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RESEARCH ARTICLE

M. Petrelli · D. Perugini · G. Poli

Time-scales of hybridisation of magmatic enclaves in regular and chaotic flow fields: petrologic and volcanologic implications

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Abstract This paper describes numerical models of advection/diffusion between enclaves and host magmas, applied with the aim of estimating time-scales during which enclaves can be homogenised. In particular, advection was simulated using a numerical system consisting of regular and chaotic regions. Results indicate that the homogenisation time of enclaves in chaotic regions is several orders of magnitude faster than in regular regions. For instance, an enclave with a diameter of 100 cm may be homogenised in the chaotic region in $\sim$ 380 years, assuming an advection velocity of 10 cm/year, whereas in the regular region it would require 6.5×10^5 years for complete homogenisation. This implies that, in the same magmatic system, large differences in the degree of homogenisation may co-exist, generating magmatic masses with large spatial and temporal inhomogeneities.

The results of this study may have significant petrological and volcanological implications. From a petrological point of view, mafic enclaves dispersed in felsic host rocks are regarded as portions of mafic magma which, trapped inside regular regions, survived the hybridisation process. Instead, host rocks are regarded as regions where efficient mixing dynamics generated hybrid magmas. The fact that a single magmatic mass may display large compositional differences at the same time undermines the assumption of most geochemical models, which assume the temporal and spatial homogeneity of the magma body. From the volcanological perspective, the presence of magmatic enclaves in volcanic rocks allows us to estimate the mixing times of magmas by analysing chemical diffusion patterns between host rocks and enclaves.

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M. Petrelli · D. Perugini (✉) · G. Poli
Department of Earth Sciences, University of Perugia,
Piazza Università 1,
06100 Perugia, Italy
e-mail: diegop@unipg.it
Tel.: +39-075-585-2652
Fax: +39-075-585-2603

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Introduction

Magma mixing has been extensively recognised and studied in both plutonic and volcanic environments (e.g. Bacon 1986; Koyaguchi and Blake 1989; Williams and Tobish 1994; Bateman 1995; De Rosa et al. 1996; Snyder and Tait 1996; Perugini et al. 2002; Perugini et al. 2003) and is considered to be one of the most important petrogenetic and volcanological processes (e.g. Poli et al. 1996; Thomas and Tait 1997; Venezky and Rutherford 1997; Blake and Fink 2000; Takeuchi and Nakamura 2001; Bryan et al. 2002; Leonard et al. 2002; Perugini et al. 2004). The ability of two magmas to mix depends on a large number of parameters such as temperature, chemical composition, and degree of crystallinity of end-members which, ultimately, influence their relative rheologies and, hence, the rate of dispersion and degree of chemical exchanges (e.g. Sparks and Marshall 1986; Poli et al. 1996; Jellinek and Kerr 1999). All these parameters are non-linearly coupled, making magma mixing an extremely complex dynamic system in continuous evolution in space and time (e.g. Flinders and Clemens 1996; Perugini et al. 2002).

Although in the last two decades many papers have been published on both the chemical and physical features of magma mixing (e.g. Oldenburg et al. 1989; Poli and Tommasini 1991; Williams and Tobish 1994; Bateman 1995; Cioni et al. 1995; Poli et al. 1996; Snyder and Tait 1996; Weinberg and Leitch 1998), several aspects of this process are still unclear, and one of the most important relates to the time during which efficient magma mixing can occur. Surprisingly, although this aspect is crucial in constraining petrological, geochemical and volcanological modelling of magma mixing, only a few papers have been devoted to its investigation (e.g. Oldenburg et al. 1989; Baker 1990; Grasset and Albarede 1994; Lesher 1994).

One of the most common indications of magma mixing is the occurrence of igneous rocks bearing magmatic enclaves with contrasting composition with respect to the host rock (e.g. Didier and Barbarin 1991; Poli and Tommasini 1991). In most cases, enclaves are thought to be the result of initial pillowing of mafic into felsic magma, and this interpretation is supported by the fact that, in several outcrops where the intrusion of mafic into felsic magma is fossilised in the initial stages, the former is disaggregated into rounded enclaves (e.g. Wiebe 1993; Wiebe et al. 2001). For these reasons, magmatic enclaves are believed to be the starting points of magma mixing processes and have been the subject of some research, mostly by numerical modelling, to constrain the possible time-scales of hybridisation of these blobs of mafic magma with their felsic host (e.g. Baker 1990; Lesher 1994; Grasset and Albarede 1994).

Existing numerical models applied to simulate hybridisation of mafic enclaves with felsic host magmas can be grouped into two main categories: i) those considering static diffusion between enclaves and host magma (e.g. Baker 1990; Lesher 1994); ii) those considering deterministic dynamic models, such as convective dispersion of the mafic magma into the felsic one (e.g. Oldenburg et al. 1989) or infiltration and subsequent advection of felsic into mafic magma (e.g. Weinberg and Leitch 1998; Grasset and Albarede 1994). Although these approaches have greatly contributed towards shedding light on the complex processes occurring during magma homogenisation, they both have several drawbacks. In particular, magma mixing systems have been recognised as dynamic systems with complex evolution in space and time (e.g. Flinders and Clemens 1996; Perugini et al. 2003) and, hence, static diffusion modelling can only be applied in very specific conditions (see below). Dynamic simulations are based on deterministic models and rarely apply to magmatic systems in which the fingerprints of chaotic dynamics have been well documented (e.g. Flinders and Clemens 1996; De Rosa et al. 2002; Poli and Perugini 2002; Perugini et al. 2003).

