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Estimates of volume and magma input in crustal magmatic systems from zircon
geochronology: the effect of modelling assumptions and system variables

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Abstract

Magma fluxes in the Earth’s crust play an important role in regulating the relationship between the frequency and magnitude of volcanic eruptions, the chemical evolution of magmatic systems and the distribution of geothermal energy and mineral resources on our planet. Therefore, quantifying magma productivity and the rate of magma transfer within the crust can provide valuable insights to characterise the long-term behaviour of volcanic systems and to unveil the link between the physical and chemical evolution of magmatic systems and their potential to generate resources. We performed thermal modelling to compute the temperature evolution of crustal magmatic intrusions with different final volumes assembled over a variety of timescales (i.e., at different magma fluxes). Using these results, we calculated synthetic populations of zircon ages assuming the number of zircons crystallising in a given time period is directly proportional to the volume of magma at temperature within the zircon crystallisation range. The statistical analysis of the calculated populations of zircon ages shows that the mode, median and standard deviation of the populations varies coherently as function of the rate of magma injection and final volume of the crustal intrusions. Therefore, the statistical properties of the population of zircon ages can add useful constraints to quantify the rate of magma injection and the final volume of magmatic intrusions.
Here, we explore the effect of different ranges of zircon saturation temperature, intrusion geometry, and wall rock temperature on the calculated distributions of zircon ages. Additionally, we determine the effect of undersampling on the variability of mode, median and standards deviation of calculated populations of zircon ages to estimate the minimum number of zircon analyses necessary to obtain meaningful estimates of magma flux and final intrusion volume.

Introduction

Magmatic systems are depicted as composed of regions of magma accumulation (magmatic reservoirs) distributed at different depths within the Earth’s crust, connected by subvertical feeding structures (e.g. Annen et al., 2006; Caricchi et al., 2014; Hildreth and Moorbath, 1988). Field studies, petrography, petrology, geochemistry, and thermal modelling support this model and additionally provide evidences for the periodic transfer of magma to the shallower portions of magmatic systems (Annen et al., 2006; Bouilhol et al., 2011; Caricchi et al., 2014; Coleman et al., 2004; Connolly et al., 2009; de Saint-Blanquat et al., 2001; 2011; Glazner et al., 2004; Havlin et al., 2013; Hildreth, 1981; Jagoutz, 2014; Paterson et al., 2011; Schaltegger et al., 2009; Schoene et al., 2012; Solano et al., 2012; 2014). In periodically replenished magmatic reservoirs, the relative volume of magma and residual melt of various compositions change over hundreds of thousands to millions of years as a function of the average rate of magma injection, the thermal properties and chemistry of the wall rocks and the topology of the pertinent phase diagrams for magmas contained within the magmatic system (Annen et al., 2006; Caricchi and Blundy, 2015a; Caricchi et al., 2014; Glazner, 2007; Melekhova et al., 2013; Nandedkar et al., 2014; Solano et al., 2012; 2014; Spera and Bohrson, 2001). The rate
of magma transfer between the different portions of a magmatic system plays a pivotal role in controlling the physical and chemical evolution of magmas from the mantle to the surface, creating an intrinsic link between temperature evolution, crystallisation and variation of residual melt composition (Annen, 2009; Annen et al., 2006; Caricchi and Blundy, 2015b; Caricchi et al., 2014; Crisp, 1984; Glazner, 2007; Stolper and Asimow, 2007; White et al., 2006). Therefore, determining magma fluxes within the Earth’s crust would allow us to establish links between the geochemistry of magmas erupted at the surface and the temporal evolution of the chemical and physical properties of magmatic reservoirs at depth. However, as most of the magma produced in the mantle is actually not erupted at the surface but crystallises at depth to form intrusions, the determination of magmatic fluxes is extremely challenging (Bacon and Lanphere, 2006; Lipman, 2007). Several approaches have been used to quantify such fluxes, including large scale geophysics (Crisp, 1984; White et al., 2006). The eruptive fluxes of various volcanoes and volcanic systems have been estimated but because the volume ratio of extruded versus intrusive products is hard to determine, it is difficult to directly link magma eruption rates with magma flux in the crust (Bacon and Lanphere, 2006; Caricchi et al., 2014; Crisp, 1984; Lipman and Bachmann, 2015; Lipman, 2007; Marsh, 1981; Muir et al., 2015; Salisbury et al., 2010).

