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Contrasting magmatic structures between small plutons and batholiths emplaced at shallow crustal level (Sierras de Córdoba, Argentina)

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ABSTRACT

Processes like injection, magma flow and differentiation and influence of the regional strain field are here described and contrasted to shed light on their role in the formation of small plutons and large batholiths their magmatic structures. The final geometric and compositional arrangement of magma bodies are a complex record of their construction and internal flow history. Magma injection, flow and differentiation, as well as regional stresses, all control the internal nature of magma bodies. Large magma bodies emplaced at shallow crustal levels result from the intrusion of multiple magma batches that interact in a variety of ways, depending on internal and external dynamics, and where the early magmatic, growth-related structures are commonly overprinted by subsequent history. In contrast, small plutons emplaced in the brittle-ductile transition more likely preserve growth-related structures, having a relatively simple cooling history and limited internal magma flow. Outcrop-scale magmatic structures in both cases record a rich set of complementary information that can help elucidate their evolution. Large and small granitic bodies of the Sierra Pampeanas preserve excellent exposures of magmatic structures that formed as magmas stepped through different rheological states during pluton growth and solidification. These structures reveal not only the flow pattern inside magma chambers, but also the rheological evolution of magmas in response to temperature evolution.

1. Introduction

Magmatic structures provide a valuable window into magma-chamber processes (Clarke et al., 2013), and have been of considerable interest from the early field studies of Balk (1937), Emeleus (1963), to more recent works (http://geology.gsapubs.org/content/42/11/1023.fullSolgadi and Sawyer, 2008; Caricchi et al., 2012; Clarke et al., 2013; Vigneresse, 2015). Most of these studies were aimed at determining the origin and meaning of magmatic structures. Early studies (Balk, 1937; Pitcher and Berger, 1972) considered that only certain structures, such as crystal alignment or enclaves, were magmatic, representing flow dominated by liquid. In the current literature, structures formed by preferred orientation of magmatic crystals, lacking evidence for solid-state deformation, are considered to be magmatic, even when the melt fraction is low and magma behaves essentially as a solid (Paterson et al., 1989, 1998; Vernon, 2000; Vernon and Paterson, 2008; Pinotti et al., 2010). Layering represents the most common and controversial structure in felsic magmatic rocks (Aucott, 1965; Hutton, 1992; Philpotts and Asher, 1994; Clarke and Clarke, 1998; Weinberg et al., 2001; Pons et al., 2006; Barbey et al., 2008; Žák et al., 2008; http://geology.gsapubs.org/content/42/11/1023.fullGlazner et al., 2008; http://geology.gsapubs.org/content/42/11/1023.fullSolgadi and Sawyer, 2008; Paterson, 2009; Glazner, 2014).

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Other structures, such as *schlieren*, are important because in many cases they record the last physical process to affect the magma, and as such they are useful in determining magma chamber dynamics and even, in some cases, the timing of intrusion and crystallization relative to regional deformation (Clarke et al., 2013). A wide variety of processes, such as flow of magma mushes, gravity settling, multiple injections including microdiapiric injections, and incomplete homogenization during advanced anatexis, have been proposed for the formation of *schlieren* (Emeleus, 1963; Clarke and Clarke, 1998; Weinberg et al., 2001; Paterson et al., 2004; Culshaw and Clarke, 2009; Dietl et al., 2010; Clarke et al., 2013). Despite intense debate on their definition and origin, studies relating the nature of magmatic structures with the growth and thermal history of magma chambers are still relatively scarce (Weinberg et al., 2001; Wiebe et al., 2007; Žák et al., 2009; Clarke et al., 2013).

Thermal maturation of a pluton and its growth conditions strongly influence the nature and preservation of magmatic structures. Two endmember situations can be established: 1) small plutons without defined zonation, more likely preserving growth-related structures; and 2) large, batholith-sized bodies with strong internal zonation, and multi-pulse intrusions, more likely preserving internal flow and hybridization processes (Stevenson, 2009; Paterson, 2009). The first endmember is expected to have a relatively simple cooling history, where internal magma flow is limited to a simple history of intrusion, flow and cooling. In contrast, the thermal evolution of the second endmember can be much more complex, because new magma inputs generate intricate internal magma flow and thermal instabilities. An excellent example of this is the thermal and flow perturbations caused by mafic replenishments into a silicic magma chamber in the Vinalhaven granite (Wiebe et al., 2007).

In this paper, we describe several outcrop-scale examples of magmatic structures from different parts of the Sierra Pampeanas, central Argentina, which record differences between the two endmembers. We start by presenting features recorded by small plutons emplaced in the brittle-ductile transition that mainly show magmatic layering. Then, we contrast them with features recorded in voluminous intrusions indicative of increased complexity. Finally, we explain the processes prevailing in the generation of the magmatic structures by the interplay between different factors, such as injection, internal magma chamber processes and the regional stress field, for both endmember plutons.

2. Small plutons emplaced in the brittle-ductile transition

In the Sierras Pampeanas of Córdoba there are several small trondhjemite plutons recording magmatic structures. They belong to the G2 group of trondhjemite-tonalite intrusions associated with the Famatinian subduction event that started at 500 Ma (Rapela et al., 1998). Fig. 1 shows their location, with the La Fronda pluton in its northern part, and Calmayo and El Hongo plutons in its southern part.

The main facies comprising these plutons is a coarse-grained, hypidiomorphic trondhjemite that contains more than 90% of plagioclase and quartz, and minor biotite and muscovite. Accessory minerals include epidote, apatite, magnetite, zircon and titanite. Idiomorphic epidote with allanite core is common as inclusions in biotite. In addition, plutons show chilled margins with very fine-grained trondhjemite. Rb-Sr isochron yielded an age of 474 $\pm$ 6 Ma for the emplacement of the La Fronda trondhjemites (Rapela et al., 1998), whereas zircon yielded U-Pb ages of 500.6 $\pm$ 4.5 Ma for the El Hongo and 512.1 $\pm$ 3.4 Ma for the pluton the Calmayo pluton (D'Eramo et al., 2013).

Detailed structural studies were carried out in the Calmayo, El Hongo and La Fronda plutons combining information from country rocks with structural and magnetic fabric data from the trondhjemites (D'Eramo et al., 2006a, 2006b and 2013). The La Fronda pluton is a small massif elongated N-S (25 km^2), whereas the Calmayo (10 km^2) and El Hongo (4 km^2) plutons are elongated ENE–WSW (Fig. 1). The contacts with country rocks are sharp, steeply dipping and discordant. These plutons include large blocks and septa of country rocks, where trondhjemite sheets are separated by abundant *in situ* xenoliths, which still preserve the foliation of the country rocks. The La Fronda pluton shows spectacular examples of numerous, hundred-metres long septa of country rocks, in NW-SE trending corridors, with foliation-parallel injections of trondhjemite.

The metamorphic foliation trajectories in the country rocks of the Calmayo and El Hongo plutons suggest an asymmetric boudin-like structure (Fig. 2). This led D'Eramo et al. (2013) to propose that large-scale asymmetric boudinage may be an efficient mechanism controlling magma emplacement and that boudin necks acted as low-pressure magma traps, where magma accumulated. The same authors also proposed that magma ascent was channelled through en-échelon dilatational fractures located in the boudin necks. No thermal aureoles developed around the Calmayo and El Hongo plutons because of the high-grade thermal conditions reached in the country rocks during peak regional metamorphism at ~520 Ma (Rapela et al., 1998). Instead, the plutons have chilled margins, indicating that the country rocks were cold at the time of intrusion. Furthermore, the emplacement of the Calmayo pluton triggered the development of low-temperature shear zones, with S-C tectonites in the easternmost part of the pluton and surrounding country rocks. Thin sections of mylonitic country rocks, cut parallel to the XZ plane of deformation, reveal strain partitioning between microlithons (1–2 cm-thick S-domains), where older coarse grains of quartz with chessboard extinction (Fig 3a) are still preserved, and narrow layers (1 mm-thick C-domains) with small grains of quartz with elongate shape and grain boundary bulging recrystallization (Fig. 3b). Such fabric attests to a solid-state deformation that evolved from sub-solidus (T $>$ 650 °C) to low-temperature (T $\approx$ 300 °C) conditions (Mainprice et al., 1986; Sadeghian et al., 2005; Law, 2014). It is worth noting that the development of S-C tectonites led to advanced chloritization of the metamorphic country rocks, which also indicates low-temperature conditions. These data suggest that the emplacement level of the trondhjemite bodies roughly coincides with the brittle-ductile transition.

2.1. Magmatic structures recorded by small plutons

Despite their homogeneous overall composition, these plutons show conspicuous magmatic layering. Some of them preserve spectacular folded and sheared magmatic layering and, less commonly, structures related to injection of mafic magmas.

