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Top-down structures of mafic enclaves within the Valle Fértil magmatic complex (Early Ordovician, San Juan, Argentina)

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ABSTRACT

Magmatic structures related to the mechanical interaction between mafic magmas and granitoids have been studied in the Valle Fértil calc-alkaline igneous complex, Argentina. Excepcional outcrops with vertical walls of more than 300 m high allow us the study of three-dimensional geometries of individual blobs of mafic magma as well as the geometry of pipe-like structures in which mafic microgranular enclaves are concentrated in more than 50 times the normal abundance in the granodiorite mass. The shape of enclaves and pipe-like structures are interpreted as the ressult of top-to-down intrusions of a mafic magma into a granodiorite-tonalite mass. These sinking structures are the result of a reverselly stratified magma chamber with gabbros and diorites at the top and granodiorite-tonalite at the bottom. They may account for most of the structures found in microgranular enclaves and magma mingling zones that characterize calc-alkaline batholiths. Synplutonic intrusions from the top is the only plausible mechanism to account for the observed structures. The model may be of general application to calc-alkaline batholiths characterized by the presence of mafic microgranular enclaves. An implication of these reverselly stratified magma chambers is the presence of a petrological inversion which may be the consequence of cold diapirs emplaced below the mantle wedge in a suprasubduction setting.

KEYWORDS **Enclaves. Synplutonic intrusions. Calc-alkaline batholiths. Argentina. Famatinian belt.**

INTRODUCTION

The presence of mafic microgranular enclaves (MME) in granitoid rocks is the most conspicuous feature of common silicic plutonic bodies that appear forming large batholiths in active continental margins and collision-related orogens (Didier, 1987; Didier and Barbarin, 1991). Geochemical and isotopic relations of MME, considered together with those of the host granitoid, reveal that both magmatic systems share many relevant features which must be taken into account in any petrogenetic model. A study of the origin of MME is out of the scope of this paper, which is focused on the rheological processes controlling their generation and dispersal through the hosting granitoid, a matter that have not been explained, and documented with unambiguous field relations. Two distinct groups of models are currently applied to interpret the origin of MME, namely cogenetic and external. In our view, both models may have operated separately giving rise to very similar magmatic structures, such as synplutonic dikes and globules of mafic magma. The usually observed association of MME and massive mantle-derived mafic rocks (gabbros and diorites) points to an external origin. However, this observation is not in conflict with the possibility that some kind of MME may have been derived by magma immiscibility from a parental silicic magma, largely represented by the hosting granitoid. Experimental studies recently carried out by part of this team (Castro and Moreno-Ventas, in preparation), reveal that liquid immiscibility is a plausible hypothesis that must be taken into account for the generation of a great part of the MME. This is not incompatible with the presence of MME derived by fractionation of a mafic magma coeval with the formation and emplacement of the host granitoid. In the case of Valle Fértil both mechanisms are possible and perhaps they have generated MME with slightly different compositions. Although the aim of this paper is only to describe and interpret magmatic structures related with the shape and distribution of MME in the Valle Fértil complex, the closed association with mafic, mantle-derived magmas in this area, points to an external origin for most of the MME described in this paper. This interpretation does not exclude that some of the MME of Valle Fértil were derived by internal processes, namely liquid immiscibility. A further geochemical study of these bodies may reveal more details about petrogenesis, but this matter is out of the scope of this paper.

In general, and particularly in the case studied here, MME have a whole chemical composition close to diorites and quartz-diorites with silica contents in the range 52 to 60 wt.%. Measured isotopic ratios are compatible with derivation from a parental wet basalt, possibly modified by some kind of fractionation and hybridization with crustal material (Pankhurst et al., 2000). Field relations in nearly all plutonic associations of this kind indicate that MME and host granitoids represent coeval magmas (Vernon, 1984; Vernon et al., 1988). These relations are often used to argue in favour of a mantle magma input as the cause of crustal melting and granitoid generation (Holden et al., 1987). Although they were coeval magmas at the time of emplacement into the upper continental crust, some differences in ages are found for the time of magma generation. For instance, age determinations of basic rocks and granitoids reported in the Avila batholith in Spain (Bea et al., 1999) are not compatible with the general believe that mafic magma are the “basic precursors” that caused heating and melting of the continental crust to generate the silicic magmas in which they are enclosed. Similar timing relationships are found in the Valle Fértil plutonic complex, the subject area of this study, where precise age determinations indicate that the basic rocks are slightly earlier with respect to the generation of granites (Zircon ages: Gabbros 478 ±4 Ma, Granodiorite 470 ±5 Ma; Pankhurst et al., 2000). These age relations are crucial to understand the observed field relations between gabbros and granitoids, and they are in agreement with the general observation in the area about the sequence of intrusion. These indicate that the mafic rocks reached the site of emplacement earlier than the granitoids. As a whole, the Valle Fértil plutonic complex is a calc-alkaline association of granodiorite-tonalite rocks and gabbro-diorites intruding into pelitic migmatites. It is interesting to note the existence of a compositional gap between the tonalite-granodiorite group and the mafic rocks as reported by Pankhurst et al. (2000). The complex is a typical I-cordilleran type batholith (Pitcher, 1997) associated to the Famatinian magmatic system developed at the margin of Gondwana during the Ordovician period (Casquet et al., 2001; Vujovich et al., 2004). As in many other calc-alkaline batholiths, a general feature is the presence of mafic microgranular enclaves. It is clear that MME have strong petrogenetic implications for both the host granitoids and the possible processes of hybridization between mafic and felsic magmas. However, the lack of a plausible explanation for the scattered distribution of enclaves within granitic masses, their shape, textures, etc., is a big handicap for the application of any petrogenetic model. An origin by disruption of synplutonic dykes have been suggested (Vernon et al., 1988; Fernández and Barbarin, 1991). However, the fact that enclave magma (mafic) is denser than the host magma (felsic) makes impossible the gravitatory ascent of the mafic magma into the felsic one. Also the amalgamation of enclaves in narrow pipes seems to be incompatible with ascending surges or laminar magma flow because of density relations. We present in this paper a study of enclaves of the Valle Fértil complex, in which it is possible to observe vertical walls of granodiorite and tonalite rocks showing well-preserved relations between enclaves and host granite. These magnificent exposures allow us to reconstruct the three dimensional geometry of enclaves in both isolated bodies and pipe-like structures. The results of this study on enclave geometry and enclave-rich pipes open a new insight on enclave generation that may serve as the basis for a new gravity-dominated dynamic model of general application in calc-alkaline plutonic complexes.

GEOLOGICAL SETTING AND PETROLOGICAL FEATURES

The magmatic complex of Sierra de Valle Fértil (San Juan province, Argentina) consists of igneous and metamorphic rocks generated during the Early Ordovician period, as a part of the Famatinian magmatic arc. This paleo-arc grew in the overriding plate while a Laurentia-derived terrane was approaching to the western margin of Gondwana (Pankhurst et al., 1998; Pankhurst et al., 2000). The age of magmatism in this sector is fairly constrained between 513 and 465 Ma (Pontoriero and Castro de Machuca, 1999; Pankhurst et al., 2000).