In this contribution, we report the results of numerical simulations of the dispersion of magmatic enclaves into a compositionally different magma in the magma chamber, using models of coupled chaotic advection and diffusion with the aim of estimating the time-scales over which hybridisation of magmas can occur. The possibility of generating large volumes of hybrid magmas is discussed by comparing estimated hybridisation time-scales with the typical lifetimes of magma chambers. We also propose a method of estimating mixing time-scales by analysing chemical transects passing from enclaves to host rocks in volcanic systems.

Numerical simulation of magma mixing

We modeled the magma mixing process using the solution of the advection/diffusion equation (e.g. Oldenburg et al. 1989; Grasset and Albarede 1994):

$$\frac{\partial C(x,y,t)}{\partial t} = D \cdot \nabla^2 C(x,y,t) + v(x,y,t) \cdot \nabla C(x,y,t) \quad (1)$$

where $C(x, y, t)$ is the chemical concentration field in the 2D (x, y) space domain at time t, D is the chemical diffusion coefficient, $v(x, y, t)$ is the velocity field, and terms ∇ and ∇^2 are expressed as:

$$\nabla^2 = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) \quad (2)$$

$$\nabla = \left(\frac{\partial}{\partial x} + \frac{\partial}{\partial y}\right) \quad (3)$$

The first term on the right side of Eq. (1) describes the diffusion process and the second term regards advection. 'Advection' means the process moving a certain amount of fluid from one location to another by the action of flow fields (e.g. Aref and El Naschie 1995; see below). In the models, both magmas are assumed to be above their liquidus temperature and the effect of crystals is therefore neglected. In this respect, the temperature range of applicability of our system may vary, depending on the composition of end-member magmas, and may range from 900 to 950°C in the case of mixing between felsic magmas (e.g. dacite and rhyolite) up to 1,300°C in that between felsic and mafic magmas (e.g. basalt and dacite). However, as shown by Frost and Mahood (1987), in order to keep both magmas above their liquidus temperatures, a sufficient amount of high-temperature mafic magma is required. For instance, Frost and Mahood (1987) indicate that the amount of mafic magma should exceed ~50–60% of the system in mafic-felsic magma mixing, although this value may be lower in the case of mixing between felsic magmas in which the temperature difference is lower.

Magmas are assumed to have similar rheologies but different chemical compositions (see below for more details on this point). In addition, the presented models are intended to simulate laminar mixing between incompressible magmas in a high-pressure magma chamber, so that the effect of magma vesiculation may be neglected.

In order to obtain a model free from dimensional constrains, we make all parameters dimensionless using the following scaling relationships:

$$\hat{C}(x,y,t) = \frac{C(x,y,t) - C_{\text{enclave}}(x,y,t)}{C_{\text{host}}(x,y,t) - C_{\text{enclave}}(x,y,t)}$$

$$\hat{x} = \frac{x}{a};\ \hat{y} = \frac{y}{a};\ \hat{v} = \frac{va}{D};\ \hat{T} = \frac{T \cdot D}{a^2}$$

$$Pe = \frac{v_{\max} \cdot a}{D};\ \widehat{\text{HT}} = \frac{HT \cdot D}{a^2} \quad (4)$$

where C_{enclave} and C_{host} are the original concentrations of a chemical element in mafic and felsic magmas, respectively, v_{max} is the reference maximum velocity attainable by the system, a is the diameter of the enclave, and T is physical time. In addition, Pe is the Peclet number and $\widehat{\mathrm{HT}}$ is the dimensionless homogenisation time (see below for a detailed definition of homogenisation time).

The numerical solution of Eq. (1) is obtained using a semi-Lagrangian approach. According to Staniforth and Coté (1991), using semi-Lagrangian schemes overcomes the problem of the introduction of unwanted length scales and reduces the time step restriction encountered when using Eulerian schemes. More details on the advantages of the semi-Lagrangian approach to solve advection/diffusion problems can be found in Staniforth and Coté (1991). The advection and diffusion terms were solved by the Matlab software package using a 4th-order Runge-Kutta solver (e.g. Albarede 1995) and an implicit alternating direction (ADI) finite difference method (Press et al. 1990), respectively.

The advection term in Eq. (1) is modelled using a chaotic dynamic system known as the sine-flow (e.g. Liu et al. 1994; Clifford et al. 1999). It is defined by two motions:

$$\begin{aligned}(\hat{v}_x,\hat{v}_y) &= (\sin 2\pi y, 0), \quad 2nk \le \hat{T} < (2n+1)k \\ (\hat{v}_x,\hat{v}_y) &= (0, \sin 2\pi x), \quad (2n+1)k \le \hat{T} < (2n+2)k\end{aligned} \tag{5}$$

where $\hat{v}_x$an $\hat{v}_y$ are the component of the velocity field in directions x and y, respectively, k is half the flow period, n is the number of periods, and $\hat{T}$ is time. The flow is defined on a 2D torus, meaning that whenever a particle exits the unit square, it re-enters the box through the opposite side. This flow scheme induces the dispersion of one magma into the other by stretching and folding, and is composed of regular and chaotic regions in which mixing occurs at different intensities. Stretching and folding are non-linearly coupled processes and are the prerequisites for chaotic behaviour (e.g. Ottino 1989; Muzzio et al. 1992; Liu et al. 1994; Aref and El Naschie 1995). Stretching induces elongation of fluids, whereas folding bends and redistributes them through the mixing system.