2.1.1. Magmatic layering and foliation

Remarkable compositional layering defined by rhythmic alternation in biotite content is common in all trondhjemitic plutons from the Sierras de Córdoba. Two kinds of layering have been recognized depending on the biotite content and distribution: isomodal and modally-graded layering (Barbey et al., 2008). Isomodal layering consists of quartz- and plagioclase-rich leucocratic bands with minor biotite that alternate with thinner melanocratic bands, dominated by biotite homogeneously distributed (Fig. 4a). Modally-graded layering is marked by a sharp basal contact of biotite-rich bands that decreases progressively in biotite content towards the top contact (Fig. 4 b). Inside the layers, biotite and plagioclase crystals are oriented preferentially parallel to layer contacts. Band thicknesses of both types usually vary between a

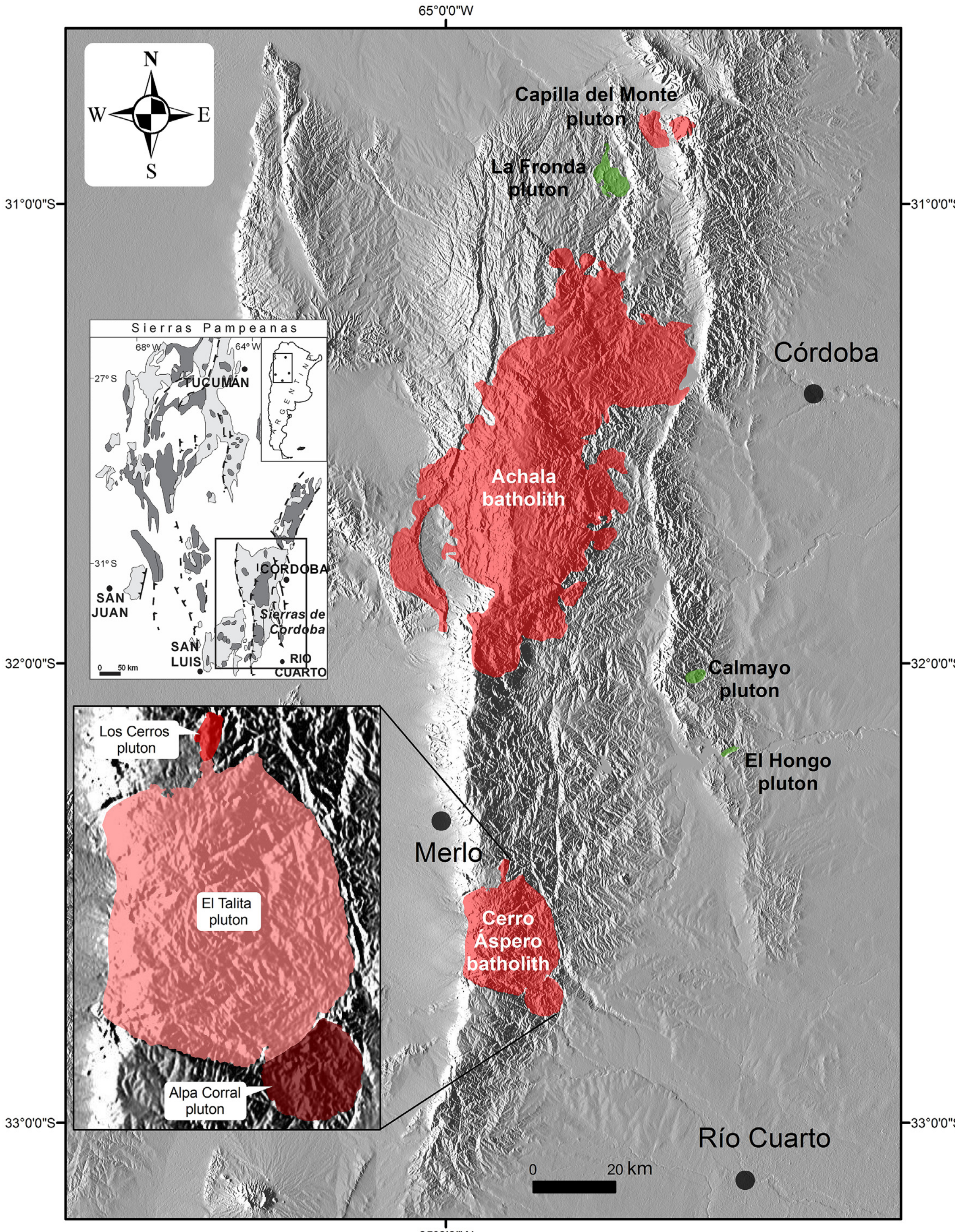

Fig. 1. Digital elevation model of the Sierras de Córdoba, showing location of the Cambrian-Ordovician small plutons (5–25 km^2 – shaded in green), and the large Achala (4000 km^2) and Cerro Áspero (440 km^2) batholiths, along with the Capilla del Monte pluton, belonging to Devonian magmatism (shaded in red). Inset at the top: Location of the Sierras de Córdoba (solid rectangle) in the context of the Sierras Pampeanas. Inset at the bottom: Location of the plutons comprising the Cerro Áspero batholith, from north to south: Los Cerros pluton, El Talita pluton and Alpa Corral pluton. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

few centimeters and more than 1 m, and they commonly define regular, parallel and anastomosed patterns. In some cases, isomodal layering shows less regular patterns, narrowing and widening along the bands, with a heterogeneous distribution of biotite. Depositional structures similar to sedimentary gravity flow (http://geology.gsapubs.org/content/42/11/1023.fullSolgadi and Sawyer, 2008) are common. These structures include rhythmic successions of modally-graded layers, with low-angle branching, unconformities, and cross-bedding.

Layering can be continuous over several tens of meters and sometimes they show textural variations, with significant grain size increase in biotite-poor bands. Syn-magmatic dikes commonly

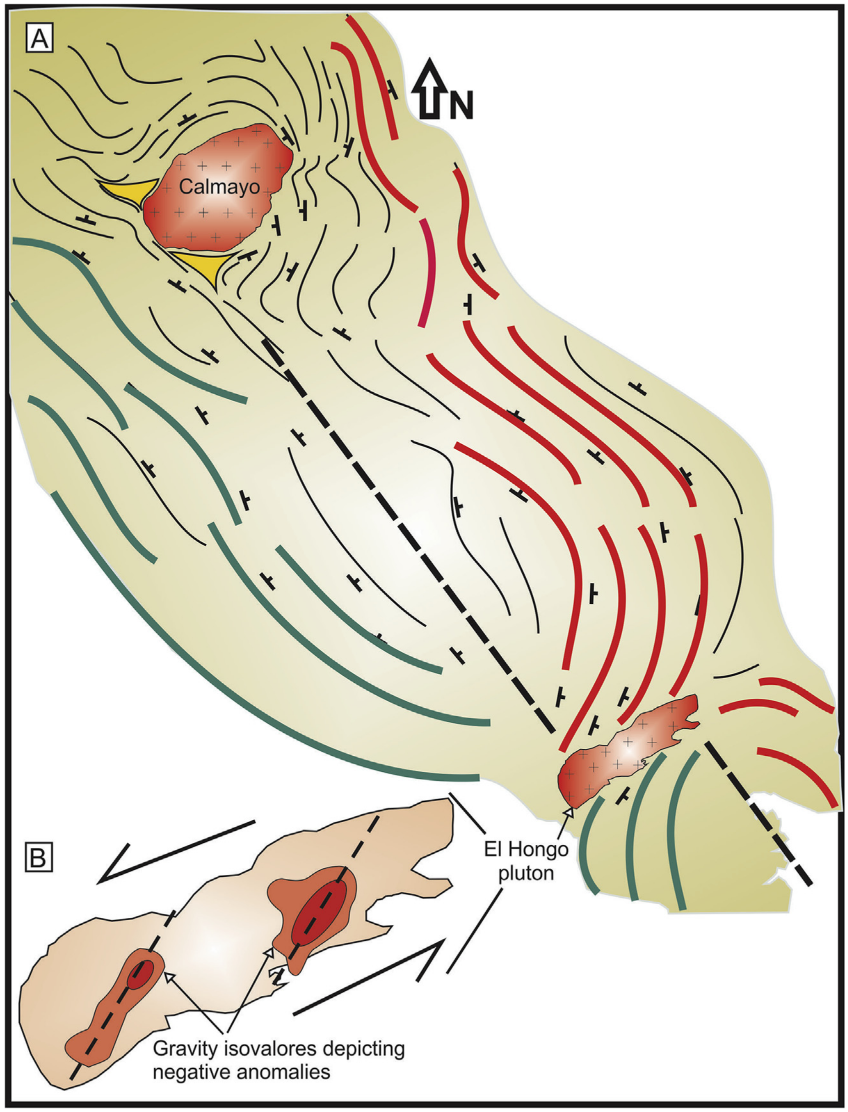

Fig. 2. (A) Sketch showing the regional foliation traces defining regional scale boudins, and the location of the trondhjemite Calmayo and El Hongo plutons in boudin necks. The red and green lines mark the eastern and western edges of the boudins, respectively. The yellow colour outlines foliation triple points around the Calmayo pluton. Close to the El Hongo pluton, a sinistral displacement along the boudin neck is evidenced when the boudin median-lines are taken as reference. (B) The same shear sense can be inferred from en-échelon arrangement of the two conduits, revealed by two negative gravity anomalies located below the El Hongo pluton (modified after D'Eramo et al., 2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

have sinuous and lobated contacts, indicating low rheological contrast with the host trondhjemite. Dikes can also be internally layered, with layers of varying biotite content, similar to those in the host trondhjemite. In other cases, dikes have margin-parallel layered aplite and pegmatite bands (Fig. 4c) that generally cross-cut magmatic layering of the host trondhjemite (Fig. 4d).

