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Model for the Origin and Significance of Microgranular Enclaves in Calc-alkaline Granitoids

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ABSTRACT

The origin and significance of microgranular enclaves as indicators of the occurrence of magma mixing and/or mingling episodes between basic magmas and anatectic acid magmas, either I- or S-type, are re-evaluated. A model for studying microgranular enclave and host rock associations has been developed, based on the geochemical characteristics and the outcrop relationships observed in microgranular enclave-bearing granitoid suites.

The model consists of three main stages, concerning the injection (stage 1), the evolution (stage 2), and the mixing (stage 3) processes that basic magmas experience when injected into anatectic crustal environments. In stage 1, an acid magma is intruded by one or more injections of almost completely liquid basic magma which is hotter and less viscous than the acid magma. The two systems do not mix easily, but remain as discrete entities until thermal equilibrium and comparable viscosities are reached, and freezing of the basic magma and superheating of the acid magma are operative along their boundaries. In stage 2, the basic magma experiences both the physical processes of stretching, convective stirring, and mingling with the acid magma, and the chemical processes of crystal fractionation, and contamination with the acid magma (CFC process). Repeated cycles of these physical and chemical processes result in the formation of both microgranular enclaves and an evolved liquid which is thermally equilibrated with the acid magma. Accordingly, microgranular enclaves record the steps of evolution of the basic magma. In stage 3, the evolved products of the basic magma (tonalitic to granodioritic in composition) and the acid magma participate in a two-endmember mixing process which accounts for the geochemical evolution of granitoid plutons bearing microgranular enclaves.

The model sheds new light on the magmatic processes occurring in plutonic environments during the formation of composite batholiths, and also suggests some ideas on the petrogenesis of tonalitic plutons. Finally, the observed scale-independent property of microgranular enclaves suggests that fractal geometry, a relatively new topic of mathematics, can play a determinant role in the understanding of the chaotic flow mechanics of viscous fluids, i.e., the kinematics of the mingling and stretching of basic magmas.

INTRODUCTION

The origin and significance of enclaves in granitoid plutons is still a matter of debate, in particular with regard to the so-called microgranular enclaves [microgranitoid inclusions or enclaves, and mafic inclusions or enclaves; see Didier (1973) for a review]. Microgranular enclaves are widespread in most granitoid plutons whose genesis is related to a collisional tectonic setting (e.g., Reid *et al.*, 1983; Vernon, 1984; Frost & Mahood, 1987; Vernon *et al.*, 1988; Poli *et al.*, 1989), and can readily be distinguished from schistose or granoblastic metamorphic enclaves on field and/or petrochemical grounds.

There is disagreement between the models proposed to explain the origin of the microgranular enclaves on whether the enclaves are restite (e.g., Chappell *et al.*, 1987; Chen

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et al., 1989), or blobs of basic magmas derived from the mantle (e.g., Vernon, 1984; Bacon, 1986; Holden *et al.*, 1987) or from the lower crust (e.g., Eberz *et al.*, 1990). This paper attempts to test the latter hypothesis by re-evaluating the origin and the importance of microgranular enclaves as indicators of magma mixing and/or mingling episodes between both I- and S-type anatectic acid magmas and basic magmas. In this paper, the term mixing is used to indicate the process of chemical interaction between different magmas to form a completely blended homogeneous hybrid. In contrast, the term mingling is used to indicate the process of physical interaction between different magmas to form a rock product which preserves compositional heterogeneities (Vernon, 1984; Sparks & Marshall, 1986).

The petrochemical features of microgranular enclaves are examined to propose a 'working model' for their origin, leading to a more fertile approach to the study of magmatic processes occurring in plutonic environments. Parallels between microgranular enclaves and tonalitic plutons are also discussed.

Essentially, our model is derived from research in progress on the Carboniferous microgranular enclave-bearing I-type granitoids in the Sardinia–Corsica Batholith (Poli *et al.*, 1989), and on the Mio-Pliocene microgranular enclave-bearing S-type granitoids in the Tuscan Archipelago (Poli, submitted).

