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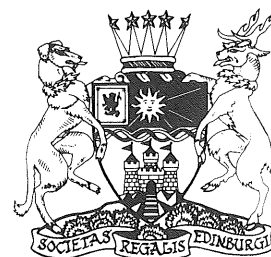
Trace element and isotopic exchange during acid–basic magma interaction processes

G. Poli, S. Tommasini and A. N. Halliday

ABSTRACT: Interaction processes between acid and basic magmas are widespread in the Sardinia–Corsica Batholith. The resulting hybrid magmas are extremely variable and can be broadly divided into: (i) microgranular mafic enclaves with geochemical characteristics of both magmatic liquids and cumulates; (ii) basic gabbroic complexes with internal parts mainly formed by cumulates and with interaction zones developing only in the marginal parts; and (iii) basic septa with the form of discrete, lenticular-like bodies often mechanically fragmented in the host rock. Different styles of interaction, ranging from mixing to mingling, have been related to variations in several physico-chemical parameters, such as: (i) the initial contrast in chemical composition, temperature and viscosity; (ii) the relative mass fractions and the physical state of interacting magmas; and (iii) the static versus dynamic environment of interaction.

A model is presented for the origin and history of interaction processes between basic and acid magmas based on the geochemical characteristics of hybrid magmas. Physico-chemical processes responsible for the formation of hybrid magmas can be attributed to: (i) fractional crystallisation of basic magma and contamination by acid magma; (ii) loss of the liquid phase from the evolving basic magma by filter pressing processes; (iii) mechanical mixing between basic and acid magmas; and (iv) liquid state isotopic diffusion during the attainment of thermal equilibrium.

KEY WORDS: Acid–basic interaction, Sardinia–Corsica Batholith, mixing, mingling, physico-chemical parameters.



The interaction between acid and basic magmas is increasingly considered to be one of the main mechanisms for the genesis of composite batholiths (e.g. Halliday *et al.* 1980; Reid *et al.* 1983; Frost & Mahood 1987; Holden *et al.* 1987; Poli *et al.* 1989; Didier & Barbarin 1991a).

The generation of felsic magmas mainly occurs in those portions of the continental crust to which hotter mafic magmas have access (Huppert & Sparks 1988). The coexistence of at least two magmas of different composition and different temperatures is inherent in these models. There is abundant field, petrographic and petrochemical evidence that comingling and mixing do occur in the plutonic environment, not only on a local scale, but to produce considerable batches of magma. It has been suggested that large volumes of calc-alkaline magma, now represented by granitic, granodioritic and tonalitic plutons, may be generated by mixing (e.g. Barbarin 1988; Poli *et al.* 1989).

Much remains to be understood regarding how and when this interaction takes place and what parameters are involved. To better understand the physical and chemical mechanisms that control interaction processes, we review the occurrence of hybrid magmas in the Hercynian Sardinia–Corsica Batholith (SCB). This is condensed into an outline, and from this a model is proposed regarding the possible origin and history of interaction processes between basic and acid magmas.

1. Associations of basic and acid rocks in the Sardinia–Corsica Batholith

The SCB was formed during the Hercynian orogeny and consists of metamorphic terranes, multiple coalescent granitoid plutons and subordinate gabbroic complexes. The magmatic activity related to the Hercynian orogeny developed during a time span of 70 million years, from 350 to 280 Ma, and has a

typical continent–continent collision, calc-alkaline signature (e.g. Poli *et al.* 1989; Rossi & Cocherie 1991; Carmignani *et al.* 1992). The sequence of intrusive events can be divided in three cycles on the basis of relationships with metamorphic rocks and structural features: (a) intrusions emplaced in a compressive syn-tectonic regime, representing 1–2% of the whole area of the batholith, and consisting of peraluminous granites *sensulato*; (b) intrusions emplaced in a late-post-tectonic regime, representing the main frame of the batholith (c. 70%), and consisting of metaluminous granites *sensulato*; and (c) intrusions emplaced in a distinctly post-tectonic regime, representing 20–25% of the whole area of the batholith and consisting of metaluminous leucogranites.

In general, the field occurrence and petrographic and geochemical characteristics of hybrid magmas are extremely variable (e.g. Didier & Barbarin 1991b). In the SCB (Fig. 1) they can be divided into three broad groups (e.g. Poli *et al.* 1989; Tommasini & Poli 1992; Tommasini 1993).

1. Microgranular mafic enclaves (MME) with geochemical characteristics of both magmatic liquids and cumulates.
2. Basic complexes (BC) in the form of discrete entities in acid plutons, with internal parts mainly formed by cumulates and with interaction zones developing only in the marginal parts.
3. Basic septa (BS) in the form of discrete, lenticular-like bodies with peninsular-like connections to the main wallrocks that do not have known floors (Best 1982); they are often mechanically fragmented in the host rock. These represent the link between groups (1) and (2) as they are similar in terms of petrography and geochemistry.

Mafic microgranular enclaves are ubiquitous in all plutons of the second group and are absent in the third group. Their abundance varies from c. 10% in tonalites and granodiorites to 1–2% in monzogranites.

