

# Dissolution of tonalitic enclaves in ascending hydrous granitic magmas: An experimental study

O. García-Moreno <sup>a,\*</sup>, A. Castro <sup>b</sup>, L.G. Corretgé <sup>a</sup>, H. El-Hmidi <sup>b</sup>

<sup>a</sup> *Dpto. Geología, Univ. Oviedo, C/J.A. Velasco s/n 33005, Oviedo, Spain*

<sup>b</sup> *Dpto. Geología, Univ. Huelva, Avda. de las Fuerzas Armadas s/n. 21071, Huelva, Spain*

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## Abstract

Dissolution of natural mafic magmatic enclaves in a hydrous leucogranitic synthetic melt has been tested experimentally. Results suggest that the mechanism of enclave dissolution is a potential hybridization process in granitic systems. Experiments performed in decompression, simulating ascending magmas, show interesting results: from 10 kbar to 4 kbar, for a given temperature, enhanced dissolution of the tonalitic enclave into the melt has been observed, compared with experiments at constant pressure. Furthermore, the composition of the melt changed to higher CaO, FeO and MgO contents. Dissolution textures on relict crystals from the tonalitic enclave were monitored. These results have implications for the generation of peraluminous monzogranites and granodiorites and an example for the Cabeza de Araya (Cáceres, Spain) from the “serie mixta” of the Iberian Massif is given. The tonalitic enclaves that are partially dissolved may be early or coeval intrusions into the granite magma or even into the source migmatitic area. Many mineralogical, geochemical and isotopic features of monzogranites (e.g.: reverse zoning in plagioclase, low Sr isotopic ratios) are accounted for by this mechanism of enclave dissolution during ascent and emplacement. © 2006 Elsevier B.V. All rights reserved.

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## 1. Introduction

Most granites forming large batholiths emplaced in the upper crust depart in their compositions from that of the granite minimum first determined by Tuttle and Bowen (1958). This is so even for cordierite-bearing peraluminous monzogranites, which are apparently products of anatexis of pelites, but are richer in Ca compared with migmatite leucosomes and experimental melts derived from pelitic or semipelitic materials (Vielzeuf and Schmidt, 2001). These and other geo-

chemical features have led to the suggestion of a hybrid origin for those granites in which a mantle component can be easily identified (Patiño Douce, 1999). Although the required mantle component may be provided by the interaction with intermediate magmas represented by mafic magmatic enclaves (MME) (Barbarin, 2005), the mechanism by which these enclaves have contributed to the hybrid magma is not completely understood. The study of mafic magmatic enclaves and their implications for granite petrogenesis has become among the most important points of interest in the recent history of granite petrology (Didier, 1973; Didier and Barbarin, 1991). The fact that MME have nearly identical features in granites of varying ages and in varying tectonic

\* Corresponding author. Fax: +34 98 5103103.

E-mail address: [olga.garcia@geol.uniovi.es](mailto:olga.garcia@geol.uniovi.es) (O. García-Moreno).

settings suggests that an understanding of these features may provide insight into basic processes of melt generation. This is especially true for I-type granites (Chappell and White, 1974; Chappell et al., 1987), which are the most abundant granites, forming the large granite batholiths that characterize orogenic environments, either in continental active margins (e.g. the Andes and Sierra Nevada) or in collisional belts (e.g. the Caledonian and Variscan batholiths of Europe). Several lines of evidence suggest a magmatic origin for MME. Among these are field relations, indicating synplutonic injection of mafic dikes (Pitcher, 1991; Barbarin, 2005), textural relations indicative of crystallization from a liquid (Vernon, 1990, 1991) and geochemical and isotopic signatures indicating that MME are hybrids (e.g. Holden et al., 1987; Vernon, 1990; Elburg, 1996).

Although several studies of MME-bearing granitoids have shown a genetic link between MME and their host granitoids (e.g. Holden et al., 1987), these links have not received much attention possibly due to the finding of contradictory and paradoxical relations. For example, in many cases, both the MME and their granite hosts may have reached equilibrium for Sr isotopic ratios but not for Nd isotopic ratios (Holden et al., 1987, 1991; Di Vincenzo et al., 1996; Waigh et al., 2000). In other cases, where a complete isotopic equilibrium between MME and host granites has been shown, magma mixing and mingling may be the main hybridization mechanism as pointed out in the recent study of Barbarin (2005) on MME of the central Sierra Nevada batholith.

Decoupling of the isotopic relations has been explained in terms of contrasting diffusion rates (Leshner, 1990, 1994), which should be slower for Nd than for Sr. Since geochemical homogeneity between enclave–host pairs is commonly observed (Holden et al., 1991) and isotopic equilibrium is more easily attained than chemical equilibrium for major elements, this decoupling must be explained in terms of a different mechanism than only different diffusion rates. Differences in the Nd isotopic ratios (but in Sr ratios) should be a consequence of an alternative process responsible for selective homogenization. Petford et al. (1996) suggested that advection is more effective than diffusion in transporting chemical components between acidic magma and enclaves. They consider Sr equilibration, but Nd and REE disequilibrium. They explained this lack of equilibration as a consequence of Nd and REE being retained in early crystallized phases and excluded from the melt. Hence, distribution coefficients for Sr, Nd and REE are key to our study of enclave dissolution.

In this paper, we propose an alternative to models of magma mixing/mingling to account for the presence of MME in granites and how these MME may interact with the hosts. Experimental work presented here demonstrates that the dissolution of solid MME occurs during decompression in a water-undersaturated magma. Experiments have been performed to constrain the natural conditions at which dissolution can take place. The results of this study may have implications for the understanding of hybridization processes between granites and mafic intrusions, and may account for the observed decoupling between isotope systems and elements in such interaction processes.

## 2. Rationale

Addition of CaO and other mafic components, including MgO and FeO to minimum melt granite compositions, has been inferred from geochemical trends in monzogranites and granodiorites around the world (e.g. Patiño Douce, 1999), pointing to some kind of hybridization processes in their genesis. Characteristics of Iberian Crd-bearing peraluminous monzogranites (Capdevila et al., 1973) strongly suggest that granitic melts that were supposedly formed by partial melting of metasedimentary rocks acquired a more mafic signature at some stage during crystallization or magma ascent and emplacement (García-Moreno, 2004). The best example of the Iberian Crd-bearing peraluminous monzogranites in the Iberian Massif (Spain and Portugal), the cordierite monzogranites of Cabeza de Araya (Corretgé, 1971), have been the subject of an experimental study (García-Moreno, 2004). In that study, a non-primary origin for the cordierite monzogranites (García-Moreno et al., 2003) was inferred, suggesting a hybrid origin for this special type of granites. A characteristic feature supporting the addition of a mafic component is the relatively low Sr initial isotopic ratios displayed by these granites (Castro et al., 1999). However, some petrological evidence, which will be discussed below, as well as mass balance calculations, make the process of magma mixing unlikely. Other mechanisms of hybridization, such as assimilation, were also tested in the study of García-Moreno (2004).