We recently developed a method that uses the distribution of precise U-Pb dates obtained from single grains of zircon to determine the rate of assembly and final volume of magmatic intrusion in the crust (Caricchi et al., 2014). The foundation of this method is that zircon crystallises within a given range of temperature ($T_{zr}$; a function of magma composition and zirconium concentration; Boehnke et al., 2013; Hanchar and Watson, 2003; Miller et al., 2003) and its crystallisation can be dated by
radio-isotopic methods (e.g. Schaltegger et al., 2015). Under the assumption that the number of zircons crystallising within a given time interval is proportional to the magma volume within $T_z$, the distribution of dates of a population of zircons provides an image of the time-integrated evolution of temperature in a magmatic reservoir (Caricchi et al., 2014). To quantify the relationships between magma flux, final volume and the characteristics of the resulting population of zircon ages, we performed thermal modelling. The results reveal that the mode, median and standard deviation of the calculated populations of zircon ages vary systematically as a function of magma flux and final volume of the intrusion. Therefore, the comparison between the synthetic age populations and those retrieved in natural magmatic systems can provide information on the final volume of the intrusion and the rate at which the pluton was accreted (Caricchi et al., 2014). The statistical characteristics of the calculated populations of zircon ages depends on the range of temperature at which zircon crystallises, from the depth of emplacement (i.e., the temperature of the wall rocks), and the geometry of the intrusion (Caricchi et al., 2014). Here we present a detailed investigation of the effect of considering different ranges of zircon saturation temperature (700-750, 700-800, 700-850°C), as well as different intrusion geometries, and wall rock temperatures, on the mode, median, and standard deviation of the calculated zircon age distributions, which were not explored in Caricchi et al. (2014). Additionally, we assess the impact of undersampling to determine the minimum number of zircons required to apply the method we propose.

**Methods**

*Thermal modelling and calculation of synthetic populations of zircon ages*
We use heat conduction-advection theory to determine the distribution and evolution of temperature in a crust that experiences magma injection and cooling. The basic equation of heat conduction-advection theory is a mathematical statement of conservation of energy combined with Fourier’s Law of heat conduction. For an axisymmetrical geometry, this equation can be written as:

\[
\rho C_p \left( \frac{\partial T}{\partial t} + u_r \frac{\partial T}{\partial r} + u_z \frac{\partial T}{\partial z} \right) = \frac{1}{r} \frac{\partial}{\partial r} \left( r k \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + \rho L \frac{\partial \chi_c}{\partial t}
\]  

(1)

where \( T \) is the temperature, \( t \) is the time, \( r \) is the horizontal distance relative to the symmetry axis, \( z \) is the depth, \( u_r \) and \( u_z \) are the solid velocities in the \( r \) and \( z \) directions, respectively, \( k \) is the thermal conductivity, \( \rho \) is the density, \( C_p \) is the specific heat per unit mass, \( L \) is the latent heat of fusion per unit mass and \( \chi_c \) is the crystal fraction. The crystal fraction is assumed to vary with temperature according to

\[
\chi_c = 1 - \frac{1}{1+e^{\theta}}
\]

(2)

where

\[
\theta = \frac{800-T}{23}
\]

The velocities \( u_r \) and \( u_z \) depend on the intrusion geometry and magma injection rate. This formulation was selected to fit the variation of crystallinity with temperature observed for magma of granodioritic composition (Piwinskii and Wyllie, 1968). Most calculations were performed assuming outward inflating spherical magma chambers, though we tested sensitivity to the intrusion geometry by comparing these results with horizontally expanding cylinders and vertically accreting cylinders. The velocities \( u_r \) and \( u_z \) depend on the intrusion geometry and magma injection rate. During the intrusion phase, \( u_r \) and \( u_z \) are constant in time, whereas they are zero after intrusion has ceased. They are simply determined by providing the space for each newly intruded pulse. For example, for an outwardly inflating cylinder, the radial velocity...
for all points adjacent to the intrusion is simply $u_r = dr/dt$ where $dr$ is the radius of the
intruded pulse and $dt$ is the time interval between pulses, while the vertical velocity
($u_z$) is zero.

The initial temperature was assumed to be a constant geothermal gradient. For
boundary conditions, the temperature was assumed to be constant on the upper (i.e.,
the surface) and lower ($z=30$ km) boundaries. The right boundary was assumed to be
zero horizontal heat flux. Magma injection was implemented by modifying the
temperature (to the liquidus temperature) of nodes within the newly injected portion
of the magma chamber. Parts of the $r=0$ boundary not influenced by magma injection
were assumed to have zero horizontal heat flux. Solutions to Equation 1 were
obtained with the Petrov-Galerkin Finite Element Method on 4-node quadrilaterals.

Unless specified otherwise, all calculations were performed with the following
parameter values: initial geothermal gradient 30°C km$^{-1}$, intrusion depth = 10 km,
thermal conductivity 2.7 W m$^{-1}$ K$^{-1}$, heat capacity 1 kJ kg$^{-1}$ °K$^{-1}$, rock density 2700 kg
m$^{-3}$, latent heat of fusion 350 kJ kg$^{-1}$, intrusion temperature 900°C.

