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The pace of crustal-scale magma accretion and differentiation beneath silicic caldera volcanoes

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ABSTRACT

Crustal-scale magmatic systems act as filters between the mantle and the atmosphere, and can generate large volcanic eruptions that pose significant hazards while altering Earth's climate. Quantifying the growth rates, magma fluxes, and duration of storage at different crustal levels is crucial for understanding such systems, but these parameters are poorly constrained due to the scarcity of exposed crustal sections. Here we present the first detailed reconstruction of magma emplacement and differentiation time scales of a complete crustal-scale igneous system exposed in the southern Alps (Ivrea-Sesia region, northern Italy) to quantify the magma fluxes and duration of transcrustal magmatism. Integrated zircon U-Pb petrochronology and numerical modeling provides unprecedented evidence that the volcanic and plutonic bodies are directly related to each other both chemically and temporally, suggesting that the entire magmatic system grew rapidly from its deepest roots to the erupted products. In the entire crustal section, zircons record 4 m.y. of magma accretion, but the bulk of the magma was emplaced within approximately 2 m.y. during an episode of enhanced magma flux from the mantle. Our results show the synchronous growth and differentiation of discrete magma bodies at various crustal levels beneath silicic caldera volcanoes and reconcile modeling and geochronological results on crustal-scale heat and mass transfer.

INTRODUCTION

Understanding the inner workings of crustal-scale magmatic systems is a fundamental topic of geosciences, as these processes control the style, volume, and composition of volcanic eruptions (e.g., Cashman et al., 2017; Hildreth and Moorbath, 1988; Lipman and Bachmann, 2015). These magmatic processes also generate igneous rocks that form the building blocks of Earth's continental crust (e.g., Keller et al., 2015), making the crust a crucial component for the mass and heat balance between the mantle and the atmosphere. Hence, quantifying the rates of mantle-crust mass transfer is important, but in many situations, our observations are restricted to erupted material or upper-crustal plutonic units (<10 km depth), while coherent records of crustal-scale magmatic systems are few and commonly deeply affected by post-emplacement orogenic processes. A thorough understanding of the lifetime and evolution of crustal-scale magmatic systems is crucial for assessing under which conditions and at which rates volcanic systems grow and evolve to ultimately generate large-scale silicic eruptions, which has been debated for the past decades.

At the center of this debate are the physical state of crustal magma reservoirs and their lifetime in the crust prior to eruption (e.g., Barboni et al., 2016; Rubin et al., 2017; Szymanowski et al., 2017). Some studies suggest short time scales for the assembly of eruptible magma pockets that form large eruptions (10^1–10^2 yr; e.g., Flaherty et al., 2018; Pamukcu et al., 2015), with magma reservoirs potentially spending most of their lifespan below their solidus and rising above the solidus in short intervals following recharge (10^2–10^3 yr; e.g., Cooper and Kent, 2014; Rubin et al., 2017; Shamloo and Till, 2019). In contrast, others suggest longer melt-extraction time scales (10^4–10^5 yr; see Bachmann and Huber, 2018, and references therein) in mush regions stored at near-solidus temperatures (Szymanowski et al., 2017). All of these studies, however, focus on upper-crustal magma reservoirs, while direct observations of crustal-scale magmatic systems including their lower-crustal roots are limited, making it difficult to assess the temporal, thermal, and chemical processes occurring throughout entire igneous distillation columns.

GEOLOGIC BACKGROUND

To quantify the lifetime of crustal-scale magmatic systems, we studied a world-famous locality that exposes volcanic and plutonic rocks from different crustal depths. The Ivrea-Verbano zone and Serie dei Laghi magmatic system, collectively named the Sesia Magmatic System, were formed during Permian extension and are now exposed on the southern slopes of the Alps in northern Italy (e.g., Barboza and Bergantz, 2000; Fountain, 1976; Rivalenti et al., 1981; Zingg et al., 1990) (Fig. 1A). The Sesia Magmatic System represents part of a larger tectono-magmatic province that generated a number of Permian magmatic centers (Schaltegger and Brack, 2007), extending for hundreds of kilometers throughout the southern Alps. Many of these magmatic centers produced large-volume silicic eruptions. While the erupted volume of Sesia Magmatic System rhyolites is poorly constrained and primarily consists of caldera-fill deposits including megabreccias, other erupted centers such as the Bozen-Etsch valley caldera preserve voluminous ignimbrite deposits (1300 km^3 of erupted material; Willcock et al., 2013) suggesting that large silicic eruptions are a common feature of this magmatic province.