In order to understand the significance of magmatic layering, we need to determine how it correlates to the overall internal structure of the pluton. We have combined a study of the anisotropy of magnetic susceptibility (AMS) with field structural data and microstructural observations within the ferromagnetic El Hongo pluton (Figs. 1 and 5). These structural data have been complemented by a gravity survey to obtain a detailed 3D image of the pluton's shape (D'Eramo et al., 2006a). The magnetic foliation strikes north–south and dips steeply to the west across the pluton, except in the marginal trondjhemite facies, where it rotates to become parallel to the ENE–WSW pluton contact (Fig. 5a). Gravity modelling indicates that the El Hongo pluton is a flat-lying sheet located above two negative anomalies having a NNE–SSW elongation (Fig. 2b). Thus, this pluton is not a vertical plug but a very thin, flat-lying granite tongue above two root zones, likely representing feeder dikes that exploited en-échelon tension fractures (D'Eramo et al., 2006a). The rhythmic granite layers (Figs. 4 and 5a) have a uniform north–south strike, and dip steeply nearly parallel to the AMS foliation. The Calmayo pluton is also a thin and flat sheet with a N–S-trending root zone located below its central portion. It also shows parallelism between rhythmic modal layering and magnetic foliation, with magnetite grains usually found as elongate inclusions parallel to the (001) cleavage of the host biotite crystals (D'Eramo et al., 2006a). Layering, magnetic foliation and the elongation of the root zone all broadly share the same trend (Fig. 5b).

2.1.2. Magmatic folds

Layering in the La Fronda pluton (Fig. 1) defines magmatic folds in a variety of scales (Fig. 6). Fold profiles are typically complex and disharmonic, with open to tight folds occurring without hinge

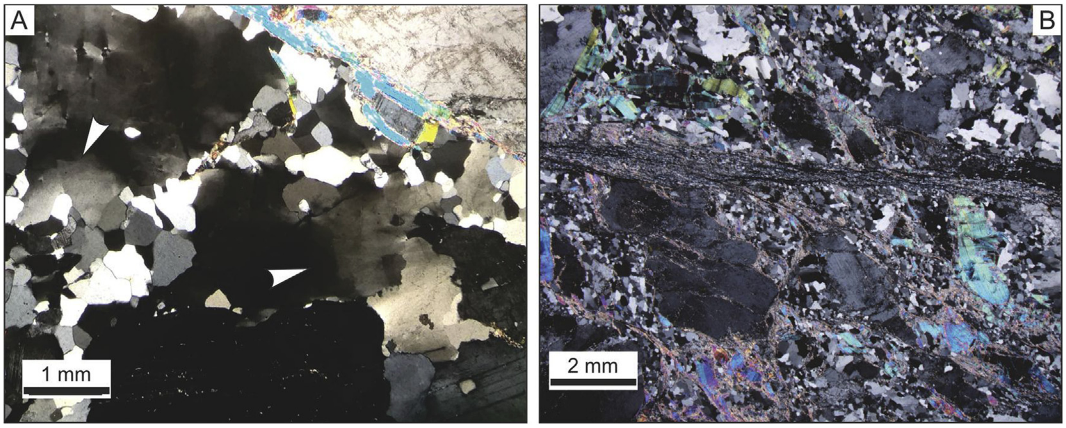

Fig. 3. Photomicrographs of XZ planes of strain of mylonitic trondhjemites. (A) Strain partitioning into narrow shear zones (horizontal in figure) between microlithons (S-domains), with coarse grains of quartz showing chessboard extinction (arrows). (B) General view of the narrow layers (C-domains) with elongate-shaped, fine-grained quartz and grain boundary bulging recrystallization.

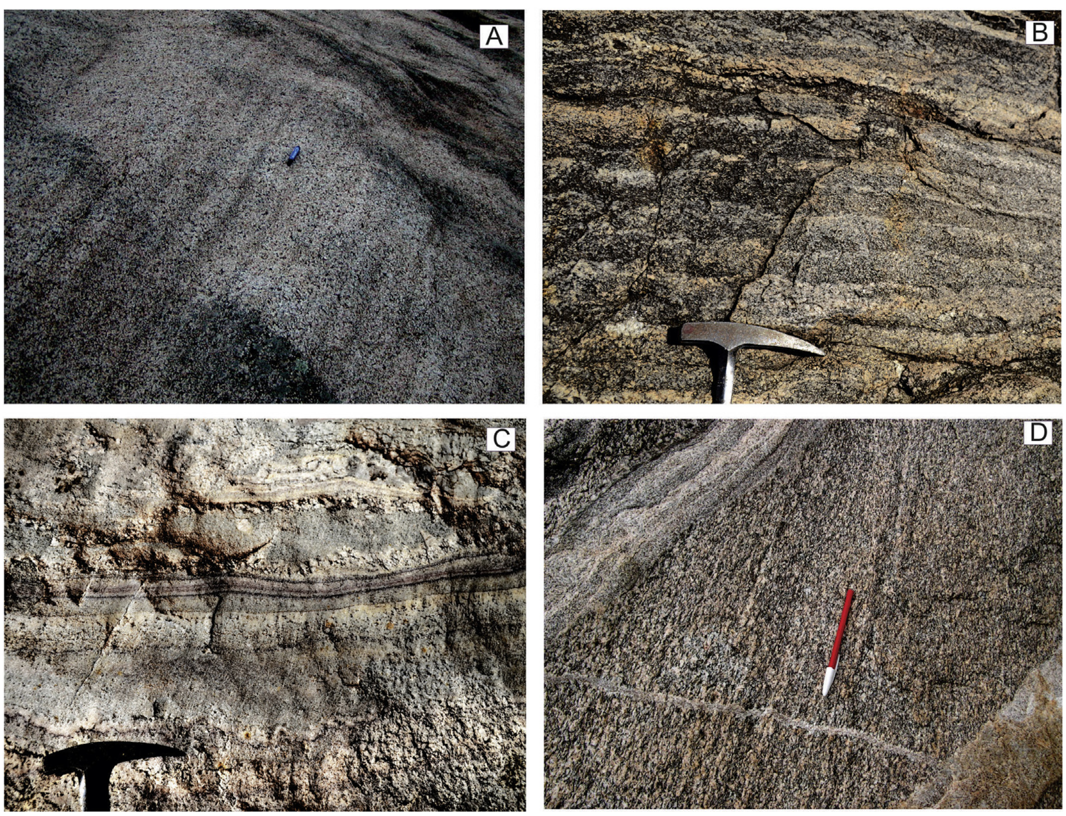

Fig. 4. Different types of layering. (A) Rhythmic isomodal layering defined by alternating bands of mostly quartz–feldspar composition (only minor biotite) and mafic bands with high biotite contents, homogeneously distributed throughout them. (B) Modally-graded layering marked by a sharp biotite-rich contact at the base and progressive decrease in biotite content towards the top contact. (C) Dike layering consisting of margin-parallel layered aplite and pegmatite bands. (D) Dike layering consisting of layers with varying amounts of biotite similar to layering in the host trondhjemite.

thickening (parallel folds, Fig. 6a). Axial planar foliation is present where strong magmatic folding is observed. Fig. 6b shows an example where layers define an upright, tight fold, within which igneous biotite is roughly parallel to the axial plane. This foliation is better developed in felsic layers, whereas biotite remain parallel to layering in mafic layers (Fig. 6b).

The La Fronda pluton records low to moderate solid-state deformation represented by chessboard extinction in quartz, and mechanical twinning and bent twin lamellae in plagioclase. These structures represent high-temperature deformation, close to the magma solidus (Paterson et al., 1998).

