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CHAPTER 3
Chaotic mixing of magmas in the Tuscan Magmatic Province

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3.1 INTRODUCTION

Magmatic interaction processes have been widely recognized and studied in both the plutonic and volcanic environment (e.g. Thomas and Tait, 1997; Blake and Fink, 2000; Poli *et al.*, 1996). Although a considerable number of studies based on geochemical investigations as well as on analogue and numerical fluid dynamic simulations are reported in literature (e.g. Oldenburg *et al.*, 1989; Poli and Tommasini, 1991; Williams and Tobish, 1994; Snyder and Tait, 1996; Weinberg and Leitch, 1998), only recently it has been suggested that the mixing of magmas can be studied using principles of Chaos Theory (Flinders and Clements, 1996; Perugini and Poli, 2000).

In this chapter, using natural examples of magma mixing structures occurring in plutonic bodies constituting the Tuscan Magmatic Province (Central Italy), we illustrate that the mixing of magmas can be regarded as a chaotic process able to generate wide spatial and temporal in-homogeneities in magmatic masses.

3.2 MAGMA MIXING STRUCTURES IN THE TUSCAN MAGMATIC PROVINCE

Figure 1 shows some examples of magma mixing structures generated by the interaction between mafic (dark coloured) and felsic (bright coloured) magmas occurring in some plutonic bodies of the Tuscan Magmatic Province.

Macroscopically these structures show that magmas underwent mixing processes producing intimate dispersion of the more mafic magma through the felsic one. A closer look at these structures evidences that inside the same system there is the contemporaneous occurrence of (i) filament-like regions generated by the intimate commingling of magmas (hereafter Active Regions, AR; Fig. 1), and (ii) globular regions of the mafic magma that did not disperse through the felsic one (hereafter Coherent Regions, CR; Fig. 1).

It is noteworthy that the contemporaneous occurrence of filament-like regions (AR) and globular regions (CR) has been widely documented in studies dealing with chaotic mixing of fluids in both real and simulated systems (Fig. 2; e.g. Ottino *et al.*, 1988; Liu *et al.*, 1994; Aref and El Naschie, 1995).

3.3 THE CHAOTIC MIXING OF MAGMAS

A natural system can be defined as chaotic if its evolution in time and space can be characterized by a «strange attractor» (e.g. McCauley, 1993). A «strange attractor» is a

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dynamical structures existing in the «phase space» of the system whose topological dimension has a non-integer value, that is the structure is a fractal (e.g. McCauley, 1993).

The chaotic nature of magma mixing structures has been documented by Poli and Perugini (2002) utilizing structures occurring in the volcanic environment. Structures were analysed using a new technique focused on image analysis procedures and based on the extraction of time series, representative of the relative change in composition across the structures. Time series were then used to reconstruct the attractors underlying the magma mixing process and to calculate their fractal dimensions. Results have shown that attractors possess fractional dimensions (i.e. they are «strange attractors») and, therefore, the mixing of magmas can be regarded as a chaotic process. Since magmas interaction structures are chaotic, the simulation of magma mixing processes needs to be carried out utilizing chaotic dynamical systems.

The basic dynamics leading to chaotic mixing of magmas are stretching and folding processes (Fig. 3A). Stretching and folding are