FIELD AND PETROCHEMICAL FEATURES OF MICROGRANULAR ENCLAVES

Microgranular enclaves range from quartz diorites to granodiorites, commonly have ellipsoidal, flattened shapes and fine-grained textures, and frequently display features suggesting plastic behaviour at the moment of their incorporation into the granitic magma. Their plastic rheology is shown by their crenulated margins and diffuse contacts with the host rock (grain-to-grain mechanical fragmentation, Fig. 1C; e.g., Frost & Mahood, 1987; Vernon *et al.*, 1988). The degree of fragmentation of the microgranular enclaves is indicated by the extreme variability of dimensions, ranging from metre- to centimetre-sized fragments, to fine-grained clots of ferro-magnesian phases and An-rich plagioclases within the granites (e.g., Vernon *et al.*, 1988). Furthermore, host rock xenocrysts commonly occur within the enclaves (Fig. 1B; e.g., Didier, 1987), and, in turn, microgranular enclaves are randomly distributed within the host rock, and are elongated in the direction of the flow lines of the granitic magma (Fig. 1A; e.g., Vernon *et al.*, 1988). The extreme degree of irregularity in shapes and distribution remains constant through successive magnifications used to view the microgranular enclave and host granite relationships, i.e., from the meso-scale (outcrop) to the micro-scale (thin section). This scale-independent property, i.e., the self-similarity described by Mandelbrot (1982), is very distinctive of dynamical systems (e.g., Becker & Dörfler, 1989), and suggests that the same processes affected all of the decimetre- and millimetre-sized enclaves.

Microgranular enclaves display magmatic textures similar to subophitic textures of basic igneous rocks. They have higher contents of ferro-magnesian phases and plagioclase, and lower contents of quartz and K-feldspar than those found in the host granite (Eberz & Nicholls, 1988). The mineral assemblage present in microgranular enclaves is host rock controlled: the occurrence of biotite and/or hornblende within the micrograular enclaves is mostly correlated with the occurrence of the same phase(s) found in the host granite. Moreover, relics of An-rich plagioclase cores (typically with patchy zoning texture) and pyroxenes are frequently found in microgranular enclaves (e.g., Frost & Mahood, 1987; Poli *et al.*, 1989).

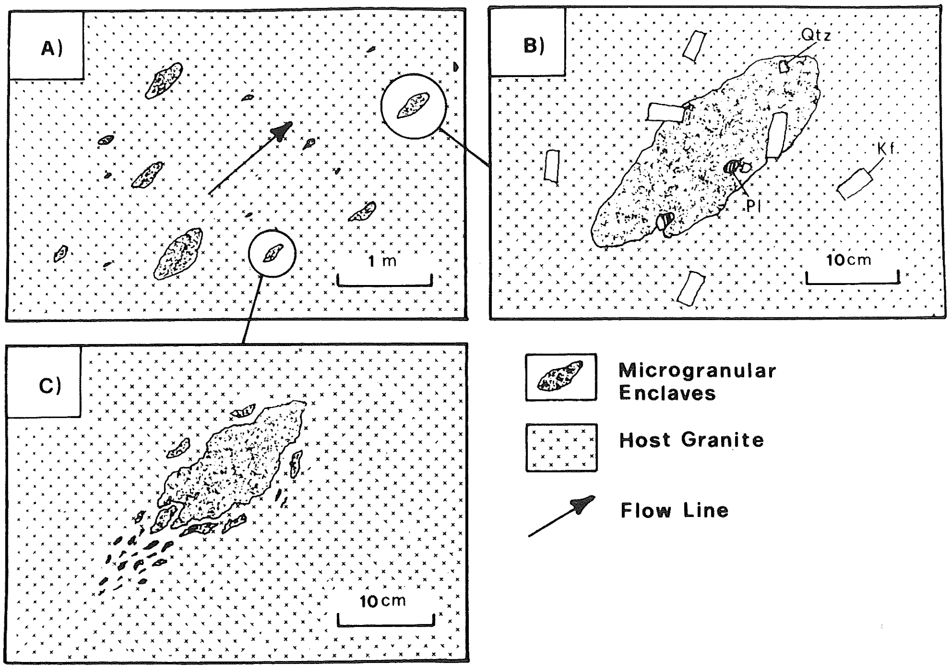

FIG. 1. Typical view of the outcrop relationships exhibited by the microgranular enclaves and the host rock. (A) Mesoscale view: flattened microgranular enclaves, from a few millimetres to decimetres in size, elongated in the direction of the flow lines of the host rock. Detailed view: (B) host rock xenocrysts of K-feldspar, quartz, and plagioclase within the enclave; (C) mechanical fragmentation of a microgranular enclave into the host rock.