The lack of a likely mechanism of hybridization and the presence of scarce MME, interpreted as remnants of synplutonic intrusions of diorite magma (e.g. Pitcher, 1991; Barbarin, 2005) points to these intrusions as a potential source for those mafic signatures.

Tonalitic enclaves are scarce in these granites compared to other granites in the Iberian Massif

(García-Moreno and Corretgé, 2000); scarcity of MME is a common feature of two-mica leucogranites and “serie mixta” granites in the Iberian Massif (Capdevila

et al., 1973). Nevertheless, the scarce enclaves show characteristics that provide evidence for some sort of interaction between enclaves and host. Fig. 1 shows

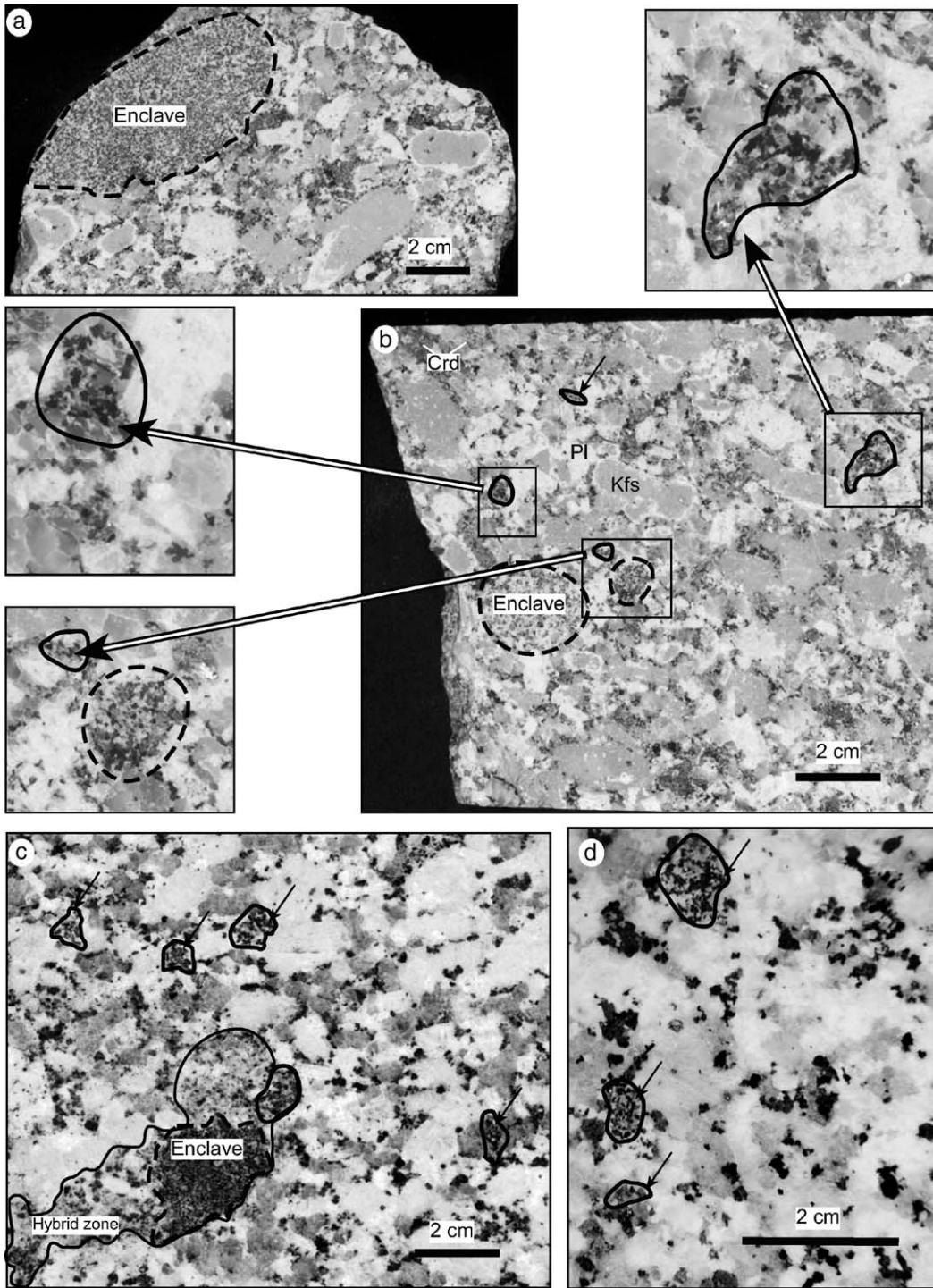


Fig. 1. Photographs of four different rock samples showing disaggregation of enclaves. Black bar is 2 cm. a and b correspond to Cabeza de Araya granites (Cáceres, Spain). K-feldspar is stained in yellow (grey in half-tone picture) with cobaltinitrite. Dashed lines enclose enclaves; black continuous lines enclose partially disaggregated enclaves. c and d illustrate two other Iberian granites.

examples of disaggregation of enclaves in two different kind of granitic rocks with diverse degree of hybridization between the enclaves and granite host. The first example corresponds with the Cabeza de Araya granites (Cáceres, Spain). Fig. 1a shows an excellent example of one of the scarce enclaves in the less differentiated facies of these granites, corresponding to a cordierite monzogranite. Fig. 1b shows the same rock example in which some textural features are distinguished that represent partially dissolved enclave fragments hybridized with the monzogranite host. This figure also shows some examples of this mechanism in two other Iberian granites (Fig. 1c and d), where very small biotite–quartz–plagioclase clusters represent remnants of almost fully dissolved enclaves.

These features of hybridization between enclave and host show the interaction of granite magma with enclaves, when the former was already solid or nearly so. Experimental work on of this style of interaction sheds light upon hybridization mechanisms that can take place in granite systems.