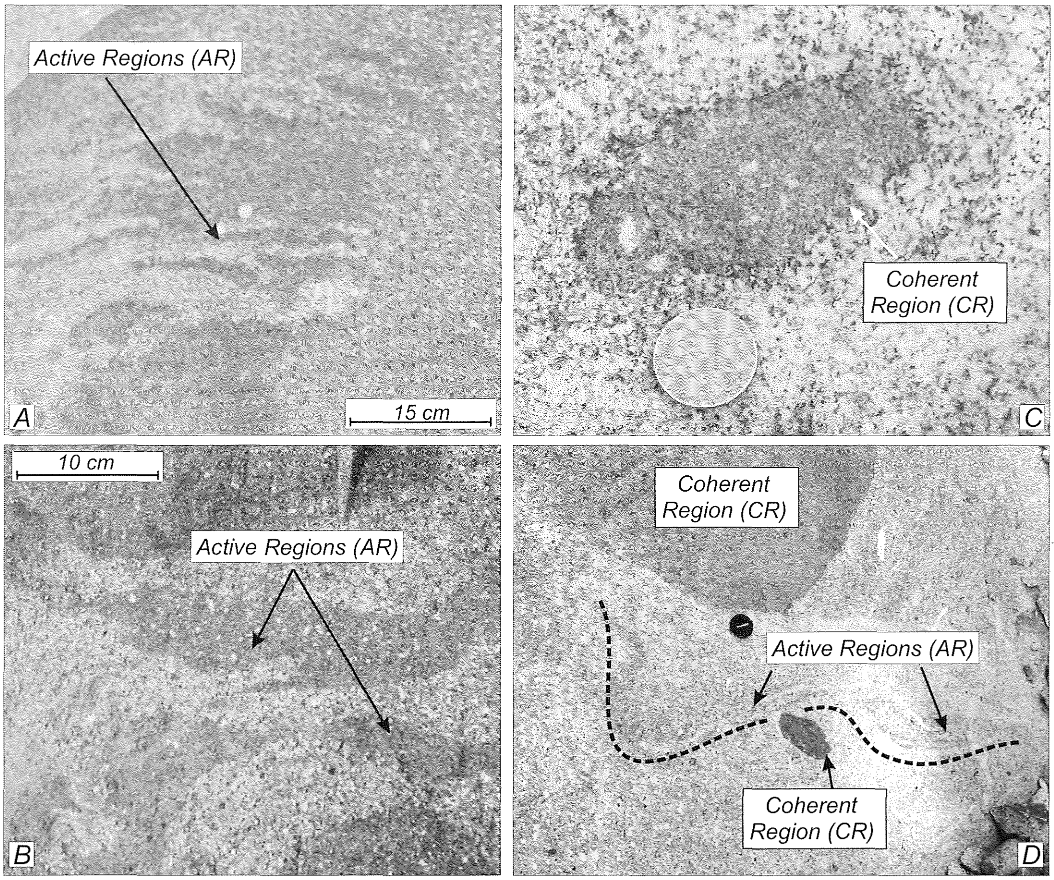

Fig. 1 – Examples of mixing structures in plutonic rocks from the Tuscan Magmatic Province (Italy); A) and B) flow structures from Pomonte quarry, Elba Island; C) Mafic Microgranular Enclave (MME) from S. Andrea area, Elba Island; D) contemporaneous occurrence of flow structures and MME in a section of Pomonte quarry outcrop, Elba Island.