Several authors have demonstrated that the sine-flow scheme reproduces with very good approximation the morphological structures observed in real mixing systems, independently of the geometries in which the process occurs (e.g. Liu et al. 1994; Ott and Antonsen 1989). In particular, it clearly reproduces structures generated by magma mixing (e.g. Perugini et al. 2003). Sine-flow is suitable for simulating laminar mixing between newtonian fluids having similar rheology (e.g. Liu et al. 1994; Perugini et al. 2003) and, in this respect, its applicability to magmatic systems is worth discussing. A great number of works indicate that magmas can mix efficiently only when their rheologies are similar (e.g. Sparks and Marshall 1986; Grasset and Albarede 1994; Bateman 1995; Poli et al. 1996) and these physical conditions occur when: (i) magmas have similar rheology from the beginning of the interaction process, and (ii) different magmas achieve similar rheology in response to evolutionary processes (e.g. Sparks and Marshall 1986; Poli et al. 1996). Since our interest here was on efficient mixing of magmas, we focused attention on magmatic systems in which end-members magmas have similar rheologies. This does not imply that the two magmas have the same chemical composition. In fact, it has been shown experimentally that compositionally different magmas (e.g. basalts and dacites) can attain similar rheologies and hence mix, as the thermal contrasts between the two are smoothed but still retain their different geochemical compositions (e.g. Kouchi and Sunagawa 1983; Kouchi and Sunagawa 1985).

The sine-flow dynamic system requires the choice of a suitable value for parameter k. As reported above, k is half the flow period and its value regulates the relative amount of system area covered by regular and chaotic regions (e.g. Liu et al. 1994; Perugini et al. 2003). In particular, increasing k values correspond to decreasing size of regular regions and increasing size of chaotic ones (e.g. Liu et al. 1994; Perugini et al. 2003). Since larger chaotic regions correspond to higher mixing efficiencies, k is thus a parameter which regulates the intensity of mixing. Comparing natural occurrences and numerical simulations, Perugini and Poli (2004) suggested that k values of 0.3-0.4 are suitable for magmatic systems; accordingly, $k = 0.4$ was used in the simulations reported here. For this value, chaotic regions in which magmas undergo efficient stretching and folding (dotted areas in Fig. 1A) co-exist with regular regions (close orbits in Fig. 1A) in which these processes are inefficient. These features of the flow can be better appreciated in Fig. 1B–F. Fig. 1B shows a regular grid placed over the domain of the flow and Fig. 1C its deformation due to the action of the flow. Cells in chaotic regions are strongly deformed, but those in regular regions are far less so. This effect is also shown in Fig. 1D and E, illustrating the deformation of circular enclaves. After some time, enclaves in the chaotic region undergo extensive stretching and folding, generating lamellar structures, whereas those in the regular region show very little deformation and preserve their circular morphology. Figure 1F shows the increase in contact interfaces between the host magma and two enclaves in the chaotic and regular regions, respectively. In the regular region, the contact interface does not vary in time, but it increases exponentially in the chaotic one.

In chaotic regions, the stretching and folding dynamics undergone by magmas greatly influence the development of chemical diffusion processes, because large interfacial areas are generated. Therefore, hybridisation times for enclaves in chaotic regions must be estimated using the advection/diffusion numerical model (Eq. (1)). Instead, for enclaves in regular regions, chemical diffusion is the only process leading to hybridisation, and hybridisation times can be estimated by applying the static diffusion equation for circular morphology (e.g. Crank 1975).

In the advection/diffusion simulations, the initial configuration is represented by a square domain with characteristic length L filled by a felsic host magma; a circular blob of mafic magma with diameter a is positioned in the chaotic region (see Fig. 2A). As discussed above, the decision to