From a geochemical viewpoint, microgranular enclave and host granite associations commonly display three different trends in Harker's diagrams:

(a) a trend characterized by a negative correlation with increasing evolution; this trend is followed by ferro-magnesian elements (Mg, Ni, Cr, Co, etc.);

(b) a trend defining a positive correlation with increasing evolution; this trend is usually followed by Rb, sometimes light rare earth elements (LREE), Th, and, to a lesser extent, K_2O;

(c) a trend fitting a bell-shaped, concave-downward curve, with the microgranular enclaves plotting along the part of the diagram with a positive trend; this trend is usually followed by most large ion lithophile elements (LILE), high field strength elements (HFSE), and REE.

As an example, representative diagrams of these three different trends displayed by microgranular enclave and host granite associations from the Sardinia–Corsica Batholith are shown in Fig. 2 [see Poli *et al.* (1989) for the geological outline].

It should be noted that the particular bell-shaped pattern can hardly be explained by the restite model proposed for the origin of microgranular enclaves (e.g., Chappell *et al.*, 1987). In addition, an almost ideal isotopic equilibrium is often observed in microgranular enclave and host granite pairs (Holden *et al.*, 1987; Pin *et al.*, 1988; Eberz *et al.*, 1990). However, the initial Nd isotopic ratios are sometimes higher in the microgranular enclaves than in their host rocks by 1–2ε units. Again, this fact rules out a restite origin for microgranular enclaves, inasmuch as their isotopic signatures should be identical to those of their host rocks. In

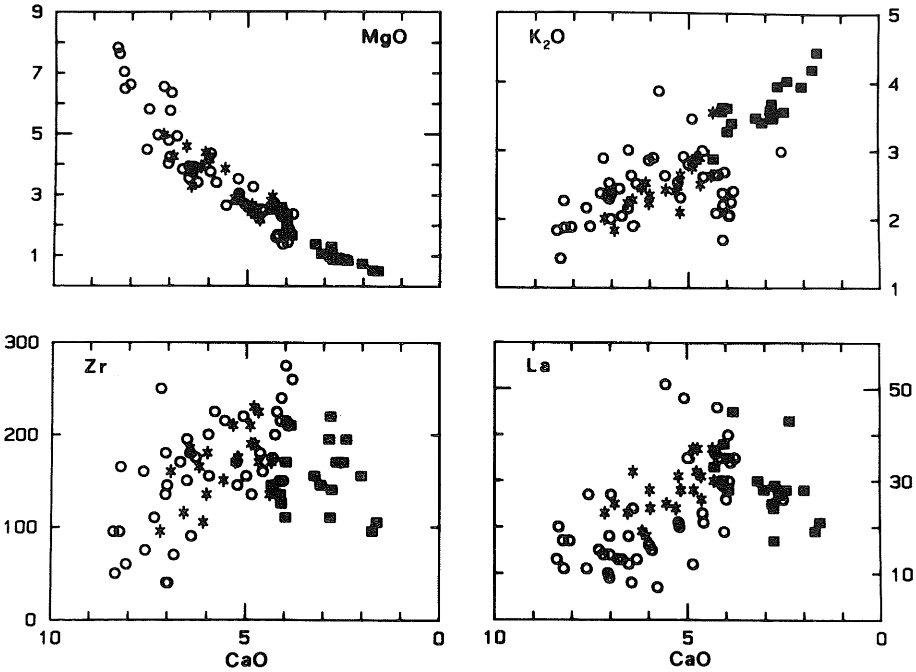

FIG. 2. Representative diagrams of the three different trends displayed by microgranular enclave and host rock association from the Sardinia–Corsica Batholith [data from Bralia *et al.* (1982)]. Open circles: microgranular enclaves; asterisks: tonalites; closed squares: granodiorites and monzogranites.

contrast, the observed isotopic differences in εNd are explicable if the microgranular enclaves represent blobs of basic magma. In fact, liquid-state isotopic homogenization, occurring by a combination of self- and tracer-diffusion (Baker, 1989), is easily one to two orders of magnitude faster than element homogenization (10^{-9}–10^{-10} cm^2/s, with the exception of the alkaline elements), and can reasonably account for either partial or complete isotopic re-equilibration of microgranular enclave and host granite pairs over the long cooling times (10^6 y order of magnitude) occurring in plutonic environments.