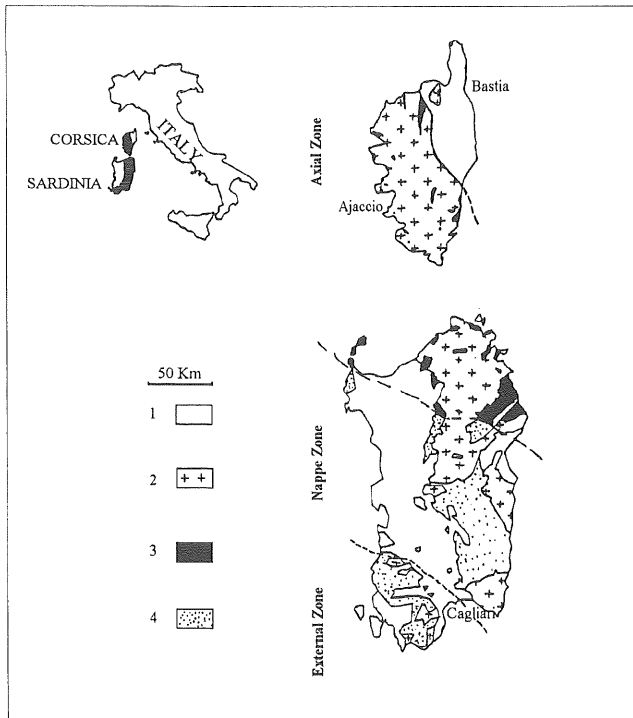


Figure 1 Geological sketch maps of the Sardinia-Corsica Batholith. (1) Post-Permian formations. (2) Granitic plutons and basic complexes belonging to the Hercynian orogenic cycle. (3) Hercynian metamorphic rocks of amphibolite facies and migmatites. (4) Hercynian metamorphic rocks of greenschist facies and anchimetamorphism.

Basic stratified complexes have been found in association with late tectonic intrusions. These outcrop over small areas and consist of gabbros and diorites with some cumulitic facies. Such complexes represent <5% of the whole area of the batholith and they are often found as septa or as large enclaves within granodioritic and monzogranitic plutons. Their emplacement is coeval with the host granites facies and mingling phenomena along the contacts indicate that such basic magmatism had an important role in the genesis of the SCB (Tommasini 1993).

Mafic microgranular enclaves vary in composition from gabbros and diorites to tonalites and generally have fine-grained hypidiomorphic equigranular textures, although ophitic textures are present in the less evolved samples. Mono- and polymineralic fragments of the host granite are ubiquitous in hand specimen. The main minerals are quartz + plagioclase \pm K-feldspar + biotite \pm amphibole \pm clinopyroxene, whereas the accessory phases are oxides + apatite + zircon \pm titanite \pm allanite. Clinopyroxenes may occur as relics enclosed within hornblende cores and plagioclase displays complex zonation patterns with patchy textures. Other textures attributable to magma mixing—for example, acicular apatite, spike zones in plagioclase, poikilitic/oikocrystic K-feldspar and quartz (Hibbard 1991)—are often found.

Basic complexes and septa consist of medium-grained amphibole-bearing gabbros and quartz gabbros with autoalloctriomorphic and cumulate textures. In the outer parts of the BC and BS, samples are medium- to fine-grained with hypidiomorphic porphyritic textures and glomerocrystals of plagioclase and amphibole. The main minerals are the same as for the MME, but mafic phases are modally more prevalent, together with amphibole-clinopyroxene textures, and patchy zoning in plagioclase. When present, the K-feldspar is found only as an interstitial phase.

Metaluminous granitoids consist of medium-coarse-grained rocks with hypidiomorphic heterogranular textures due to

K-feldspar megacrysts. The main minerals are quartz + plagioclase + K-feldspar + biotite \pm amphibole, whereas the accessory phases are oxides + apatite + zircon \pm titanite \pm allanite. In the tonalitic rocks plagioclase commonly has a patchy zoning texture and within hornblende cores clinopyroxenes may occasionally be found.

Elements representative of different geochemical behaviour are plotted in Figure 2 to give an overview of the main trends followed by the calc-alkaline magmas in the SCB. The arrows indicate the trends caused by various processes. The white arrow indicates the evolutionary trend of mantle-derived magmas caused by simple fractional crystallisation or contamination plus fractional crystallisation processes (CFC; Poli & Tommasini 1991a). This process produces magmas rich in lithophile elements and poor in compatible elements (Fig. 2). Most MME and the outer zones of gabbroic masses and BS, in contact with the enclosing granitoids, are representative of these magmas. It is worth noting, however, that most inner zones of gabbroic masses and basic septa show high values of all the elements at low silica content (hatched arrow, Fig. 2). This can be due, in part, to having plotted in the diagrams all the data from the different areas of the batholith, though other processes are also superimposed. Samples plotting along the hatched arrow, in fact, have petrographic and geochemical characteristics (e.g. rare earth element pattern, Fig. 3A) suggesting that they have experienced crystal accumulation, mainly of phases such as amphibole and accessory minerals (Co, La, Th, Zr, Fig. 2). High contents of Rb and K are probably caused by replacement of amphibole by biotite (e.g. Johnston & Wyllie 1988). In addition, it is notable that samples belonging to MME have geochemical characteristics (Fig. 2 and 3B) of both evolved (white arrow trend) and cumulate (hatched arrow trend) rocks, though none has petrographic textures evidencing cumulus processes. Such a feature is fairly common and it is supposed to be the result of filter pressing processes (e.g. Hibbard 1995), which are likely to occur during the interaction between magmas of different viscosities. Thus MME can be representative of either evolved basic liquids or basic magmas with cumulus-like geochemical signatures caused by mechanical squeezing.

The other two arrows in Figure 2 point to the two main evolutionary processes of acid magmas. The grey arrow trend is caused by interaction processes with evolving basic magmas. Two distinct periods of interaction can be envisaged namely (i) during the attainment of thermal equilibrium mainly mingling processes occur (Poli & Tommasini 1991a) and (ii) after the attainment of thermal equilibrium mainly mixing processes occur between derivative products of basic magmas (trend followed by grey arrow) and acid magmas (e.g. Frost & Mahood 1987; Poli & Tommasini 1991a). The black arrow trend is mainly caused by crystal fractionation processes. It is notable that leucogranites follow only this trend as they do not have any field, petrographic and geochemical evidence of interaction processes with basic magmas, such as, for instance, the presence of microgranular enclaves and patchy zoning of plagioclase.