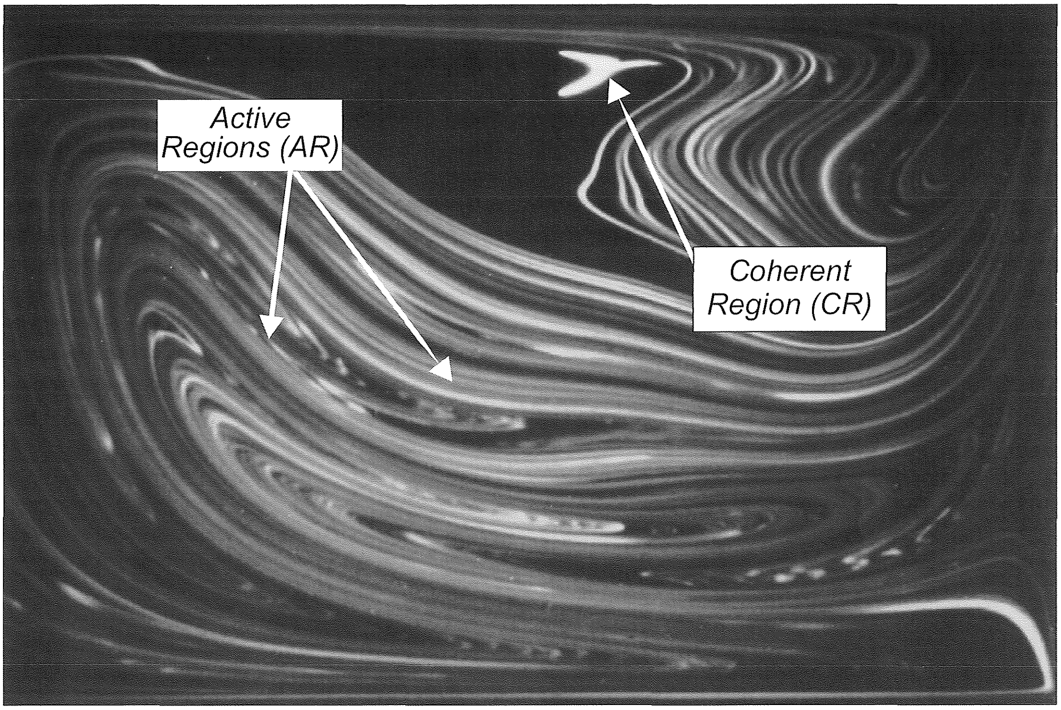

Fig. 2 – Simulation of fluid mixing showing the occurrence within the same system of Active Regions (AR) and Coherent Regions (after Bresler *et al.*, 1997).

non-linearly coupled processes: the first induces elongation of fluids (Fig. 3A, t=1), whereas the latter bends and redistributes them through the mixing system (Fig. 3A, t=2). This kind of kinematical evolution of the mixing system generates lamellar structures (Fig. 3A, t=n) with wide distribution of length scales that span many order of magnitude (e.g. Alvarez *et al.*, 1998; Ottino *et al.*, 1993; Perugini *et al.*, 2002).

To test the hypothesis that magma mixing processes in the plutonic bodies of the Tuscan Magmatic Province can be simulated using chaotic dynamical systems, the process of dispersion of one magma inside another is simulated using a chaotic dynamical system consisting of repeated stretching and folding processes (Fig. 3B and C). In figure 3B is reported the flow field of the chaotic system. The image shows that regular regions, consisting of closed trajectories, coexist with irregular regions, where precise trajectories cannot be defined. Bearing in mind that the efficiency of mixing lies in the ability of the components involved in the process to spread across the system, possibly in an irregular way (e.g. Ottino *et al.*, 1988; Liu *et al.*, 1994), it follows that irregular and regular regions in figure 3B are regions where fluids are well mixed (Active Regions, AR) and poorly mixed (Coherent Regions, CR), respectively. To understand better this concept figure 3C shows the evolution of a magma mixing system in which a dark coloured mafic magma mixes with a white coloured felsic magma. The figure shows that within Coherent Regions (CR) the mafic magma is poorly mixed, whereas inside Active Regions (AR) it experiences strong stretching and folding processes generating filament-like structures analogous to those