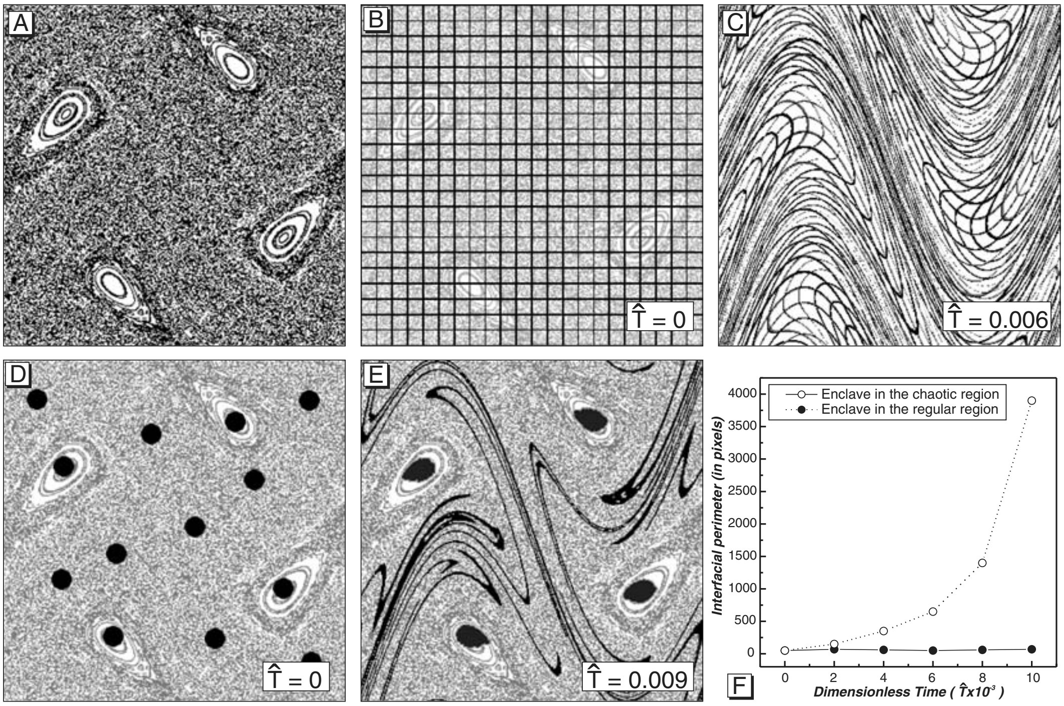


Fig. 1 **A** Poincaré section of sine-flow dynamic system for k=0.4; **B** regular grid positioned over domain of sine-flow; **C** deformation of grid in (**B**) by action of sine-flow; **D** circular enclaves of mafic magma positioned in different dynamic regions constituting domain of sine-flow; **E** deformation of circular enclaves in (**D**) by action of sine-flow; **F** variations in time of contact interface of two enclaves placed initially in chaotic and regular regions of sine-flow, respectively (from Perugini et al. 2003)

use a circular enclave was dictated by the observation that the most poorly mingled magmas (i.e. in which the process has been "frozen" in its initial stages) are characterised by rounded enclaves of mafic magma in a more felsic host (e.g. Bacon 1986; Blake and Fink 2000; Wiebe et al. 2001).

Simulations were performed at varying a/L ratios, in order to investigate the influence of this parameter on the results. In particular, a/L values of 0.1, 0.2 and 0.3 were examined.

To quantify the degree of hybridisation of the mixing system, we used a parameter known as "intensity of segregation" (*IS*; e.g. Oldenburg et al. 1989) defined as:

$$\mathrm{IS} = \frac{\sigma^2}{\sigma_0^2} \tag{6}$$

where σ^2 is the variance of composition calculated within the entire space domain at time T, and $\sigma_0{}^2$ is the variance of the system at $T = 0$. At $T = 0$, i.e. in the absence of diffusion, *IS* is 1.0, meaning that the two magmas still maintain their original composition. With the passing of time, chemical diffusion acts and *IS* diminishes progressively, tending to zero. The criterion used for terminating a simulation was that variance σ^2 of the composition field was less than 0.001; this threshold value was chosen as differences in composition are barely detectable below this value. Since $\sigma_0{}^2$ varies with varying a/L, hybridisation is achieved when *IS* falls below 0.015 for $a/L = 0.3$, 0.033 for $a/L = 0.2$ and

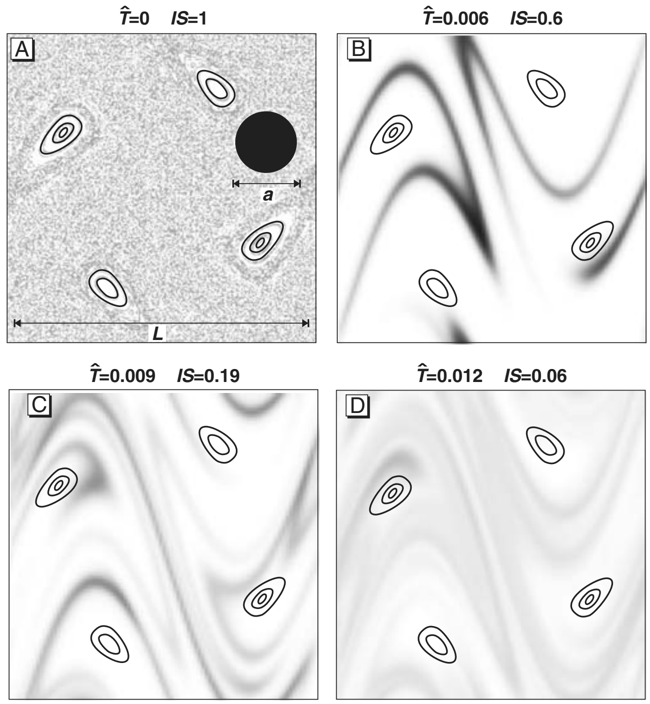


Fig. 2 **A** Initial configuration of magma mixing system; **B–D** dispersion of enclave in (**A**) by action of chaotic advection/diffusion system. System parameters are: $Pe = 100$ and $a/L = 0.2$ $\hat{T}$ and *IS* values reported above each picture