Synthetic zircon-age distributions were calculated on the basis of the thermal
calculations using the following procedure:

1) The final cooled pluton was divided into numerous discrete equal-volume
cells.

2) The temperature evolution of each cell was tracked back in time from a cold
state to the time when each cell was initially intruded. Note that the position of
the cells change in time due to progressive intrusion.

3) Each constant volume cell was assumed to grow zircons at a constant rate
when its temperature was within a specified zircon crystallisation window $T_{zr}$
($700$-$750$°C, $700$-$800$ °C and $700$-$850$ °C). The lower temperature was chosen
to be close to the granitic water saturated minimum (Johannes and Holtz, 1996).

4) The total number of zircons in all cells within the pluton is tracked in time, giving the zircon-time distribution.

Zircon dating

U-Pb age determinations on zircon may be carried out using high-precision, bulk dating techniques (chemical abrasion, isotope dilution, thermal ionization mass spectrometry; CA-ID-TIMS), or spatially resolved, spot analyses using an ion microprobe (secondary ion mass spectrometry; SIMS) or laser ablation linked to an inductively coupled plasma mass spectrometer (LA-ICP-MS). The three techniques differ largely in terms of sampled volumes and precisions; accuracy of the techniques depends on a well-calibrated tracer solution in the case of CA-ID-TIMS (Condon et al., 2015) or on external reference materials in the case of the two in-situ techniques. CA-ID-TIMS utilizes whole grains or parts of grains, inevitably mixing growth zones of different age, and achieves a typical precision and accuracy of 0.05-0.1% (2σ) in $^{206}\text{Pb}/^{238}\text{U}$ date (up to ~0.3% for 1 Ma old zircon; Wotzlaw et al., 2015), contrasting to the ca. 1-2% typical uncertainties for both SIMS and LA-ICP-MS (Schaltegger et al., 2015).

The geochronological method of choice to satisfy the preconditions of our model approach needs to be capable of resolving timescales of magmatic crystallization, which are commonly in the range of $10^4$ to few $10^5$ years for crustal plutons (e.g. Broderick et al., 2015; Leuthold et al., 2012; Schoene et al., 2012). This implies that in-situ U-Pb dating techniques do not provide sufficient age resolution in magmatic
systems older than 15-30 Ma, because of the inherent 1-2% external uncertainty of these methods (Schaltegger et al., 2015).

We therefore required to use high-precision \(^{206}\text{Pb}/^{238}\text{U}\) dates produced using CA-ID-TIMS techniques on entire or fragments of zircon grains. Any such date will provide time-averaged information, weighted for volume of the different zircon sectors and their U-content. We will show below that despite the lack of spatial resolution, the resulting dates provide an image of the time-integrated evolution of temperature in a magmatic reservoir and can be used to calculate fluxes and volumes using our method.

Results

The method we proposed in Caricchi et al. (2014) consists of using zircon age populations to retrieve information on magma fluxes and the final volume of the reservoir in which the zircon crystallised. The zircon age data are first transformed into a time sequence, posing time zero equal to the oldest zircon age. The population (in kilo-years) is then bootstrapped to obtain ranges of mode, median and standard deviation. These three ranges are then plotted using contoured figures of mode, median and standard deviation such as Figure 3 of (Caricchi et al., 2014) and the area defined by the intercept of the three ranges provide estimates of magma flux and volume (see also Caricchi et al., 2014). In the following we present (i) the influence that various factors may have on the final results; (ii) a quantification of the minimum number of zircons required to obtain meaningful results using the approach we propose; (iii) discuss possible artefacts arising from the selection of the wrong analytical technique by applying our method to datasets of low precision data (iv) and
shows an application of our method to published data for Mt. Capanne pluton (Elba island, Italy).

Thermal modelling

Thermal modelling shows that the average temperature of a magmatic reservoir drops throughout the period of injection and once the injection of magma comes to an end, the rate of decrease of the average temperature increases (Fig. 1). During magma injection, the average temperature tends to values that are directly proportional to the magma flux and inversely proportional to the duration of the intrusion. As expected, the duration of cooling once the injection of magma stops increases with increasing final volume of the intrusion (Fig. 1).