Some previous experimental studies by Khodorevskaya and Zharikov (2001) and Khodorevskaya et al. (2001, 2003) dealt with the interaction between a granite melt and a basic rock at different  $P$ – $T$ –wt.%  $H_2O$  conditions. The experiments presented here also deal with felsic–basic interaction, but are distinct from earlier work in terms of capsule design and decompression conditions. Some experimental results about decompression experiments by Martel and Schmidt (2003) were restricted to movement of a “pure” silicic magma in a volcanic conduit and by Hammer and Rutherford (2002) focused on crystallization induced by decompression in water-saturated melts.

Because granite minimum liquidus curves have positive slopes within the undersaturated field (Holtz et al., 2001), it is expected that the melt fraction of an ascending magma will increase if solid material is available in the system, before reaching water saturation. In the absence of a significant volume of crystals in the ascending granite magma, microgranular enclaves may be partially dissolved and may be incorporated as components into the granite magma. The supply of chemical components from the enclaves to the host granite may be dependent on the phases undergoing partial dissolution. With these premises, we have designed a series of crystallization-during-decompression experiments and the results are evaluated in this paper.

The starting materials and experimental conditions selected in this study were chosen to evaluate the behavior of a hydrous granitic melt (generated by partial

melting of crustal material) when it is emplaced at lower pressure level. One important aspect of the study is the documentation of the interaction of the granitic melt with early formed dykes or intrusions of intermediate compositions (now represented by the enclaves). The major contribution presented here is the demonstration of quite effective dissolution of enclaves under reasonable conditions.

### 3. Experimental procedure

A specific type of experimental capsule was designed to study the process of dissolution of tonalitic magmatic enclaves by hydrous granitic melt (Castro et al., 2002b). A hydrous granitic glass was synthesized using pure oxides and  $Al(OH)_3$ . Water was added to the glass as  $Al(OH)_3$  as described by Schmidt (1996). Stoichiometric proportion of Al in the hydroxide has then been calculated and corrected for the total amount of Al in the glass composition. The final hydrous glass had a 7 wt.%  $H_2O$ . The hydrous glass was finely crushed and enclosed in the experimental capsule with a very small ( $1\text{ mm}^3$ ) fragment of a natural tonalitic magmatic enclave of extremely fine-grained texture (grains < 200 microns diameter). These small enclave fragments were chosen under the binocular to be homogeneous.

Approximately 0.010 mg of hydrous glass was placed into a gold capsule, followed by the natural enclave fragment which corresponded to approximately 10 wt.% of the total starting material. Then another small quantity of hydrous glass was added to the top of the charge so that the enclave fragment was completely enclosed in the glass material. This arrangement was intended to simulate the process that would occur when a mafic enclave is enclosed in a granitic melt.

With the aim of simply observing the glass behaviour and phase relations in the granitic system at the chosen experimental conditions in the absence of enclave interaction, one of the experiments was performed using the hydrous glass without adding any enclave fragment. The starting materials for experiments correspond with natural rock compositions. The natural enclave chosen for these experiments is a microgranular enclave from the Quintana Granodiorite (Los Pedroches Batholith). The microgranular enclaves of the Quintana Granodiorite have been studied by Castro (1990). The chosen enclave, consisting mainly of plagioclase, biotite, quartz and apatite, is representative of the most widespread tonalitic enclaves in the Iberian Granites. A synthetic glass was fabricated with the composition of a selected leucosome from a migmatite of the Ollo de Sapo Gneiss from Sanabria

(Zamora, Spain) (Castro et al., 2003). This composition is very close to the granitic minimum composition. Both compositions, for the synthetic glass and tonalitic enclave, are shown in Table 1.

To study the effects of melt–enclave interaction during decompression (ascent of magma) at isothermic conditions, experiments were first performed at constant pressures of 10 and 8 kbar at three different temperatures (900 °C, 850 °C and 750 °C), followed by decompression experiments. Decompression was simulated as follows: each run was held at 10 kbar (8 kbar for 900 °C) for 4 days after which pressure was brought isothermally to 4 kbar. This final pressure was maintained for another four days. Results are summarized in Table 2, together with the average of experimental melt compositions.

Experiments were carried out in end-loaded, solid-media piston-cylinder apparatus at the University of Huelva (Spain). Cell assemblies with 12.7 mm (0.5 in.) diameter were used, NaCl-graphite cells were used for experiments at 10 kbar and CaF<sub>2</sub>-graphite cells were used for experiments at 4 kbar. Gold capsules, with a 2.4 mm inner diameter with 0.3 mm wall, containing the total 10 mg experimental charge (glass+enclave) were stored in a drying oven overnight at 120 °C to avoid any adsorbed water in the mixtures, and then were welded shut. Durations of experiments (Table 2) were from 96 h to 216 h. Capsules were examined for tears after experiments. Oxygen fugacity in our graphite-based cell assemblies is limited, as it has been demonstrated by Patiño Douce and Beard (1994, 1995), to a well-defined interval below the QFM buffer (between QFM and QFM-2). These redox conditions are very close to those of the parent magma of the rocks under study

(García-Moreno, 2004). The QFM buffer is in the range between the ilmenite and magnetite series (Takahashi et al., 1980). Temperatures were measured and controlled with Pt100–Pt87Rh13 thermocouples. Temperature stability was  $\pm 5$  °C during all the experimental runs. Pressure fluctuations were manually corrected and the estimated error is 0.5 kbar. For further experimental procedure details, see Castro et al. (1999). After the experiments, capsules were mounted in epoxy, sawed in half and polished for study.

Glass (quenched melt) and crystalline phases were analysed using a LINK-ISIS energy-dispersive spectrometer on a scanning electron microscope (JEOL-JSM5410) at the University of Huelva. Na loss was minimized by applying corrections for glass composition measurements (López et al., 2005). Melt and phase proportions were estimated by image analysis using back scattered electron images and NIH Image software (Rasband, 1999).

#### 4. Experimental results

Table 2 provides a summary of experimental conditions and results.

Results at 10 kbar show little change in melt composition from the original host (granite) composition for the lowest temperatures (750 °C). At this low temperature, there is partial crystallization of the granitic melt, without any evidence of enclave dissolution, so the solid enclave preserves unaffected and the melt fraction does not increase. On the other hand, for higher temperature (900 °C), partial dissolution of the tonalitic enclave in the hydrous melt occurs. Dissolution textures in the enclave mineral phases appear at this high temperature. Also the composition of the melt in equilibrium with these phases is modified compared with the initial glass composition, becoming more calcium-rich (Fig. 2). It can be argued that it is unlikely to have a granitic magma of sufficient temperature (900 °C) to bring about dissolution and experiments in decompression at a lower temperature may result in more plausible conditions for dissolution to occur.

