

## Assembling a pluton...one increment at a time

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How long does it take to form a large granitic pluton, and how are plutons related in time and space to magma chambers and their erupted products? These questions are at the heart of a spirited and ongoing debate in the crustal igneous petrology community over how to reconcile field observations of plutons with increasingly precise geochronology coming out of felsic plutonic and volcanic rocks. An excellent example that will help inform this debate is provided by the Miocene Torres del Paine pluton (Patagonia), examined and dated with the U-Pb zircon method (isotope dilution–thermal ionization mass spectrometry [ID-TIMS]) in the study by Michel et al. (2008) on p. 459 of this issue of *Geology*.

Michel and others' data show that the Torres del Paine pluton comprises several granitic sills that were injected sequentially into the shallow crust to form a laccolith intrusion over a time period of  $90 \pm 40$  ka, and that the oldest sill was at or below the solidus when the youngest sill was intruded. The age resolution achieved by the authors is in the range of 20 k.y., which fills an important gap between the ca. 100 ka time scales thus far resolved in plutons (Coleman et al., 2004; Matzel et al., 2006) and volcanic time scales that extend down to the 1000–100 yr time frame (e.g., Reid, 2003; Bacon et al., 2007; Morgan et al., 2006).

Continual improvements in analytical techniques, and especially the development of chemical abrasion and thermal annealing techniques (chemical abrasion TIMS [CA-TIMS]; Mattinson, 2005) for mitigating lead loss in zircon (long the scourge of U-Pb geochronology), have resulted in clear improvements in U-Pb concordancy, and dramatically decreased the uncertainties associated with radiometric zircon dates. Achieving  $2\sigma$  uncertainties of  $\sim 0.1\%$  or less on error-weighted means of a set of single zircon analyses is now routine in laboratories doing high-precision ID-TIMS, meaning that age differences between adjacent sills in a shallow and rapidly cooled intrusion, like the Torres del Paine laccolith, can now be resolved. The largest remaining sources of uncertainty in U-Pb geochronology are tracer calibration uncertainties, decay-constant uncertainties (e.g., Mattinson, 2005; Schoene et al., 2006), and the inability to assess the accuracy of the disequilibrium correction, which must be applied to young zircon dates<sup>1</sup>.

These dramatic improvements in concordancy and reduced uncertainties in U-Pb dates have also called into question the extent to which a pluton may have existed as a magma chamber at any one instant in time, and have led to a reassessment of where and how compositional and isotopic variation in plutons arises. The times scales of pluton growth and solidification also have implications for magma transport and emplacement mechanisms.

Two notable high-precision U-Pb zircon studies that preceded Michel et al.'s work on Torres del Paine are those of Coleman et al. (2004) on the Cretaceous Tuolumne batholith (Sierra Nevada, California),

and Matzel et al. (2006) on the Cretaceous Mount Stuart batholith (North Cascades, Washington), both in the U.S. Cordillera. These authors dated the intrusions at a spatial resolution that had not been attempted previously, and showed that the individual mapped units of these large intrusions (as defined by mapped internal contacts) contain zircons that give concordant crystallization ages spanning several million years—time frames that are considerably longer than solidification times predicted by single-pulse, conductive cooling models for the depths of emplacement typical of Tuolumne and Mount Stuart (Glazner et al., 2004; Matzel et al., 2006). They concluded that the plutons must have grown by emplacement of distinct pulses or increments of magma over a period of time that exceeded the solidification times of magma chambers with the same dimensions as the plutons. Neither of the intrusions could have been one large, internally differentiating magma chamber (e.g., Bateman and Chappell, 1979), although in the case of the Mount Stuart batholith, flux estimates based on conservative volume assumptions and the U-Pb dates allow for a contiguous magma reservoir on the order of several hundred cubic kilometers in volume during emplacement of the largest mapped unit (Matzel et al., 2006).

Complicating the Mount Stuart and Tuolumne studies is the observation that several samples from both intrusions yielded concordant zircon dates that failed to give statistically meaningful weighted-mean U-Pb ages because the individual ages obtained on the zircons were statistically different, as measured by the standard MSWD metric. Miller et al. (2007) attributed this dispersion primarily to recycling of zircon 'antecrysts,' but neither study utilized the CA-TIMS method; hence, some of the dispersion of zircon dates could be caused by minor lead loss, which, because of the relatively young ages, would move zircons essentially parallel to or along Concordia.

