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# WHERE RADIOACTIVE ISOTOPES MEET DIFFUSION: TIME SCALES OF IGNEOUS PROCESSES FROM PLUTONIC OR VOLCANIC CRYSTALS.

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## INTRODUCTION

In the last 10 to 15 years there has been a major advance in igneous petrology because we have been able to determine the duration and rates of magmatic processes with an unprecedented level of precision, age range, and spatial resolution. In this presentation we briefly outline the approach and results of using the diffusion equation to the rates of magmatic processes of volcanic and plutonic rocks. We combine these with results of age determinations from radioactive isotope clocks mainly obtained from crystals. The intention is to establish if there is a contrast between the time information using different approaches, and if magmatic processes at volcanic and plutonic systems operate at the same rates or not.

## THE DIFFUSION EQUATION TO RETRIEVE TIME SCALES OF IGNEOUS PROCESSES

One of the main differences between volcanic and plutonics rocks is their temperature-time path since begining of crystallization till solidification. This is very important to take into account when modeling the zoning patterns of crystals or when obatining ages from plutons. The two cases a treated below.

### The isothermal case: volcanic rocks

In volcanic rocks the cooling rate from magmatic to room temperature is very fast, and one can safely assume a single temperature in the model. Although it is rather common that mineral zoning patterns record multiple thermal pulses (e.g., Singer et al., 1995), if they vary within an intermediate value without a trend, the time retrieved from this intermediate temperature is the same as that from a model with thermal oscillations (e.g. Lasaga, 1998). For an isothermal case we can use a second Fick's law (1 dimension, D independent of C or x):

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

where C = concentration, D = diffusion coefficient, x = distance, and t = time. We can use constant initial and boundary conditions, although variations at the boundary with time were reported in volcanic rocks (e.g., Costa and Chakraborty, 2004).

### A cooling history: the case of plutonic rocks

If the plutonic rocks have experienced a prolonged thermal history we need to consider that D is dependent on T. Since T varies with t, we have a dependence of D on t. e.g., D(t) = Do exp [E/RT(t)], with Do = pre-exponential factor, E= activation energy, R= gas constant. It is common that the composition at the boundary changes with T and t, and we need to also introduce this in the model (e.g., Lasaga, 1998).

### Closure temperatures and profiles: where radioactive isotopes meet diffusion

A more interesting case is the relation between the times obtained from radiogenic isotope clocks and those from diffusion. These are clearly related with the notion of closure temperature, which quantifies the extent that a radioactive system has been closed to exchange (via diffusion) with the environment. The initial formulation by Dodson (1973) has been improved recently by more general models (Ganguly and Tirone, 2001) but still using a single cooling rate. Alternatively we can calculate a closure temperature profile using a variable cooling rate with a modified diffusion equation of the form:

$$\frac{\partial C_{DA}}{\partial t} = D(t)_{DA} \frac{\partial^2 C_{DA}}{\partial x^2} + \lambda \text{ No} \exp(-\lambda t)$$

where the subscript DA = daughter isotope, lambda = decay constant, No = number of radioactive parents at t = 0.

## TIME SCALES OF IGNEOUS PROCESSES

### The volcanic perspective

The diffusion equation has been mostly applied to open system processes. For example, magma mixing in the reservoir may occur in days to several decades prior to eruption (see Fig.1 and references therein), similar to the times obtained for magmatic assimilation (1 to 200 years). The remobilization of completely or partially crystallized rocks to yield silicic eruptions can happen in 10 to 5000 years. The time information about magma differentiation is limited, and has been modelled to be much longer than previous processes, *ca.* 100 ky for a large silicic magma.

The process durations of a decade to a few ky are shorter than those obtained from in situ dating of accessory minerals. For example, the residence times and perhaps differentiation of many large volume (> 50 to 5000 km$^3$) silicic magmas varies between 10 to 400 ky (Fig. 1). Thus it appears that for differentiation times both approaches give coherent results. The discrepancy in the short time range might have several sources and interpretations. The phenocrysts used in dating could be recycled from older parts of the system. In this context it is worth noting that the whole rock decreases in Ra/Th with increasing SiO$_2$ (or Th ppm) give time scales of differentiation of few ky which is in good agreement with estimates from thermal models for cooling of magmas in the mid crust (e.g. George et al., 2004). These are maxima especially if assimilation processes are involved and if two end-member mixing occurs, differentiation could be effectively instantaneous. Older U-Th mineral ages (which often conflict with the presence of Ra disequilibria) probably reflect cumulate recycling (e.g. Turner et al. 2003).

### The plutonic perspective

Most determinations of time scales from plutons are not approached within the same framework as those of volcanic rocks. They typically involve the growth or cooling histories of large complexes rather than a single and small pluton of comparable size to the 1-100 km$^3$ of most eruptions. Despite the abundant evidence for major and trace element zoning patterns in 'plutonic' crystals, only a few applications have been done of the diffusion equation without involving radioactive dating (Fig. 1). The available data for melt migration and reaction in cumulates or the times for assimilation vary between a few decades to a few ky, although the entire magmatic history recorded in garnets can be as long as 10 My.