Based on field and petrologic studies, four rock units have been recognized (Mirré, 1976; Vujovich et al., 1996; see Fig. 1): (1) A layered mafic unit including ultramafic, Ol-rich and Px-rich cumulates. This unit is dominated by amphibole-rich layered gabbro (norites) and diorites enclosing a suite of chilled mafic dikes. (2) A tonalite-dominated igneous unit comprising coarse-grained biotite tonalites and extremely heterogeneous rocks with mafic enclaves, Bt-rich bands and mafic layers. (3) A felsic igneous unit making up a batholith-scale Bt ± Amph granodiorite which hosts chilled mafic dikes, enclaves, and blocks of Amph-bearing gabbros. This unit includes late-magmatic felsic dikes, and sporadically grades to monzogranite. (4) Migmatites (metatexite to diatexite) appearing as kilometric strips interlayered with igneous mafic, intermediate and felsic rocks. This supracrustal unit also contains marble/calcsilicate beds. Grt-bearing leucogranites, which were derived after partial melting of the pelitic-migmatites, appear widespread through the sierra as tabular or lensoidal bodies. The two silicic units, tonalites and granodiorites, contain abundant mafic microgranular enclaves, heterogeneously

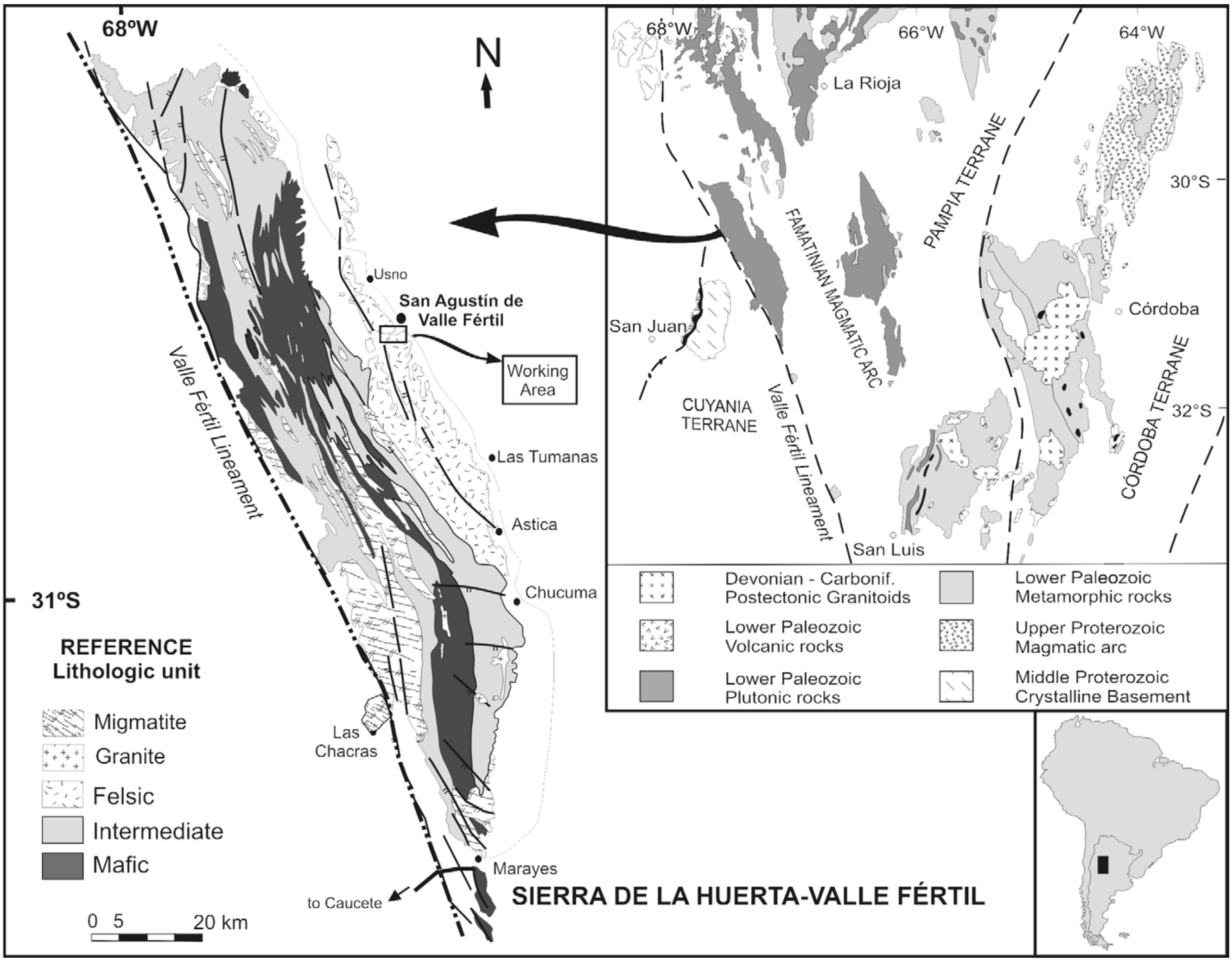

FIGURE 1 **Simplified geologic map of the Sierras de Valle Fértil – La Huerta taken after the geological maps of Mirré (1976). The larger inset shows the geological map of the Famatinian paleo-magmatic arc with the distribution of major lithostratigraphic units.**

distributed within the complex, that are the subject of this study.

The most common rock from the mafic unit is an Amph-rich gabbronorite mainly consisting of plagioclase + amphibole + orthopyroxene with the modal proportion of the two first minerals highly variable (21-53 % for plagioclase and 7-49 % for amphibole). Gabbronorites typically have SiO_2 < 52 wt.%. They appear interlayered with diorites having SiO_2 contents between 52 and 57 wt.% (Fig. 2). The petrogenesis of these basaltic rocks have is under study by this research team. Among the most outstanding features are the calc-alkaline affinity of the whole magmatic complex and the petrogenetic link between mafic rocks and microgranular enclaves forming a continuous trend of magmatic differentiation. Field relations strongly support that the basic magmatism and the silicic one, represented by tonalites and granodiorites, were coeval, or at least emplaced at the same time in the crust. Original intrusive contacts between the mafic rocks and the hosting migmatites are frequently observed; mafic rocks developing chilled margins. The whole massif was deformed and several shear zones slightly modified the original emplacement relations and textures. However, shearing only affected narrow bands of no more than tens of meters wide. Large portions of the intrusion were preserved of solid-state deformation and maintain the original magmatic structures. This is the case of the magmatic structures defined by orientation of microgranular enclaves in granodiorites and tonalites, that tend to form subvertical, pipe-like strucrtures that have not been seriously modified from the original position in the intruding magmatic complex or composite magma chamber where they were formed. These structures are the subject of this paper and they will be described and interpreted below.