Decompression experiments showed that dissolution of the tonalitic enclave into the hydrous melt is enhanced by decompression. This is likely due to getting melt–water contents close to water saturation values at lower pressure (Holtz et al., 2001): the position of the liquidus depends on melt water concentration in the Qtz–Ab–Or system (see discussion below and Fig. 3a).

Dissolution textures in tonalitic enclave phases are clearly visible in changes from decompression experiments.

Table 1  
Composition of starting material

Analysis	GC2859904L <sup>a</sup>	CQ7C <sup>b</sup>
SiO <sub>2</sub>	74.47	62.09
TiO <sub>2</sub>	0.09	0.94
Al <sub>2</sub> O <sub>3</sub>	14.87	16.29
FeO	0.67	5.03
MgO	0.24	2.70
CaO	0.99	3.83
Na <sub>2</sub> O	3.40	4.42
K <sub>2</sub> O	5.28	2.41
H <sub>2</sub> O <sup>a</sup>	0.00	0.78
Total	100.00	98.56

Total iron as FeO.

<sup>a</sup> Anhydrous glass chemical composition: it corresponds to a leucosome from a migmatite of the Ollo de Sapo Gneiss from Sanabria (Zamora, Spain) (Castro et al., 2003).

<sup>b</sup> Chosen MME formed mainly by Pl, Bt, Qtz and Ap.

Table 2  
Experimental conditions and melt (glass) composition in experiments

Run no.	P (kbar)	T (°C)	Duration (h)	Vol.% melt	Mineral assemblage	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	MgO	MnO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Total
<i>Hydrous leucogranitic glass with MME</i>															
OG83	10	750	90.5	25	R: Pl, Bt, Qtz, Ap N: Pl, Kfs, Bt, Sil Al	66.38	0.00	12.81	0.00	0.00	0.00	0.89	2.91	3.89	86.87
EH1	10 to 4	750	96+96	40	R: Pl, Bt, Qtz, Ap N: Pl, Kfs, Bt, Sil Al	70.55	0.00	12.60	0.35	0.00	0.00	0.47	3.37	4.27	91.59
EH7	10	850	96	50	R: Pl, Bt, Qtz, Ap N: Pl, Kfs, Bt	67.74	0.03	13.78	0.50	0.19	0.00	0.80	3.36	4.51	90.92
OG88	10 to 4	850	96+96	90	R: Bt, Qtz, Ap N: Pl, Opx	67.03	0.13	13.62	0.88	0.24	0.00	1.07	2.99	4.53	90.48
OG80	8	900	96	95	R: Bt, Pl, Ap N: Pl, Bt	62.62	0.29	15.49	0.82	0.45	0.00	1.71	3.27	4.31	88.97
OG81	8 to 4	900	120+96	95	R: Bt, Pl, Ap N: Pl, Bt, Opx	62.86	0.23	14.91	0.74	0.50	0.00	1.49	3.15	4.42	88.31
<i>Hydrous leucogranitic glass</i>															
EH3	10 to 4	850	96+96	73	Kfs, Qtz, Opx	72.41	0.04	12.51	0.42	0.11	0.00	0.39	3.37	5.01	94.25

Note: Abbreviations by Kretz (1983).

R: Relict phases.

N: Neoformed phases in the granite melt.

The composition of melts in equilibrium with these phases becomes more CaO-, MgO- and FeO-rich, compared with the starting glass composition (Fig. 2 and Table 2) as a consequence of this process. K<sub>2</sub>O content is slightly smaller in all resulting glasses compared to the starting glass probably due to the

crystallization of newly formed alkali feldspar and biotite (Table 2). In run OG88, with the smallest K<sub>2</sub>O difference compared to the starting glass, some K<sub>2</sub>O may have been incorporated in plagioclase or some alkali feldspar may have been unidentified. After the melt is water saturated, further decompression should cause crystallization of anhydrous phases as has also been shown experimentally (Hammer and Rutherford, 2002; Martel and Schmidt, 2003).

Experiments carried out at 850 °C best illustrate the process of dissolution of the enclave fragment during decompression. At 10 kbar (Fig. 3b), the enclave fragment remains untransformed. When pressure is lowered (Fig. 3c), the dissolution process intensifies. This is shown by plagioclase and to a lesser extent, by quartz and biotite, which are dissolved into the melt (Fig. 3d and e).

At 850 °C at 10 and 4 kbar, analytical profiles along melts generated close to the enclave fragment outwards to the capsule wall show different rates of cation diffusion in the melt phase (Fig. 4). Aluminium and silicon show the greatest concentration differences between the enclave end and the capsule wall. In contrast, these profiles show the alkalis diffusing more readily in the melt. Variations in FeO, MgO and TiO<sub>2</sub> concentrations are very small to describe diffusion behaviour of these elements in the melt phase.

Plagioclase crystals show inverse zoning after dissolution, as a result of overgrow onto pre-existing

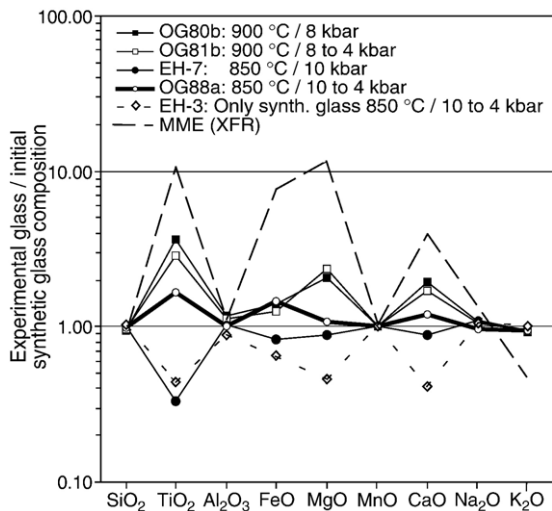


Fig. 2. Differences in major oxides composition between melts generated in our experiments and the starting leucogranitic glass composition. XRF analysis of the tonalitic enclave is also shown in the graphic. Dashed lines and white squares correspond with the composition of the melt generated in the run without enclave fragment (EH-3) for reference.