THREE-STAGE MODEL

In summary, the main features common to all microgranular enclaves occurring in granitoid plutons are:

(1) their igneous fine-grained textures, suggestive of rapid crystallization following an episode of under-cooling;

(2) their ductility at the moment of incorporation into the granitic magma;

(3) the peculiar bell-shaped pattern displayed by microgranular enclave and host granite associations in some trace element variation diagrams;

(4) their complete or partial isotopic equilibrium with the host granite.

To explain all these features we postulate a magmatic origin for the microgranular enclaves, and consider that the enclaves are remnants of disrupted basic magmas injected into acidic magmas.

The explanation of the acid–basic association in calc-alkaline environment is still a matter of debate (e.g., Pitcher, 1987, and references therein). In this context, this paper takes the position followed by many authors that mantle-derived magma underplating of the crust supplies heat and causes elevation of the geothermal gradient, determining crustal partial melting (e.g., Holden *et al.*, 1987; Huppert & Sparks, 1988). Once a region of the crust has become ductile, and has undergone extensive partial melting, it provides an effective density barrier to arrest successive inputs of mantle-derived magmas. In such a scenario, basic magmas are injected into already formed acidic magmas. However, these basic magmas need not be of single-stage mantle derivation, but could be represented by partial melting of a mafic lower crust (Eberz *et al.*, 1990). Whatever the origin of the basic magmas, the crucial point of the proposed model is the coexistence of partially molten basic and acid magmas.

The physico-chemical factors regulating the different styles of interaction exhibited by basic magmas which intrude into anatectic environments (mixing vs. mingling processes) depend upon the relative mass fractions of the interacting magmas, and upon differences in temperature, viscosity, and chemical composition (Sparks & Marshall, 1986; Frost & Lindsay, 1988).

The bell-shaped patterns (Fig. 2) displayed by the microgranular enclave and host granite associations in some trace element variation diagrams preclude a simple two-endmember mixing process. In addition, mixing between basic and acid magmas can also be ruled out on the basis of thermodynamic constraints (Campbell & Turner, 1985, 1986; Sparks & Marshall, 1986).

Another hypothesis is based on the assumption that microgranular enclave and host granite associations (including tonalite, granodiorite, and monzogranite plutons) are produced by a continuum process involving fractional crystallization of a basic magma and the addition and mixing of an acid magma (MFC process; DePaolo, 1981). Geochemical and field constraints, for example, crude chemical mass balances, as well as the relative mass fractions in the entire suite of microgranular enclaves and the host rocks ($<5\%$; Vernon *et al.*, 1988; Chen *et al.*, 1989; Poli *et al.*, 1989), indicate that large mass fractions of acid magma must be involved in the mixing process; i.e., the mixing/crystallization ratio is greater than unity. However, the possibility that such large amounts of acid magma can be involved during the crystallization of the basic magma is not thermodynamically feasible, owing to temperature and viscosity differences between acid and basic magmas (Sparks & Marshall, 1986).

In contrast, the following three-stage working model bypasses the thermodynamic objections, and is able to explain both the geochemical and the outcrop relationships observed in microgranular enclave-bearing granitoid suites. The assumption that must be made is that the process occurs under dynamic rather than static conditions, as is suggested by field relationships between microgranular enclaves and host rocks (Fig. 1).

Stage 1—Injection of basic magma

The acidic crystal-mush magma, of either I- or S-type, during its emplacement in the crust, is intruded by one or more injections of almost completely liquid basic magma(s) (Fig. 3A) that are not necessarily at the same degree of evolution (B and/or B′ of Fig. 4). The basic magma(s) are hotter and less viscous than the acidic magma. The mechanism of fountain-like injection of low-viscosity silicate melts into more viscous magma has been thoroughly discussed by Campbell & Turner (1985, 1986), who demonstrated that basic magmas do not mix easily with granitic magmas, but remain as discrete entities within the granitic magma until thermal equilibrium and comparable viscosities are reached. At this stage, the phenomena of freezing of the basic magma and superheating of the acid magma (Fig. 3A) take place along their boundaries (Marshall & Sparks, 1984).