The average temperature of the intrusion drops even during magma injection because while the rate at which magma (and enthalpy) is supplied to the system remains constant in our models, the rate of heat release increase because the surface over which enthalpy is lost to the wall rocks increases (Caricchi et al., 2014; Marsh, 1981). Hence, during the assembly of a magmatic intrusion, the thermal structure of the reservoir evolves and the relative volumes of magma within different temperature ranges change in time (Fig. 2). The flux of magma within the magmatic reservoir exerts a first order control on the relative volume of magma within different temperature ranges. As a consequence, magma fluxes also control the time span over which residual melts of various compositions are present (in different relative proportions) within a reservoir. While we will not dwell long on this aspect, such results indicate that the rate of magma input in subvolcanic reservoirs affects the long-term probability of magmas of different compositions to be sampled during volcanic eruptions (Caricchi and Blundy, 2015c; Melekhova et al., 2013). On the other hand, in
magmatic systems that are assembled extremely rapidly and cool over time, the
probability of magma with a given composition to be present within the magma
reservoir is exclusively controlled by the topology of the phase diagram (Marsh,

The thermal modelling results show that from the beginning of the injection event,
magma cools through the range of zircon saturation temperature leading to the
continuous crystallisation of zircon (Figs. 3, 4). The resulting distribution of synthetic
zircon ages is directly linked to the rate of magma input and the final volume of
intruded magma (Fig. 4; Caricchi et al., 2014).

Effect of zircon saturation temperature

The range of zircon saturation temperature varies as function of magma chemistry
(Boehnke et al., 2013; Hanchar and Watson, 2003; Miller et al., 2003) and this should
be taken into account when applying the method we propose (Caricchi et al., 2014).

For this reason we calculated synthetic zircon age populations for three ranges of
temperature: 700-750°C, 700-800°C and 700-850°C (Figs. 5, 6; Table 1). The
comparison shows that the difference in mode, median and standard deviation for
zircon age populations calculated considering the three different ranges of zircon
saturation temperature at the same magma flux and final volume are very similar and
only differ by 0.1-0.2 log units (Figs. 5, 6). This is true for all models performed
within the range of magma flux (10⁴-10¹ km³/y) and final volume (30-10000 km³)
investigated here (Fig.6; Table 1). We also tested the effect of decreasing the solidus
temperature and therefore the lower limit of Tzr from 700 to 680 °C. The resulting
synthetic population of zircon ages show a difference slightly lower than 0.1 log units
in mode and median values. Such variations are small and do not produce any
significant difference in the values of magma flux and volume. The wide range of
zircon saturation temperature used in these tests indicates that our method can be
applied to magmas of various compositions.

Effect of intrusion geometry, wall rock temperature and magma injection temperature
Thermal calculations were repeated for the same rate of magma input and final
volume but different geometries of the intrusions (Table 1). The variability of mode,
median and standard deviation observed by changing intrusion geometry is always
lower than 0.2 logarithmic units, and have, therefore, only a minor impact on the
estimated values of magma flux and final volume obtained applying our method to
natural populations of zircon ages (Caricchi et al., 2014). More complicated intrusion
descriptions can be envisaged, however, because of the intrinsic mechanical and
thermal instabilities of irregular boundaries in magmatic systems, thermal anomalies
tend to evolve rapidly to sub-spherical or cylindrical shapes over time (Gudmundsson,
2012; Paulatto et al., 2012). This implies that more complex geometry can potentially
change some details of the zircon crystallisation time population but not change
significantly mode, median and standard deviation of the population and therefore not
affect significantly the estimates obtained with our method.

Tests for magma injection temperature and temperature of the wall rocks were already
performed in Caricchi et al. (2014) and show similarly limited effect on the synthetic
populations of zircon crystallisation times.

Number of zircons required
The calculated populations of zircon ages are obtained by considering all zircons that
crystallised during the entire supersolidus history of the simulated intrusion. Clearly,
the number of zircons analysed in a geochronology study always represents a
subsample of all zircons present in magmatic rocks. Therefore, it is important to
address the effect of undersampling on mode, median and standard deviation of a
natural population of zircon ages on the final estimates of magma flux and volume of
the intrusion. This allows us to estimate the minimum number of zircons required for
the results obtained by our method to be meaningful. To test the impact of
subsampling on the statistical parameters (i.e. mode, median and standard deviation)
required for the estimation of magma fluxes and volumes, we randomly sub-sampled
two populations of ages with different characteristics. In the first example, we
consider a normal distribution of zircon ages (no. 10,000) with a standard deviation of
10 ky and a median age of 100 ky (Fig. 7). Three tests were performed in which each
subsample consists of 10, 30 and 50 ages, respectively. For each subsample we
calculated mode, median and standard deviation and repeated the procedure 10,000
times. The spread in mode, median and standard deviation obtained with this
procedure is shown in Figure 7, where the red circle represents the mode, median and
standard deviation for the distribution shown in panel a. The results show that for a
normal distribution that spans a relatively limited range of ages, already ten ages are
sufficient to determine the mode, median and standard deviation within a two-sigma
value of about 0.2 logarithmic units (Fig. 7), which, as shown in Figure 6, is sufficient
to constrain magma fluxes and final volume of the magmatic reservoir. Clearly,
increasing the number of analysed zircons decreases the uncertainty on the mode,
median and standard deviation of the population of zircon ages. We considered
another scenario in which the population of zircon age is positively skewed with
mode, median and standard deviation values of 50, 80 and 60 ky, respectively. In this
case, bootstrapping shows that ranges of mode, median and standard deviation
become significantly tighter when 30 to 50 zircon age determinations are performed (Fig. 8).