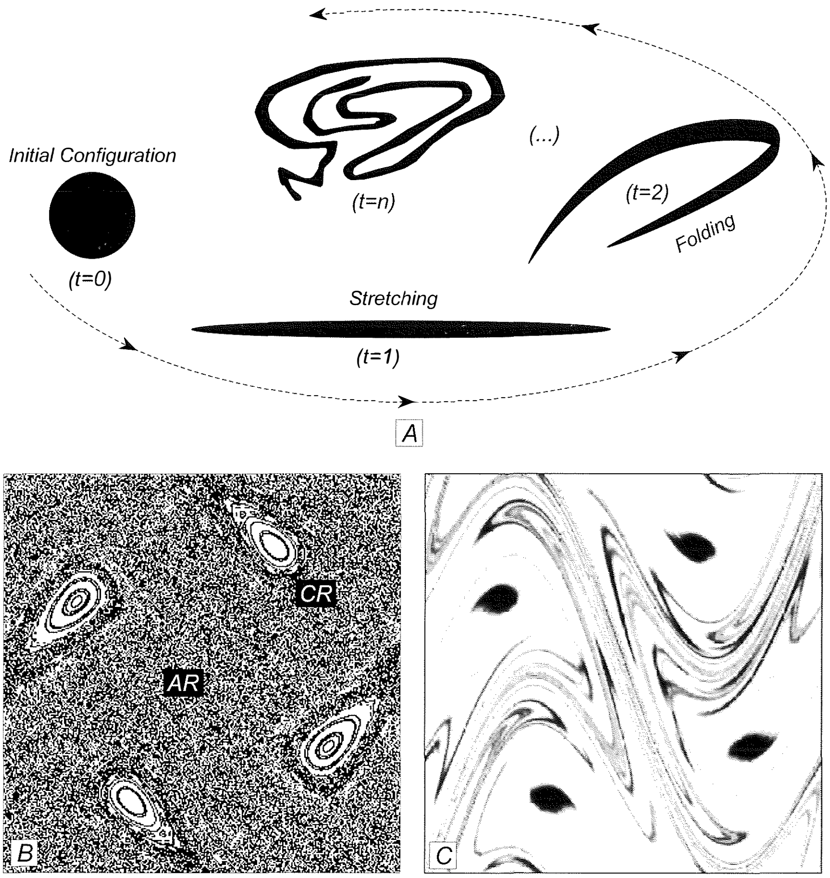

Fig. 3 – A) schematic representation of the stretching and folding process (t is the dimensionless time); B) flow fields of the dynamical system utilized to simulate the chaotic mixing of magmas; C) mixing structures obtained using the dynamical system shown in (B).

observed in natural magma mixing structures (Fig. 1).

Figure 4 shows a comparison between the structures obtained with the simulation of chaotic mixing of magmas and the structures occurring in plutonic rocks of the Tuscan Magmatic Province. There is a striking similarity between the simulated structures and those present in natural mixed rocks and this argues in favour of the hypothesis that the mixing of magmas can be suitably simulated utilizing chaotic dynamical systems. In particular, filament-like regions in which the mixing magmas underwent strong mixing processes generating wide contact surfaces (Active regions; Fig. 4A and D) and regions of the more mafic magma that experienced very poor mixing processes [Mafic Microgranular Enclaves, MME (Fig. 5B and E)] can be observed in both simulation and Nature.

Therefore, mixing processes are characterized by the occurrence, within the same system, of chaotic regions in which magmas interact very efficiently producing large portions of magmas having variable degree of hybridisation (Active Regions, AR)