Field and geophysical evidence suggests that the Ivrea-Verbano zone represents a section through deep crust (Mueller et al., 1980), which was tilted nearly 90° such that the exposed surface can be viewed as a vertical cross-

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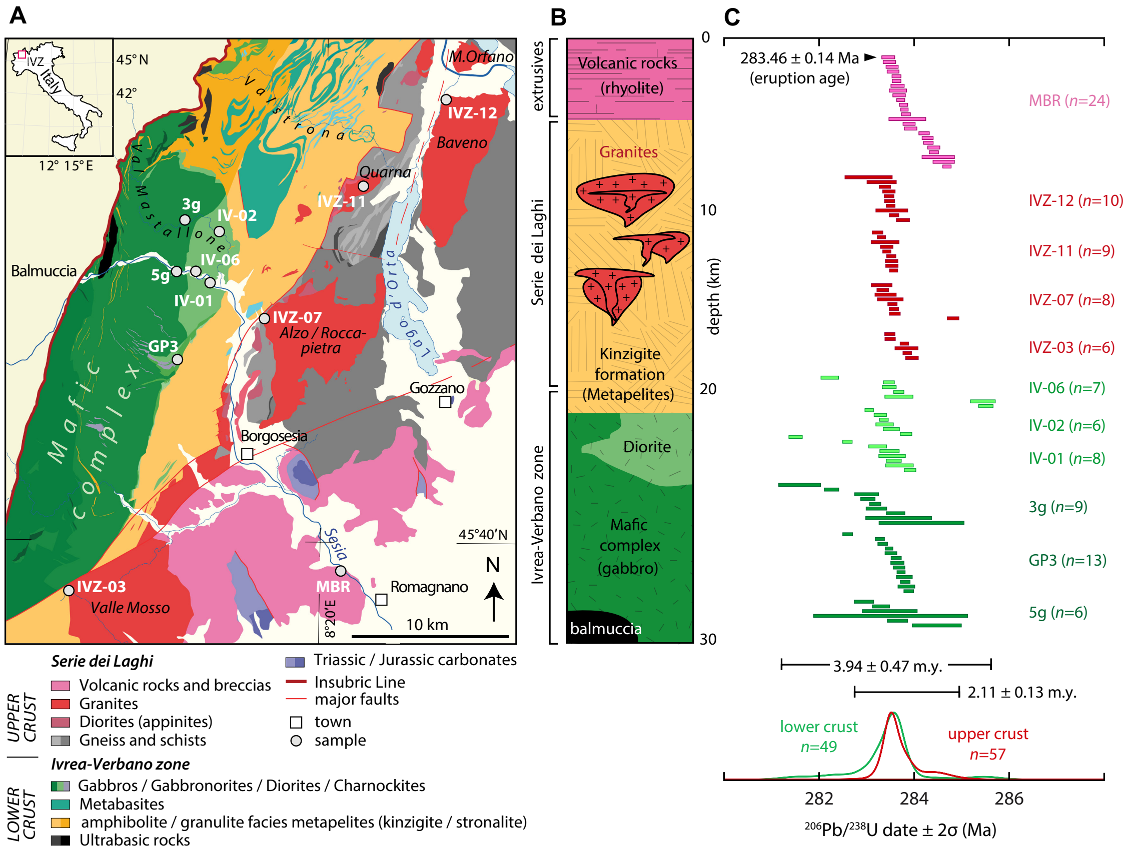

Figure 1. Crustal-scale architecture and geochronology of Sesia Magmatic System, southern Alps (northern Italy). A: Geologic map of Ivrea-Verbano zone and Serie dei Laghi magmatic province with sample localities. Location of studied crustal section within northern Italy is shown in figure inset. B: Schematic crustal column of Sesia Magmatic System. Geologic map and crustal column are created after Quick et al. (2009) and Brack et al. (2010). C: Single-zircon $^{206}Pb/^{238}U$ chemical abrasion–isotope dilution–thermal ionization–mass spectrometry dates from sampled magmatic units throughout crustal section and kernel distribution of dates from lower- and upper-crustal units. Indicated are total lifetime of magmatic system based on duration of zircon crystallization (3.94 ± 0.47 m.y.), duration of peak magmatism (2.11 ± 0.13 m.y.), and age of caldera-forming eruption (283.46 ± 0.14 Ma).

