *in* Memeti, V., Paterson, S.R., and Putirka, K.D., eds., Formation of the Sierra Nevada Batholith: Magmatic and Tectonic Processes and Their Tempos: Geological Society of America Field Guide 34, p. 43–74, https://doi.org/10.1130/2014.0034(04).

Miller, J.S., Matzel, J.E.P., Miller, C.F., Burgess, S.D., and Miller, R.B., 2007, Zircon growth and recycling during the assembly of large, composite arc plutons: Journal of Volcanology and Geothermal Research, v. 167, p. 282–299, https://doi.org/10.1016/j.jvolgeores.2007.04.019.

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, https://doi.org/10.1130/GES00146.1.

Paterson, S.R., 2009, Magmatic tubes, pipes, troughs, diapirs, and plumes: Late-stage convective instabilities resulting in compositional diversity and permeable networks in crystal-rich magmas of the Tuolumne batholith, Sierra Nevada, California: Geosphere, v. 5, p. 1–32, https://doi.org/10.1130/GES00214.1.

Paterson, S.R., Žák, J., and Janoušek, V., 2008, Growth of complex sheeted zones during recycling of older magmatic units into younger: Sawmill Canyon area, Tuolumne batholith, Sierra Nevada, California: Journal of Volcanology and Geothermal Research, v. 177, p. 457–484, https://doi.org/10.1016/j.jvolgeores.2008.06.024.

Paterson, S.R., Memeti, V., Mundil, R., and Žák, J., 2016, Repeated, multiscale, magmatic erosion and recycling in an upper-crustal pluton: Implications for magma chamber dynamics and magma volume estimates: The American Mineralogist, v. 101, p. 2176–2198, https://doi.org/10.2138/am-2016-5576.

Paterson, S.R., Ardill, K., Vernon, R., and Žák, J., 2018, A review of mesoscopic magmatic structures and their potential for evaluating the hypersolidus evolution of intrusive complexes: Journal of Structural Geology, v. 125, p. 134–147, https://doi.org/10.1016/j.jsg.2018.04.022.

Schoene, B., Latkoczy, C., Schaltegger, U., and Günther, D., 2010, A new method integrating high-precision U-Pb geochronology with zircon trace element analysis (U-Pb TIMS-TEA): Geochimica et Cosmochimica Acta, v. 74, p. 7144–7159, https://doi.org/10.1016/j.gca.2010.09.016.

Słaby, E., and Götze, J., 2004, Feldspar crystallization under magma-mixing conditions shown by cathodoluminescence and geochemical modeling—A case study from the Karkonosze pluton (SW Poland): Mineralogical Magazine, v. 68, p. 561–577, https://doi.org/10.1180/0026461046840205.

Słaby, E., Galbarczyk-Gąsiorowska, L., Seltmann, R., and Müller, A., 2007a, Alkali feldspar megacryst growth: Geochemical modelling: Mineralogy and Petrology, v. 89, p. 1–29, https://doi.org/10.1007/s00710-006-0135-7.

Słaby, E., Seltmann, R., Kober, B., Muller, A., Galbarczyk-Gasiorowska, L., and Jeffries, T., 2007b, LREE distribution patterns in zoned alkali feldspar megacrysts from the Karkonosze pluton, Bohemian Massif—Implications for parental magma composition: Mineralogical Magazine, v. 71, p. 155–178, https://doi.org/10.1180/minmag.2007.071.2.155.

Słaby, E., De Campos, C.P., Majzner, K., Simon, K., Gros, K., Moszumańska, I., and Jokubauskas, P., 2017, Feldspar megacrysts from the Santa Angélica composite pluton—Formation/transformation path revealed by combined CL, Raman and LA-ICP-MS data: Lithos, v. 277, p. 269–283, https://doi.org/10.1016/j.lithos.2016.09.016.

Swanson, S.E., 1977, Relation of nucleation and crystal-growth rate to the development of granitic textures: The American Mineralogist, v. 62, p. 966–978.

Troll, V.R., and Schmincke, H., 2002, Magma mixing and crustal recycling recorded in ternary feldspar from compositionally zoned peralkaline ignimbrite ‘A,’ Gran Canaria, Canary Islands: Journal of Petrology, v. 43, p. 243–270, https://doi.org/10.1093/petrology/43.2.243.

Vernon, R.H., 2010, Granites really are magmatic: Using microstructural evidence to refute some obstinate hypotheses: Journal of the Virtual Explorer, v. 35, p. 1–36, https://doi.org/10.3809/jvirtex.2011.00264.

Vernon, R.H., and Paterson, S.R., 2008, How late are K-feldspar megacrysts in granites?: Lithos, v. 104, p. 327–336, https://doi.org/10.1016/j.lithos.2008.01.001.

Whitney, J.A., 1988, The origin of granite: The role and source of water in the evolution of granitic magmas: Geological Society of America Bulletin, v. 100, p. 1886–1897, https://doi.org/10.1130/0016-7606(1988)100<1886:TOOGTR>2.3.CO;2.

Zák, J., Paterson, S.R., and Memeti, V., 2007, Four magmatic fabrics in the Tuolumne batholith, central Sierra Nevada, California (USA): Implications for interpreting fabric patterns in plutons and evolution of magma chambers in the upper crust: Geological Society of America Bulletin, v. 119, p. 184–201, https://doi.org/10.1130/B25773.1.

Zellmer, G.F., and Clavero, J.E., 2006, Using trace element correlation patterns to decipher a sanidine crystal growth chronology: An example from Taapaca volcano, Central Andes: Journal of Volcanology and Geothermal Research, v. 156, p. 291–301, https://doi.org/10.1016/j.jvolgeores.2006.03.004.

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