2.1.3. Interactions between magmas: enclave corridors and back-veining

The small La Fronda body (Fig. 1) also shows magmatic structures related to the intrusion of hot mafic magmas. The hotter mafic magmas cools in contact with the felsic magma (Fernandez and Gasquet, 1994), and if both magmas remain above the solid-liquid

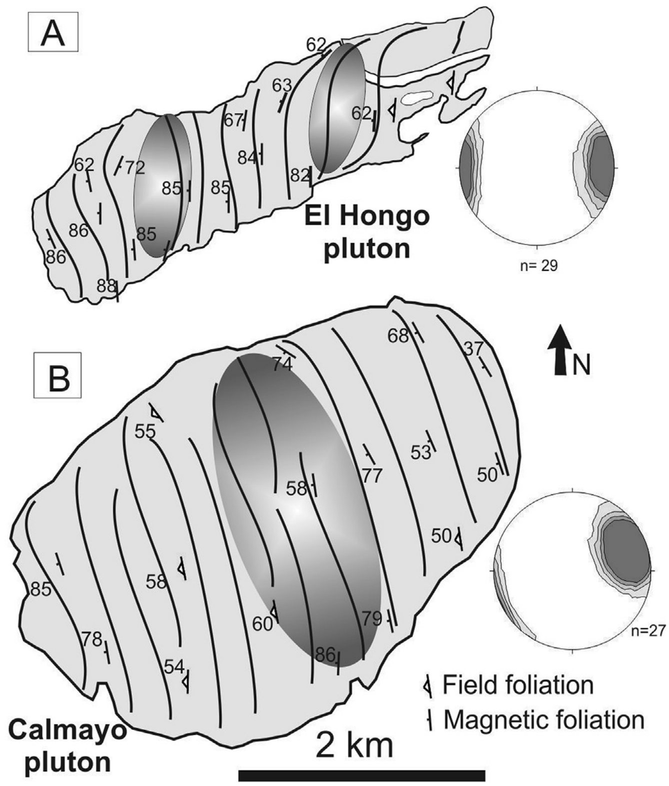

Fig. 5. (A) El Hongo and (B) Calmayo pluton maps showing magmatic foliation trajectories from field and magnetic fabric data. Schematic ellipses represent the roots determined by gravimetric survey. Note parallelism between foliation trajectories and major axes of the roots in both plutons (modified from D'Eramo et al., 2013).

transition (SLT; Rosenberg and Handy, 2005), the felsic magma will have a higher viscosity than its mafic counterpart (Fernandez and Gasquet, 1994). With continued cooling, the mafic magma reaches the SLT before the felsic one because of its higher solidus temperature, thus inverting the viscosity relationship. When this happens, the more viscous mafic magma may be back-veined by the felsic one (Sederholm, 1923). Fig. 7a shows a mafic dike intruding the trondhjemite of the La Fronda pluton. The mafic dikes are thin and planar, indicating relatively high intrusion rates. However, their margins are lobated, suggesting that the mafic dikes were less viscous than their surroundings at that time. Continued cooling and solidification of the mafic dike led to it breaking up and back-veining by the felsic magma (see also Fig. 7c).

In another sector of the La Fronda pluton, a small mafic intrusion forms a dome-shaped body, 50 cm in diameter, with a clear concentric foliation both inside and outside the dome (Fig. 7b), suggesting that the mafic magma formed a small diapir intruding the suprasolidus trondhjemite. The presence of layers enriched in mafic minerals in the trondhjemite close to the contact suggests that interstitial magma has been extracted from its interstices. A similar example is given in Fig. 7d, where the mafic intrusion forms small lobes into the trondhjemite.

2.1.4. Syn-magmatic shearing

Syn-magmatic shearing is common in plutons (Fig. 8) but relatively rarely described (e.g. Blumenfeld and Bouchez, 1988; Gleizes et al., 1998; Symington et al., 2014). A well-exposed example from the La Fronda pluton is shown in Fig. 8a where two mafic dikes are displaced by several syn-magmatic shear zones and one of them is outlined by late quartz filling. Usually such shear zones are recognizable only by the displacement of mafic layers, because subsequent magma flow heals the shear zone. In Fig. 8b, a *schliere*, folded, thinned and disaggregated by a set of shear bands, attests to the syn-magmatic character of shearing.

3. Batholiths emplaced in shallow-crustal levels

This section describes magmatic structures from the Cerro Áspero batholith (CAB) and Capilla del Monte pluton (Fig. 1) that belong to the post-orogenic G3 group of Rapela et al. (1998). The G3 granites represent the final Paleozoic magmatism in the Sierras Pampeanas, dated between 380 and 360 Ma (Stuart-Smith et al., 1999; Llambías et al., 1998). These igneous bodies are dominated by monzogranite with inequigranular to porphyritic textures. Perthitic K-feldspar megacrysts are conspicuous, with plagioclase, quartz and biotite as the main phases in the medium-grained matrix. The biotite modal content and the anorthite content in plagioclase are variable; magnetite, titanite, allanite and zircon are the main accessory minerals. Mafic microgranular enclaves of tonalite to granodiorite composition are abundant.

Most of these Devonian batholiths display elongate shapes (Fig. 1) and are composed of circular plutons arranged in a N-S to NW-SE orientation. Contacts with the host rocks are commonly sharp and discordant, crosscutting all previous structures and defining polygonal geometries (Pinotti et al., 2002). Pressure and temperature conditions of <2 kb and ~800 °C are estimated for the emplacement of some of these granitoids based on Crd + Bt + And mineral assemblages in samples from the wide thermal aureoles in host rocks (Pinotti et al., 2002). These conditions are broadly shared by most of the Devonian batholiths (Llambías et al., 1998) and point to shallow emplacement levels consistent with the brittle behavior of the host rocks during magma emplacement.

The Cerro Áspero batholith, covering more than 440 km^2, resulted from the sequential crystallization of three major plutons: the Alpa Corral, El Talita and Los Cerros plutons (Fig. 1). They are aligned in a NNW trend and mainly intrude mylonitic rocks from the Guacha Corral shear zone. Each pluton displays its own textural and mineralogical variations, showing external, internal and roof units, as well as dike swarms in country rocks. The intrusion sequence, evidenced by crosscutting relationships, started with the Alpa Corral pluton, followed by the El Talita pluton and ending with the Los Cerros pluton. The modal proportion of biotite strongly decreases and plagioclase composition changes from medium oligoclase to albite, from the older to the younger pluton.

3.1. Magmatic structures in the batholiths

3.1.1. Suspension flow: crystal alignment and mafic microgranular enclaves

Several structures formed in magmas with suspended crystals prior to the “solid-to-liquid transition” (SLT) or the “rheological critical melt percentage” (RCMP; Arzi, 1978; Van der Molen and Paterson, 1979), can be recognized in the porphyritic rocks of these Devonian plutons and batholiths. They are defined by phenocryst and enclave alignment lacking significant solid-state deformation and interpreted to mark magma flow direction (Fig. 9a). Phenocrysts with orientations systematically oblique to the magma flow direction are also common in these granites (Fig. 9a). Similar magmatic structures have been described in other K-feldspar-bearing granites and interpreted as tiling (Vernon, 1986, 2000; Blumenfeld, 1983; Paterson et al., 1989; Bouchez, 1997).

K-feldspar megacrysts can be incorporated into mafic magma enclaves (Fig. 9 b,c) as is common in magma mingling environments. Large K-feldspar clusters can also develop in the vicinity of mafic enclaves and create logjams that act as filters (Weinberg