Michel et al. used the CA-TIMS method on the Torres del Paine pluton; thus lead loss is not a factor in their age interpretations. The dates reported by the Michel et al. are very "clean," in that individual single zircon analyses from each sample yield statistically indistinguishable ages, but the weighted means of zircon analyses from two samples from the structurally highest sill and two samples from the structurally lowest sill are separated by  $90 \pm 40$  ka. Zircons from the sills show no evidence of source inheritance, and thus the magmas were likely undersaturated in zircon during anatexis. The zircon dates obtained by Michel et al. also appear to reflect 'autocrystic' zircon growth (Miller et al., 2007) in that they clearly grew only within the discreet magmatic increments that gave rise to each sill, and incorporation of zircon antecrysts from earlier magmatic inputs at the intrusion level did not occur. This is probably because, as the authors point out, zircon did not saturate in the magma until near-solidus temperatures, and the sills had very short solidification times at their shallow emplacement depths. The ages reported by Michel et al. also allow them to infer construction from the top down because the structurally highest sill is demonstrably older than the structurally lowest sill. The rapid cooling times of the sills also means that the intrusion was never one large magma chamber that underwent internal differentiation, as had been previously thought (Michael, 1984; 1991).

Ultimately, incremental growth of plutons must also accommodate occasional outpourings of large volumes of silica-rich magma in caldera-forming eruptions. Such eruptions provide unequivocal evidence for the existence of very large magma chambers (many hundreds

<sup>1</sup>Application of the U-Pb method assumes that the activities of short-lived intermediate daughters in the  $^{238}\text{U}$ - $^{206}\text{Pb}$  decay series are equal (the condition of secular equilibrium). However, the preferential incorporation of U relative to Th in zircon results in a  $^{206}\text{Pb}$  deficit (owing to an initial  $^{230}\text{Th}$  deficit) that must be accounted for to obtain an accurate age. The deficit can be corrected for by comparing the fractionation of Th and U between zircon and the magma ( $f = \text{Th}/\text{U}_{\text{zircon}}/\text{Th}/\text{U}_{\text{magma}}$ ; Schärer, 1984). For plutonic rocks, the Th/U of the magma is usually estimated from the bulk rock Th/U. At the levels of uncertainty now achievable by ID-TIMS, for young rocks, the disequilibrium correction potentially becomes the dominant source of uncertainty (e.g., Crowley et al., 2007).

to thousands of cubic kilometers), even if their chemical and physical links to large plutons are not always straightforward (e.g., Lipman, 2007; Glazner et al., 2008). Supersized eruptions of silica-rich magma require minimally 1 m.y. of preconditioning of the crust via input of heat and mass from magmatic intrusion (de Silva and Gosnold, 2007; Lipman, 2007; Reid, 2008). Such long volcanic precursor time scales are entirely compatible with the long intrusion times measured for large plutons like Tuolumne and Mount Stuart, and suggest that large volcanic eruptions have even larger complementary plutonic underpinnings. Large volumes of silica-rich magma are more easily stored in high-crystallinity mushes (Bachmann and Bergantz, 2004), which can be maintained at temperatures above their solidi for long times given measured magmatic heat fluxes (e.g., Jellinek and DePaolo, 2003). Rejuvenation of the mush by sufficient input of heat and volatiles (from magma injection) and/or melt extraction via a variety of processes (e.g., Sisson and Bacon, 1999; Bachmann and Bergantz, 2004, 2006) may then lead to large, eruptible volumes of magma relatively quickly.

The work by Michel et al. will no doubt further stoke the debate over how to interpret magmatic processes inferred from field relationships and geochemical and isotopic data in plutons and their host rocks. Incremental growth of plutons is becoming more widely recognized across a range of scales and in different tectonic environments. If there is to be a ‘paradigm shift’ in our understanding of how plutons grow and how they relate physically, chemically, and temporally to magma chambers, it will depend on continuing to decipher the age systematics of zircon in plutons at small spatial scales, and on finding more convincing examples like the Torres del Paine laccolith (e.g., Walker et al., 2007). Michel et al.’s work will be cited frequently in the coming years as an excellent and very clear-cut case of incremental, top-down growth of a pluton—perhaps the best example yet documented.

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#### REFERENCES CITED

- Bachmann, O., and Bergantz, G.W., 2004, On the origin of crystal-poor rhyolites: Extracted from batholithic crystal mushes: *Journal of Petrology*, v. 45, p. 1565–1582.
- Bachmann, O., and Bergantz, G.W., 2006, Gas percolation in upper-crustal silicic crystal mushes as a mechanism for upward heat advection and rejuvenation of near-solidus magma bodies: *Journal of Volcanology and Geothermal Research*, v. 149, p. 85–102.
- Bacon, C.R., Sisson, T.W., and Mazdab, F.K., 2007, Young cumulate complex beneath Veniaminof caldera, Aleutian arc, dated by zircon in erupted plutonic blocks: *Geology*, v. 35; p. 491–494; doi: 10.1130/G23446A.1.
- 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. 1465–1482.
- 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, doi: 10.1130/G20220.1.
- Crowley, J.K., Schoene, B., and Bowring, S.A., 2007, U-Pb dating of zircon in the Bishop Tuff at the millennial scale: *Geology*, v. 35, p. 1123–1126, doi: 10.1130/G24017A.1.