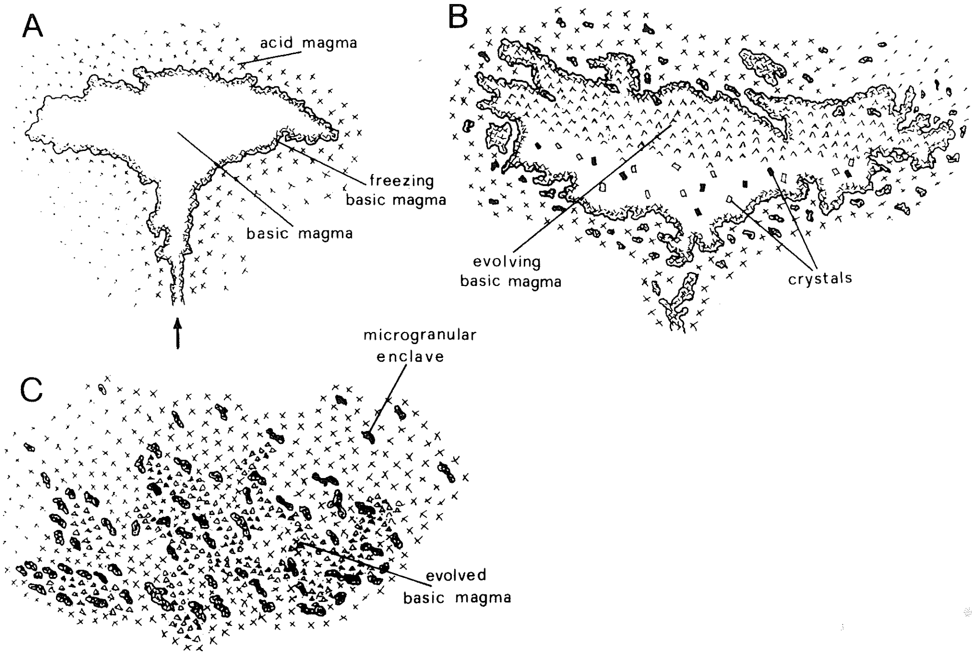

FIG. 3. Schematic diagram illustrating the three-stage model. (A) Injection of the basic magma into the acid magma (stage 1). (B) Acid–basic system during one cycle of the physical and chemical processes of mingling and crystal fractionation plus contamination (stage 2; see text). (C) Acid–basic system at the end of stage 2 (see text).

Stage 2—Evolution of basic magma

During the attainment of thermal equilibrium, the basic magma simultaneously experiences both *physical* and *chemical* processes.

Physical processes include stretching, convective stirring, and mingling with the acidic magma (Fig. 3B). These processes, which continue with increasing intensity until stage 3, result in the formation of blebs whose dimensions vary from a few millimetres to decimetres (microgranular enclaves; Figs. 1 and 3B). Moreover, rapid crystallization occurs in the basic magma because of the temperature contrast between the acid and basic systems [see also Sparks & Marshall (1986)].

Chemical processes include the evolution of the basic magma as a result of crystal fractionation of pyroxenes + plagioclase ± olivine, and contamination with the acidic magma (CFC process; Fig. 4). The assimilation of acid magma material is due to the heat released by the basic magma along the boundaries between the magmas. However, far from the boundaries, viscosity and temperature differences between the two magmas remain high, and inhibit a large-scale contamination, i.e. the contamination rate vs. crystallization rate (R of Fig. 4) is low. In addition, the high liquid-state diffusivities of the alkaline elements (K, Rb, and Na) promote the replacement of the early formed phases and the direct crystallization of biotite and Ab-rich plagioclase within the basic magma, so that only relics of pyroxenes and An-rich plagioclase cores are preserved. Isotopic re-equilibration also begins at this stage through self- and tracer-diffusion (Baker, 1989). Sr isotopes are more likely to re-equilibrate than are Nd isotopes (Holden *et al.*, 1987), and the patchy zoning of plagioclase, the major repository of Sr, suggests significant re-equilibration with the acid magma, whereas the accessory phases, which are the major repository of Nd (apatite, zircon, and allanite) generally show no evidence of recrystallization.