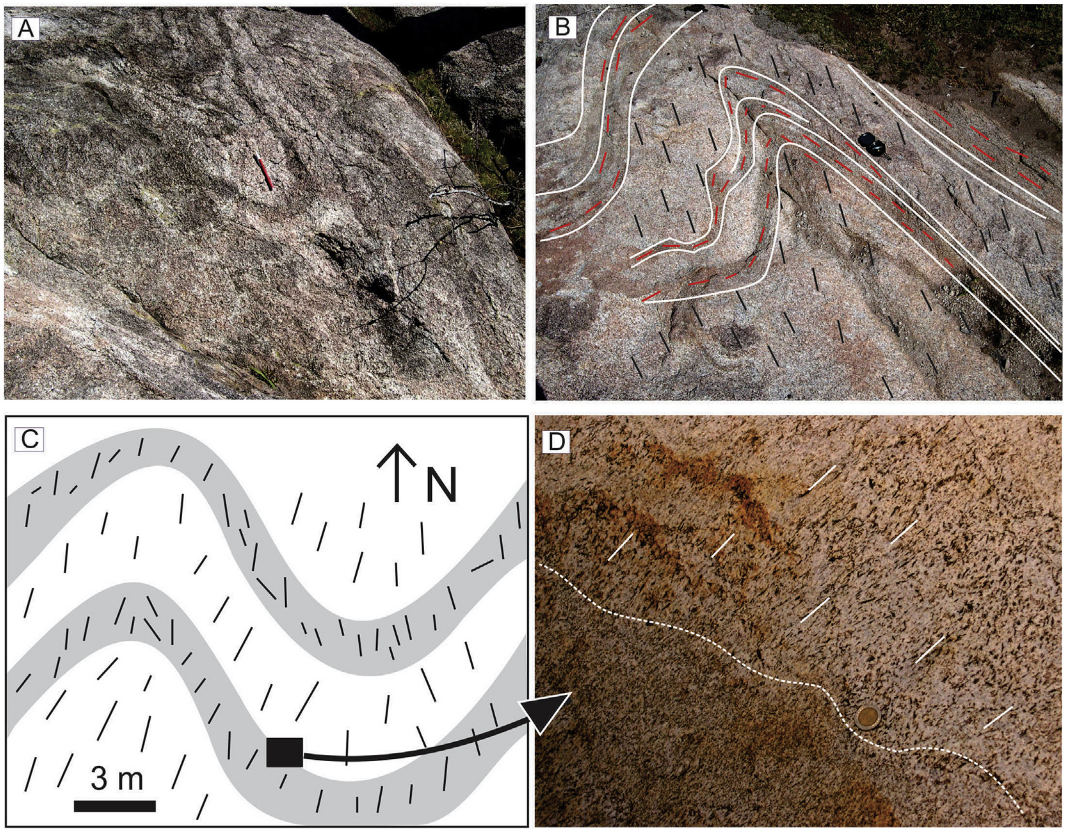

Fig. 6. Magmatic folds. (A) Tight fold with only minor hinge thickening. (B) Tight fold with weakly developed but recognizable axial planar foliation. White solid lines delineate folds, black lines show biotite orientation in felsic layer, red lines, parallel to layering, show biotite orientation in more mafic layers. (C) Line drawing of folded magmatic layers in the La Fronda pluton showing the axial planar orientation of biotite in all layers. Grey layers are richer in biotite. Black rectangle marks location of (D). (D) Axial planar foliation defined by biotite perpendicular to layering. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2001). This occurs for example when a large diorite blob starts to break up (Fig. 10a) and megacrysts concentrate at the entrance to the opening and growing fracture, allowing only megacryst-free melt to pass into the expanding crack (Fig. 10b). K-feldspars may also concentrate around the mafic dike walls and enclaves due to filter-pressing and expulsion of the interstitial melt fraction (Fig. 10c). In the large batholiths of the Sierra de Córdoba some K-feldspar clusters or cumulates with up to 80% modal percent of megacrysts and larger than 10 m in diameter (Fig. 11) could result from flow necking and log-jamming processes, as described by Weinberg et al. (2001) and Paterson (2009).

3.1.2. *Ladder dikes or tubes*

These structures are perhaps the most enigmatic ones in granitoids. Reid et al. (1993) described them in the Tuolumne batholith as narrow dikes with irregular walls, which can be several tens of meters long, and have an alternation of crescent-shaped dark and light layers inside. Each curved layer of these ladder dikes is nested, usually conformable and is younger in the concave side. Weinberg et al. (2001) discussed the genesis of ladder dikes in the Tavares pluton (Brazil) and described possibly related structures which they called snail structures. Paterson (2009) described other examples from the Tuolumne batholith and, disregarding their internal structure, called them tubes instead of ladder dikes, based on their cylindrical shapes.

Ladder dikes are also frequent in the Córdoba granitic bodies where the diameter of the tubes varies from tens of centimeters to a few meters. The tubes have weak variations of composition and texture, with mafic *schlieren* becoming more felsic in composition and macroscopically similar to the host magma (Fig. 12). The leucocratic layers are dominated by quartz and K-feldspar while the mafic layers mainly contain biotite and plagioclase. Crosscutting relationships between *schlieren*-bounded layers allow determination of younging directions of the ladder dikes and thus provide information regarding their evolution with time (Fig. 12 d,e).

Weinberg et al. (2001) linked such structures to local laminar flow resulting from the thermal or compositional convection in a crystallizing mushy magma chamber with ~50% of crystals. They found mesoscale plumes associated with ladder dikes that indicate that small, localized heat input related to mafic intrusions may cause a drop in density of the surroundings, and a drop in magma viscosity and drive gravitational instabilities. *Schlieren* in this case are a result of shear flow sorting against a rigid wall and the ladder dyke a result of slow magma flow in relation to the source of the rising magma, analogous to the process of thermal plumes (hot-spot), whereas “snail structures” would form in stationary regions of the magma chamber.

Paterson (2009) added that the percentage of crystals in the mush at the time of formation of these structures may be greater than 50%, arguing that these structures would collapse at higher melt fractions. His observations indicate that the magma hosting the tubes was stiff enough over the time scales of tube formation to resist mingling and collapse of the tube, but weak enough to move into and through tubes, or to re-intrude and break the tubes. He also provided examples of “stationary” tubes, several tubes overlapping and decreasing in radii with time.

Hodge et al. (2012) working on the same examples from the Tuolumne batholith, added experimental data to the debate. Unlike

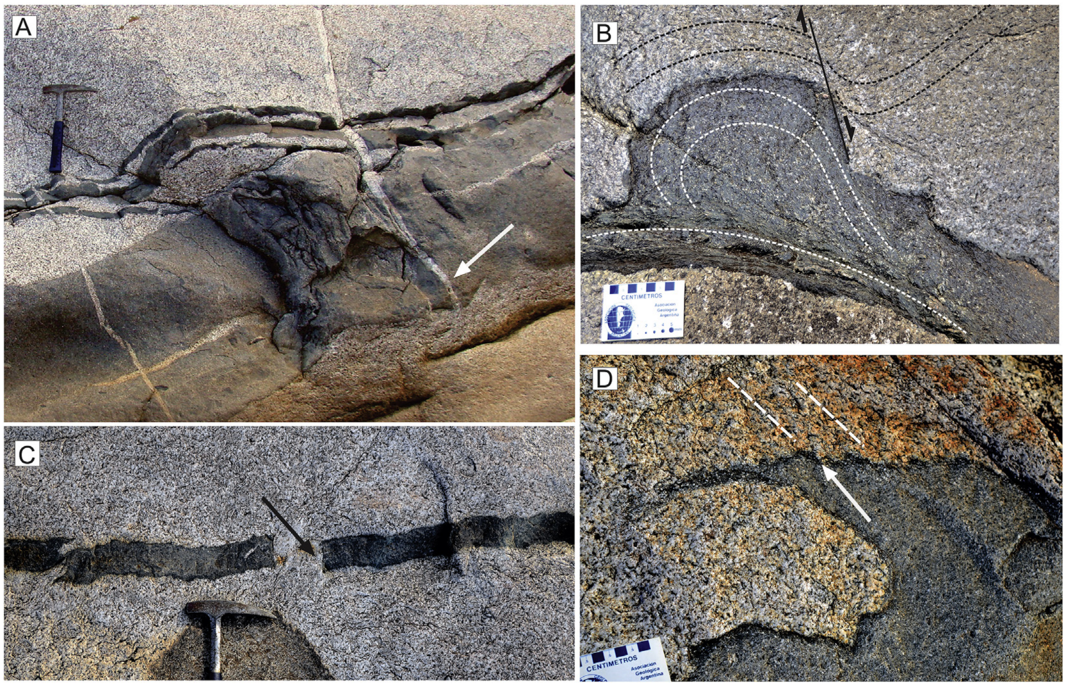

Fig. 7. Magmatic structures showing coexistence of two rheologically different liquids, as hot mafic magma intruded a still molten trondhjemitic body. (A) Lobate contacts between the two magmas and segmentation of mafic dike re-intruded or back-veined by the trondhjemitic magma. White arrow marks a more leucocratic trondhjemitic vein crossing mafic dike, indicating that evolved interstitial melt was extracted from the trondhjemite during back-veining. (B) Diapir from the less viscous mafic magma sheet intruding host trondhjemite magma. Note concentric foliation (white dashed lines) preserved inside the diapir and how the host trondhjemite foliation (black dashed lines) was folded and sheared close to the contact. (C) Mafic sheet margin, enriched in mafic minerals, are dragged (white arrow) into the foliation in the trondhjemite forming an irregular contact. (D) Mafic dike broken apart and intruded by interstitial magma extracted from the host (black arrow).