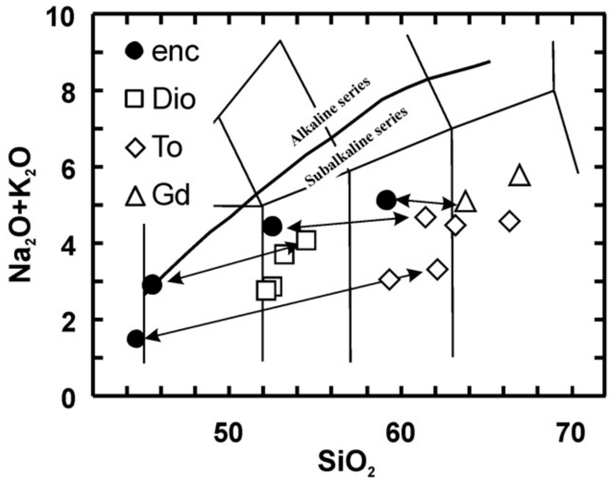

FIGURE 2 **Total alkalis versus SiO_2 diagram for the Valle Fértil granitoids and their enclosed microgranular enclaves. Granitoids display a typical subalkaline trend. Arrows connect the composition of each analyzed inclusion with its host granitoid.**

MAFIC ENCLAVES AND PIPE-LIKE STRUCTURES

Criteria for coeval magmas

Microstructures and contact relationships between enclaves and host granitoids in the studied area, show all kind of evidences of coeval liquids reported elsewhere (Vernon, 1984; Vernon et al., 1988). Among these, the following relations are frequently observed in Valle Fértil:

Grain size. Enclaves are always finer grained compared to the host granitoid, so evidencing quenching of an intermediate to basic liquid against a relatively cooler, felsic melt or magma.

Liquid-liquid contacts. Although some phenocrysts were present in the mafic and felsic magmas at the time of interaction and enclave formation, both systems were essentially liquids as suggested by the contact geometries with abundant liquid-liquid cuspate contacts.

Two-liquid layer alternations. The presence of very narrow (1-10 cm) laminar alternations and liquid-liquid relationships between granodiorites and anatectic granites developed around partially digested migmatites from the top of the intrusion, also are in support of a low-crystal content, and hence a near-newtonian behaviour for the silicic magmas.

Mingled blobs. The contacts between tonalites-grandiorites that form the inner part of the complex and the surrounding gabbros is always by mingled blobs of the mafic magmas within the silicic ones and by irregular veins of tonalite melt invading the gabbros and isolating rounded portions of mafic magma that will evolve to isolated enclaves by partial disaggregating and disruption.

Figure 3 shows an example of one of the gabbro-tonalite contacts in Valle Fértil. A sharp and simple contact is never found. By contrast, these contacts are marked by the presence of magma mingling zones, supporting the general hypothesis that gabbros and tonalites intruded at the same time, being the gabbros forming an external carapace with the felsic magmas (tonalites and granodiorites) at the core of the intrusion. These may be the places where enclaves are generated at the top of the complex. The detailed observation of these mingled zones reveals interesting geometries. In places, mafic magma blobs are disaggregated and digested by the felsic tonalite that includes mafic minerals from the enclaves. The lack of gradational transitions, with intermediate compositions, strongly suggests that these were immiscible magmas. Only mechanical mixing of crystals that may have dragged by relative flow of one magma

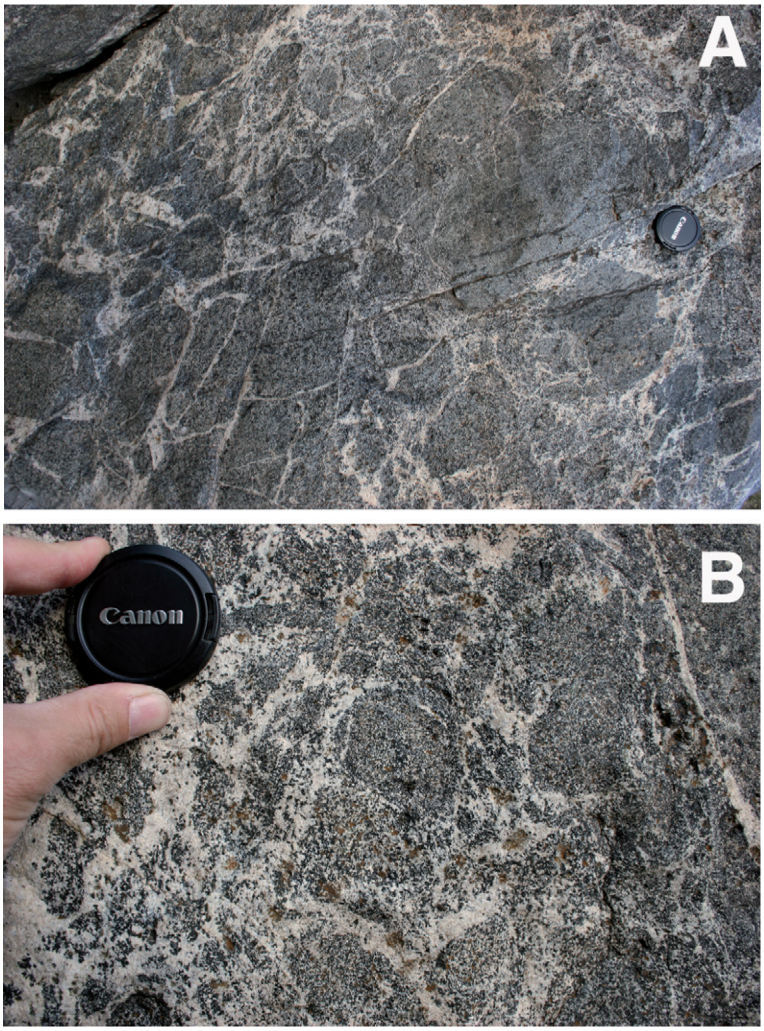

FIGURE 3 **Magma mingling structures at the contact between the tonalites and diorites at the Salazar area (Valle Fértil). Multiple tonalite veining surrounding mafic magma blobs with typical rounded shapes (A). In detail (B) the contacts between mafic magma and tonalite veins are sharp, without apparent chemical reaction.**

against the other may produce transitional facies, characterized by a very heterogeneous composition at the scale of cm. It is expected that cm-scale layering acquired by magmatic flow of two immiscible liquids is preserved during crystallization producing the usually observed compositional layering defined by concentrations of a mafic mineral (biotite and/or amphibole). Figure 4 shows a detailed map of a horizontal outcrop near one of the contacts between diorites and tonalites (Salazar creek). It can be noted the cuspate shapes of the mafic magma against the lobate shape of the felsic tonalite. The photographs in B and C show the shape relations of these contacts in the vertical section (B) and in the horizontal section (C). Vertical flow movement is evident from these structures characterized by strong elongation of magmatic bodies in the vertical direction and necking strangulations with the development of star-like structures in the horizontal section. The rheological implications of these star-like structures will be discussed later on in this paper.