For the sake of clarity we assume that, from a geochemical point of view, evolutionary trends during basic acid magma interaction can be subdivided into three main types on the basis of three parameters: the compositions of acid (C_a) and basic (C_b) magmas and the bulk partition coefficient (D) of a given element in the basic magma (Poli & Tommasini 1991a). For elements with $D < 1$ and $C_a \approx C_b$, mafic microgranular enclaves and outer zones of gabbroic masses and basic septa (e.g. Zr and La, Fig. 2) follow an upward trend determined by simple fractional crystallisation or contamination plus fractional crystallisation processes acting during the attainment of

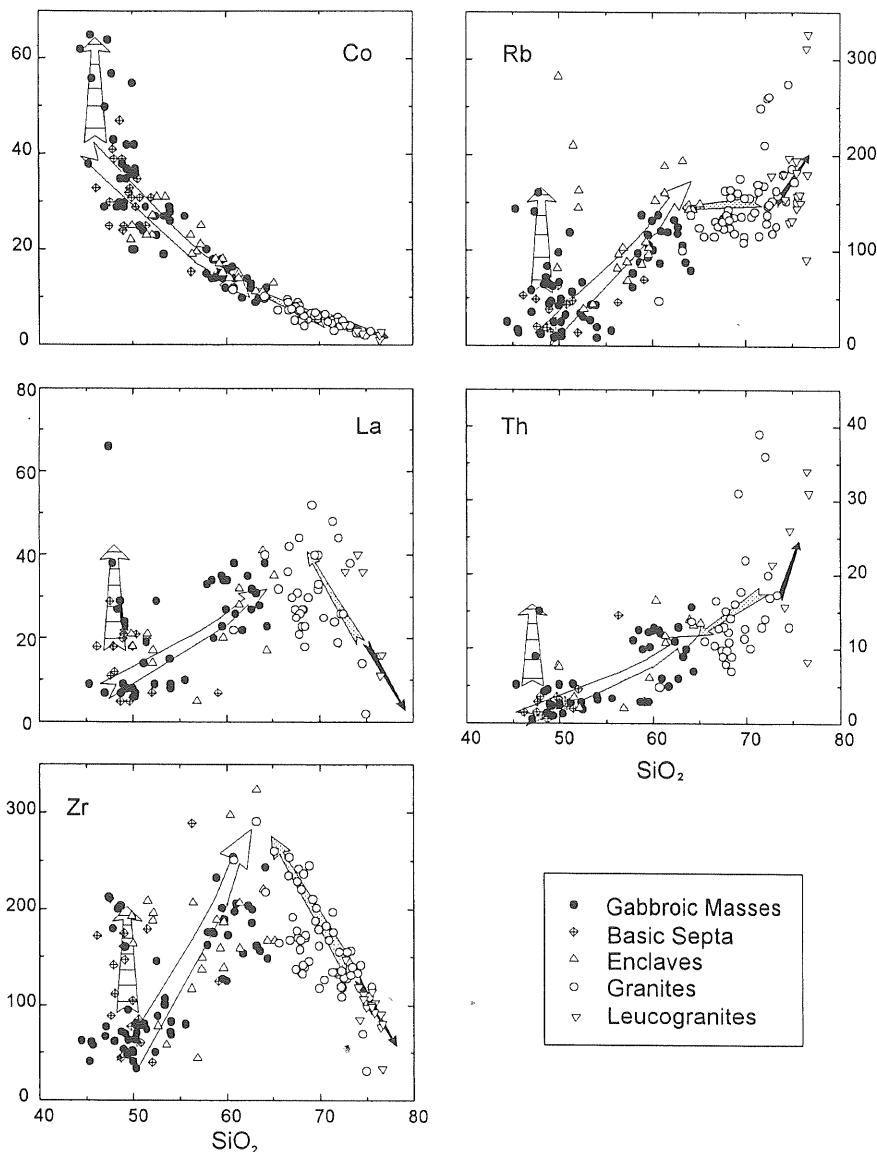


Figure 2 Harker diagrams illustrating the main trends exhibited by rock samples of the Sardinia-Corsica Batholith. General trends caused by different processes are indicated by arrows (see text for explanation): white arrows, evolution of basic magmas by CFC processes; hatched arrows, evolution of basic magmas by cumulus and/or filter pressing processes; grey arrows, evolution of acid magmas by interaction processes; and black arrows, evolution of acid magmas by crystal fractionation processes. Data from Tommasini (1993).

thermal equilibrium. As soon as this is attained the evolved magmas mix with the acid magma to give hybrid granitoids and in the geochemical space a bell-shaped pattern can be recognised (e.g. La and Zr, Fig. 2). For elements with $D < 1$ and $C_b \ll C_a$ in the geochemical space an upward trend for all the groups can be recognised (e.g. Th and Rb, Fig. 2). For elements with $D > 1$ and $C_b \gg C_a$ a downward trend for all the groups can be recognised (e.g. Co, Fig. 2).

2. Isotope geochemistry: case study of the Punta Falcone, northern Sardinia

From an isotopic point of view the problem seems more complex, as the isotopic characteristics of the products of interaction between acid and basic magmas cannot be explained by simple CFC processes. Microgranular mafic enclaves and granites are relatively uniform in isotopic terms, whereas the internal facies of gabbros and septa are slightly more distinct from granites. This behaviour is common in the Sardinia-Corsica Batholith (Tommasini 1993), but also in other associations of MME and BC and granitic plutons (e.g.