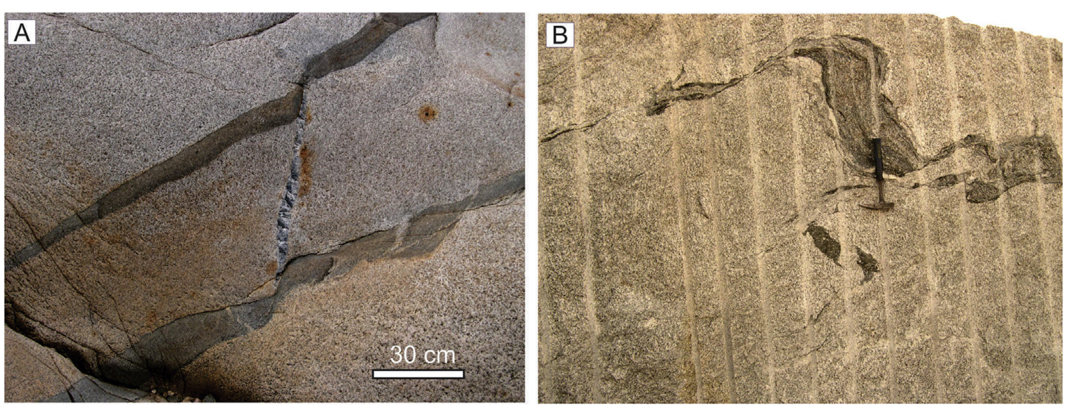

Fig. 8. (A) A pair of mafic dikes sheared in several locations. Note that shearing generally does not extend into adjacent trondhjemite, demonstrating its synmagmatic nature. In one locality, trondhjemite intrudes the shear zone (red arrow), in another quartz infills the shear zone that connects the two dikes. (B) Syn-magmatic shear bands folding, thinning and disaggregating a *schlieren*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Weinberg et al. (2001), these authors argued that the vertical dike becomes rigid enough to break under tension induced by convection in the chamber. Stretching and tilting caused by shearing within the chamber finally breaks the outer mafic margin of the plume and reveals its flowing granodiorite core with the characteristic ladder dike features.

Recently, Clarke et al. (2013), based on observations from the Halifax pluton, suggested that ring *schlieren* (the term they used for “ladder dikes” and snail structures) result from the action of supercritical hydrous fluids interacting with crystal-rich magmas. The multiple rings in a single structure would result from rising bubble trains using discrete ascent pathways, and shear flow around the bubble margins causing segregation of solids according to grain size. The time sequence from the large outer rings to the smaller inner ones may result from larger bubbles being followed by smaller ones, or from constant bubble size and expansion of the rings as each bubble rises.

The Sierras de Córdoba batholiths confirm the close relationship between tubes or ladder dikes and mafic diorite to tonalite injections. These injections, generating compositional and thermal gradients, are found as fragmented remnants represented by the numerous mafic enclaves observed in the vicinity or inside the tubes. As observed by Paterson (2009) and Hodge et al. (2012), in the tubes of the Sierras de Córdoba batholiths the host granitic magma may re-intrude and break apart the tubes (Fig. 12c).

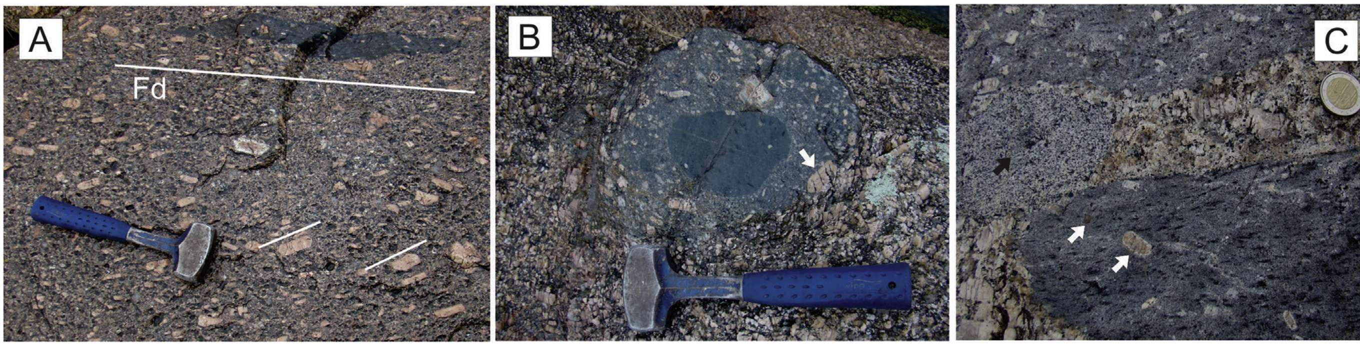

Fig. 9. (A) Foliation defined by the alignment of phenocrysts and enclaves. Note the occurrence of K-feldspar megacrysts oblique to the flow direction (Fd). (B) Composite enclave comprising a fine-grained mafic core and a K-feldspar megacrystic mafic rim in a megacrystic granite. Megacrysts (white arrow) in the outer rim are similar in size to those in the granite, suggesting their transference from granite to enclave. (C) Diorite enclave in a coarse-grained monzogranite. Quartz and K-feldspar xenocrysts have been incorporated into more mafic magma (white arrows), in mingled zones. Black arrow points to an intermediate enclave formed by hybridization.

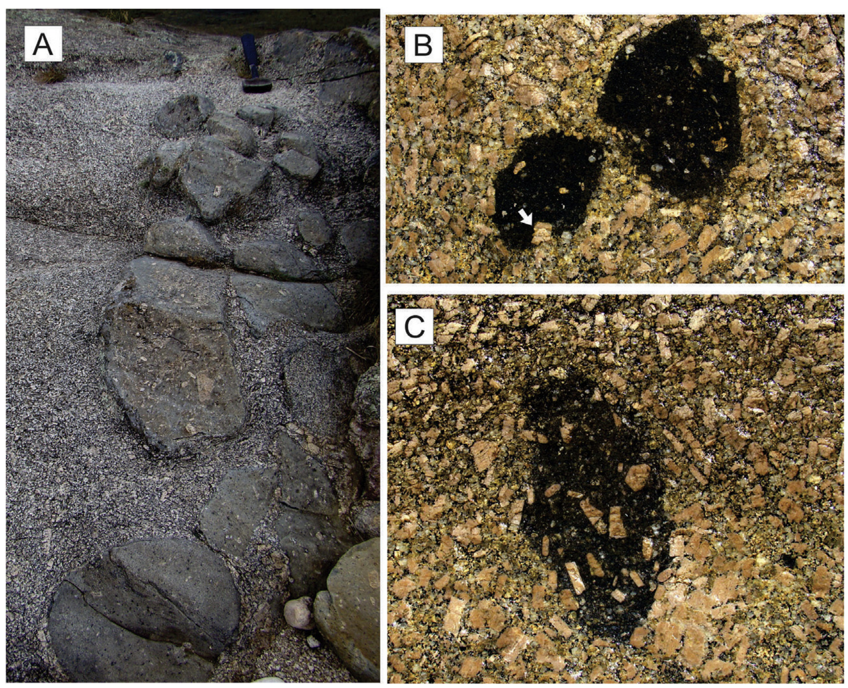

Fig. 10. (A) Large diorite fragmented into a swarm of enclaves in a porphyritic granite. (B) Two mafic enclaves containing xenocrysts from the granite separated by a megacryst-free narrow channel suggesting filtering of megacrysts as the granite intruded into and fragmented the mafic enclave. White arrow shows a K-feldspar megacryst incorporated into the mafic enclave. (C) K-feldspar aggregates around mafic enclaves.

3.1.3. Troughs

Troughs are similar to cut-and-fill structures with truncations reminiscent of sedimentary structures. In the Capilla del Monte pluton, a large channel with trough width of 15 m and 1.5 m in amplitude was found (Fig. 13). This erosional channel was filled by a white leucogranite contrasting with the hosting red granite and showing a clear isomodal layering that outlines the curvature of the channel (Fig. 13). The isomodal layering consists of alternating layers with variable biotite contents. According to Žák et al. (2008) and Paterson (2009) this is analogous to sedimentary flow channels in which the channels have a bedload that form a porous medium. Magma flow is likely parallel to the axis of the trough, as inferred by mineral alignment in the biotite-rich layers. Variable processes, such as crystal mush avalanches, gravity-driven channelized flows, convection-driven flow along irregular mush zone margins, and downward return flow during ascent of new magmas were suggested to explain such structures (Paterson, 2009).

3.1.4. Melt segregation structures

The construction of batholiths involves the growth and coalescence of plutons formed from magma injections through different feeder conduits. As a consequence, large parts of many batholiths consist of domains subjected to interactions between neighboring intrusions. The Cerro Áspero batholith provides an excellent example of segregation of residual melts caused by the interplay between growing plutons during batholith building. Outcrop-scale structures in the Alpa Corral pluton were complemented with detailed field and AMS measurements, allowing the reconstruction of the structural pattern of this pluton. The original structures formed during the Alpa Corral pluton emplacement, the first one to intrude, were systematically deformed and reoriented by a N-S flattening (Fig. 14) driven by the southward expansion of the El Talita pluton. N-S flattening occurred while the Alpa Corral pluton was not fully crystallized (Pinotti et al., 2006), leading to high-temperature deformation close to the contact with the El Talita

Fig. 11. (A) K-feldspar megacryst cumulate 10 m in diameter in the El Talita pluton. (B) Detail showing high modal percentage of K-feldspar megacrysts in this type of aggregates.

mush were expelled by filter pressing into tensional gashes, radially distributed around the contact between both plutons (white ellipses in Fig. 14). These leucogranitic segregations in the Alpa Corral pluton contrast with the surrounding granite. Away from where leucogranite segregations occur, the granite shows magmatic structures characterized by oriented but strain-free, euhedral crystals of plagioclase and biotite, coexisting with equiaxial aggregates of quartz devoid of intracrystalline deformation (Fig. 14b).