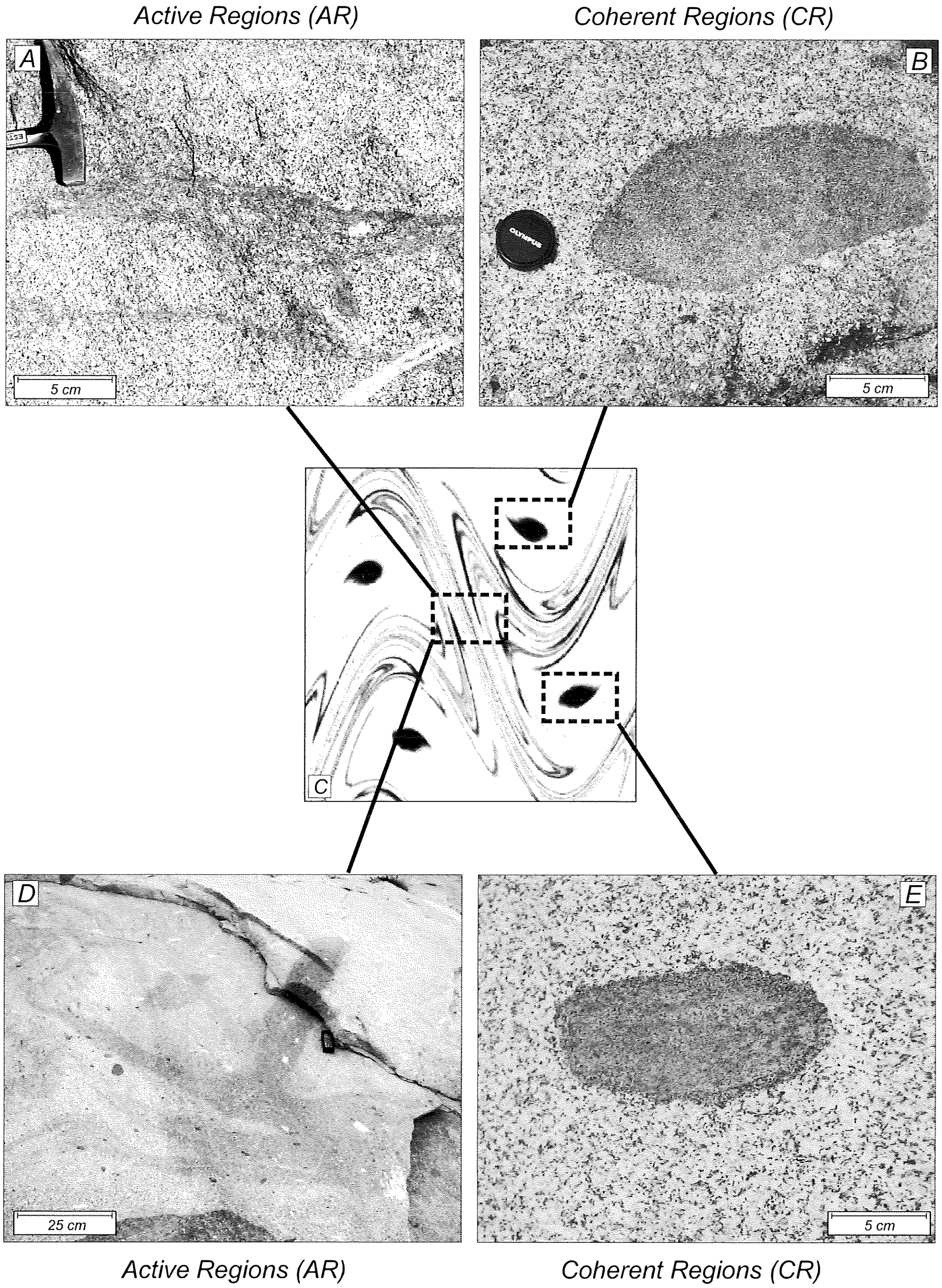

Fig. 4 – Comparison between the structures obtained by the simulation of magma mixing (C) using the chaotic dynamical system reported in figure 3B and the mixing structures occurring in natural rocks from the Tuscan Magmatic Province (Italy); A) and B) flow structures and magmatic enclave from the San'Andrea are, Elba Island; D) flow structures from Pomonte quarry, Elba Island; E) MME from Sant' Andrea area, Elba Island.