Halliday *et al.* 1980; Holden *et al.* 1987, 1991; Pin *et al.* 1990). This does not necessarily prove a genetic connection between mafic bodies and granites (e.g. Stephens *et al.* 1991), but nevertheless remains a particular characteristic that must be taken into account in petrogenetic modelling of the interaction between acid and basic magmas.

The Punta Falcone gabbroic complex was emplaced into a granitic magma during the Hercynian orogeny (Poli & Tommasini 1991b; Tommasini & Poli 1992). The complex has a stratified subvertical structure and consists of three zones developing from the bottom to the top of the magma chamber. An interaction zone (IZ), a maximum of 2 m wide, can be recognised along contacts with the surrounding granite and consists of finer grained and more evolved rocks than the interior of the gabbroic complex. Trace element geochemistry indicates that the IZ is the result of the processes of fractional crystallisation plus contamination by the acid magma (CFC process, Tommasini & Poli 1992).

Strontium isotopic analyses of representative samples of the Punta Falcone complex are reported in Table 1. Isotopic modelling indicates that the mantle source of the Punta

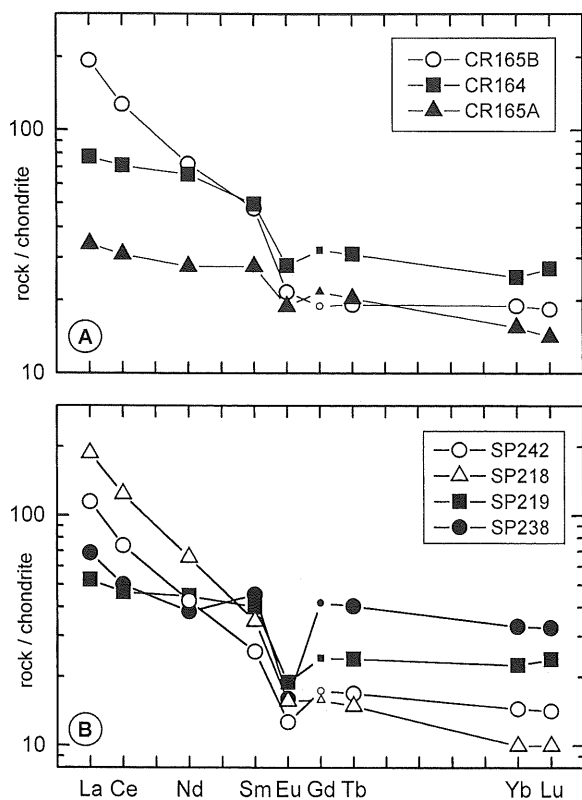


Figure 3 Chondrite-normalised (Haskin *et al.* 1966) rare earth element patterns of selected rocks from the Sardinia-Corsica Batholith. (A) Basic septa that experienced no (open symbol) or variable amounts (closed symbols) of amphibole accumulation; (B) mafic microgranular enclaves that experienced (closed symbols) or did not experience (open symbols) filter pressing processes. Normalised values for Gd are interpolated.

Falcone basic magma was enriched in incompatible elements via sediment entrainment through subduction in the Ordovician (Tommasini *et al.* 1995). This explains the radiogenic Sr isotope characteristics of the inner parts of the complex which did not suffer low pressure contamination processes with the surrounding granites. Applying the CFC process to reproduce Sr isotopic ratios in IZ samples, there are significant discrepancies between the observed and calculated compositions, both using the value of r (contamination rate over fractionation rate; DePaolo 1981) estimated for trace elements by Tommasini and Poli (1992) ($r=0.3$; broken lines in Fig. 4), as well as trying to use higher r values ($r=0.7$; dotted lines in Fig. 4), which are thermodynamically unlikely and which are not consistent with the absolute trace element

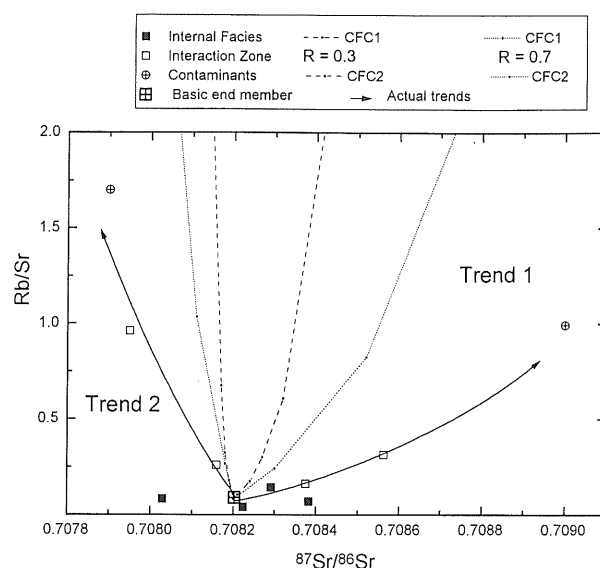


Figure 4 Evolution lines of the CFC process applied to the Sr isotopes of the Punta Falcone complex. Bulk partition coefficients (D) of the evolution lines for $r=0.3$ (broken lines) are the same as those used for trace elements (Tommasini & Poli 1992; Tommasini 1993). The values of D are ${}^{Rb}D_{CFC1}=0.1$, ${}^{Rb}D_{CFC2}=0.7$, ${}^{Sr}D_{CFC1}=1.05$ and ${}^{Sr}D_{CFC2}=1.25$. Evolution lines for $r=0.7$ (dotted lines) are calculated using the same bulk partition coefficients. Intervals (10%) of degree of fractionation (F) are reported as small closed circles. The actual lines are hand-drafted (solid lines). Contaminating magmas: for trend 1 SP58 and for trend 2 an hypothetical composition on the basis of SP146 sampled at the contact with IZ is assumed (Tommasini 1993).