4. Discussion

Our studies in the Sierras Pampeanas granites allow us to establish two intrusion endmembers: 1) small plutons emplaced in the brittle-ductile transition, that have grown incrementally through multiple low volume magma pulses; and 2) batholiths, emplaced in shallow crustal levels, with a strong internal zonation, crystallized from multiple voluminous pulses. In the first case, a large magma chamber may never be established (Annen, 2009), and each pulse expands into a growing, effectively solid body, and interacts with small volumes of melts that may remain in the pluton. In such case, the early-formed magmatic structures may be overprinted by stresses related to the emplacement of late pulses, or by external stresses.

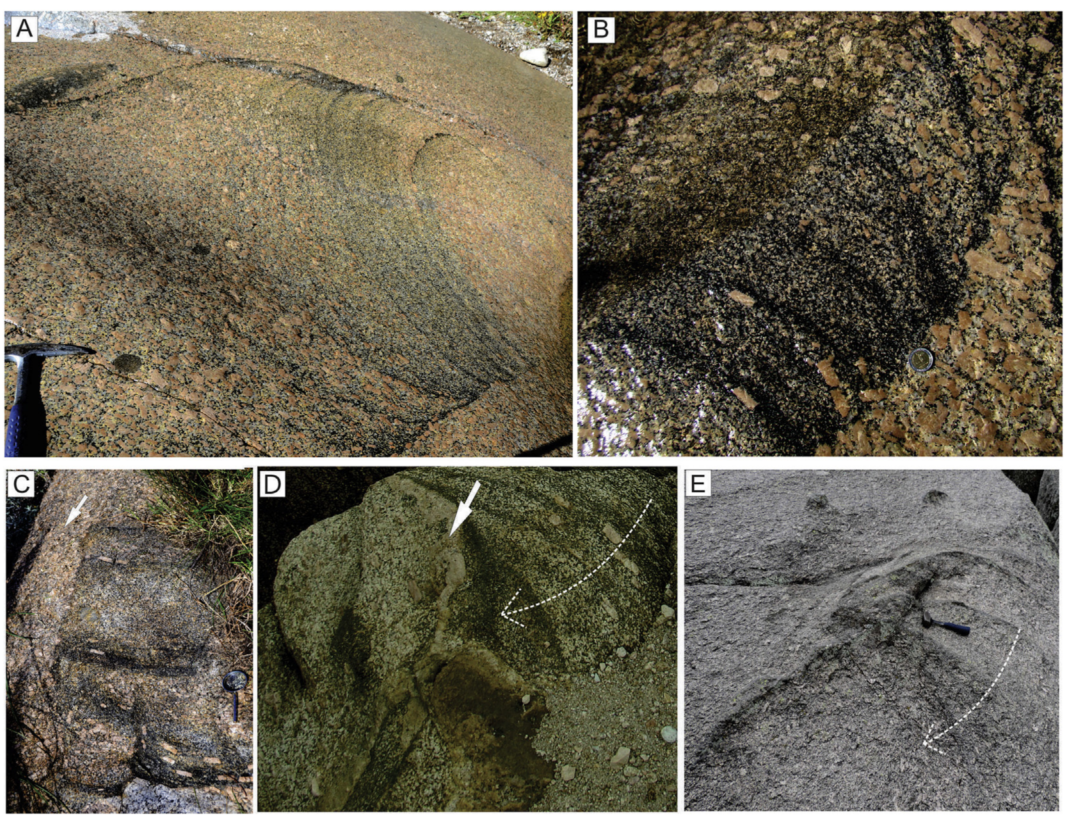

Fig. 12. (A) Crescent-shaped dark and light layers forming tube or ladder dikes, Capilla del Monte granite. Mafic *schlieren* grade into more felsic compositions that are macroscopically similar to the host granite. Note K-feldspar megacrysts oriented parallel to *schlieren*, and these are truncated by a sharp contact, at high angle to the *schlieren* in the lower part of the photograph. The radius of the *schlieren* decreases in the concave side (to the right). (B) Section of a ladder dike where both dark and light layers are modally different to host granite. K-feldspar megacrysts are elongated parallel to *schlieren*. (C) Broken section of a ladder dike with angular contact with intruding host granite. K-feldspar megacrysts are parallel to *schlieren*. (D) and (E) Crosscutting relationships between *schlieren*-bounded layers indicate younging direction (white dashed lines), El Talita pluton. In D white arrow shows a K-feldspar megacryst layer as the youngest tube margin. In this case tube axis is vertical and the horizontal surface exposes a perfect circular section.

pluton. The microstructural record of high-temperature deformation includes mechanical twins in plagioclase, myrmekite rims at the borders of K-feldspar crystals, bent crystals of plagioclase, kink bands in biotite and quartz aggregates with mosaic subgrains. Moreover, evolved interstitial leucogranitic melts of the Alpa Corral

By contrast, zoned batholiths represent long-lived magma chambers where several internal processes interact leading to increased complexity. These processes include: magma

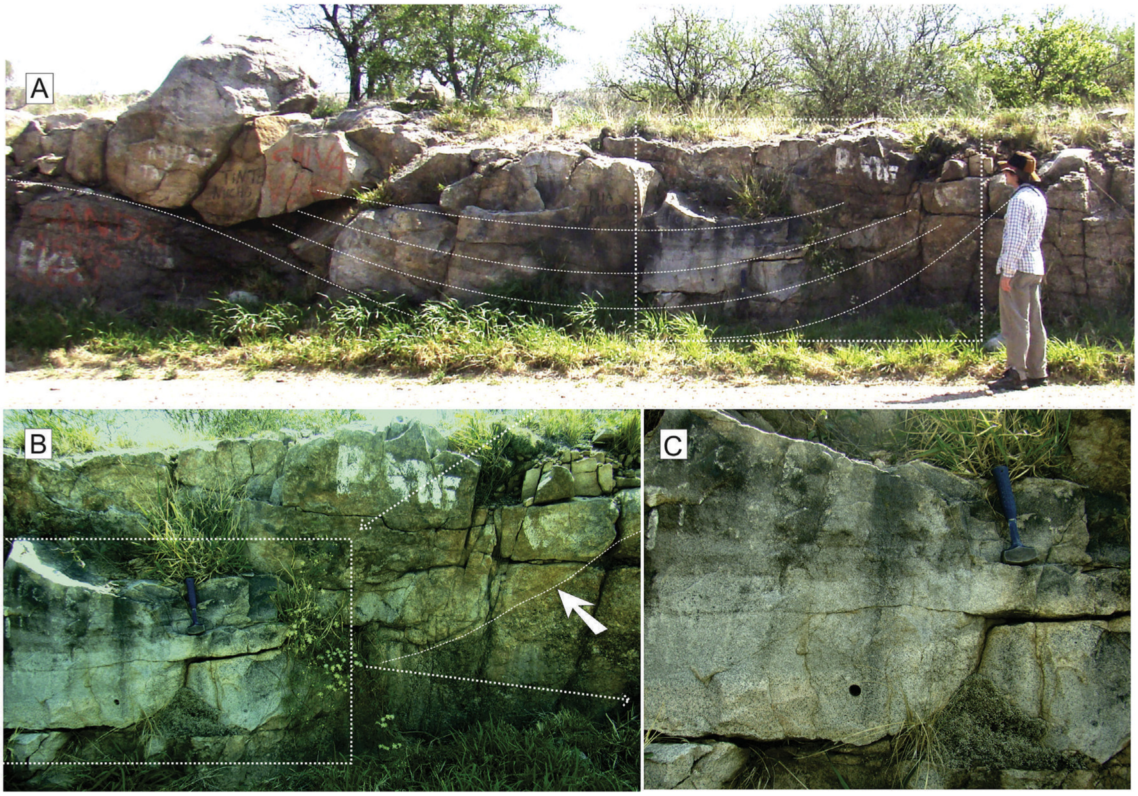

Fig. 13. (A) Erosional channel or trough in red granite, 15 m-wide and ~1.5 m in amplitude, filled with leucogranite with isomodal layering (B and C) that follows the curvature of the channel (white dashed lines in A and B). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fractionation and convection, magma addition/removal, as well as externally-driven deformation, dependent on the tectonic context. These processes take place during the solidification history of the magma, where late structures overprint and obliterate early ones. Each of these processes may prevail at different times and in different parts of the pluton and their relative importance, as recorded by magmatic structures and as a function of pluton size, are discussed in this section.