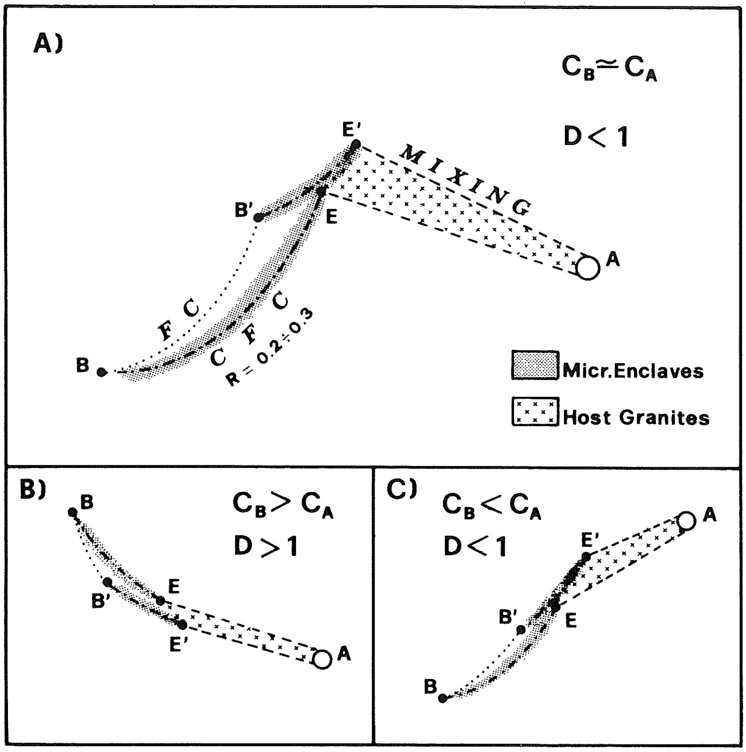

FIG. 4. Common geochemical patterns exhibited by microgranular enclave and host rock associations in inter-elemental variation diagrams. (A) Incompatible trace elements ($D < 1$) with $C_B \approx C_A$, (B) compatible trace elements ($D > 1$) with $C_B > C_A$, and (C) incompatible trace elements with $C_B < C_A$ (see text for explanation). C_A and C_B refer to the trace element abundance in acid and basic magmas, respectively. B and B′ are the hypothetical basic endmembers, related only by crystal fractionation processes (line BB′); E and E′ represent the compositions of the evolved products of the basic liquids. BE and B′E′ represent the liquid lines of descent related to the CFC process experienced by B and B′, respectively; R is the contamination rate vs. the crystallization rate (DePaolo, 1981). AE and AE′ represent mixing lines between the evolved products of the basic liquids and the acid magma. The distribution of the microgranular enclave and host granite associations produced is also shown.

The evolution of the basic magma must be regarded not only as a whole, but also at a local scale. This means that thermal equilibrium can readily be attained in a local finite volume along the boundaries, whereas the basic magma as a whole needs much more time to attain thermal equilibrium, during which it can fractionate (Fig. 3B).

Repeated cycles of these *physical* and *chemical* processes result in both the extreme fragmentation of the basic magma (microgranular enclaves) and the formation of an evolved liquid thermally equilibrated with the acid magma (Fig. 3C). Accordingly, compositional variations of microgranular enclaves record the steps of evolution of the basic magma (Fig. 4).

Stage 3—Mixing between the evolved basic magma and the acid magma

The tonalite to granodiorite magmas formed from the basic magma during stage 2 (E and/or E′; Fig. 4) and the acid magma are in thermal equilibrium and have comparable viscosities. Therefore, they can participate in a two-endmember mixing process to form completely blended homogeneous hybrid rocks. This process accounts for the geochemical evolution of granitoid plutons bearing microgranular enclaves (lines AE and/or AE′; Fig. 4). The mixing process between the evolved products of the basic magma and the acid magma is not hindered by the thermodynamic barriers that prevent mixing between the 'basic' and 'acid' magmas, because the differences in physical properties are now greatly reduced.