In-situ versus whole zircon techniques

The method proposed here has been developed for high-precision $^{206}\text{Pb}/^{238}\text{U}$ dates from entire zircon grains (CA-ID-TIMS) with the implicit assumption of the model that the mass of zircon that crystallises within a given time period is proportional to the mass of magma within the range of zircon saturation temperature. The method can also be applied to zircon U-Pb dates determined via spot analysis, however, the age determinations from different zones of a zircon should be weighted using a quantitative volumetric model for concentrically grown zircon (e.g., Samperton et al., 2015), in order to reflect the mass of zircons of a particular age and its U concentration. For example, if a population is constituted of zircons with large rims and small cores of equal U concentration, performing one measurement for the rim and one for the core without weighting the ages would artificially increase the statistical weight of older ages. This would lead to a decrease of the values of mode and median (of the population of ages converted in times) and potentially result in an underestimate of the final volume of the magmatic reservoir (Fig. 6). Because of the geometry of the contours in Figure 6 the estimates of magma flux would be less affected by not performing the weighting procedure. An additional aspect to consider is the analytical uncertainty on the U-Pb dates that is increased by a factor of 20-40 for in-situ versus whole grain techniques (Schaltegger et al., 2015). Since we bin our dates for the averaged two-sigma error of individual analyses, larger errors would result in smoother age distributions with smaller ranges of mode, median and standard deviation obtained by bootstrapping. For a normal distribution of imprecise zircon
ages with individual uncertainties exceeding the duration of the magmatic process we
intend to characterize (Fig. 7), our statistical values would be entirely defined by the
analytical parameters of our U-Pb age determination. The resulting smaller range of
mode, median and standard deviation would provide tight constraints of magma flux
and final volume, which, however, would be a direct measure of the internal
reproducibility of the U-Pb dating procedure. For a skewed distribution as shown in
Figure 8, our statistical values would be calculated from an arbitrary mixture of
analytical variance with protracted duration of zircon crystallization and generate a
pure artefact.

This implies that our method can be applied using CA-ID-TIMS $^{206}\text{Pb}/^{238}\text{U}$ dates with
a state-of-the-art uncertainty of 0.05% up to a maximal age of about 500 Ma; beyond
this age we may be able to use highest-precision $^{207}\text{Pb}/^{206}\text{Pb}$ dates of concordant
zircon grains in rare cases (e.g., Zeh et al., 2015).

Application: magmatism in Elba Island, Italy

A large dataset of high precision data (168 CA-ID-TIMS zircon age determinations)
has been recently published by (Barboni and Schoene, 2014; Barboni et al., 2015) for
a series of magmatic intrusions exposed in Elba island (Italy). We applied our method
to these data to show an example of the procedure to follow and to validate our
approach.

The largest number of analyses was performed for zircons included in megacrystals of
orthoclase recovered from the S. Andrea facies of the Mt. Capanne pluton (94 age
determinations; Barboni and Schoene, 2014). The Mt. Capanne pluton has been
divided on the basis of field and geochemical analyses in three main facies, which
from the structurally higher to the lower are identified in the literature as S. Andrea, S. Francesco and S. Piero (Rocchi et al., 2010).

We first exclude ages that are older than the oldest measured age by more than the average two-sigma error of the measurements (Fig. 9). Ages are transformed in “time” by subtracting to the oldest age the single ages, so that the oldest age corresponds to zero time (Fig. 10). Ranges for mode, median and standard deviation for each population (now transformed in time populations) are obtained by resampling each time distribution 1000 times (bootstrapping). Once the 95% confidence intervals for mode, median and standard deviation of the populations are determined the contours shown in Figure 6 can be used to obtain estimates of the intrusion volume and the average magma flux at which the pluton was constructed (Fig. 11; Table 2).