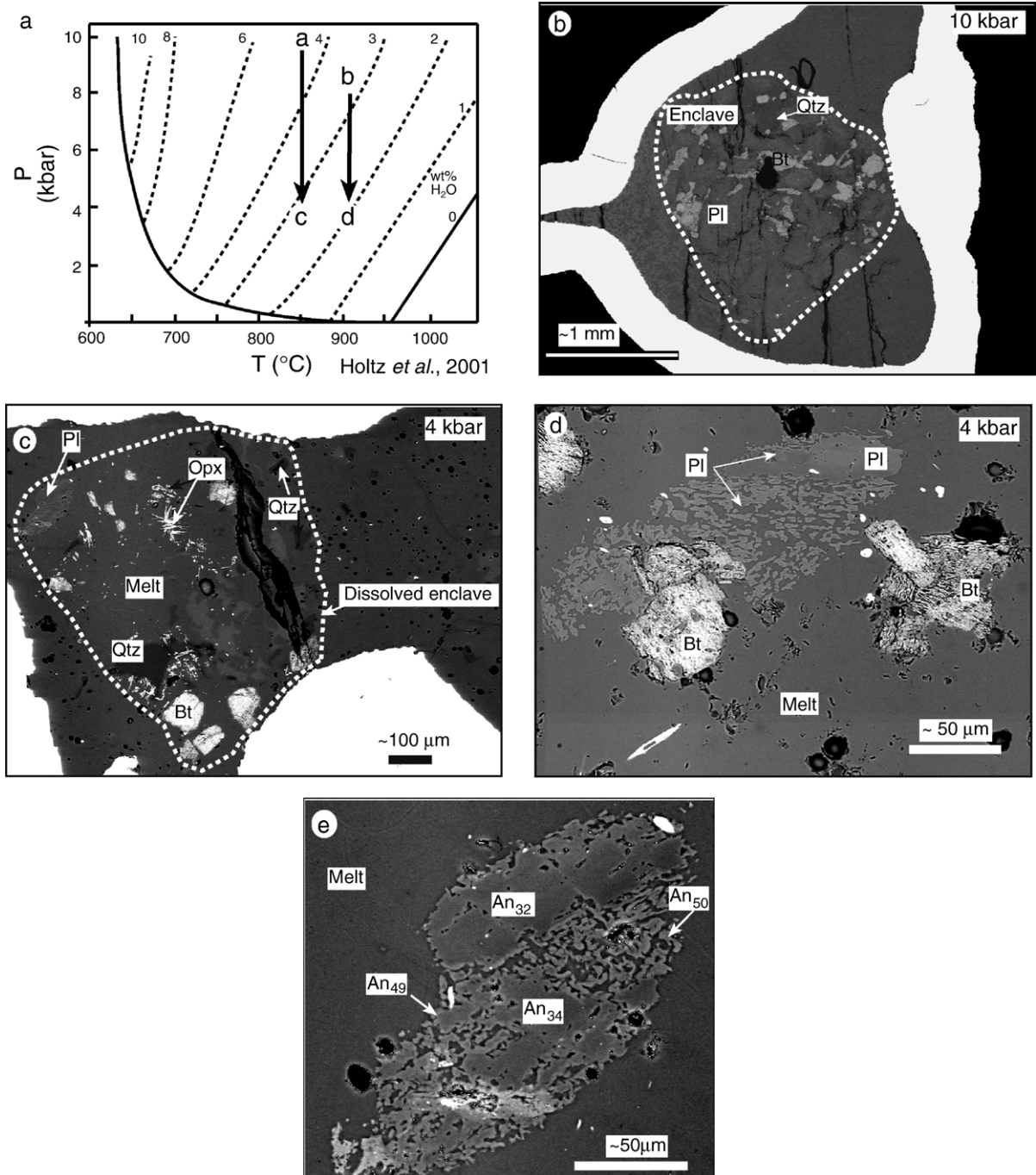


Fig. 3. (a) Liquidus diagram from Holtz et al. (2001) representing the change in water saturation values with pressure. (b to e) Photographs correspond to back scattered electron images (Z-contrast). Dashed white lines demarcate enclave fragment position in the capsule. Experimental results at high pressure (b) and after decompression at lower pressure at 850 °C (c) and 900 °C (d). Textural details of plagioclase crystals in the experiments in d and e at 4 kbar. Brighter (more Ca-rich) plagioclase areas are newly formed crystals growing on relict (darker) plagioclase from the enclave fragment.

crystals. Newly formed labradorite crystals grew over former oligoclase–andesine crystals from the enclave (Fig. 3d and e). Labradorite crystallizes from melts that were relatively calcium-rich. This Ca excess may be

acquired during the dissolution process in decompression. Many examples of inverse zoned plagioclase crystals have been found in granites that show evidence of hybridization (Holden et al., 1991; Elburg, 1996;