The CFC process undergone by the basic magma, combined with the mixing process undergone by the evolved products of the basic magma, also provides a feasible explanation for the three different geochemical patterns observed. Taking the relative abundances of trace elements in the basic and acid magmas and the bulk distribution coefficients (*D*) of the trace elements during the crystal fractionation process occurring in the basic magma (stage 2) into account, three different groups of trace elements can commonly be distinguished:

(1) incompatible trace elements (most LILE, HFSE, and REE) with comparable relative abundances in both the basic and the acid magma ($C_B \approx C_A$), which will produce a bell-shaped pattern (Fig. 4A);

(2) compatible trace elements (transition metals) with higher relative abundances in the basic magma ($C_B > C_A$), which will produce a negative correlation (Fig. 4B);

(3) incompatible trace elements (e.g., Rb, and sometimes LREE and Th) with lower relative abundances in the basic magma ($C_B < C_A$), which will produce a positive correlation (Fig. 4C).

It is noteworthy that, depending upon whether one or more basic magmas is injected into the granitic host magma (e.g., B and/or B′; Fig. 4), a more or less scattered distribution of microgranular enclaves will result in interelemental variation diagrams (e.g., Zorpi *et al.*, 1989). Also, variable compositions of the evolved products of the basic magma(s) (E and/or E′; Fig. 4), combined with possible compositional heterogeneities of the acid magma (A; Fig. 4), can cause scatter along the mixing lines AE and/or AE′.

Further refinements of the proposed model should consider processes superimposed on the three stages, such as chemical modification of enclaves by closed-system crystal/liquid fractionation, diffusion, and metasomatism (Eberz & Nicholls, 1990), as well as differentiation of the hybrid magmas, formed in stage 3, by mechanisms operating during acid magma evolution (e.g., McCarthy & Fripp, 1978; Michael, 1984).

CONCLUDING REMARKS

The model proposed in this paper has further implications for the evolution of acid–basic systems in calc-alkaline environments. We cannot explore all of them in detail, but offer the following ideas as worthy of further study.

The relative mass fraction of the basic magma interacting with the granite magma plays a determinant role in the mixing process responsible for the evolution of the granite magma, inasmuch as it is strictly linked to the mass fraction of the evolved products of the basic magma which will mix with the acid magma after the attainment of thermal equilibrium. However, the volume of derivative liquids which mix with the acid magma will only determine a more or less large spread of the geochemical variations of granitoids (line AE; Fig. 4), but it does not invalidate the proposed model.

In analyzing the anatomy of composite batholiths, one must consider the fact that microgranular enclaves occur not just in monzogranitic and granodioritic plutons, but also, and in larger amounts, in tonalitic plutons. Most tonalitic plutons display mineralogical and geochemical characteristics similar to those of microgranular enclaves at the same degree of evolution [see Fig. 2, and, e.g., Frost & Mahood (1987), Poli *et al.* (1989), and Dorais *et al.*

(1990)]. Therefore, we argue that tonalitic plutons may have the same origin as enclaves, i.e., they may be considered as having formed during stages 1 and 2 described above, although on a much larger scale. It is further suggested that the factor determining whether microgranular enclaves dispersed within a host granite or tonalitic plutons form is the relative mass fraction of the basic magma interacting with the granite magma. Microgranular enclaves will occur when the mass fraction of the basic magma is about 30–40% of the total system [see also Frost & Mahood (1987)], whereas tonalitic plutons will occur when the mass fraction of the basic magma is substantially higher (~60–70%). Consequently, detailed study of microgranular enclave and host granite pairs (mesoscale viewpoint) can be a useful means by which to understand the petrogenesis of composite batholiths (macroscale viewpoint), because of the possible similarity in the processes occurring in the development of both granitoid plutons bearing microgranular enclaves and the batholith as a whole.

Finally, the observed self-similarity of the petrochemical features of the microgranular enclaves, at whatever scale, suggests that the mechanics of mingling may be governed by fractal geometry (Mandelbrot, 1982). Ottino (1989), in describing the flow mechanics of viscous fluids, stated that 'mingling is stretching and folding, and stretching and folding is the fingerprint of chaos'. In other words, the spatial distribution of microgranular enclaves within host granites and their relative boundaries will be extremely irregular, convoluted, and chaotic, and can only be modelled through fractal geometry. Therefore, we suggest that a major contribution to the understanding of the kinematics of the mingling and stretching of a basic magma by an acidic magma could result from applying this new branch of mathematics to the chaotic flow mechanics of viscous fluids (Ottino, 1989).

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