Structures and enclave geometries

One of the most relevant features of the granodiorites is the presence of pipe-like, subvertical structures characterized by an extraordinary accumulation of enclaves, with a typical enclave-to-granite proportion of about 6:1. These structures may be observed in vertical walls of more than 100 m high and a maximum width of 20 m (Fig. 5). Enclave abundance is constant across the pipe, the separation with the host granodiorite is sharp, but no intrusive contact or discontinuity between the host granodiorite and that containing the enclaves is appreciated. These structures are discontinuous, at the scale of the map, in horizontal sections, ending in a narrow tip (Fig. 5). The host granodiorite also contains enclaves in less abundance (about 1 vol.%) and smaller than those appearing within the pipes. There, enclaves are imbricate and elongated following a subvertical preferred orientation for the major axes. They have a fish shape with acute tips, and also with a lobate bottom and an acute upper end, similar to drops (tear-like shape). In some places, it can be observed that these vertical pipes, that are elongated in the horizontal section, widen at the upper part acquiring a funnel-shaped geometry. Enclaves at the top of these funnel-like structures are subhorizontally orientated, with the lineation dips increasing towards the core of the pipe. In other places, the whole pipe shows a tear-like shape, narrowing towards the top and being rounded at the bottom, over a vertical section of more than 30 m. In the interior of the pipes, enclaves may be attached showing magmatic shear zones at the contact between two adjacent enclaves, indicating a subhorizontal shortening. In horizontal section within the pipe structures, enclaves are randomly orientated and abundant circular schlieren are present. These are identical to those described by Wiebe et al. (2007) and attributed to vertical movement of a dense body within the felsic magma. The circular schlieren represent the tail of mafic minerals (mostly biotite) left behind the sinking body of mafic magma due to mechanical erosion at the contact with the hosting magma. Figure 6 shows two examples of these tail-like structures. Biotite-rich schlieren are around a microgranular enclave. Nearly circular schlieren are observed in these horizontal outcrops together with irregularly shaped enclaves. The same structures in the vertical section are strongly elongated defining a well marked magmatic lineation.

Outside of the pipe-like structures, the granitoid also contain MME in less abundance, less than 1 vol.% as mentioned above. It is interesting to note that these isolated enclaves are elongated defining a nearly vertical structure. Also interesting is the shape displayed by most of these isolated enclaves. They normally have a drop-like shape with a rounded bottom and an acute tip at the top (Fig. 7). The acute tip may be single or composed. Enclaves ending in two tips at the top ("batman-like") are frequently observed (Fig. 7B). Also enclaves with composite lobes at the bottom are occasionally observed (Fig. 7A). The possible interpretation of these geometries as due to vertical movement by sinking of mafic magma blobs is discussed below. These shapes in vertical sections strongly contrast with the shape shown by the same enclaves in horizontal sections, perpendicular to the lineation defined by their major axes. Some representative examples of these horizontal sections are displayed in Fig. 8. These are characterized by alternating lobate and acute bends that give a star-like structure, identical to the structures observed in the vicinities of the gabbro-tonalite contacts that were previously described in the Salazar creek (Fig. 4). The combined observation in vertical and horizontal sections is used to reconstruct the three-dimension geometry of these complex bodies.

RHEOLOGIAL AND DYNAMIC INTERPRETATIONS

Figure 9 shows an idealized 3D geometry for isolated enclaves showing single and multiple acute tips at their tops. The acute tips are formed by dragging of one system against the other during sinking. This shape reconstruction is based on observations of distinct shapes in sections variably orientated with respect to the flow direction. These are not the result of variable flow processes, they are simply the result of distinct sections to the same struc-

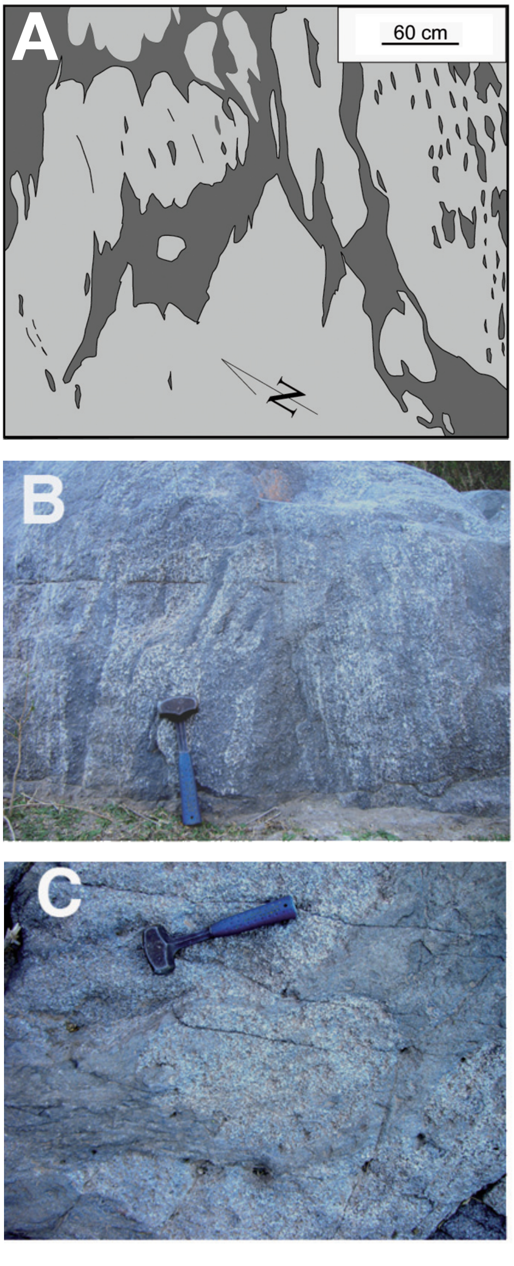

FIGURE 4 **Detailed relations on the magma mingling zone of Salazar (see Figure 1). A) Outcrop-scale map showing a horizontal section of the magmatic structures in the mingled zone. It can be noted the angular shapes of the mafic magma contrasting with the lobate shape of the hosting tonalite. The pictures in B and C show the aspect of these contacts in the horizontal section (C) and at the vertical section (B).**