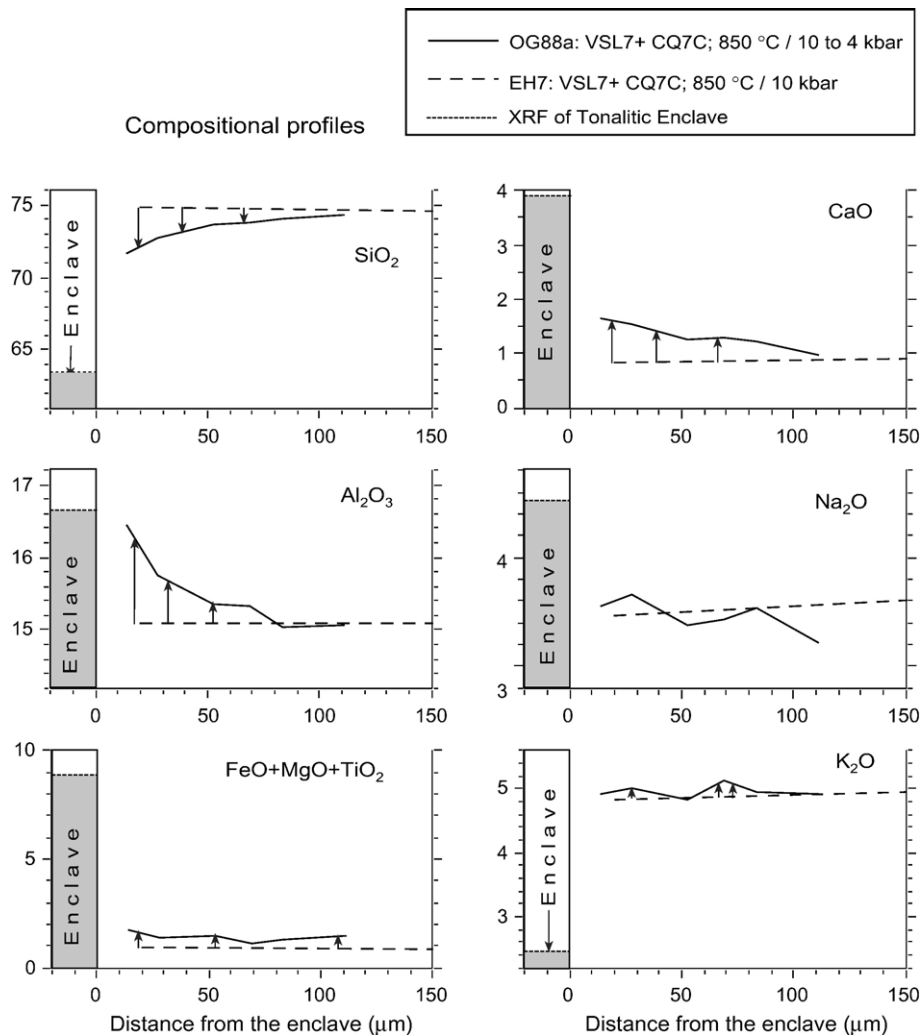


Fig. 4. Analytical profiles along generated melts from areas close to the enclave fragment outwards for 850 °C at both pressures: 10 and 4 kbar.

Waigh et al., 2000), but also in some MME, as those described by Elburg (1996).

## 5. Discussion

### 5.1. Some previous experimental constraints

Some previous experiments have been done on the contamination of rhyolitic melts by enclaves of dacitic composition (Baker, 1991) in hydrous systems. The present work provides the first experimental test of the interaction of a hydrous melt with a natural rock and, more importantly, the effect of the release of pressure on the capability of the granitic melts to dissolve enclave fragments, during magma ascent.

The effect of decompression on dacitic magmas was studied by Blundy and Cashman (2001). They observed

the resorption of feldspar crystals during isothermal decompression as undersaturated magmas get close to water saturation ( $a_{\text{H}_2\text{O}}=1$ ), similar to dissolution of plagioclase in our hydrous melts.

The results of this study show how the composition of the water-rich melt enclosing the enclave fragment is modified as a result of the dissolution of certain mineral phases of the natural enclave in that melt. We use the term dissolution instead of melting for these mineral phases in the sense of Smith and Brown (1988): "...both congruent and incongruent *melting* require nucleation of the melt phase, whereas in *dissolution* a melt or fluid phase is already present", as these phases were in equilibrium with the melt before ascent.

The dissolution process persists until the appropriate minimum melt water content (Holtz et al., 2001) for those  $P$ – $T$  conditions is reached. Actual  $P$ – $T$  conditions

at which this occurs can only be estimated because experimental liquidus curves are applicable only to strictly ternary minimum compositions. Addition of components to the melt would affect the position of the liquidus curves. For the same water content at lower pressure, melts are closer to their water saturation point and in order to obtain a new equilibrium state, melts just below water saturation will continue to dissolve crystals. Dissolution of some phases from the enclave fragment increases the melt fraction in the system. This increasing in the melt fraction is isothermal in our experiments and it should be also isothermal in the case of a rapid magma ascent. The presence of more melt only affects dissolution because this melt is closer to water saturation.

The experiments of Baker (1991) showed that an increase in the melt water content enhances cation diffusion rates between two melts of contrasted composition. A similar effect has been observed in our experiments, though there are not two melts with different composition. Water promotes diffusion between melt and mineral phases, which begin to dissolve in the melt (Paillat et al., 1992). According to Baker (1991) diffusion increases, first caused by OH<sup>-</sup> species that break (Si,Al)–O bonds in the melt and later because of an increase in H<sub>2</sub>O in the melt, as the total water content increases (Doremus, 2000). This increase in H<sub>2</sub>O is expected in decompression experiments, as melts get closer to water saturation values. Experiments presented here show that there is an effect of pressure on cation diffusivities for hydrous systems.

Plagioclase is the mineral phase most easily dissolved by the hydrous melts compared with biotite and quartz, which are less affected by the dissolution process (Fig. 3c and d). Some plagioclase crystals relict from the enclave in our experiments show inverse zoning (Fig. 3e) after the dissolution process. Waigh et al. (2000) describe feldspar textures with normal and oscillatory zoning with a neofomed outer rim of more calcium-rich feldspar. These authors explain these calcium-rich zones as a consequence of feldspar growth after an event of magma mixing. Similar textural features have been described by Elburg and Nicholls (1995). Although these calcium-rich rims could be explained by the process of magma mixing, our experimental results demonstrate that the enclave dissolution process can also produce this type of inverse zoning in the plagioclase crystals. Plagioclase zoning can be interpreted in terms of the kinetics of crystallization for a system with a certain bulk composition, pressure, temperature and water content (see review of Smith and Brown, 1988 and effect of melt water content,

Castro, 2001). In the process of enclave dissolution described by the experimental results shown in this paper, melt composition is enriched in CaO, due to dissolution of plagioclases crystals from the enclave into the melt phase during decompression. At the final stage of the experimental run, at constant *T* and *P*, the hydrous silicate melt could have reached Ca-saturation and neofomed plagioclase could nucleate over residual plagioclase crystals (from the enclave), with a new composition (more Ca-rich) according to the actual melt composition, explaining textures shown in Fig. 3d and e.

### 5.2. Magma mixing–mingling versus dissolution

The process of magma mingling is the most popularly accepted among granite petrologists to explain the presence of MME in granites and their relations with the host (e.g. Vernon, 1990; Castro et al., 1991; Elburg and Nicholls, 1995; Di Vincenzo et al., 1996; Maas et al., 1997; Silva and Neiva, 2001; etc.). The cornerstone of this hypothesis is that MME represent globules of (mantle derived) basic or hybrid magmas that are mingled and incompletely mixed with the host magma (felsic and crustal derived). However, this suggested process cannot explain a selective incorporation of Sr isotopes and not of Nd. Some granitic suites bear evidence against the magma mixing hypothesis. For example, the higher concentration of REE and LILE in some enclaves in comparison with the granite host (Di Vincenzo et al., 1996; Elburg, 1996; Silva et al., 2000) is difficult to explain if enclaves represent basic mingled magmas. In the process of magma mixing, granites should have higher REE concentration than enclaves if those granitic magmas come from a crustal source. Holden et al. (1991) tried to explain the higher REE concentration in enclaves by effective mixing and chemical exchange between MME and host granites only for the feldspar phases, excluding the ferromagnesian phases so that REE would be retained in the enclave. Nevertheless, the higher REE content of rocks with intermediate composition seems to be primary and not acquired in the crust, as has been shown by Castro et al. (2003) for rocks of intermediate composition of the Sanabria area of northern Spain.