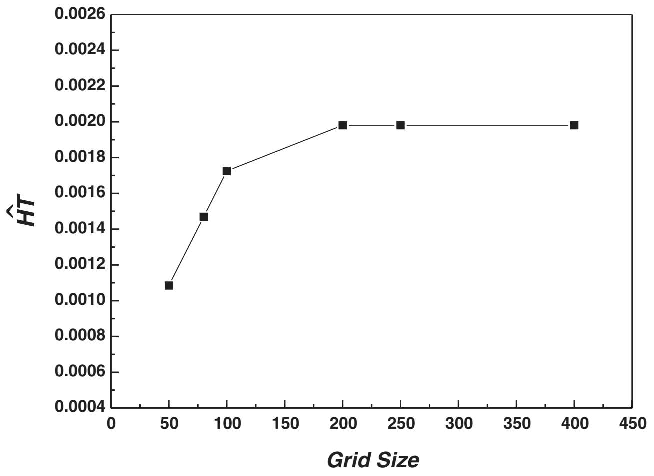


Fig. 3 Variations in $\widehat{\text{HT}}$ against grid size, showing saturation of $\widehat{\text{HT}}$ values for grids over 200×200 resolution

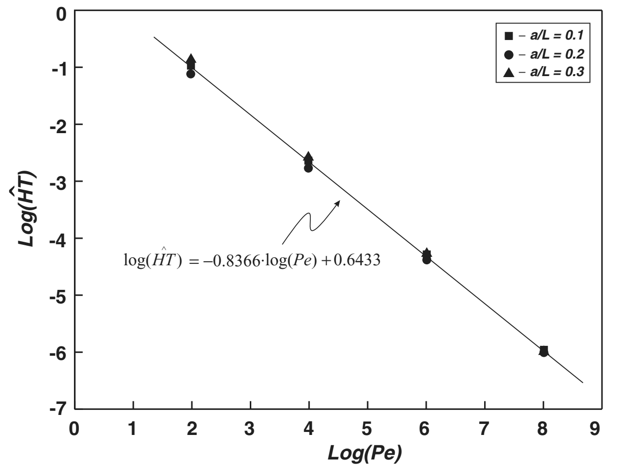


Fig. 4 Variations in Log($\widehat{\text{HT}}$) against Log(Pe) for advection/diffusion numerical simulations with different a/L ratios. Also shown: equation of best fit ($r^2 = 0.99$)

0.13 $a/L = 0.1$; the time at which this occurs is considered as the homogenisation time ($\widehat{\text{HT}}$).

Tests were performed in order to select the optimal grid resolution for simulations. $\widehat{\text{HT}}$ was estimated by performing simulations with resolutions ranging from 50×50 to 400×400, in a system with $a/L = 0.2$ and $Pe = 10^4$. Figure 3 shows the variation of $\widehat{\text{HT}}$ with increasing grid resolution, and indicates that, above a 200 × 200 mesh grid, results converge towards constant values of $\widehat{\text{HT}}$. Accordingly, simulations were performed at a resolution of 250 × 250.

Figure 2 B–D show some typical outcomes of the numerical simulation of the chaotic advection/diffusion dynamic system. As mixing time increases (Fig.2 B–D), the original enclave is progressively deformed by the action of the flow field and, at the same time the whole system becomes progressively blurred because of chemical diffusion. With the passing of time, *IS* gradually decreases until it falls below the threshold value.

Figure 4 displays the variation of Log($\widehat{\text{HT}}$) vs. Log(Pe). A good linear ($r^2 = 0.99$) negative correlation exists between these two parameters, indicating that increasing Pe corresponds to strongly decreasing $\widehat{\text{HT}}$. The graph also shows that all experiments performed with various a/L ratios plot along the same linear trend (Fig. 4), indicating that that $\widehat{\text{HT}}$ values are not influenced by this parameter. This is because the enclave is positioned in the chaotic region, where the stretching field propagates uniformly at all length scales and hence, on average, fluid volumes of different size undergo the same amount of stretching. In order to illustrate this occurrence, we calculated the stretching field within the sine-flow system, following the variation in length of an infinitesimal vector **I** as it is advected by the flow (see Liu et al. 1994 for details). This variation is given by:

$$\frac{d\mathbf{I}}{dt} = (\nabla \mathbf{v}) \cdot \mathbf{I}, \quad \mathbf{I} = \mathbf{I_0} \quad \text{at} \quad t = 0 \tag{7}$$

The stretching undergone by the vector is defined as $\lambda = \mathbf{I}/\mathbf{I}_0$ (Liu et al. 1994). λ is calculated by considering a set of 62500 initial vectors located on each point of the 250×250 grid after 25 periods of the flow. Figure 5A shows the calculated stretching field. As expected, high rates characterise chaotic regions and low ones are typical of regular regions. Focusing on the chaotic region, the probability density functions of stretching were reconstructed for the whole chaotic region and for those regions occupied by enclaves, in systems with differing a/L ratios (Fig. 5B). The distribution of the stretching rate is essentially the same for both the whole chaotic region and for those sub-regions occupied by enclaves, indicating that the degree of deformation undergone by an enclave is on average the same in any portion of that region. Therefore, two enclaves in systems with the same Pe but different a/L ratio will undergo the same amount of stretching, producing the same result in terms of $\widehat{\text{HT}}$. This explains why all experiments plot exactly along the same trend in the log($\widehat{\text{HT}}$) vs. log(Pe) diagram (Fig. 4).