Our calculations show that the 18 age determinations for the matrix of S. Andrea facies of the Mt. Capanne pluton (Barboni and Schoene, 2014) were not sufficient to obtain meaningful estimates of magma flux and volume of the intrusion (Fig. 11a). This indicates that the real distribution of zircon ages is complex and 18 zircons ages are not sufficient to fully determine the relevant statistical parameters of the age distribution required for our analysis. On the other hand, our method provides tight constraints for magma flux ($10^{-2.7}$-$10^{-2}$ km$^3$/y) and intrusive volume (300-1000 km$^3$) when the 90 age determinations for zircons retrieved in megacrystals of orthoclase from Barboni et al. (2014) are used (Fig. 11b). This suggests that in this case, 90 dates are sufficient to describe the distribution of zircon ages during the growth of the megacrystals. While we do not develop any geological interpretation for the significance of the population of zircon ages included in the megacrystals and retrieved from the matrix of the S. Andrea facies, we discuss these results on the basis of flux and total volume.
It is interesting to note that the volume estimates from zircons in the megacrystals from the Mt. Capanne intrusion, are significantly larger than the volumes of the different facies of the Mt. Capanne estimated from fieldwork (~250 km³; Farina et al., 2010; Fig. 11b). This suggests that, in agreement with petrological and thermal modelling results (Barboni et al., 2015; Farina et al., 2010), the zircons crystallised at depth within a larger reservoir and only a limited number of zircons number crystallised at emplacement depth.

Discussion

An important issue regarding our method is the portion of the magmatic system about which zircon age populations provide information on volume and rate of assembly. Because we consider the age of a zircon to represent the time at which it crystallises, our method provides information on the magmatic reservoir where most or all the zircons crystallise. For instance, if zircons dated in a pluton crystallised at depth (Barboni et al., 2015; Schoene et al., 2012), the method we propose will provide information on the magma fluxes and the volume of the reservoir at a deeper crustal level (Broderick et al., 2015). Importantly, if zircons are mobile within magmatic systems, zircon age populations could provide important information on the development and final volume of inaccessible portions of magmatic systems.

Several evidences exist for the mobility of zircons in magmatic systems: In one of our previous publications (Caricchi et al., 2014), we showed that the spread in zircon ages for specimens retrieved in porphyritic plugs associated with ore deposits is too large to be explained by in-situ crystallisation of zircons at emplacement depth. These plugs are volumetrically small with respect to the volume of magma required to generate the ore deposits (Steinberger et al., 2013), and therefore would cool through zircon
saturation temperature rapidly producing a limited spread in zircon ages (Caricchi et al., 2014). A spread in ages of 200-500 ky obtained from analyses of zircons separated from single hand specimens (Broderick et al., 2015; Schaltegger et al., 2009; Schoene et al., 2012), provide additional support for the mobility of zircons within magmatic systems, given that a hand-size parcel of magma cannot cool through the range of zircon crystallisation temperature over half million year. Analyses of zircons in volcanic products also suggest that they are mobile and can be extracted from partially crystallised magmatic mushes before or during an eruption, as also shown for other minerals (Cooper and Wilson, 2014). For zircons retrieved in volcanic products, if evidences exist for re-heating above the zircon saturation temperature and rejuvenation (e.g. Bachmann and Bergantz, 2003) in the period preceding an eruption, our method will need to be applied with caution. Resorption or lack of zircon crystallisation in the period preceding the eruption would produce a depletion of the younger portions of the zircon populations, which, in turn, would result in a decrease of the mode, median and standard deviation recalculated following our approach (Bindeman and Simakin, 2014). Figure 6 shows how a decrease of the value of these parameters leads to an underestimation especially in the final volume of the magmatic reservoir. Such effect is evident when applying of our method to zircons retrieved from the products of the Fish Canyon Tuff for which pre-eruption re-heating was suggested (Caricchi et al., 2014; Wotzlaw et al., 2013). The results of our analysis show magma fluxes compatible with those expected for super eruptions while the estimated volume is even lower than the volume of erupted magma (see Fig. 4 of Caricchi et al., 2014). Estimates of magma flux are less affected by this process because of the topology of the contours we obtained by computing the synthetic populations of zircon ages by thermal modelling.
Concluding remarks

• We provide a model approach to use age distributions from high-precision \(^{206}\text{Pb}/^{238}\text{U}\) dates for estimating volumes and fluxes of the magmatic system the zircons crystallized in. The dates must offer sufficient precision to resolve the duration of magmatic processes, otherwise applying our method will lead to statistical artefacts confounding analytical precision with age dispersion.

• The mobility of zircons within magmatic systems is essential for our method to provide information on the thermal evolution of magmatic systems. The existence of zircon crystals that crystallized over several hundred thousands of years in one hand-sample evidences that physical processes mingle zircon populations therefore increasing the probability of sampling zircon-age populations on a statistically representative basis.

• The computed volumes and fluxes represent the magma portion from which zircon crystallized, e.g., a magma storage area in the middle or lower crust, and do not necessarily represent the volume and flux of the shallower and potentially exposed part of a magmatic system.

• Estimating the intrusive fluxes and the final volume of the magmatic system associated with much smaller-volume, upper crustal mineralised intrusions will therefore yield quantitative information on the relationship between magma fluxes and volumes and total metal endowment of magmatic ore deposits (Chelle-Michou et al., 2015).