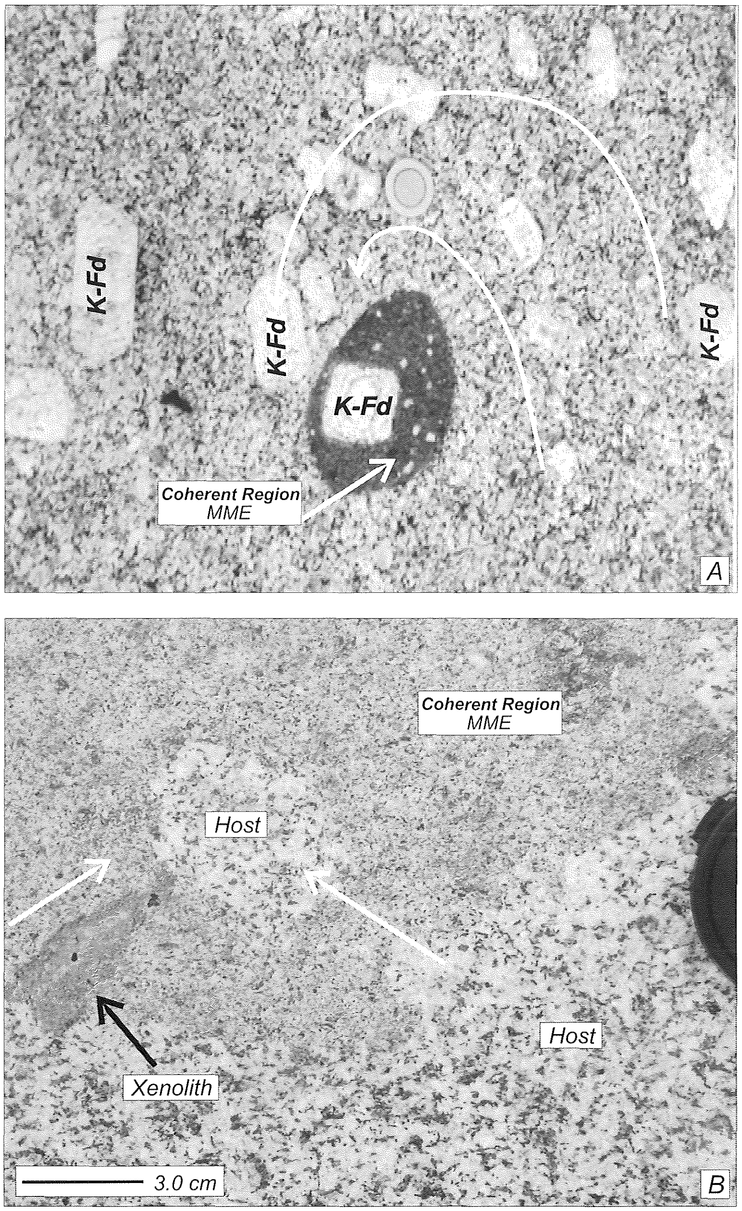

Fig. 5 – A) K-feldspar megacrysts defining a circular structure around a MME. The MME contains a K-feldspar belonging to the host magma (Sant'Andrea area, Elba Island); B) example of MME showing the partial transfer of a metamorphic xenolith from the host magma. The same MME also contains a subspherical potion of host magma as indicated in the picture (Giglio Porto area, Giglio Island).

and regions in which magmas do not undergo efficient mixing (Coherent Regions, CR). Following these considerations, Mafic Microgranular Enclaves (MME) found dispersed in the calc-alkaline plutons of the Tuscan Magmatic Province are interpreted as Coherent Regions in which the mixing dynamics was much less efficient than in the rest of the system (e.g. Flinders and Clemens, 1996; Perugini and Poli, 2000).

However, defining MME as coherent regions may require further considerations. In fact, from a theoretical point of view, CR should not exchange matter with the surrounding host magma because they should behave as completely isolated system in which pathlines are always tangential to their boundaries (e.g. Bresler *et al.*, 1997). On the contrary, mass transfer from the host magma to enclaves is a commonly observed feature [e.g. xenocrysts (e.g. Fig. 5A), xenoliths (e.g. Fig. 5B) or even portions of the felsic magma (e.g. Fig. 5B)]. It should be noted, however, that CR can be perturbed by geometrical variations of the system (e.g. Bresler *et al.*, 1997) and geometrical variations are inherent to magmatic systems. For instance, magmas crystallize and the newly formed mineral phases act as geometrical perturbations of CR because they are transported by flow fields. Crystals that are transported along pathlines, close to enclaves, may be incorporated into the enclaves depending on their ability to align along these pathlines, and this ability is closely related to their mineral habit. For example, feldspar crystals belonging to the host magma are commonly found inside enclaves (e.g. Fig. 5A and 6C), whereas in the case of biotite it is much less common. This may be due to the fact that the prismatic habit of feldspar does not allow the mineral to align itself perfectly along the pathlines and consequently it can be easily caught up into the enclaves (Fig. 6C). Biotites, on the other hand, characterized by a tabular habit, can adapt well to the direction of the pathlines and, hence, are likely to remain in the host magma (Fig. 6A and C). Support to this hypothesis is given by the fact that feldspar xenocrysts are commonly found everywhere within enclaves (Fig. 6C) whereas biotite xenocrysts are found disposed along enclaves boundaries (Fig. 6C). The fact that feldspar crystals commonly penetrate within enclaves implies that also liquid from the host magma penetrates through enclaves inducing dilution of the mafic magma (Fig. 6A). This can explain why commonly enclaves do not retain completely the geochemical signature of the original mafic magma but display various degrees of geochemical contamination with the host felsic magma.