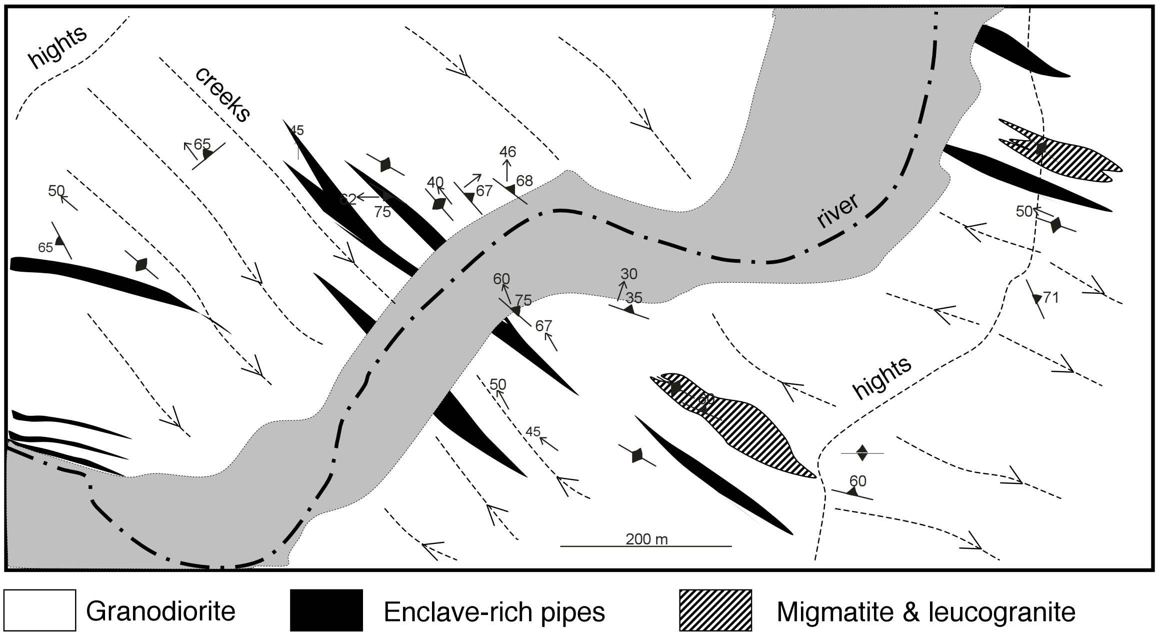

FIGURE 5 **Areal distribution and plan-view geometry of the subvertical, pipe-like structures of the Valle Fértil granodiorite. These are flatten pipes of few tens of meters width and extending for more than 200 m. Some are anastomosed and fish-shaped. They follow the magmatic foliations in the host granodiorite. Lineations, defined by the major axis of elongated enclaves are subvertical but dominantly dipping to the north.**

ture. We have summarized at the bottom (Fig. 9) the most commonly observed as longitudinal and transversal sections; however, many other complex intersections may be obtained by sectioning the model descending body at other angles. Early crystals and immiscible liquid portions may be attached to the magma-magma interface and may be in part retarded from the vertical movement giving rise to a tail of mafic minerals. This mechanism is contaminating the host magma that becomes richer in mafic minerals by mechanical incorporation at the tails and the interface during differential flow. This differential flow is a requirement to produce any mechanical interchange between the two magmas. Because the two systems are in a magmatic stage, the only driving force to produce differential movement between enclave and host is gravity. All the observed structures are pointing to gravity instabilities and vertical flow by sinking of the more dense globules of mafic magma into the felsic host.

In the granodiorite mass surrounding the pipes, microgranular enclaves show geometries indicating vertical movement by sinking within the host felsic magma, identical to the sinking geometries displayed by most of the enclaves within the pipes. They are characterized by a drop-shaped geometry indicating vertical movement by sinking of a blob of mafic magma within a granite liquid or magma. The lobate shapes of the felsic magma against the mafic one (star-like structures) clearly indicate that the more viscous medium is the granite compared with the magma of the enclave. They imply that the felsic magma had a low crystal content at the time of interaction and coeval flow of both magmatic systems was active. This possibly happened before the point of viscosity inversion that occurs due to crystallization of the more mafic system (Fernández and Barbarin, 1991). In this situation it is likely that the felsic magma was before the first rheological threshold (*op. cit.*) and behaved as a Newtonian fluid, accounting for the observed relations. It is interpreted that flow towards the centre of each star-like structure is accommodated by vertical flow and the reduction of the surface at this horizontal section perpendicular to the flow direction. The response is that the more viscous fluid (the granodiorite) tends to "intrude" into the less viscous mafic magma forming dome-like structures that are separated by acute protrusions of diorite magma. These structures represent a "strangulated neck" of a sinking magma blob. The flattened shape, in horizontal section, of these bodies is acquired at the time of intrusion. Mayor elongation is parallel to mayor axis of the large pipe-like structures. These indicate that sinking of the mafic magma blobs that generated the microgranular enclaves was coeval with a regional magma flow, possibly associated to the ascent of the whole batholith that developed subvertical laminar flow in the granodiorite. In absence of a regional movement, enclaves will have an isotropic structure in the horizontal section. These shapes are clearly indicative of sinking of blobs of the mafic melt represented by the enclaves into the felsic host. The mechanical erosion that seems to be operative at the tips of the sinking bodies may give rise

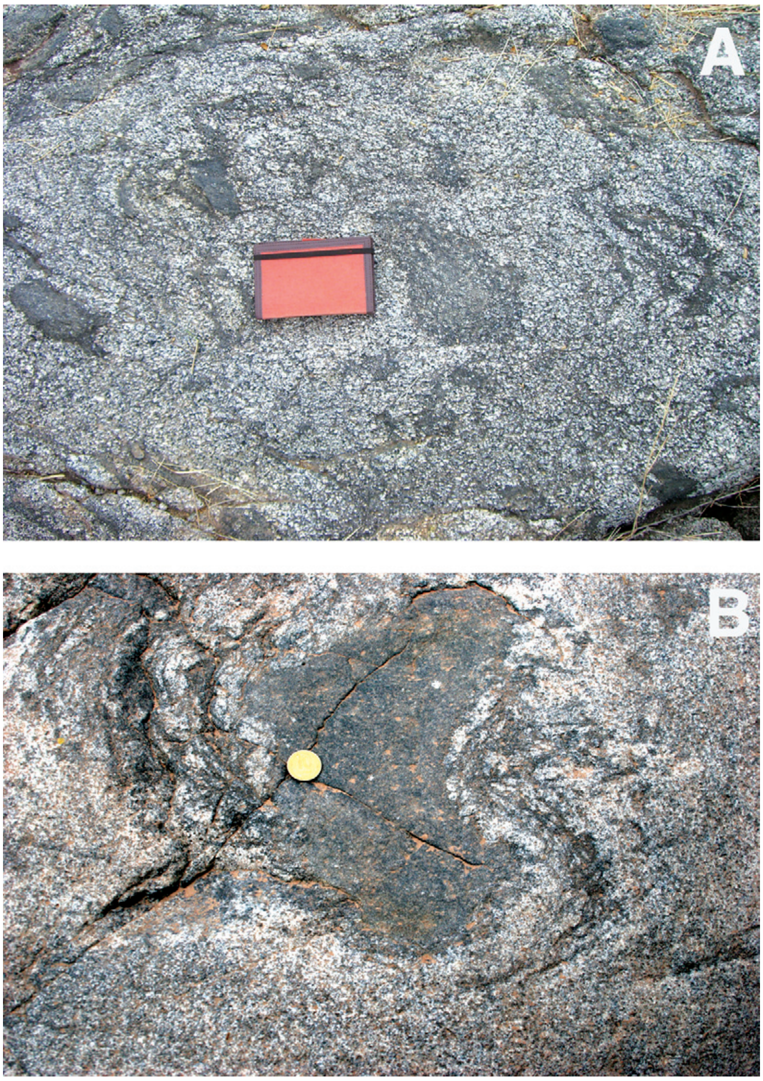

FIGURE 6 **Circular schlieren in horizontal sections within the pipe structures of Valle Fértil. A) Biotite-rich schlieren are around a microgranular enclave. B) Curved, near circular, schlieren and irregular enclaves. The same structures in the vertical section are strongly elongated defining a well marked magmatic lineation.**

to schlieren-like structures (Fig. 6) and may contribute to the development of hybrid compositions in narrow bands, similarly to the gravity structures described by Wiebe et al. (2007).