concentrations in the IZ samples. This suggests that isotopic variations in the IZ samples are controlled by other mechanisms in addition to a CFC process, which would have caused only slight variations in Sr isotopes (Fig. 4). Alternatively, Sr isotope variations in the IZ samples could have been determined by a liquid state diffusion in addition to contamination during the attainment of thermal equilibrium. In this case of liquid state chemical diffusion it is essential to take into account the values of chemical and thermal diffusion coefficients (Blake & Koyaguchi 1991). As thermal diffusion coefficients are many orders of magnitude (certainly more than 4–5; Hoffman 1980) greater than chemical diffusion coefficients, thermal equilibrium is reached much sooner than chemical equilibrium. This, along with the fact that diffusion coefficients are inversely correlated with temperature (e.g. Hofmann 1980), notably limits the effects of chemical interaction processes due to diffusion mechanisms during the attainment of thermal equilibrium, at least as far as the diffusion of elements is

Table 1 Rb–Sr isotopic data: All Sr isotopic analyses were normalised to ${}^{86/88}\text{Sr}=0.1194$. Repeated analyses of NBS987 standard gave an average of ${}^{87}\text{Rb}/{}^{86}\text{Sr}$ of 0.71025 ± 1 (2σ , $n=20$). Uncertainties in measured and initial isotopic ratios refer to least significant digits and represent $\pm 2\sigma$ run precision and $\pm 2\sigma$ error propagation. GIF, Gabbroic Internal Facies; IZ, Interaction Zone; GR IZ, Granite-Interaction Zone; and HGR, Host Granite.

Sample	Unit	Rb	Sr	${}^{87}\text{Rb}/{}^{86}\text{Sr}$	${}^{87}\text{Sr}/{}^{86}\text{Sr} \ 2\sigma$	${}^{87}\text{Sr}/{}^{86}\text{Sr}_i \ 2\sigma$
SP96	GIF	18.44	223.1	0.2391	0.708995 \pm 31	0.70803 \pm 3*
SP39	GIF	12.08	299.3	0.1168	0.708695 \pm 17	0.70822 \pm 2
SP77	GIF	26.06	381.4	0.1978	0.709182 \pm 21	0.70838 \pm 2
SP81	GIF	42.16	299.9	0.4067	0.709935 \pm 13	0.70829 \pm 2
SP67	IZ	43.24	266.4	0.4697	0.710273 \pm 14	0.70838 \pm 2
SP102	IZ	78.89	252.5	0.9042	0.712217 \pm 31	0.70856 \pm 3
SP147	IZ	74.37	287.1	0.7496	0.711188 \pm 21	0.70816 \pm 2
SP32	IZ	136.6	142.0	2.785	0.719203 \pm 19	0.70795 \pm 2
SP146	GR IZ	118.2	203.3	1.683	0.714768 \pm 16	0.70797 \pm 2
SP55	HGR	131.1	200.8	1.891	0.716139 \pm 13	0.70850 \pm 2
SP58	HGR	155.2	156.6	2.872	0.720584 \pm 15	0.70898 \pm 2

*Initial Sr isotopes have been calculated at 284 Ma, i.e. the most probable age of PF complex based on Rb/Sr isochrone (MSWD=1.05; age 284 ± 7 Ma (Tommasini 1993).

concerned. On the other hand, experimental studies (Baker 1989; Leshner 1990, 1994) pointed out that isotope diffusion coefficients are much (at least more than three orders of magnitude) higher than chemical diffusion coefficients, indicating that isotope re-equilibrium occurs more rapidly than chemical re-equilibrium.

Quantitatively, using Equation (1), an increase of 10^4 in the diffusion coefficient changes the order of magnitude of the effective area of diffusion by a factor of two, i.e. from centimetres to metres. Therefore the probability that chemical changes take place in a basic magma interacting with an acid magma while reaching thermal equilibrium is greater for isotopes than for trace elements. Thus it is reasonable to hypothesise that the CFC evolution of the IZ was associated with diffusion processes which substantially modified the Sr isotopes, but did not have any major influence on trace elements.

To assess the importance of diffusion processes, we assumed that the isotopic differences between the values modelled by the CFC process using trace elements (Fig. 4; CFC trends for $r=0.3$, broken lines) and the values on the actual trends (Fig. 4; solid lines) have been caused by diffusion. It was further assumed that the initial values for the starting basic end member are the same, whereas the acid end-members are different. It is noteworthy that in trend 1 the basic end-member has lower Sr isotope values than the acid end-member, whereas the opposite holds for trend 2. Although CFC and diffusion processes act together, the net result can be modelled for each sample as the sum of isotopic ratios deriving from the two processes. This means that in modelling isotope diffusion, we considered the isotopic ratios and Sr values calculated using CFC process as initial composition of the basic end-member for each sample.

Strontium isotope diffusion in the IZ of the gabbroic complex has been calculated using the equation for a semi-infinite plane sheet medium with initial concentration C_0 (gabbroic mass) and constant surface concentration C_1 (host granite). The general solution [Equation (1)] for a diffusion process in such a geometry can be found in Crank (1975: eq. 3.13)

$$\frac{C-C_1}{C_0-C_1} = \text{erf} \frac{x}{2(Dt)^{1/2}} \quad (1)$$

where erf is the error function, C is the concentration at the distance x from the contact, D is the diffusion coefficient and t is the time elapsed from the beginning of the process.

To resolve such an equation as a function of x we need an estimation of the time scale of the duration of the interaction process. Furlong *et al.* (1991: 441) reported equations for such a problem and we have used their eq. 7

$$T = T_0 + (T_1 - T_0) * \left[\frac{1}{2} \left(\text{erf} \frac{\zeta + 1}{2\tau^{1/2}} - \text{erf} \frac{\zeta - 1}{2\tau^{1/2}} \right) \right];$$

$$\tau = \frac{kt}{a^2}; \quad \zeta = \frac{x}{a} \quad (2)$$

where T is the temperature at the distance x from the contact, T_0 is the initial temperature of the host granite, T_1 is the initial temperature of the gabbroic mass, k is the thermal diffusivity, t is the time elapsed from the beginning of the process and a is half of the thickness of the gabbroic mass.