3.4 Concluding remarks

It is suggested that magmatic interaction processes in the Tuscan Magmatic Province have been governed by chaotic dynamics that generated wide spatial and temporal inhomogeneities within magmatic masses. In particular, these processes generated portions of magmas completely homogenized (host rocks) coexisting with portions of magmas displaying lower degrees of interaction.

These results are strictly related to the local structure of flow fields inside magmas induced by the onset of chaotic dynamics that generate different dynamical regions (AR and CR) in which mass transfer processes acted very differently in relationship with the extension of contact interfaces between interacting magmas.

The use of Chaos Theory allows us to provide new insights to the occurrence of magmatic enclaves found dispersed inside plutonic rocks. Magmatic enclaves are interpreted as coherent regions of the more mafic magma that, thank to the structure of flow fields, did not suffer large degrees of interaction with the felsic host magma and survived the mixing process. It follows that host rocks can be regarded as portions of the magmatic system in which the more efficient mixing dynamics produced larger and variable degrees of hybridisation.

As it is suggested by numerical modelling, the basic dynamics that induce magmas to mix

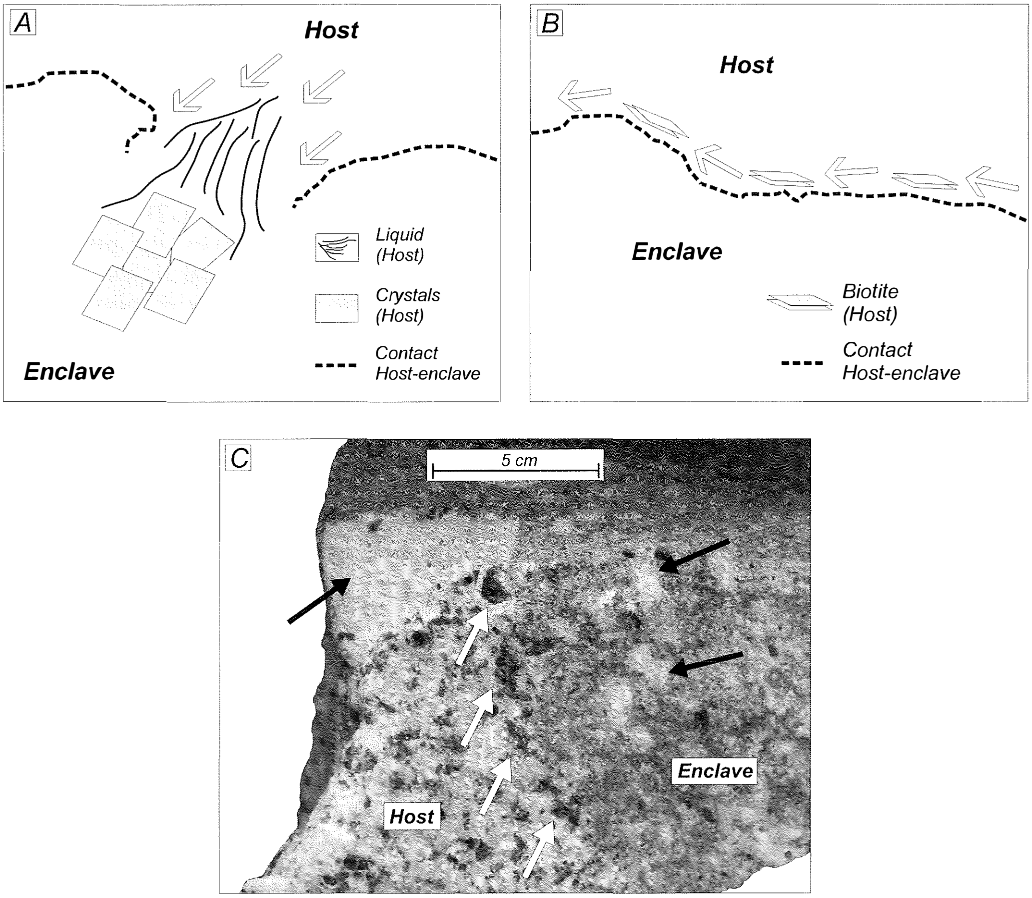

Fig. 6 – (A) Schematic representation of the transfer of mineral phases (feldspars) and liquid from the host magma to the enclave magma; (B) schematic representation of the orientation of biotite crystals, within the host magma, tangentially to the boundary between the host magma and the enclave; C) macroscopic sample showing the contact between the host granitoid rock and a Mafic Microgranular Enclave (MME) documenting the orientation of biotite crystals (indicated by white arrows) along the enclave periphery and the transfer of feldspars (indicated by black arrows) from the host magma to the MME. The sample shown in (C) is from the Sant'Andrea area, Elba Island.