• Volume and flux estimates from volcanic rocks can be useful to estimate intrusive-extrusive ratios, but caution should be used when evidence for extensive zircon resorption exist.
It is essential that multiple populations of zircons, which did not crystallise continuously within the same magmatic system, are not analysed at the same time. The result would be an overestimate of the volume of the magmatic system, resulting from an increase of the values of the standard deviation (Fig. 6).

The thermal modelling and statistical analysis performed in this contribution, shows that population of zircon ages reflect the thermal evolution of crustal magmatic intrusions. Because the temporal evolution of temperature in magmatic systems strongly depend on the rate at which enthalpy (i.e. magma) is supplied to the magma reservoirs and on its volume, population of zircon ages offer an opportunity to quantify magma fluxes in the Earth’s crust.

REFERENCES


**FIGURE CAPTIONS**

**Figure 1**: Temporal evolution of the average intrusion temperature for thermal models performed at injection fluxes of 0.01 and 0.001 km$^3$/y for panels a, c and b, d, respectively. The modelled final volumes were 500 and 1000 km$^3$ for panels c, d and a, b, respectively.

**Figure 2**: Temporal evolution of the volume fraction of magma within different temperature intervals (coloured lines). The black line shows the fraction of magma at temperature lower than the solidus (700°C).

**Figure 3**: Schematic representation of the evolution of the relative volume of magma above (red circles) and below (light blue circles) the range of zircon saturation temperature in time. The black line shows the evolution in time of the average temperature of the intrusion.

**Figure 4**: Combined temporal evolution of the average temperature of the intrusion and resulting population of zircon crystallisation times. The shape of the zircon crystallisation time population reflects the evolution in time of the relative volume of magma within the range of zircon saturation temperature. Magma fluxes and final volumes are the same as in Figure 1.

**Figure 5**: Mode, median and standard deviation of population of zircon crystallisation times obtained for a constant magma flux of 0.01 km$^3$/y, final volume of 1000 km$^3$. doi:10.1130/G34366.1.
and different ranges of zircon saturation temperatures.

**Figure 6:** Contours of mode (a, d, g), median (b, e, h) and standard deviation (c, f, i) for zircon age spectra obtained from thermal modelling. The number within the contours shows the logarithmic values of the respective parameters in kilo-years. Values presented in panels a, b and c were obtained for a range of zircon crystallisation temperature ($T_{zr}$) of 700 to 750 °C, panels d, e, f for $T_{zr}$ between 700 and 800 °C and panels g, h, i for $T_{zr}$ between 700 and 850 °C.

**Figure 7:** a) Normal distribution of ages characterised by a modal and median values of 100 ky and a standard deviation of 10 ky. b, d, f) Each black point in the panels shows the values of mode, median and standard deviation obtained by bootstrapping of the population of zircon crystallisation times represented in panel a. Distributions of the values of mode and median obtained by sampling the distribution reported in panel a, 10, 30 and 50, time respectively. The procedure has been repeated 10,000 times for each subsample of 10, 30 and 50 ages. c, e, g) Distributions of the values of standard deviation and median obtained by sampling the distribution reported in panel a, 10, 30 and 50 times, respectively. The red boxes provide the 95% confidence intervals for mode, median and standard deviation.

**Figure 8:** a) Distribution of ages characterised by a mode of 50 ky, a median of 80 ky and a standard deviation of 60 ky. b, d, f) Each black point in the panels shows the values of mode, median and standard deviation obtained by bootstrapping of the population of zircon crystallisation times represented in panel a. Distributions of the values of mode and median obtained by sampling the distribution reported in panel a, 10, 30 and 50 times, respectively. The procedure has been repeated 10,000 times for each subsample of 10, 30 and 50 ages. c, e, g) Distributions of the values of standard
deviation and median obtained by sampling the distribution reported in panel a, 10, 30 and 50 times, respectively. The red boxes provide the 95% confidence intervals for mode, median and standard deviation.

**Figure 9:** Distribution of zircon age population for the S. Francesco facies of the Mt. Capanne pluton from Barboni et al. (2015).

**Figure 10:** a) Distribution of zircon crystallisation times for the S. Andrea facies from Barboni et al. (2015), b) Distribution of zircon crystallisation times for the S. Andrea facies from Barboni and Schoene (2014), c) Distribution of crystallisation times reported by Barboni et al. (2015) for all intrusions of Elba Island.