- de Silva, S., and Gosnold, W.D., 2007, Episodic construction of batholiths: Insights from the spatiotemporal development of an ignimbrite flare-up: *Journal of Volcanology and Geothermal Research*, v. 167, p. 320–335, doi: 10.1016/j.jvolgeores.2007.07.015.
- Glazner, A.F., Bartley, J.M., Coleman, D.S., Gray, W., and Taylor, R.Z., 2004, Are plutons assembled over millions of years by amalgamation of small magma chambers?: *GSA Today*, v. 14, p. 4–11, doi: 10.1130/1052–5173(2004)014<0004:APAOMO>2.0.CO;2. 213.
- Glazner, A.F., Coleman, D.S., and Bartley, J.M., 2008, The tenuous connection between high-silica rhyolites and granodiorite plutons: *Geology*, v. 36, p. 183–186, doi: 10.1130/G24496A.1.
- Jellinek, A.M., and DePaolo, D.J., 2003, A model for the origin of large silicic magma chambers: Precursors of caldera-forming eruptions: *Bulletin of Volcanology*, v. 65, p. 363–381.
- Lipman, P.W., 2007, Incremental assembly and prolonged consolidation of Cordilleran magma chambers: Evidence from the Southern Rocky Mountain volcanic field: *Geosphere*, v. 3, p. 42–70, doi: 10.1130/GES00061.1.
- 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, doi: 10.1016/j.chemgeo.2005.03.011.
- Matzel, J.E.P., Bowring, S.A., and Miller, R.B., 2006, Time scales of pluton construction at differing crustal levels; Examples from the Mount Stuart and Tenpeak Intrusions, north Cascades, Washington: *Geological Society of America Bulletin*, v. 118, p. 1412–1430, doi: 10.1130/B25923.1.
- Michael, P.J., 1984, Chemical differentiation of the Cordillera Paine granite (southern Chile) by in situ fractional crystallization: *Contributions to Mineralogy and Petrology*, v. 87, p. 179–195, doi: 10.1007/BF00376223.
- Michael, P.J., 1991, Intrusion of basaltic magmas into a crystallizing granitic magma chamber; The Cordillera del Paine Pluton in southern Chile: *Contributions to Mineralogy and Petrology*, v. 108, p. 396–418, doi: 10.1007/BF00303446.
- Michel, J., Baumgartner, L., Putlitz, B., Schaltegger, U., and Ovtcharova, M., 2008, Incremental growth of the Patagonian Torres del Paine laccolith over 90 k.y.: *Geology*, v. 36, p. 459–562, doi: 10.1130/G24546A.1.
- 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, doi: 10.1016/j.jvolgeores.2007.04.019.
- Morgan, D.J., Blake, S., Rogers, N.W., De, V.B., Rolandi, G., and Davidson, J.P., 2006, Magma chamber recharge at Vesuvius in the century prior to the eruption of A.D. 79: *Geology*, v. 34, p. 845–848, doi: 10.1130/G22604.1.
- Reid, M.R., 2003, Timescales of magma transfer and storage in the crust, in Rudnick, R.L., ed., *The Crust, Treatise on Geochemistry*, Vol. 3: Oxford, UK, Elsevier, p.167–193.
- Reid, M.R., 2008, How long does it take to “supersize” an eruption?: *Elements*, v. 4, p. 23–28, doi: 10.2113/GSELEMENTS.4.1.23.
- Scharer, U., 1984, The effect of initial <sup>230</sup>Th disequilibrium on young U-Pb ages: The Makalu case, Himalaya: *Earth and Planetary Science Letters*, v. 67, p. 191–204.
- Schoene, B., Crowley, J.L., Condon, D.J., Schmitz, M.D., and Bowring, S.A., 2006, Reassessing the U and <sup>40</sup>K decay constants for geochronology: New insights from high-precision ID-TIMS U-Pb data: *Geochimica et Cosmochimica Acta*, v. 70, p. 426–445, doi: 10.1016/j.gca.2005.09.007.
- Sisson, T.W., and Bacon, C.R., 1999, Gas-driven filter-pressing in magmas: *Geology*, v. 27, p. 613–616, doi: 10.1130/0091–7613(1999)027<0613:GDFPIM>2.3.CO;2.
- Walker, B.A., Jr., Miller, C.F., Claiborne, L., Lowery, Wooden, J.L., and Miller, J.S., 2007, Geology and geochronology of the Spirit Mountain batholith, southern Nevada: Implications for timescales and physical processes of batholith construction: *Journal of Volcanology and Geothermal Research*, v. 167, p. 239–262, doi: 10.1016/j.jvolgeores.2006.12.008.

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