are stretching and folding processes. Given the universal nature of such processes in fluid dynamic systems, they can occur potentially in any magma mixing system (Fig. 7) irrespective of the geometries in which magmatic interaction processes occur. This is a crucial point since the numerical and analogical simulations performed up to now were strongly dependent on the geometrical framework on which they operated. The use of dynamical systems based on Chaos Theory in numerical simulations may help to overcome most problems related to the dependence of magma mixing systems on the geometrical framework.

From the considerations presented above the general picture emerges that magma mixing processes exhibit all the typical features of non-linear and chaotic systems. Their evolution occurs as a non-linear cascade of events that, starting from the micro-scale, is non-linearly

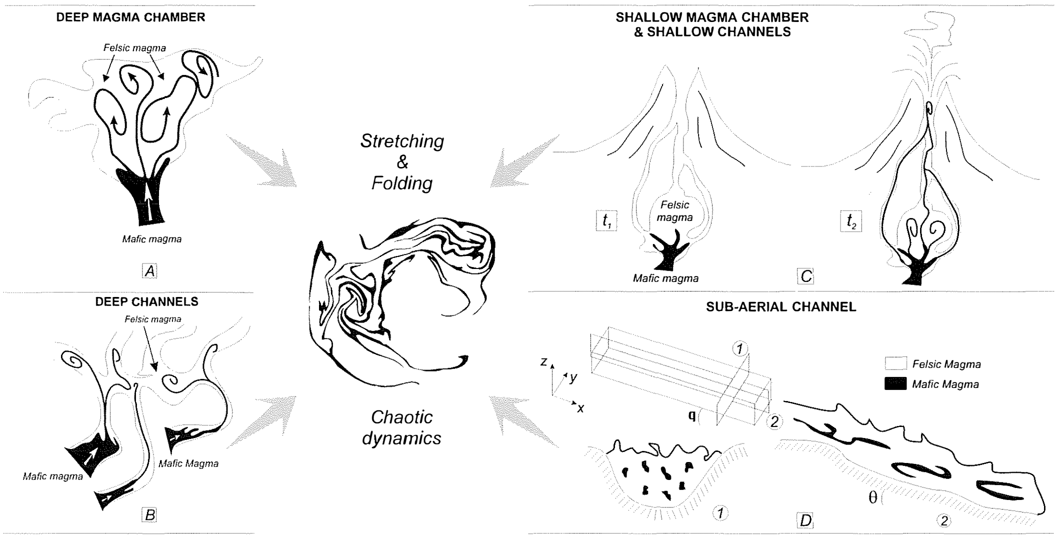

Fig. 7 – Schematic illustration of the possible geometrical frameworks on which magma mixing process can occur. A) and B) mixing process in deep magma chamber and deep channels; white arrows indicate the direction of injection of the mafic magma inside the felsic host magma; C) mixing process in a shallow magma chamber whose evolution triggers a volcanic eruption; t_1 and t_2 indicate successive times in the evolution of the system; D) 3-D sketch of a lava flow in which mixing structure are present; 1 and 2 indicate sections orthogonal and parallel to the direction of the lava flow, respectively.

amplified determining the behaviour of magmatic systems at the macro-scale. It is emphasized that chaotic dynamics can be considered suitable techniques to study the complexity inherent to petrological systems, and they represent useful methods that, used together with conventional analysis, can aid in understanding better petrological processes.

For many years geologists have complained that classical mathematics and physics are too simplistic to be useful in geology. Chaos Theory and the science of non-linearity do accurately represent many geological systems and their use in petrology may considerably extend our knowledge on geological systems and on the way Nature works.