Far more data has been obtained using U-Pb, K-Ar and Rb-Sr systems and various minerals. Plutonic complexes of 5-1000 * 10$^2$ km$^3$ require magmatism than spans between 0.3 and 50 My and leads to average magma emplacement rates of 0.01 to 0.001 km$^3$/y (Fig. 1). In general, smaller bodies have shorter emplacement times but comparable emplacement rates. Cooling rate estimates derived from the ages of minerals with different closure temperatures lead to maximum values on the order of $2*10^{-3}$ to $1*10^{-5}$ $^{o}$C/y, the faster cooling rates corresponding to smaller bodies. The time constrains above on the order of several My are longer than any yet reported but should be taken only as maximum. Moreover they also include all magmatic processes involved, from fractional crystallization to mixing, and assimilation.

## CONCLUSIONS

The information presented above leads to the following observations regarding the approaches to obtain time scales and the rates at volcanic and plutonic systems:

**(1)** Time scales recorded from diffusion studies tend to be shorter than those recorded using radioactive dating of crystals. This includes volcanic and plutonic systems. This can be in some cases due to the presence of old xenocrysts; it may also reflect that the diffusion times are only recording the duration of one event which is part of a much more prolonged magmatic evolution involving multiple histories (e.g., many intrusive episodes).

**(2)** It is apparent from Figure 1 that more determinations of the duration of processes in plutons using diffusion methods are desirable. The span of time scales from volcanic rocks overlaps with their plutonic counterparts in the range of decades to thousand of years. However, volcanic rocks record times as short as a few weeks and plutonic may extend to My. These longer times for the formation of a pluton may reflect the integrated effect of multiple processes as determined from single volcanic (small) eruptions.

**(3)** There might be a difference in time scales depending on the size of the system or on the chemistry which seems to be independent whether it is a plutonic or volcanic system. Large systems seem to take longer to develop as could be expected if magma generation rates are the same as for small systems. This is suggested by the more similar residence and emplacement times of large eruptions and plutons. The different physics of silicic and mafic magmas (e.g., viscosities and associated diffusion, nucleation and growth rates) might also lead to differences in time scales, something that needs to be tested with more data.

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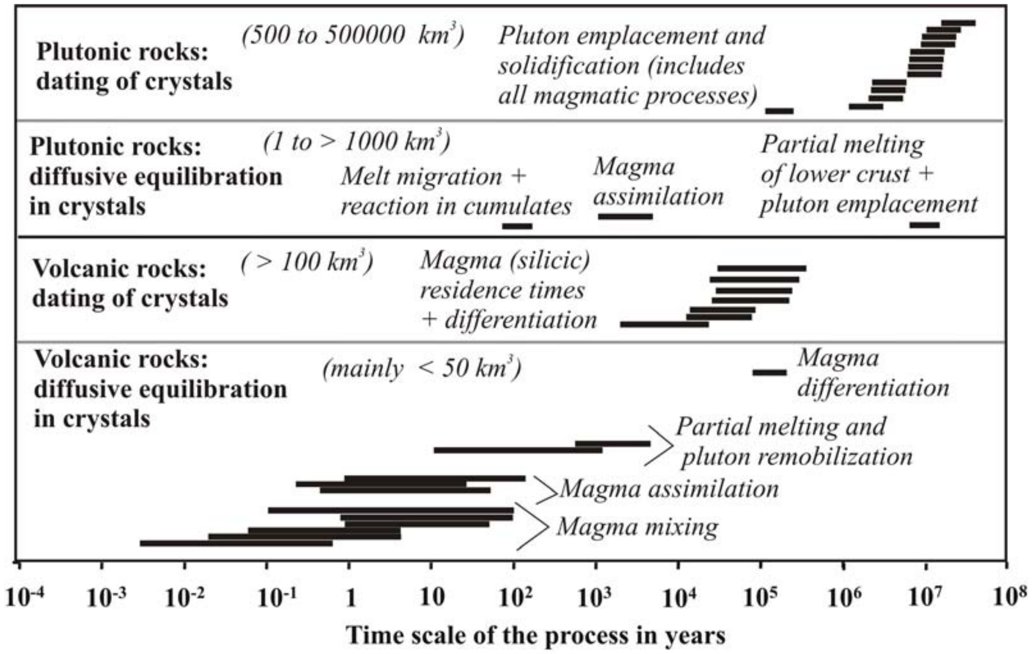

**Figure 1**

**Data sources**

*Volcanic rocks:* Bindeman and Valley, 2001; Bindeman et al., 2001; Charlier et al., 2003 and 2005; Chertkoff and Gardner, 2004; Coombs et al. 2000; Costa and Chakraborty, 2004; Costa and Dungan 2005; Morgan and Blake, 2006; Nakamura, 1995; Oberli et al., 2002; Simon and Reid, 2005; Vazquez and Reid, 2002 and 2004; Wolff et al., 2002; Zellmer et al., 1999 and 2003.

*Plutonic rocks:* Amelin et al., 1997; Coleman et al., 2004; Costa et al., 2003*;* Long et al., 2005; Maurel et al., 2004; Oberli et al., 2004, Schmitt et al., 2003; Tepley and Davidson, 2003*;* Vielzeuf et al., 2005;