4.1. Small plutons emplaced in the brittle-ductile transition

The small trondhjemitic plutons of the Sierras de Córdoba were formed by magma accumulation of numerous sporadic and small pulses at a level close to the brittle-ductile crustal transition. Their intrusion was strongly conditioned by the regional compressional field at the time, that tended to impede the generation of space for the magma and forced magma to flow towards local dilational, low mean pressure sites, such as the reginal boudin necks (D'Eramo et al., 2013). Weinberg et al. (2009) showed how low-pressure sites form effective magma traps and suggested that the volume of accumulated magma in them depends on: (1) the scale of crustal heterogeneities controlling the low-pressure sites, (2) the intensity of the pressure gradients driving magma migration, (3) availability of magma, controlled by the nature and permeability of the magma transport network, and (4) the time available. They further suggested that changes in the stress system may destroy dilatant sites and pump magma out to feed other plutons further down the pressure gradient.

Layering and foliation are the most common magmatic structures in all these plutons. Magmatic layering has been addressed by several researchers and many mechanisms have been proposed to explain their origin (Paterson et al., 1989; Barbey et al., 2008; Solgadi and Sawyer, 2008). Barbey (2009) showed that layering in granitoids is essentially the expression of four processes likely to occur concurrently in growing plutons: (1) injection, flow, mingling and hybridization of magmas of different compositions or containing various crystal proportions, (2) hydrodynamic sorting and gravity-driven crystal/melt separation, (3) fractional crystallization, (4) deformation-assisted melt emplacement or segregation. Our studies show how layer orientations characterized by field and AMS measurements are concordant with the strikes of the feeder channels identified by gravity lows below the plutons (Fig. 4; D'Eramo et al., 2006a). This suggests that layering developed during the growing stages of pluton evolution, while successive sheets of melt ascended through the feeder channels. Repeated input of magma into the chambers led to rhythmic units. The fast cooling of the resident magma before arrival of subsequent sheets resulted in a viscosity and temperature contrast between neighboring sheets and preservation of older layers (D'Eramo et al., 2006a).

The layering in the La Fronda pluton was folded while in the magmatic state. The coupling between magma injection and the regional stress field may have controlled the shape of the pluton, the magma flow history and its folding (Stevenson, 2009). An AMS study reveals that the magnetic planar fabric is parallel to either the layering or the axial plane foliation (Fig. 6b, c; D'Eramo et al., 2006b). Deformation related to space generation for magma emplacement could explain the formation of folds in magmas having low melt fractions, as proposed by Pignotta and Benn (1999). Granitic mush viscosity is sufficiently high for it to act as a coherent body and thus to transmit regional stress while there is still melt present (Paterson et al., 1989; Blenkinsop and Treloar, 2001).

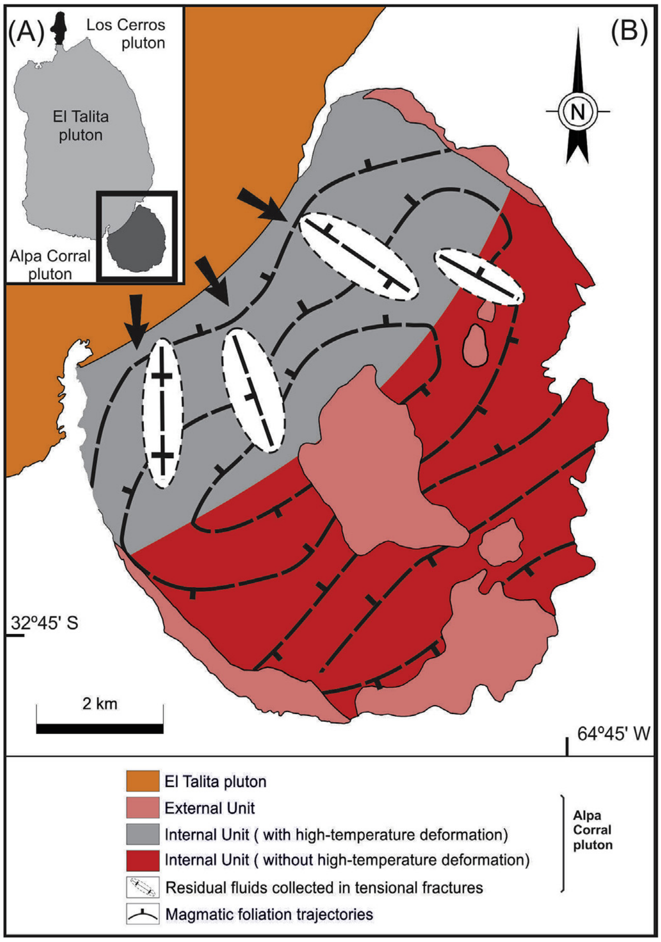

Fig. 14. (A) Plutons that comprise the Cerro Áspero batholith. (B) Magmatic foliation pattern in the Alpa Corral monzogranitic pluton (modified from Pinotti et al., 2006). Structures that formed during emplacement of the Alpa Corral pluton were systematically deformed and reoriented by N-S flattening during crystallization, caused by the southward push by the intrusion of the El Talita pluton (black arrows). White ellipses show tensional structures related to melt segregation, radially distributed from the convex side of the curved contact between both plutons.

4.2. Batholith-sized bodies with strong internal zonation, emplaced in shallow-crustal levels

As previously mentioned, the Devonian batholiths in the Sierras de Córdoba correspond to long-lived magma chambers. The incremental growth of such batholiths is maintained by the almost continuous arrival of melts. Barbey (2009) suggested that the injection process controls the large-scale zoning resulting from the aggregation of magma batches of various compositions and crystal charges, responsible for the incremental growth of plutons. The large-scale organization of plutons may also depend on the fractional crystallization and hybridization in deep-seated chambers. Fractional crystallization is probably a common process during pluton growth as shown by chemical zoning of crystals and occurrence of aplite-pegmatite segregations. However, this process does not appear to be responsible for *in situ* differentiation of the large rock units constituting most batholiths in the Sierra de Córdoba. Contrary to small and shallow intrusions, a large and long-lived chamber is the ideal environment for the development of all kinds of magmatic processes. In such chambers, the occurrence of rhythmic layering and depositional features related to gravity or flow-driven crystal-melt segregation do not necessarily imply large-scale convective overturn, but more likely result from local flow events related to density inversions, sidewall currents, eruption vents, slope failure of crystal accumulations, or small-scale convection above mafic replenishments (Paterson, 2009; Barbey, 2009; Hodge et al., 2012). Likewise, the local intrusion of hotter magmas may trigger remobilization of magmas and give rise to some of the most enigmatic magmatic structures in granitoids: the ladder dikes, and rings or snail structures, common in high-K granitoids. Such thermal fluctuations in a growing pluton have been recorded by Ti-in-quartz geothermometry in the Vinalhaven intrusive complex, USA, and interpreted to be a response to gabbro-diorite intrusions that triggered widespread magma mingling and limited mixing (Wiebe et al., 2007). Unlike the Vinalhaven complex, in the batholiths and zoned plutons of the Sierras de Córdoba, the lower compositional and rheological contrast between granodiorite-tonalite intrusions and the monzogranite host favoured more efficient mixing.

Weinberg (2006) noted that melt segregation structures are less commonly described in granites than in migmatites, and Barbey (2009) suggested that these structures may be common in syntectonic granites where regional deformation drives more efficient melt segregation. While we agree that tectonic deformation plays a significant role in the segregation of residual melts, we have shown that segregation may also occur as a result of the interplay between expanding post-orogenic plutons during batholith building, such as in the case of the Cerro Áspero batholith (Fig. 14).

5. Conclusions

Small plutons emplaced in the brittle-ductile transition in compressional settings are more likely to preserve growth-related structures than their larger counterparts. These plutons, with broadly homogeneous compositions, have a relatively simple cooling history with individual magma batches having their own emplacement and crystallization history, resulting in limited internal flow of magma and a characteristic layering parallel to feeder channels at depth. Compression during intrusion of the small plutons in the Sierra de Córdoba lead to magma migration into and trapping at tensional sites, such as regional boudin necks.

In contrast, batholiths emplaced at shallow crustal levels have a complex thermal history. The early, growth-related magmatic structures are commonly overprinted, and in some cases erased, by successive replenishments. Sections of the batholith reheated by replenishments promoted rejuvenation of the magma chamber, remobilizing mushes to form melt-rich granite plumes, giving rise to ladder dikes, K-feldspar megacryst clusters and erosional troughs. Deformation has a significant role in the segregation of residual melts from the deforming crystalline matrix, not only in syntectonic granites but also in post-tectonic granites as a result of stresses related to magma emplacement efforts. In summary, magmatic structures are a rich source of information regarding the history of plutons and their nature is fundamentally controlled by the ratio between cooling rates and magma intrusion history.

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