To take into account the latent heat of crystallisation, we considered the effective thermal diffusivity, i.e. the thermal diffusivity in a magma between its liquidus and solidus (Philpotts 1990), which is lower by about one order of magnitude with respect to thermal diffusivity. Using this approach we calculated an effective thermal diffusivity of

$10^{-7} \text{ m}^2 \text{ s}^{-1}$. Considering a system composed of a basic magma at 1200°C , an acid magma at 750°C , and the solidus of the basic magma at *c.* 900°C , we estimated a time span of *c.* 2700–4500 a for cooling to proceed 2 m from the contact.

Using such values of time in Equation (1) and using the diffusion coefficient measured by Leshner (1995) for Sr isotopes, we calculated the variation in Sr isotopes as a function of the distance from the contact. The results are reported in normalised form in Figure 5, along with the normalised values of samples from IZ. Three out of four samples fit the modelled curves fairly well, indicating that the modelled process is probably reasonable. Sample SP147 has isotope ratios very close to the basic end-member, but it was sampled close to the host. Such behaviour may be due to several causes that cannot be clearly defined in this instance, e.g. (i) the sample being very close to the host it solidified more quickly than the internal parts of the interaction zone; or (ii) as the gabbroic mass tilted (Tommasini & Poli 1992), such a sample could have been in contact with different isotopic compositions from the host.

In summary, although the method used is model-dependent, the goodness of fit of the result lends credibility to the idea that the dichotomy between trace element and isotopic evolution during basic-acid magma interaction is due to isotopic diffusion during the attainment of thermal equilibrium. Further work is, however, necessary on well constrained transects between basic and acid rocks to better constrain the topology and kinetics of the isotopic diffusion process.

3. Fluid dynamic and thermodynamic parameters

Some further general features have to be evaluated to derive a genetic model for basic-acid interaction processes. Fluid dynamic and thermodynamic parameters are also critical in controlling interaction processes.

Inertial and viscous forces associated with the movement of fluids and with the floating effect (the difference in density between the two magmas) are the main fluid dynamic parameters controlling interaction processes between magmas of different chemical compositions. Experimental studies (e.g.

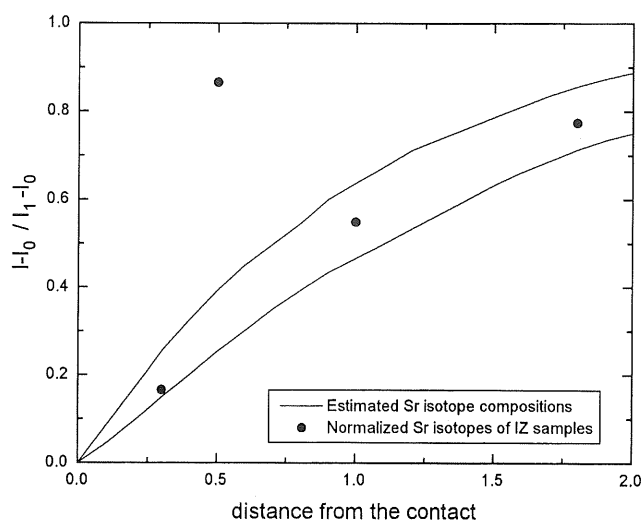


Figure 5 Calculated (solid lines) and observed Sr isotope compositions of IZ samples versus distance (m) from the granite contact. Data are presented normalised to the following equation: $(I - I_0)/(I_1 - I_0)$, where I is the Sr isotope composition of the IZ sample, I_0 the Sr isotope composition of the host granite and I_1 is the Sr isotope composition of the gabbroic complex. The estimated Sr isotope compositions have been calculated for the maximum and minimum span of time necessary for cooling to proceed 2 m inwards from the granite contact (2700–4500 a; see text).

Campbell & Turner 1985, 1986, 1989), indicate significant fragmentation and dispersion of basic magma batches into acid magma with the occurrence of extensive mechanical mixing (mingling) when the rheological behaviour of acid magma is Newtonian (e.g. Arzi 1978; Fernandez & Barbarin 1991).

When an acid magma is intruded by one or more injections of basic magma which is hotter and less viscous than the acid magma, the two magmas do not mix easily because of fluid dynamic barriers and hence remain as discrete entities while thermal equilibrium is being attained. Freezing of the basic magma and superheating of the acid magma does occur along their boundaries. The thermodynamic parameters which must be taken into account are the temperatures of the two magmas, the thermal capacities of the solid and liquid phases, the heat of fusion and the heat of crystallisation of the solid phases. These parameters, along with the relative mass fraction of basic and acid magmas, control the temperature at which the two magmas attain thermal equilibrium. At the equilibrium temperature, the final viscosities of the two magmas will be the main physical parameter controlling interaction mechanisms. Chemical mixing processes are possible when these viscosities are low and of the same order of magnitude.

Using the computer program developed by Frost and Lindsay (1988), it can be seen that, at the initial physicochemical conditions (temperature, pressure and composition) of magmas from the SCB (e.g. Tommasini & Poli 1992; Tommasini 1993), low final viscosities of the same order of magnitude in the two magmas are obtained only for high portions of basic magma in the system (c. 65–70%; Fig. 6). Therefore, the possibility of having chemical mixing processes between acid and basic magmas does not seem plausible, as it requires special conditions (very large amounts of basic magma) which cannot be considered appropriate for many interaction products. However, during the attainment of thermal equilibrium, the basic end-member is continuously evolving (Poli & Tommasini 1991a). To account for the evolution of the basic magma we used the program by Frost and Lindsay (1988) assuming, for the sake of simplicity, the radical view that during each step the interacting liquids do not contain crystals. Formally we used extreme values of the parameter σ (see Frost & Lindsay 1988) to reach this condition.