The process of enclave dissolution that has been simulated in our study avoids complicated explanations to explain the REE distribution between enclaves and host granites. The hybridization process takes place between tonalitic magmas, either partially or completely crystallized with primary high REE, and the hydrous granitic magma through dissolution. This does not contradict the idea that enclaves may be fragments of

synplutonic intrusions of early intermediate magmas into the granitic magma.

There are some rheological limitations to the magma mixing processes. For example, Leshner's (1994 and references therein) work suggest that for successfully mixing the mingling magmas should show rather small differences in chemical composition (<10% SiO<sub>2</sub>) or greater volume of the basic magma compared with the felsic one.

Vernon (1991, 1996) among others has cited the fine-grained textures of enclaves as evidences of undercooling in a more felsic, cooler melt. However, fine-grained enclaves can also be the result of other processes such as high nucleation rates achieved by silicic melts of high temperatures and low water concentration (Marsh, 1988; Cashman and Marsh, 1988; Holtz et al., 2001). In the model presented here, we favour this hypothesis for the origin of the fine-grained texture of enclaves.

The alternative hybridization mechanism presented here could also work together with magma mixing and mingling processes. In many cases, as cited by Barbarin (2005), after mixing, in the final stages of the hybridization process, "during ascent and emplacement, mingling continued and interaction between granitoid and MME involved thermal, mineral and chemical transfers", which can entail enclave dissolution by the mechanism here proposed.

## 6. Petrographic and isotopic consequences of the dissolution process: the case of Cabeza de Araya (Cáceres, Spain)

The Cabeza de Araya batholith represents the best example of one of the main granitic series of the Iberian Massif. With intermediate characteristics between those of the alkaline and calc-alkaline series (Capdevila et al., 1973; Corretgé et al., 1977), the Cabeza de Araya rocks define the so called "serie mixta" granites in the Iberian Massif. The "serie mixta" rocks are mainly granites and monzogranites with abundant cordierite, forming large epizonal plutons in different areas of the Iberian Massif, particularly in the "Extremadura Central" Batholith (Castro, 1984). Detailed descriptions of this rock series can be found in Castro et al. (1999, 2002a) and Corretgé et al. (2003). The Cabeza de Araya granites have been studied in detail by Corretgé (1971), Amice (1990), and García-Moreno (2004) from field to experimental work, and a hybrid origin for the less differentiated rocks of this series has been proposed (Castro et al., 1999; García-Moreno, 2004; García-Moreno et al., 2003). Scarcity of MME is a salient characteristic of this granite series.

In order to clarify this hybrid origin for the monzogranites, García-Moreno (2004) proposed mass balance modelling of major elements, using different data sets (similar to those proposed below) for the isotopic relations, with felsic and mafic end-members consistent with observed field relations and geochemistry data (Table 3). This model showed that mixing between felsic and mafic end-members cannot reconstruct the major element relations. Hence, a simple process of mixing between two systems is unlikely, although a more complex process of selective phase dissolution could explain the major element relations. The mixing process has also been tested for isotopic relations with Sr and Nd data from the data described in Table 3.

Calculated models for the Sr isotopic relations are presented first. Fig. 5 shows the calculated <sup>87</sup>Sr/<sup>86</sup>Sr at 303 ma (age of Cabeza de Araya, Bea et al., 2003) against the Sr concentration for a mixing model between a tonalite with the isotopic composition of Iberian MME and melts with the isotopic composition of a greywacke from the "Complejo Esquisto-grauváquico" (Fig. 5a). In this figure, the isotopic values of the monzogranite have also been represented, as well as other isotopic values from the Cabeza de Araya rocks (unpublished data). It can be observed how the composition of the monzogranitic sample of Cabeza de Araya fits the model for a range of 20–30 wt.% of basic component contribution in the isotopic composition. Other Cabeza de Araya samples have even lower Sr isotopic relations. If we consider the process of enclave dissolution as the

Table 3  
Materials for mass balance calculations

Felsic end-member	Plasenzuela Leucogranite (Castro et al., 1999) for the Sr and Nd compositions as pure anatectic granite Greywacke from "Complejo Esquisto-grauváquico" for the radiogenic Sr and Nd isotopic relations of the acid end-member (using the composition of the former leucogranite) (Castro et al., 1999)
Mafic end-member	MME from some granites and granodiorites from Gredos (Central System, Spain) (Moreno-Ventas, 1991) Zarza la Mayor Tonalite (Cáceres, Spain) (Castro et al., 1999)
Mixing	Cabeza de Araya Monzogranite, Facies A (sample GC28069603) (Castro et al., 1999; García-Moreno, 2004), as the less evolved and more basic rock of this Pluton Other Cabeza de Araya Granites (unpublished data) Campanario–La Haba Granitoids (Los Pedroches, Spain) (Alonso Olazabal, 2001)

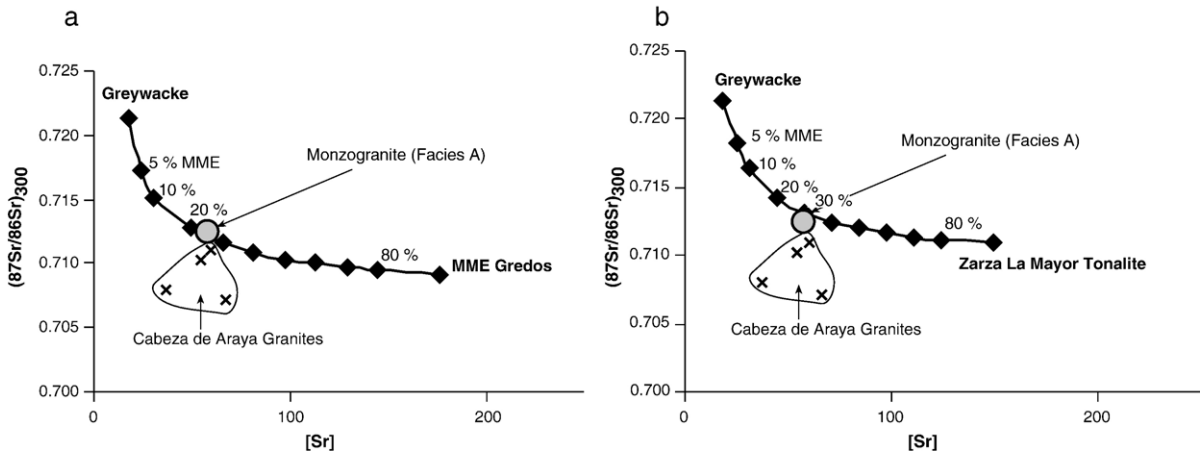


Fig. 5.  $\text{Sr}-^{87}\text{Sr}/^{86}\text{Sr}$  calculated at 300 Ma, for a mixture of: (a) greywacke–MME from Gredos Granitoids (Moreno-Ventas, 1991) and (b) greywacke–Zarza La Mayor Tonalite outcropping the Cabeza de Araya pluton area; together with the chosen monzogranite (grey circle) from Cabeza de Araya, some other Cabeza de Araya data are also plotted. See model description in text.