section of the crust (e.g., Fountain, 1976; Quick et al., 2009). In the area of Val Sesia (Italy), the Ivrea-Verbano zone predominantly consists of a large lower-crustal unit, the "mafic complex", of mainly gabbroic and dioritic composition that extends for >35 km in length and was emplaced into amphibolite- to granulite-facies metasediments (Fig. 1A). Ten to twenty kilometers southeast of the mafic complex, several tectonically separated granitoid bodies are exposed at the surface, reflecting fossil upper-crustal magma reservoirs (Fig. 1A). Volcanic rocks, dominated by rhyolitic caldera-fill deposits (Brack et al., 2010; Quick et al., 2009), crop out further to the southeast. Previous isotopic and geochronologic work suggested that these lower- to upper-crustal igneous bodies are genetically related (e.g., Quick et al., 2009; Voshage et al., 1990), providing a unique opportunity to investigate the rates and mechanisms of transcrustal magma accretion and differentiation processes.

A large number of existing U-Pb zircon and monazite age determinations (e.g., Köppel, 1974; Pin, 1990; Quick et al., 2009; Schaltegger and Brack, 2007) suggest a major Permian magmatic and metamorphic event that took place between ca. 300 and 250 Ma with a major peak in magmatic activity between ca. 279 and ca. 290 Ma. However, the exact temporal and genetic links between lower- and upper-crustal magmatism are masked by the low analytical precision of previous in situ geochronology. Quantifying the duration and rates of magma emplacement with high-precision techniques would allow the determination of precise mass and heat budgets for formation of crustal-scale magmatic systems (e.g., Barboza and Bergantz, 2000; Sinigoi et al., 2011).

GEOCHRONOLOGY AND THERMAL MODEL

We have completed an extensive high-precision U-Pb zircon geochronology campaign employing chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-ID-TIMS; see Supplementary Methods in the GSA Data Repository[1]) to date a total of 106 zircon crystals and crystal fragments from 11 samples of the Sesia Magmatic System (Fig. 1A; Table DR1 in the Data Repository), ranging from the deep-crustal gabbroic units to the erupted volcanics along an ~30 km (depth) crustal transect (Fig. 1B). CA-ID-TIMS dating was preceded by a detailed geochemical characterization of analyzed crystals to constrain the crystallization environments of dated zircons. The obtained time range was then used in a thermal model that simulates the emplacement of magmas by dikes and sills in an extensional environment at both lower- and upper-crustal levels (Karakas et al., 2017) to derive fundamental parameters such as thermal conditions and magma fluxes required to form a crustal-scale magmatic system under these conditions.

[1]GSA Data Repository item 2019257, additional analytical methods, numerical modeling details and constraints, and supplementary figures and tables, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

LIFETIME AND EVOLUTION OF CRUSTAL-SCALE MAGMATIC SYSTEMS

Zircons from lower- and upper-crustal intrusive rocks as well as from erupted products yield overlapping age distributions, suggesting that zircon-saturated melt was present simultaneously at various levels of the magmatic system (Fig. 1C; Data File DR1). ^{230}Th-disequilibrium corrected $^{206}Pb/^{238}U$ dates of autocrystic zircons range from 285.52 ± 0.15 Ma to 281.58 ± 0.44 Ma (2σ uncertainty), constraining the duration of magmatic activity to a 3.94 ± 0.47 m.y. time span. Three zircons with $^{206}Pb/^{238}U$ dates ranging from 284.83 ± 0.12 Ma to 285.52 ± 0.15 Ma are interpreted to record the initial waxing stage of the magmatic system, representing the initial, small-volume magmas that were intruded in the lower crust. Lower-crustal rocks contain the youngest dated zircons, with $^{206}Pb/^{238}U$ dates as young as 281.58 ± 0.44 Ma. These may record late-stage crystallization during the waning stage of the magmatic system, but we cannot entirely exclude minor effects of residual Pb loss despite chemical-abrasion pretreatment. The majority of zircons crystallized between 284.70 ± 0.09 Ma and 282.59 ± 0.10 Ma, reflecting the peak of magma accretion and rapid differentiation over 2.11 ± 0.13 m.y. During the total ~4 m.y. interval, all dated granitoid bodies, which are currently 30 km apart, were emplaced and crystallized in the upper crust as discrete but open-system reservoirs (assembly time scales between 0.34 ± 0.14 m.y. and 1.51 ± 0.25 m.y.), separated by metasedimentary wall rocks. Such a configuration was recently suggested for upper-crustal magma reservoirs feeding large-volume caldera-forming eruptions in Yellowstone (western United States) and elsewhere (e.g., Wotzlaw et al., 2015). Although the zircon age distributions from rhyolitic to dacitic eruptive products contain several older zircons (ca. 284 Ma), the majority of these zircons, including the youngest grains, are indistinguishable from those from dated granites, suggesting that granitoids represent unerupted parts of the eruption-feeding magma reservoirs. The youngest zircon $^{206}Pb/^{238}U$ date from the rhyolitic megabreccia approximates the age of the caldera-forming eruption at 283.46 ± 0.14 Ma.