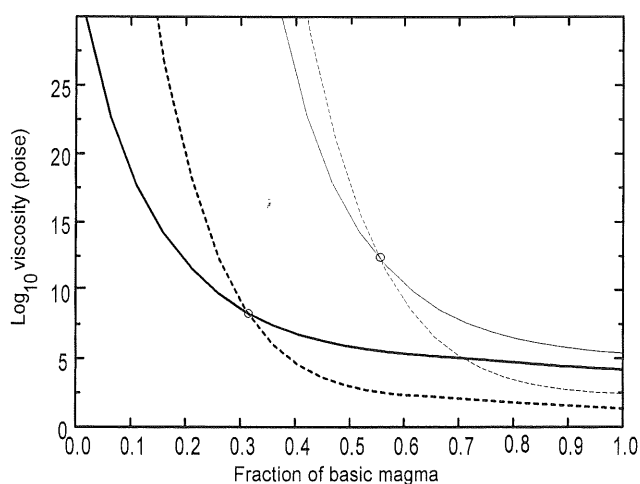


Figure 6 Variations of final viscosity in a basic (solid line) and acid (broken line) liquid at the thermal equilibrium temperature as a function of the fraction of basic magma in the system. Circles represent the points of equal viscosity for a basic magma starting at 1193°C and acid magma starting at 800°C, respectively. Light lines follow Frost & Lindsay (1988). Heavy lines assume that the interacting liquids do not contain crystals and use different evolved chemical compositions of basic magma (see text).

In addition, we divided the evolving period into many steps and used for each step a more evolved chemical composition and a different initial temperature to calculate the viscosity at thermal equilibrium. Given all these assumptions, only a first approximation model of the system can be derived. Nevertheless, the model is considered valid for acid members in view of its overheating along the contacts with the basic member (Huppert & Sparks 1985) and for the basic member in view of the fact that it is an evolved liquid and not a crystal mush, even if in actual situations it may contain some crystals.

In Figure 6 it can be seen that the amount of basic magma in the overall system can be as low as 30% for interacting magmas starting at 1200°C (basic) and 800°C (acid), respectively. Such values are much closer to those inferred for a variety of interaction products such as plutons containing MME (e.g. Didier & Barbarin 1991a).

4. Model for the association of basic and acid rocks

The geochemical and physical aspects of acid–basic magma interaction have been analysed by attempting to isolate different phenomena. The highly variable geochemical characteristics of interaction products are the result of several processes acting concomitantly following the intrusion of basic magmas into anatectic crustal environments and can be attributed to: (i) fractional crystallisation of basic magma and contamination by acid magma (CFC process, Poli & Tommasini 1991a); (ii) alkali and H₂O exchanges; (iii) loss of the liquid phase from the evolving basic magma by filter pressing processes; (iv) mechanical mixing between basic and acid magmas; and (v) isotopic diffusion processes during the attainment of thermal equilibrium. It is noteworthy, in addition, that the internal facies of the gabbroic complex and basic septa become cumulate by the settling of crystallising phases.

From the physical point of view many aspects have to be taken into account.

1. Magmas of different compositions and thermodynamic parameters do not mix because of fluid dynamic barriers and hence remain as discrete entities until thermal equilibrium is attained. As a corollary, freezing of the basic magma and superheating of the acid magma does occur along their boundaries.
2. The initial effective viscosity of acid magma acts as the main parameter for the evolution of the system. In fact, for high values, corresponding to solid–plastic rheology, mechanical mixing and interaction processes are possible along limited parts of the boundaries.
3. Chemical mixing, generating hybrid rocks, will be enhanced when the final viscosities of the two magmas are low and of the same order of magnitude, whereas mechanical mixing will take place when the viscosities are very different from each other.
4. Larger amounts of basic magma in the overall acid–basic system favours the chemical mixing process. Large initial differences in temperature, viscosity and chemical composition in the two magmas, however, tend to inhibit chemical mixing and limit the mechanical mixing interaction processes.

The MME, BS and BC are, hence, the result of the conjunction and superimposition of the physico-chemical processes suffered by basic magma after the intrusion in the crustal anatectic environment. Poli and Tommasini (1991) proposed a genetic model to explain the genesis of enclaves and it is also valid for all products with further reference to the rheology of interacting magmas. The model consists of three main stages concerning the evolution and mixing versus