mechanism of hybridization in this system, plagioclase may be the mineral phase that would be selectively dissolved, providing the low  $^{87}\text{Sr}/^{86}\text{Sr}$  component of the mixture. The relatively low Sr isotopic ratio is a well-known fact for the “serie mixta” rocks in the Iberian Massif (Castro et al., 1999, 2002a). Fig. 5b shows the same representation for the estimated model using the data from a tonalite that crops out in the Cabeza de Araya pluton area, for the end-member. In this case, the composition of the selected Cabeza de Araya sample fits the model for a 30 wt.% of basic component contribution. This high percentage of basic component does not correspond with the low percentage of enclaves that now can be found in the outcropping granites. Enclaves would have to be dissolved and disrupted as has been described in Fig. 1 and the actual enclaves that can be observed in these granites today are only part of the tonalitic material, which was not completely affected by the dissolution process.

The same isotopic relation model has been applied to the  $^{143}\text{Nd}/^{144}\text{Nd}$  system using the same mafic and felsic end-members as for the Sr model. Data for the Cabeza de Araya rocks correspond to the monzogranitic sample. Data from other “serie mixta” granitoids from Los Pedroches Batholith (Alonso Olazabal, 2001) have also been projected (Fig. 6). Obviously, none of the mixing models, using the greywacke isotopic composition with both tonalites, fit the isotopic composition of the Cabeza de Araya monzogranite or any of the data from Los Pedroches. Fig. 6 shows how the mixing lines between the  $^{143}\text{Nd}/^{144}\text{Nd}$  compositions of the selected end-members do not fit the isotopic Nd composition of any of the “serie mixta” granites.

Hence, the mixing model between the selected isotopic compositions for the felsic and mafic end-members seems to fit well for the Sr system, but not for the Nd system. We suggest that disparity can be explained in terms of selective dissolution of mineral phases in the hybridization process, with a greater contribution of plagioclase, rather than by a model of magma mixing that equally traps all phases to produce the hybrid magma.

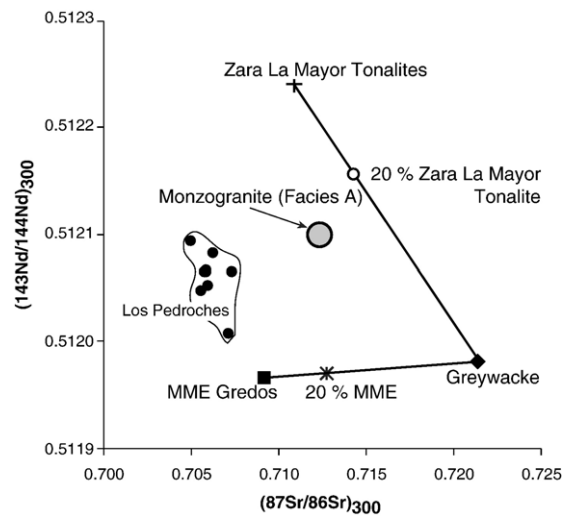


Fig. 6.  $^{143}\text{Nd}/^{144}\text{Nd}-^{87}\text{Sr}/^{86}\text{Sr}$  calculated at 300 Ma for a mixture of a greywacke with MME from Gredos Granitoids (Moreno-Ventas, 1991) and Zarza La Mayor Tonalite (20% basic end-member is highlighted in the plot); together with the chosen monzogranite (grey circle) from Cabeza de Araya, some other Serie Mixta granites data from Los Pedroches Batholith are also plotted (Alonso Olazabal, 2001). See model description in text.

## 6. Conclusions

The dissolution process is proposed as an alternative style of hybridization that may account for compositional disparities in hybrids that wholesale magma mixing cannot explain. Complete magma mixing may have had a very important role in the generation of other granitoid magmas. Considering the selective dissolution presented here, evidence for magma mixing in granites and enclaves can be reinterpreted as a consequence of enclave dissolution. For example, textural evidence described by D'Lemos (1996) in some crystal mushes for magma mixing can also be interpreted as the product of dissolution of a more basic rock by a more felsic magma during decompression or by increasing  $P_{\text{H}_2\text{O}}$ . Enclaves with a pillowed shape are commonly those of more mafic composition and have darker and finer grained boundaries. More felsic enclaves, with coarser grain size, inhomogeneous and with more diffuse margins could be affected by some dissolution. Further evidence in support of this process, is the presence of rounded plagioclase crystals in small enclaves in the granites described by D'Lemos (1996). These rounded plagioclase crystals never appear in larger enclaves nor in any of the granite facies. In these granites, the geochemical modelling showed a good correlation for all major elements excluding Na and Ca. This may be a good example of the operation of both traditional hybridism and selective dissolution of mafic enclave phases.

We propose the enclave dissolution process during the ascent of plutons as an alternative model to magma mixing-mingling to explain hybridization in granites where there is no evidence of contemporaneous input of basic magmas (as in the case of Cabeza de Araya monzogranites). Enclaves represent fragments of pre-to synplutonic injections of intermediate magmas (tonalites) formed at high temperature at depth, probably with low water contents. The volume of initial enclave material involved in the process has been estimated around 20% for the monzogranites of Cabeza de Araya. Obviously, after the process of enclave dissolution, the percentage of tonalitic material has to be smaller. Some textural features previously identified as the result of magma mixing processes can now be explained by the process of enclave dissolution. Some geochemical aspects of hybrid granites, such as the lack of Nd equilibration between enclaves and host granites, can be clarified by this process. Experiments show that pure granitic melts generated by partial melting of metasedimentary rocks can be contaminated by enclave dissolution during decompression. In many hybrid granites,

both mechanisms, mixing and dissolution, could work together. Enclaves that are now present in outcrops of hybrid granites can be interpreted as remnants of larger volumes of enclave material that was dissolved in the hybridization process.

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