DISCUSSION

Indications of top-down intrusions

Although it is clear that microstructures in enclaves can only be explained by synplutonic injection of a mafic magma into a silicic magma chamber (Vernon, 1984), the small bodies we normally observe are classically considered fragments from these synplutonic injections that have been dispersed through the magma chamber by dismemberment of large synplutonic dikes or large magma blobs. Differences in grain size in MME are normally attributed to provenance from distinct parts of the early synplutonic intrusions, the finer sized bodies corresponding to primitive chilled margins and the coarse sized ones to the cores of the dismembered intrusions. However, the classical view of synplutonic injections from the bottom of the composite magma chamber is in serious contradiction with natural observations and it is not compatible with fluid dynamics. If MME are generated by disruption of synplutonic dikes injected from the bottom of the silicic magma chamber, then a requirement is that the granite magma be near the *solidus* in order to break and accommodate more dense magma upwards by pressure gradient into a dilatant fracture, in a similar way as mafic magma ascends towards the surface assisted by a pressure gradient in the fracture and not by buoyancy. If this is so, it is very unlike that a silicic magma with high crystal content necessary for the formation of dikes may undergo plastic flow necessary to disperse the fragments through the magma chamber. In the case that this flow existed at high crystal content if must be recorded by strong orientations of minerals developing a well marked magmatic foliation. However, dispersed enclaves within the inner parts of the plutons are not associated with flow structures. By contrast, the host granite shows a very homogeneous, granular fabric and a good homogeneity, indicating that MME were dispersed when the granitic magma was nearly liquid or static or both. If MME cannot ascend by themselves because they are denser than the host magma and there is no indication of flow, and magma flow is incompatible with the high crystal content necessary to accommodate mafic dikes, the only way to disperse these MME is by sinking from the top of the magma chamber, where disruption and delamination of chilled margins of top-to-down intrusions is being developed. Furthermore, the absence of flow structures associated to these dispersed MME is indicative that the host magma was poor in crystals, possibly below the first rheological threshold (Fernández and Barbarin, 1991) behaving as a nearly-newtonian fluid. In the same way, if dispersion was due to convective currents, these are not recorded by magmatic structures in the supposedly convecting magma. Furthermore, convection currents will concentrate solid particles, like MME, along intense flow bands and not dispersed these particles over the whole magma chamber.

Implication of star-like structures

The star-like structures observed in sections perpendicular to the follow direction (horizontal sections in our case) may have important rheological implications. These structures are comparable to mullions developed in solid-state deformation of common metamorphic rocks. In the enclaves of Valle Fértil, they correspond to the tails of descending “drop-like” blobs of mafic magma. It is important to note that these geometries indicating a

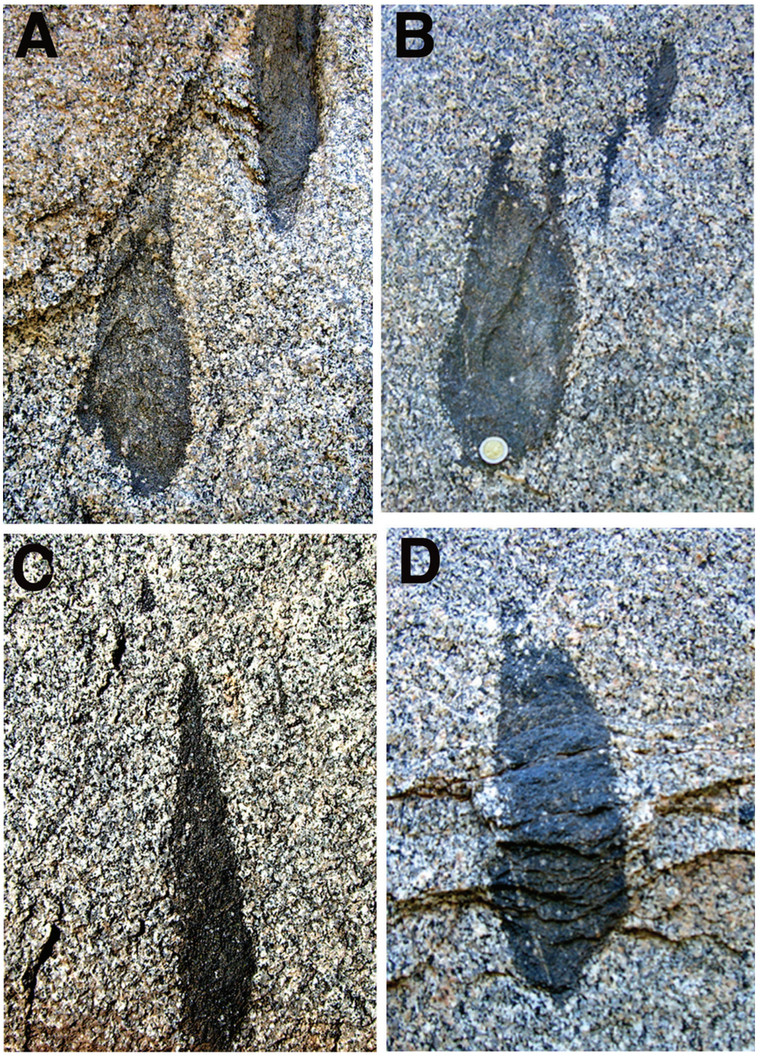

FIGURE 7 **Enclave shapes in vertical sections close to the contacts with the enclave-rich pipes. The upper acute tip is very general in most of the enclaves. Some of then show a complex lower lobe (A) and others a double tail (B). These are called “batman-type”. Most of them have a well-defined drop geometry (C) and they are called “tear -type”. It is frequent the disaggregating of the tail giving rise to a composite tail (D) in which crystals from the host granodiorite are mingled with the mafic magma. All these shapes are clearly indicative sinking of the mafic melt into the felsic host.**

FIGURE 8 **Enclave shapes in horizontal sections, nearly perpendicular to the flow structures. In all these cases there is a star-like geometry with several tips connected by curved contacts.**