The trace element composition of zircon reflects the crystallization environment with respect to co-crystallizing minerals and temperature (e.g., Fu et al., 2008; Szymanowski et al., 2017). Trace element compositions of Sesia Magmatic System zircons display a pronounced progression from deep, more primitive compositions to evolved upper-crustal compositions (Fig. 2A; Figs. DR1–DR4; Data File DR2). In the lower-crustal magmatic units, zircons display a range of rare earth element (REE) spectra. Zircon from pyroxenite cumulates and the least-evolved gabbros show no to weak europium anomalies (Eu/Eu*), suggesting that zircon saturated before significant plagioclase fractionation (Fig. 2A, lower panel; phase 1). Zircons from more evolved gabbros and diorites show a bimodal distribution with respect to Eu/Eu*, demonstrating that some zircons crystallized before and some after plagioclase saturation (Fig. 2A, phases 2 and 4). Significant plagioclase crystallization likely occurred rapidly within a relatively narrow temperature interval after initial zircon crystallization (Eu/Eu* ~1) at high temperature, consistent with high-pressure fractionation of hydrous parental magma. The most-evolved trace element compositions of some zircons from the lower-crustal rocks (Eu/Eu*<0.1, Ti <10 ppm; Fig. 2A, phase 4) likely reflect crystallization from interstitial residual melt near the solidus, as the magma reservoirs reached the final stages of crystallization. The pronounced gap in intermediate Eu/Eu* (~0.1) of zircons from the lower-crustal rocks corresponds to the Eu/Eu* of zircons from upper-crustal rocks (Fig. 2A, phase 3), showing that the entire crustal-scale system is linked chemically. This is consistent with Nd isotopic and bulk-rock geochemical evidence suggesting that a significant component of upper-crustal granitoids is derived from