**Figure 11:** The lines represent the 95% confidence interval for mode, median and standard deviation obtained by bootstrapping the populations of zircon crystallisation times presented in Figure 10 panel a and b, respectively. The coloured areas provide the estimated volume and magma flux obtained applying the method presented in this contribution. Estimates were obtained by considering a zircon crystallisation between 700 and 750°C. Using different zircon crystallisation ranges would not change the final estimates as contours in Figure 6 for different $T_{rz}$ are very similar.
Table 1: Statistical parameters obtained for the different injected volumes, injection fluxes, and ranges of zircon saturation temperature

<table>
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<tr>
<th>T zircon saturation 700-750</th>
</tr>
</thead>
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</tr>
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<td>(km^3/yr)</td>
</tr>
<tr>
<td>B36</td>
</tr>
<tr>
<td>B39</td>
</tr>
<tr>
<td>B40</td>
</tr>
<tr>
<td>B41</td>
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<td>B42</td>
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<tr>
<td>B57</td>
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<td>B44</td>
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<td>B58</td>
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<td>B59</td>
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<td>B46</td>
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<td>B48</td>
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<td>B46</td>
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<td>B44</td>
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Table 1 (continued): T zircon saturation 700-800

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<th>Log10 Volume</th>
<th>Log10 Injection duration</th>
<th>Log10 Mean</th>
<th>Log10 Mode</th>
<th>Log10 Median</th>
<th>Log10 Std. dev.</th>
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Table 1 (continued): T zircon saturation 700-850

<table>
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<th>Log$_p$ Diam.</th>
<th>Log$_p$ Volume</th>
<th>Log$_p$ Injection duration</th>
<th>Log$_p$ Mean</th>
<th>Log$_p$ Mode</th>
<th>Log$_p$ Median</th>
<th>Log$_p$ Std. dev.</th>
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<td>3.00</td>
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-1: normally growing cylindrical pluton, v: vertically growing cylindrical pluton. The results in italic were not used for the contouring in Figure 6.

Table 2: Values obtained by the bootstrapping of the zircon age populations of Barboni et al., (2015).

<table>
<thead>
<tr>
<th>Name Unit</th>
<th>No. zircons</th>
<th>No. replicated populations</th>
<th>Mode (ky)</th>
<th>Median (ky)</th>
<th>St. Deviation (ky)</th>
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</thead>
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<tr>
<td>S. Andrea in megacrystals</td>
<td>90</td>
<td>1000</td>
<td>145-385</td>
<td>380-350</td>
<td>70-105</td>
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<tr>
<td>S. Andrea</td>
<td>18</td>
<td>1000</td>
<td>60-180</td>
<td>80-170</td>
<td>55-85</td>
</tr>
</tbody>
</table>
Figure 1
Figure 2

Magma flux (km$^3$/y) = 0.01
Final magma Volume (km$^3$) = 1000

Magma flux (km$^3$/y) = 0.001
Final magma Volume (km$^3$) = 1000

End of magma injection

Vol. fraction vs. Time (kyr)

- below solidus
- 700-750
- 750-800
- 800-850
- 850-900
- 900-950
- 950-1000

Figure 2
Figure 3

(a) Low magma flux, small final volume
    End of magma injection

(b) High magma flux, large final volume
    range of zircon saturation T
Figure 4

(a) Magma flux (km$^3$/y) = 0.01
Final Volume (km$^3$) = 1000
No. zircons

(b) Magma flux (km$^3$/y) = 0.001
Final Volume (km$^3$) = 1000

(c) Magma flux (km$^3$/y) = 0.01
(km$^3$) = 500

(d) Magma flux (km$^3$/y) = 0.001
(km$^3$) = 500
Figure 5

Zircon saturation range
700-750 °C

Zircon saturation range
700-800 °C

Zircon saturation range
700-850 °C

Relative number of zircons

Time (ky)
Figure 6: Contour maps showing the relationship between mode, median, standard deviation, volume, and flux for different temperature ranges. The plots are for temperature ranges of 700-750 °C, 700-800 °C, and 700-850 °C.
Figure 8

(a) zeigt eine Histogramm-Darstellung der Altersverteilung über 400.000 Jahre. Die X-Achse repräsentiert das Alter in 100.000-jährigen Intervallen, und die Y-Achse die Häufigkeit.

(b) bis (g) zeigen Scatterplots für unterschiedliche Altersintervalle von 10, 30 und 50 Jahren. Die X-Achse steht für die Medianalter, die Y-Achse für die Modusalter. Die roten Quadrate markieren die Median, die schwarzen Punkte die Modalwerte.
S. Francesco facies
(Total No. zircons=27)

Age (Ma)

Figure 9
Figure 10

S. Andrea facies
(Total No. zircons=18)

(a)

S. Andrea facies
(Total No. zircons=90)

(b)

All intrusions
(Total No. zircons=142)

(c)

Time (ky)
Figure 11

(a) Mode
Median
St. dev.

Zircons in matrix
S. Andrea facies
(Barboni et al., 2014)
(Total No. zircons=18)

(b)

Zircons in megacrystals
S. Andrea (Barboni et al., 2014)
(Total No. zircons=90)