Magma mixing time-scales in regular and chaotic regions in magma chamber

In this section, we apply the results from dimensionless analysis to possible real case studies, in order to examine the time-scales during which magma hybridisation can occur, assuming that the mixing process takes place in a magma chamber. In particular, by constraining values of a, v_{max} and D, the relationship between Pe and $\widehat{\text{HT}}$ is used to estimate the time required to mix an enclave (HT) within a host magma in a chaotic flow field. Results are compared with time-scales of hybridisation of enclaves in regular regions.

Since our interest was on estimating the time required to reach complete hybridisation between magmas, we focused attention on those chemical elements having the slowest diffusion coefficients (D). In fact, complete hybridisation can be achieved only when chemical gradients, even for the slowest elements, are smoothed. As one of the slowest

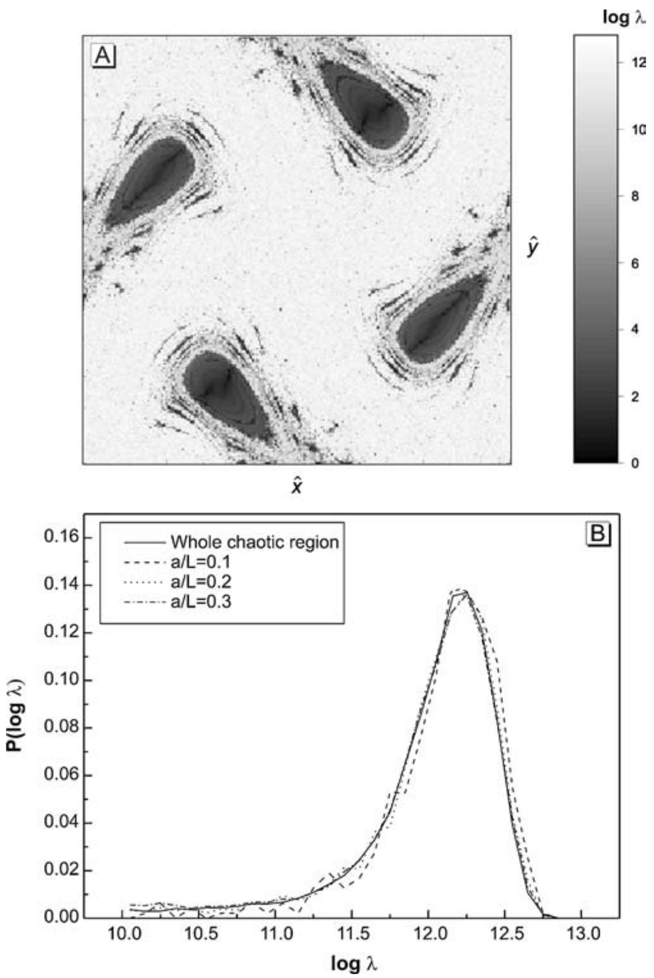


Fig. 5 **A** Stretching field calculated for sine-flow system after 25 periods; differing *grey shades* correspond to different stretching values (see *colour bar*); **B** probability density functions of stretching reconstructed for whole chaotic region and for regions occupied by enclaves in systems with differing a/L ratios

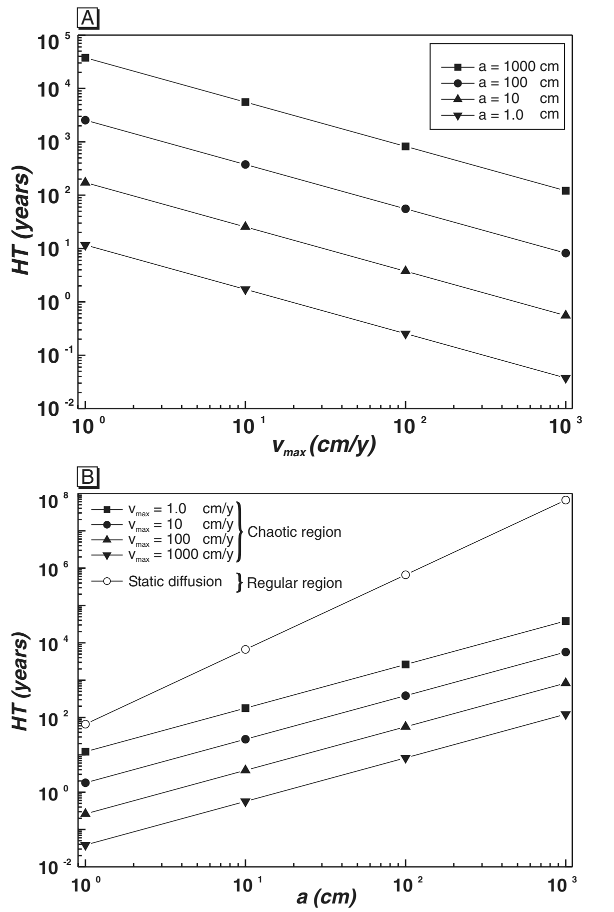


Fig. 6 **A** Variations in *HT* (in years) against $v_{\max}$ (in cm/year) for enclaves with different diameters (a); **B** variations in *HT* against a for enclaves in chaotic region at different v_{max} values and for an enclave in regular region

elements is Si (or Al) ($D\sim 1\times 10^{-14}$ m^2/s; Baker 1990), models are presented with this D value.