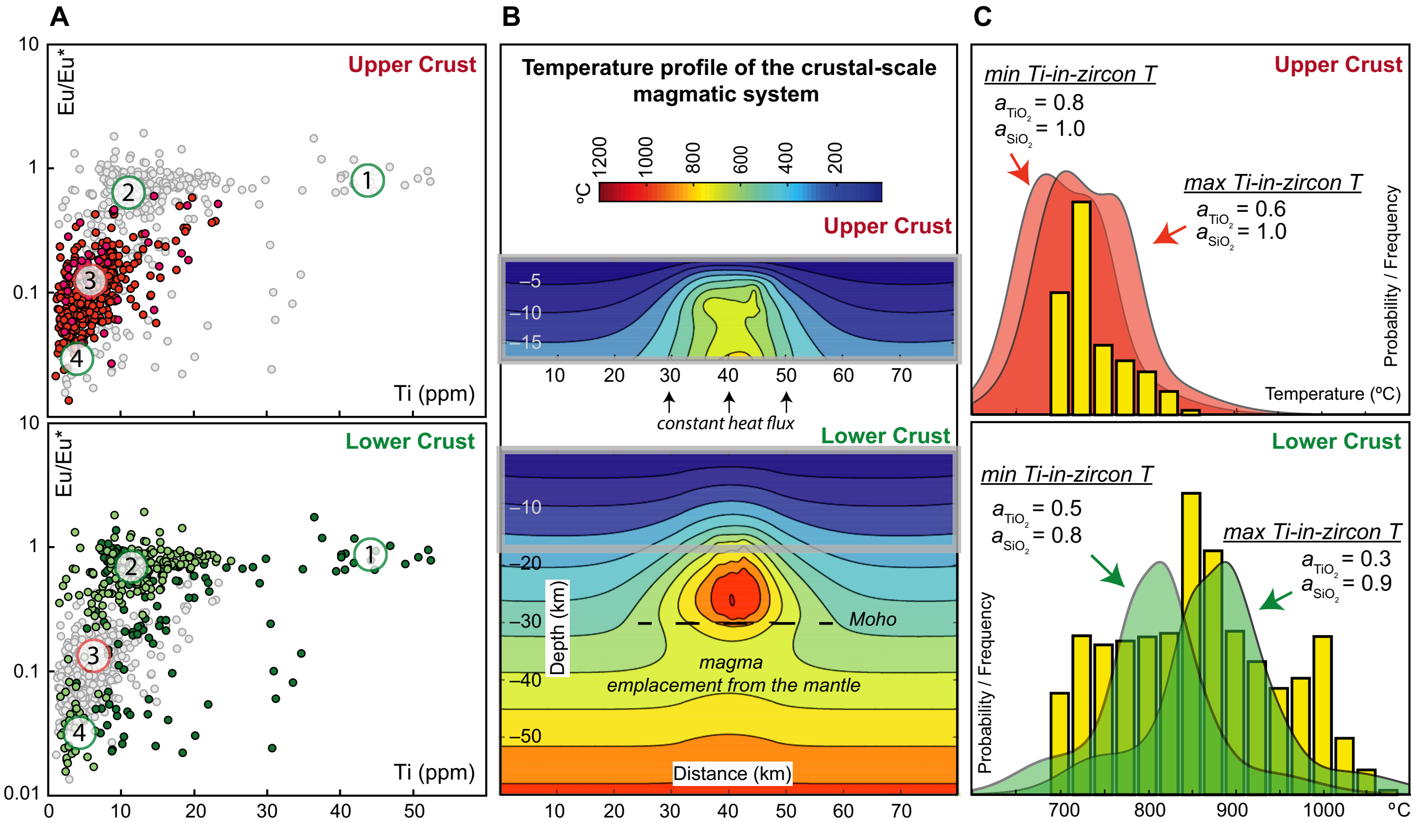

Figure 2. Zircon trace element evolution and temperature conditions at crustal scale. A: Zircon Eu/Eu* as function of Ti concentration. Lower panel: Lower-crustal zircons are shown in green, and upper-crustal zircons are shown in gray for comparison. Upper panel: Upper-crustal zircons are shown in red, and lower-crustal zircons are shown in gray for comparison. Numbering 1–4 corresponds to different phases of magma evolution: phase 1—high-temperature crystallization, zircons crystallize before plagioclase; phase 2—zircons and plagioclase co-crystallize; phase 3–compositional gap corresponding to zircons from upper-crustal rocks (lower panel), zircons crystallized from extracted silicic melt in the upper crust, forming eruptible magmas and upper-crustal silicic plutons (upper panel); phase 4—interstitial crystallization from residual, near-solidus melt. B: Two-dimensional temperature profile at crustal scale resulting from lower- and upper-crustal numerical simulations. Gray box represents the two-dimensional domain for the upper crustal simulations. Magma is emplaced in lower crust for 2 m.y., and for another 2 m.y. in upper crust, while heat flux at upper-lower crust boundary is kept constant. C: Ti-in-zircon temperatures (*T*) calculated employing calibration of Ferry and Watson (2007). Maximum (max) and minimum (min) temperature ranges are plotted in green (lower panel, lower crust) and red (upper panel, upper crust) using wide range of TiO_2 and SiO_2 activities (a_{TiO2}, a_{SiO2}). Histograms show temperature distributions from thermal model for comparison, showing cumulative temperatures at 0.5, 1.0, 1.5, and 2 m.y. in the entire melt region at four time scales, representing the evolution of the magmatic system over its lifetime.

lower-crustal magmas that fractionated significant plagioclase (Voshage et al., 1990).

An open question regarding crustal magmatic systems is whether it is thermally viable for these large bodies to form within reasonable durations and magma fluxes constrained from field and laboratory studies (e.g., Cashman et al., 2017; Dufek and Bergantz, 2005; Grunder et al., 2006; Paterson et al., 2011). Based on our geochemistry and geochronology results, we used a thermal model (see the Methods in the Data Repository; Fig. 2B) that simulates earlier magma intrusions into lower crust for 2 m.y. corresponding to the waxing stage of the magmatic system. This is followed by a second stage of intrusions of more-evolved magmas into the upper crust for 2 m.y. (Fig. 2B) corresponding to the peak stage of magmatism. During this time, the lower crust is assumed as a steady-state system with constant magma flux from the mantle and constant heat flux between the lower and upper crust (Karakas et al., 2017). Complementing our geochronology and geochemical analyses, the results of the thermal model show that it is thermally viable for an incrementally growing crustal-scale magmatic system to form within the measured time frame, with average magma fluxes of ~0.0035 and ~0.001 km^3/yr for the lower and upper crust, respectively.