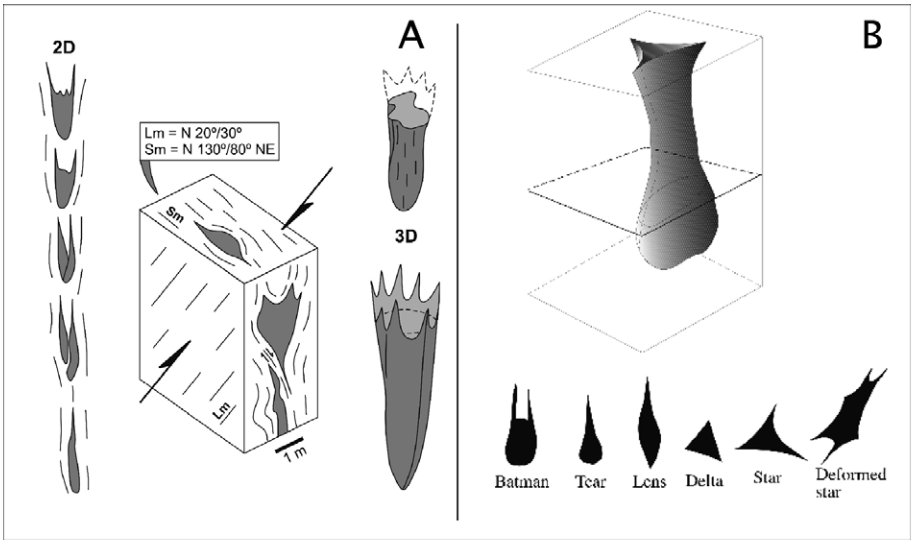

FIGURE 9 **Three-dimensional reconstruction of the geometry of a blob of dense magma sinking into a less dense fluid (the granodiorite magma). This geometry is deduced from observations in vertical and horizontal sections.The six geometries depicted at the bottom of the cartoon show the most common sections that may be obtained by sectioning vertically the sinking magma blob (batman, tear and lens), or by sectioning horizontally the blob (delta, star, and deformed star). Obviously, many complex situations may result by sectioning the blob at any oblique angle.**

"normal" arrangement of viscosities, that is the more silicic the more viscous, are developed before the inversion point in which viscosities are equal for the two systems at thermal equilibrium, being the more basic richer in crystals (Fernández and Barbarin, 1991). The fine grain size of the mafic magma, with scarce phenocrysts, together with the liquid-liquid contacts described above, strongly suggest that this system behaved as a crystal-free liquid. The observed structures indicate that both magmas were flowing one against the other before quenching, and this necessarily implies a lower crystalinity in the silicic magma due to the differences in the liquidus and solidus temperatures of both systems. It is difficult to know accurately the crystal content of the silicic magma at this stage; however, it is likely to be below the first rheological threshold, implying a near-newtonian behaviour (cf., Fernández and Barbarin, 1991), in agreement with the observation of sinking of small bodies of relatively denser blobs of mafic magma. After the inversion point, once the granodiorite magma has a crystal content of about 30 vol.% (op. cit.), the silicic magma starts to behave like a bingham body (second rheological threshold) allowing enclaves to be like floating if the size is not great enough to overpass the yield strength required to flow at the magma-magma interface.

Because these sinking structures are being developed in a magmatic system which is ascending and crystallizing at the same time, it is expected that a critical point will be reached when the silicic magma starts to behave as a bingham body. At this point, enclaves are suspended, sinking is arrested, and the still flowing granodiorite may deform the previously acquired geometry. Although the observed flattened structure of enclaves in the vertical section may in part acquired at the time of sinking, if the whole batholith is ascending and flowing, and in part acquired once sinking is arrested. In the case of Valle Fértil, enclaves are not deformed by late flow of the granodiorite magma preserving exceptionally the primary geometries acquired during sinking. Figure 10 illustrates a plausible situation triggered by gravity instabilities in a reversely zoned magma chamber. This reconstruction is based on field relations mainly in the frequency of migmatite-gabbro contacts and mingled zones at the gabbro-tonalite contacts, as well as on the observations in the west part of the batholith where migmatite xenoliths are enclosed in the granodiorite. Top-to-down intrusions of mafic magma are identified by the formation of vertical pipes with a high concentration of enclaves in the tonalite and granodiorite rocks of the core.

Petrogenetic implications

These observations and interpretations on the generation of enclaves and synplutonic intrusions of mafic magmas in granite batholiths have important petrogenetic implications. First is that felsic and basic magmatism are not accidentally produced at the same time, implying that the processes involved in the generation of the basic magmas are also related to the process of generation of felsic magmas. Second is the fact that basic magmas represent top-to-down intrusions implying that these basic magmas reached the level of emplacement before the granite magma. The most plausible hypothesis, in agreement with the field observations and rheological explanations, is that the mafic magma formed part of a composite intrusion in which the core was formed by granites and the rim, including the top, was formed by basic magmas. The implication of this zoning in calc-alkaline batholiths, frequently reported in composite intrusions of this kind, is that granite magma must have originated on a source deeper than the source of mafic magmatism. It is clear that these mafic magmas are originated in a hydrated mantle source, possibly a suprasubduction mantle wedge. Thus, a crustal source able to generate the silicic magmatism that form the granite core of the composite intrusions, must be disposed below the mantle wedge. A plausible scenario to account for this petrological inversion in which the crustal source is below the mantle source, is offered by the well contrasted cold plume hypothesis (Gerya and Yuen, 2003). New laboratory experiments, recently developed by our research team (e.g., Castro and Gerya, in press), have proven that melting of subducted melanges incorporated to the mantle by cold diapirs, may account for the generation of calc-alkaline batholiths, similar to the Valle Fértil com-