We first examined the role of advection velocities ($v_{\max}$) on homogenisation time (*HT*) for enclaves in the chaotic region. For this purpose, magmatic enclaves with different diameters (a), ranging from 1 to 1,000 cm, were considered. According to Williams and Tobisch (1994), typical flow velocities in magma chambers are below 10^3 cm/year in enclave-bearing plutonic systems; therefore, hybridisation times (*HT*) were estimated by considering $v_{\max}$ from 1.0 to 10^3 cm/year. Figure 6A shows variations in *HT* against $v_{\max}$ for different diameters a of the enclave. There is a negative linear relationship between *HT* and $v_{\max}$, indicating that increasing advection velocities dramatically reduce the hybridisation time, despite the very low values of diffusion coefficients for chemical elements in magmas. This is because of the very efficient stretching dynamics undergone by enclaves in the chaotic region which continuously generate new interfacial areas between magmas (Fig. 2F), through which chemical diffusion acts very quickly. As an example, an enclave with diameter $a = 100$ cm would be homogenised in about 2,500 years at $v_{\max} = 1$ cm/year, but only 8.2 years would be required if $v_{\max}$ were increased to 1,000 cm/year. For larger enclaves (e.g. $a = 1{,}000$ cm), hybridisation would require about 37,500 years at $v_{\max} =$ 1 cm/year, but only 120 years at $v_{\max} = 1{,}000$ cm/year.

In order to compare *HT* in chaotic and regular regions, *HT* values were estimated for enclaves in regular regions by solving the diffusion equation for static circular morphologies (e.g. Crank 1975). To facilitate comparisons, the same enclave diameters (a) used for estimating *HT* in chaotic regions were applied. Results indicate that *HT* ranges from 60 to 6.6×10^7 years for $a = 1$ and 1,000 cm, respectively (Fig. 6B).

Figure 6B shows the variations in *HT* against a for enclaves in chaotic and regular regions. Enclaves in chaotic regions homogenise faster than ones in regular regions for any value of a. Moreover, strong divergence in variations in *HT* vs. a exist for the two systems, and this produces an increasing difference in *HT* as diameter a of the mafic enclave increases. For instance, an enclave with a diameter of 1 cm would homogenise in about 60 years in a regular region, but in about 1.7 years in a chaotic region with $v_{\max}$ $= 10$ cm/year – i.e. about 35 times faster. A larger enclave in a regular region, with $a = 100$ cm, would require about 6.5×10^5 years for homogenisation but only about 380 years in a chaotic region with $v_{\max} = 10$ cm/year. In this case, an enclave in a chaotic region would homogenise about 1,700 times faster than one in a regular region.

These results indicate that, within chaotic regions, mixing can be very efficient, whereas in regular regions chemical differences between the two end-member magmas may be preserved for much longer. It should be noted that both regular and chaotic regions may co-exist in the same magmatic system, implying that the magma body may be geochemically highly inhomogeneous in both space and time. In particular, the system may be composed of portions in which mixing generates hybrid volumes of magma and other portions in which the two end-member magmas are still recognisable. These occurrences are commonly found in natural outcrops—for instance, in plutonic environments, where mafic microgranular enclaves are found dispersed in large volumes of hybrid granitoid rocks bearing both isotopic and geochemical evidence of magma interaction phenomena.

However, although natural occurrences show that extremely variable mixing efficiencies are possible in the same magmatic system, it is worth comparing the time-scales estimated for magma hybridisation with the typical lifetimes of magma chambers. The occurrence of both hybridised and non-hybridised regions does not depend only on the relative time required for homogenisation in chaotic and regular regions, but also on the overall time-span during which mixing develops. In this respect, heat flux calculations for magma chambers of a few kilometres suggest thermal lifetimes of about 10^4 years (e.g. Furlong and Myers 1985). Of course, longer lifetimes are possible (e.g. Volpe and Hammond 1991; Davies et al. 1994; Heath et al. 1998), but we prefer to be conservative in order to define the lower limits for the above processes to occur. Therefore, assuming that a period of 10^4 years is a possible lower limit for the thermal lifetime of a magma chamber, enclaves with a greater than 10 metres can successfully be homogenised in the chaotic region at an advection velocity of only 10 cm/year. If the velocity increases to 100 cm/year, the largest enclave that can be homogenised would have a diameter of 90 m. Instead, in regular regions, only enclaves with diameters of under 12 cm can be completely homogenised.

Petrological and volcanological implications

The above results have several implications, regarding both petrologic and volcanologic aspects of magma mixing processes.