The temperatures found in the numerical simulations and Ti-in-zircon temperatures overlap both for the lower- and upper-crustal magma bodies (Fig. 2C). Ti-in-zircon temperatures in the lower-crustal system spans a wide range, likely showing the high-temperature zircon crystallization at >900 °C (Eu/Eu* ~1), peaking at 800–900 °C, and finally showing near-solidus temperatures, where the system dies off and low–Eu/Eu* zircons crystallize (Eu/Eu* <0.1). Our thermal model reproduces this pattern, using input parameters from field and compositional data as well as our new geochronological constraints suggesting that moderate (~10^{-3}–10^{-2} km^3/yr) magma fluxes over 2 m.y. are sufficient to produce crustal-scale magmatic systems. The temperature profile produced by the thermal model shows formation of a large lower-crustal magma body within this time frame (Fig. 2C, lower panel). In the upper crust, the Ti-in-zircon temperatures are lower, ranging from solidus to 900 °C, while the thermal model suggests a slightly narrower range between 700 and 850 °C, because of the temperature-melt fraction range in the phase diagram of the intruded melt from Serie dei Laghi compositions, calculated using rhyolite-MELTS software (Gualda et al., 2012) (Fig. 2C; Fig. DR5).

EVOLUTION AND DIFFERENTIATION OF CRUSTAL-SCALE MAGMATISM

The narrow age range of dated zircons with overlapping distributions throughout the entire crust tightly pieces together the crustal-scale magmatic system and constrains the duration of magma accretion and evolution across multiple crustal levels. The total duration of 3.94 ± 0.47 m.y. and the duration of the volumetrically most-important pulse of magmatic activity of 2.11 ± 0.13 m.y. are significantly shorter than previous suggestions based on in situ geochronology (Data File DR3; Figs. DR2 and DR6; Klötzli et al., 2014; Quick et al., 2009). During the 4 m.y. interval, magmatism started with intrusions in the lower crust, then accelerated and evolved to produce a silicic caldera-forming eruption within 2 m.y. (Fig. 3). Our study represents the first high-precision investigation of a single crustal-scale magmatic plumbing system that unravels the time frame of crustal-scale magma accretion and differentiation leading to caldera-forming silicic eruptions. We suggest that a mature crustal igneous system in an extensional setting, including the venting of significant amounts of evolved magma at the surface during eruptions, can form rapidly, within a few million years. Magmas are mostly stored at high crystallinity but include some fraction of melt-rich lenses that can move up, chemically evolve further, and vent to the surface with a range of eruptive volumes, up to large-volume caldera-forming silicic supereruptions.

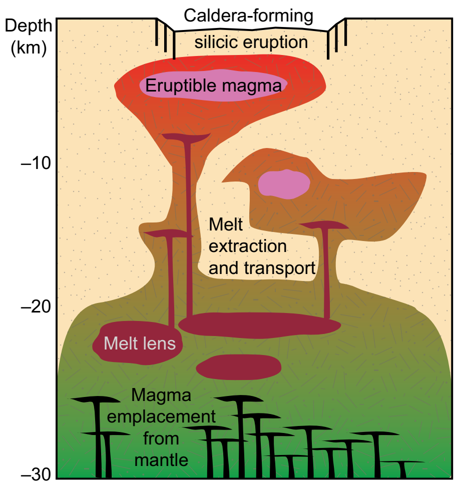

Figure 3. Schematic sketch of crustal-scale magmatic system, forming large mush bodies with melt pockets in the lower and upper crust. At crust-mantle boundary, mafic magma intrudes into lower crust incrementally. Lower-crustal system evolves over time with continuous magma emplacement. Zircons record different stages of crystallization (pre– and post–plagioclase crystallization) at different temperatures. Fractionation in lower crust generates intermediate melt, which is extracted and moves to the upper crust. Over time, eruptible silicic magmas form in the upper crust and generate rhyolitic eruptions at surface. Most melt crystallizes in the upper crust as silicic plutons. There is continuous melt transfer from the lower to upper crust, showing that the entire system is active during the same time interval.

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