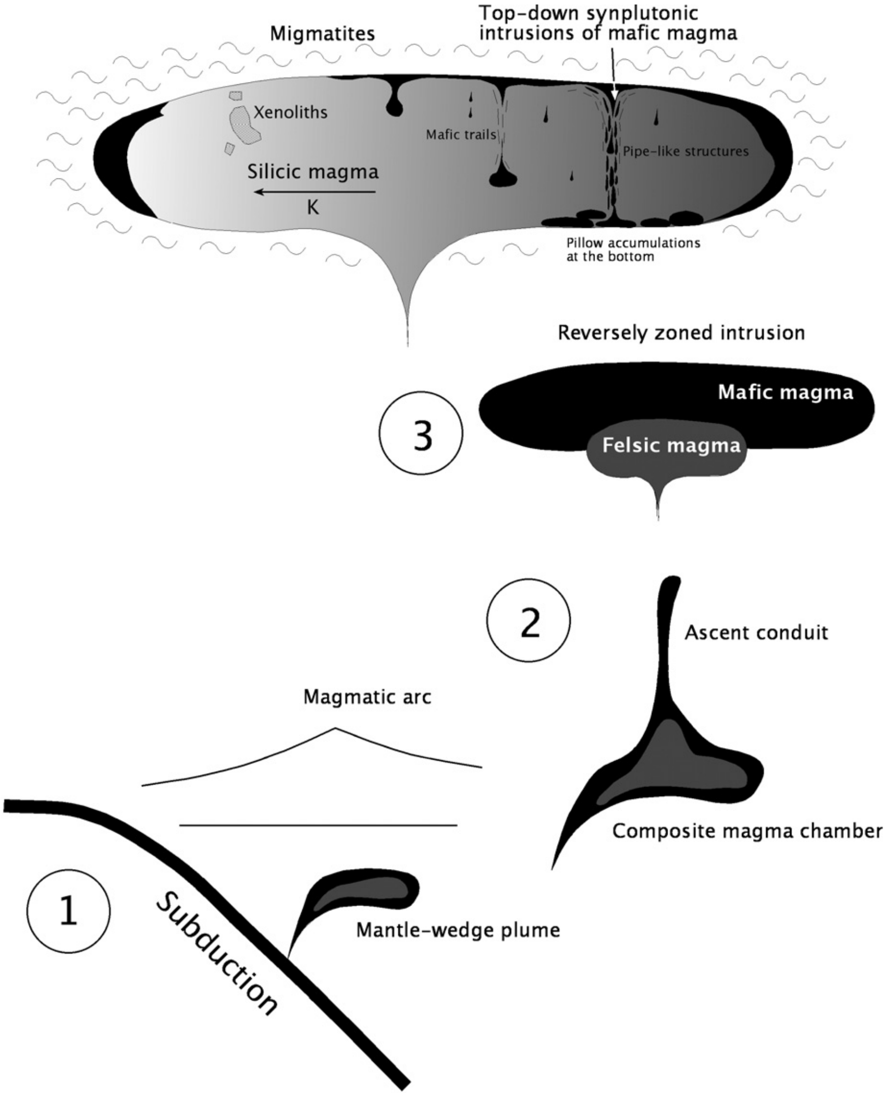

FIGURE 10 | **Cartoon showing the possible evolution of an instable composite magma chamber with a granitic core and a gabbroic carapace. The formation of the composite and instable magma chamber is possibly inherited from the zoned composition of mantle wedge plumes (Gerya and Yuen, 2003) formed as a consequence of rheological instabilities due to the subduction of hydrated oceanic crust and sediments. These processes in the mantle wedge are ideally shown in this cartoon in a time sequence from 1 to 3. Mafic magmas from the hydrated mantle carapace surrounding the felsic core of the plume (op. cit.) ascend earlier and form the first intrusion below the magmatic arc. Felsic magmas from the core of the plume intrude into the mafic magma chamber giving rise to the reversely zoned magma chamber where the top-down intrusions are developed. Details about the magmatic implications of mantle wedge plumes are given in Castro and Gerya (2007). It is also depicted in the cartoon the effect of sinking migmatite bloks that produced local assimilation and the observed increase in the K content of the batholith towards one of its margins.**

plex. The reversely stratified magma chamber observed in this complex, being the responsible of the top-to-down synplutonic intrusions, may be accounted for in a subduction-related scenario with the implications of cold plumes that dragged fertile, silicic materials down the mantle wedge where the basic magmas were generated.

CONCLUSIONS

Gravity instability in a reversely composed magma chamber is the responsible for the formation of top-to-down intrusions and the generation of mafic microgranular enclaves. Contact relations between the studied enclaves are indicative of liquid-liquid relationships and these are not compatible with a high crystal content in the granitic magma. Magma transport from the top of the magma chamber is assisted by the formation of pipe-like channels in which all kind of structures indicating sinking of mafic blobs are observed. Synplutonic intrusions from the top are the only plausible mechanism to account for the observed structures. The model may be of general application to any calc-alkaline batholith characterized by the presence of mafic microgranular enclaves. An implication of these reversely stratified magma chambers is the presence of a petrological inversion related to cold diapirs emplaced below the mantle wedge in a suprasubduction setting.

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REFERENCES

Bea, F., Montero, P., Molina, J.F., 1999. Mafic precursors, peraluminous granitoids, and late lamprophyres in the Avila batholith: A model for the generation of Variscan batholiths in Iberia. Journal of Geology, 107, 399-419.

Casquet, C., Pankhurst, R.J., Rapela, C.W., Galindo, C., Fanning, C.M., Chiaradia, M., Baldo, E., González-Casado, J.M., Dahlquist, J.A., 2001. Involvement of the Argentine Precordillera terrane in the Famatinian mobile belt: U-Pb SHRIMP and metamorphic evidence from the Sierra de Pie de Palo. Geology, 29, 703-706.

Castro, A., Gerya, T., in press. Magmatic implications of mantle wedge plumes: Experimental study. Lithos.

Didier, J., 1987. Contribution of enclave studies to the understanding of origin and evolution of granitic magmas. Geologische Rundschau, 76, 41-50.

Didier, J., Barbarin, B. (eds.), 1991. Enclaves and Granite Petrology. Developments in Petrology. Amsterdam, Elsevier.

Fernández, A., Barbarin, B., 1991. Relative rheology of coeval mafic and felsic magmas: Nature of resulting interaction processes and shape and mineral fabrics of mafic mineral enclaves. In: Didier, J., Barbarin, B. (eds.). Enclaves and Granite Petrology. Amsterdam, Elsevier, 263-276.

Gerya, T.V., Yuen, D.A., 2003. Rayleigh-Taylor instabilities from hydration and melting propel "cold plumes" at subduction zones. Earth Planetary Science Letters, 212, 47-62.

Holden, P., Halliday, A.N., Stephens, W.E., 1987. Neodymiun and strontium isotope content of microdiorite enclaves points to mantle input to granitoid production. Nature, 330, 53-56.

Mirré, J.C., 1976. Descripción geológica de la Hoja 19e, Valle Fértil, Provincias de San Juan y La Rioja. Servicio Geológico Nacional, Boletín N° 147. Ministerio de Economía, Buenos Aires, 70 pp.

Pankhurst, R.J., Rapela, C.W., Fanning, C.M., 2000. Age and origin of coeval TTG, I- and S-type granites in the Famatinian belt of NW Argentina. Transaction Royal Society of Edinburgh: Earth Sciences, 91, 151-168.

Pankhurst, R.J., Rapela, C.W., Saavedra, J., Baldo, E., Dahlquist, J., Pascua, I., Fanning, C.M., 1998. The Famatinian magmatic arc in the central Sierras Pampeanas: an Early to Mid-Ordovician continental arc on the Gondwana margin. In: Pankhurst, R.J., Rapela, C.W. (eds.). The Proto-Andean Margin of Gondwana. Special Publication. Geological Society, London, 343-368.

Pitcher, W.S., 1997. The nature and origin of Granite. Glasgow, Chapman & Hall, 321 pp.

Pontoriero, S., Castro de Machuca, B., 1999. Contribution to the age of the igneous-metamorphic basement of La Huerta range, province of San Juan, Argentina, II South American Symposium of Isotopic Geology, Proceedings, 101-104.

Vernon, R.H., 1984. Microgranitoid enclaves in granite-globules of hybrid magma quenched in a plutonic environment. Nature, 596, 438-439.

Vernon, R.H., Etheridge, M.A., Wall, V.J., 1988. Shape and microstructure of microgranitoid enclaves: indicators of magma mingling and flow. Lithos, 22, 1-11.

Vujovich, G.I., van Staal, C.R., Davis, W., 2004. Age constraints on the tectonic evolution and provenance of the Pie de Palo Complex, Cuyania composite terrane, and the Famatinian Orogeny in the Sierra de Pie de Palo, San Juan, Argentina. Gondwana Research, 7, 1041-1056

Vujovich, G.I., Godeas, M., Marín, G., Pezzutti, N., 1996. El complejo magmático de la Sierra de La Huerta, provincia de San Juan, Actas XIII Congreso Geológico Argentino y III Congreso de Exploración de Hidrocarburos, Argentina, 465-475.

Wiebe, R.A., Jellinek, M., Markley, M.J., Hawkins, D.P., Snyder, D., 2007. Steep schlierem and associated enclaves in the Vinañlhaven granite, Maine: possible indicators of granite rheology. Contributions to Mineralogy and Petrology, 153, 121-138.

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