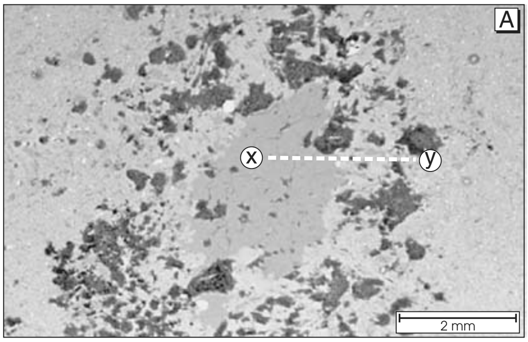
From a petrological point of view, it has been shown that magma bodies undergoing magma mixing may display very variable degrees of hybridisation during the mixing process, leading to magma volumes with extremely variable geochemical composition, depending on the intensity of stretching and folding in the different regions. Our results give new insights on the occurrence of magmatic enclaves found dispersed inside host rocks, in both plutonic and volcanic environments: magmatic enclaves are interpreted as regular regions of mafic magma which, because of the structure of flow fields, did not hybridise completely with the felsic host magma and thus survived the mixing process. Instead, host rocks may be regarded as portions of the magmatic system in which more efficient mixing dynamics produced high degrees of hybridisation.

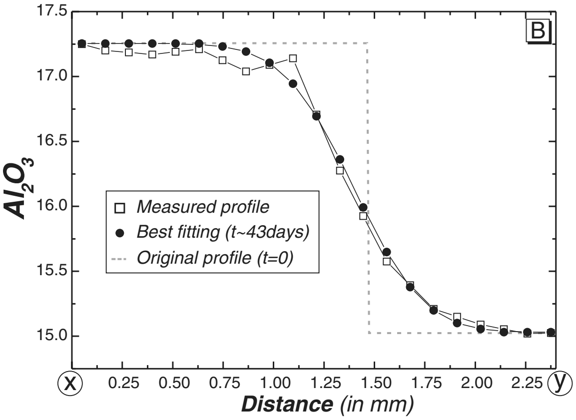
These results have profound implications on geochemical models of magma interaction. Existing models assume the spatial and temporal homogeneity of the magma body, and our analysis clearly indicates that such an assumption can no longer be considered valid. From this point of view, our results may be considered as a starting point towards more evolved geochemical models in which the high degree of complexity of magma interaction systems is taken into account.

Regarding volcanological implications, magma mixing is considered one of the most powerful forces in generating extremely explosive volcanic eruptions (e.g. Sparks and Sigurdsson 1977; Leonard et al. 2002; Perugini et al. 2004). Therefore, knowledge of time-scales for magma mixing in volcanic systems is of fundamental importance, because it may provide information on the timing of explosive eruptions triggered by magma mixing.

Several works have reported that chemical diffusion profiles can be used to constrain the time-scales of mixing in magmatic systems (e.g. Knesel et al. 1999; Zellmer et al. 1999; Hawkesworth et al. 2004). However, Perugini and Poli (2004) showed that diffusion profiles are extremely unpredictable in chaotic regions, because of the chaotic nature of mixing itself, so that they cannot easily be used for constraining mixing time-scales. Instead, in regular regions, enclaves are only weakly deformed and chemical diffusion is not influenced by flow fields. It follows that enclaves can be used for extracting diffusion profiles and thus for estimating the time during which magmas have been in contact. Although in principle this approach applies to enclaves in any type of rock, in practice it can only be applied to enclaves in volcanic rocks with low crystallinity. In plutonic or highly crystallized volcanic rocks, it is practically impossible to reconstruct the effects of crystal growth on the compositional gradients generated by the diffusion process between enclaves and host magma.

Figure 7A shows an enclave of a Qz-trachytic magma occurring in a rhyolitic lava flow on Lesbos, across which micro-analysis by electron microprobe was performed (Perugini et al. 2003). Figure 7B shows variations in Al_2O_3 across the analysed transect, with a typical diffusion pattern passing from the internal part of the region to the host magma. This pattern was fitted using the analytical solution of the diffusion equation for a sphere (Crank 1975), starting from the initial diffusion profile shown in the graph. A value of 10^{-14} m^2/s was considered for diffusion coefficient D of aluminium. This value is suitable for magmas with rhyolitic compositions, like those making up the mixing structures of Lesbos (Baker 1990). Figure 7B shows that the best fit of the measured diffusion profile is achieved at $T\sim0.12$ years ($\sim$43 days). According to the results presented here, this value should be considered as the





C

Composition of end-member magmas		
	Qz-Trachyte	Rhyolite
SiO_2	69.54	74.62
TiO_2	0.07	0.23
Al_2O_3	17.30	15.04
FeO	0.64	0.39
MgO	0.67	0.58
CaO	1.06	0.81
Na_2O	3.54	4.10
K_2O	6.80	4.54
Total	99.63	100.29

Fig. 7 **A** Back-scattered electron image, showing a coherent region in Lesbos lava flow. Dashed line from *x* to *y:* path followed by electron microprobe analysis; **B** chemical diffusion profile measured along *x-y* transect in A, used to calculate time during which magmas were in contact; **C** whole-rock composition of end-member magmas analysed by electron microprobe

time during which magmas were in contact in the Lesbos magmatic system. Of course, we cannot claim that this estimate is the true period for magma mixing in Lesbos, since chemical analyses must be performed on a statistically representative number of enclaves, rather than on only one enclave. However, it is clear that our approach is applicable and that it may be considered as an additional volcanological tool towards better understanding of the time-scales of eruptions triggered by magma mixing processes.

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