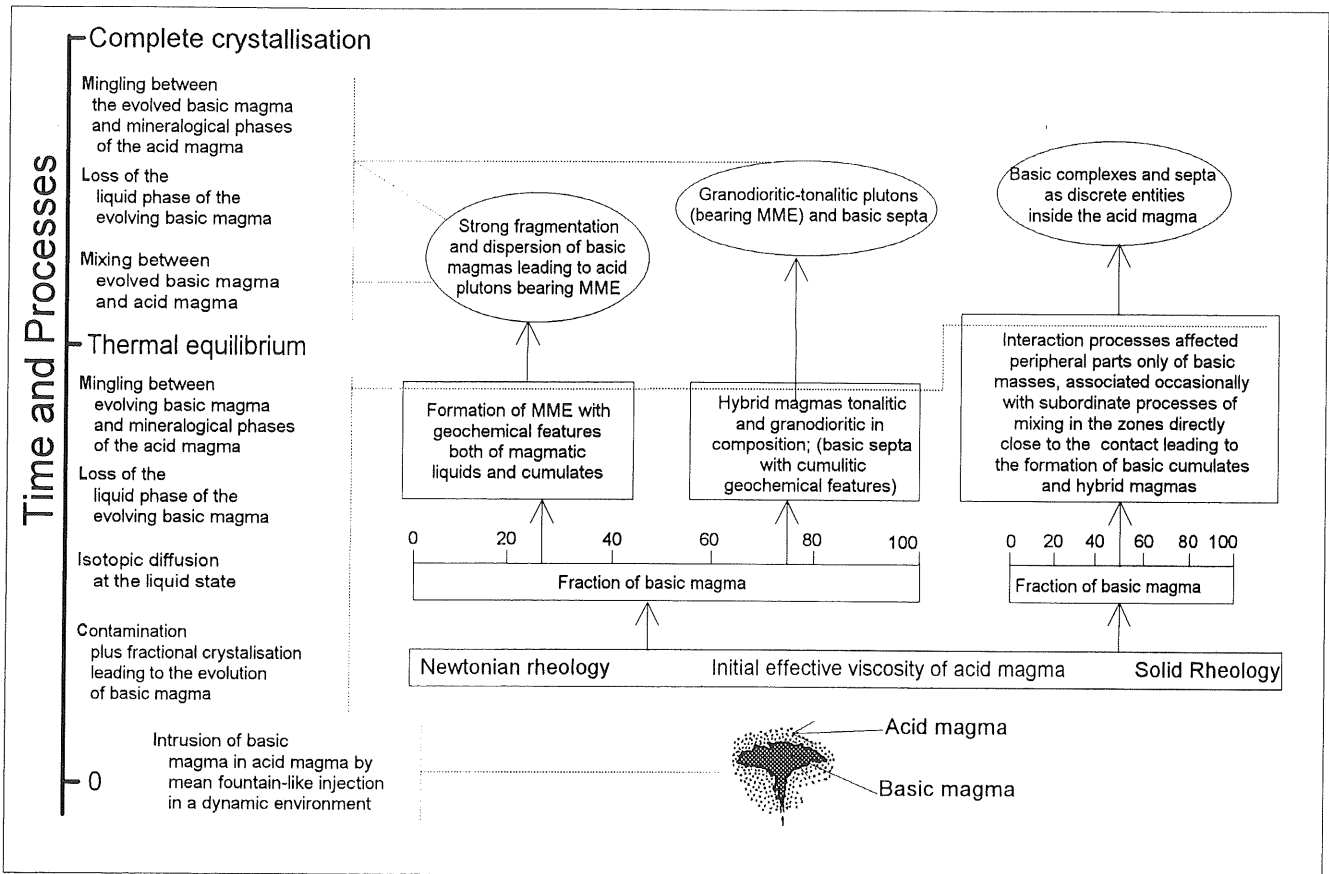


Figure 7 Schematic diagram summarising various environmental settings of interaction processes among basic and acid magmas.

mingling processes which basic magmas experienced, once injected into anatexic crustal environments.

A schematic picture of the different environmental settings during basic acid magma interaction is shown in Fig. 7. A mechanism of fountain-like injection is considered, but processes of internal instability of the basic magma leading to fingering of the acid in the basic magma and vice versa must also be taken into account. During the attainment of thermal equilibrium the evolution of the basic magma is determined by (i) contamination plus fractional crystallisation along with (ii) liquid state isotopic diffusion, (iii) mechanical mixing of the evolving magma with mineralogical phases of the acid magma and (iv) loss of liquid phase of the evolving magma.

The different products of interaction depend on two physical parameters: the relative fraction of basic magma and the initial effective viscosity of acid magma, i.e. the viscosity of bulk magma taking into account the pressure, temperature, chemical composition and percentage and texture of suspended crystals. Two main cases can be envisaged: (i) granitic magmas with rheology intermediate between visco-plastic and solid; and (ii) granitic magmas with rheology intermediate between Newtonian and visco-plastic.

In the first case, the fraction of basic magma is relatively important as the rheological behavior of acidic magma does not allow the fragmentation of basic magmas which preserve their shape discrete from acid magmas and hence during the attainment of thermal equilibrium these processes occur only along the borders, and no significant effect of mixing between the acid and evolved basic magma along the contacts can be recognised after thermal equilibrium has been attained. Therefore in this setting only BC and BS can be found as discrete entities within acid magma. The internal parts of these

bodies behave as simple gabbroic complexes leading to cumulitic rocks.

In the second setting (Newtonian rheology of acid magma), the fraction of basic magma is important in understanding the interaction processes. For low values of basic magma during the attainment of thermal equilibrium, basic magma is subject to all the described processes, leading to the formation of an evolved magma that can undergo processes of mixing and mingling with the acid magma and the formation of dispersed MME in granitic plutons. The rheological behaviour of the host acidic magma and the relatively low amount of basic magma in the system gives rise to strong fragmentation of the evolved magma and the MME are representative of the evolutionary processes undergone by the basic magma after intrusion into the crustal anatexic environment.

When the fraction of basic magma is high, during the attainment of thermal equilibrium, basic magma is subject to all these processes, leading to the formation of large amounts of hybrid magma of tonalitic-granodioritic composition that can undergo, after thermal equilibrium has been attained, processes of mechanical mixing and loss of the liquid phase.

Such mechanical mixing can lead to the formation of BS with geochemical characteristics of both magmatic liquids and cumulates, but MME can also be found in this instance. Relatively less extreme values of the basic magma fraction and/or relatively low differences in temperature and chemistry between the acid and basic magmas allow fragmentation of the evolving magma. Therefore this environmental setting leads to the formation of hybrid magmas with tonalitic to granodioritic compositions and BS with geochemical characteristic of both magmatic liquids and cumulates.

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