

Cordierite and Leucogranite Formation during Emplacement of Highly Peraluminous Magma: the El Pilón Granite Complex (Sierras Pampeanas, Argentina)

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*Cordierites and highly peraluminous granites within the El Pilón granite complex, Sierras Pampeanas, Argentina, were emplaced during a medium-*P*, high-*T* metamorphic event during the initial decompression of a Cambrian orogen along the southwestern margin of Gondwana. Very fresh orbicular and massive cordierite bodies with up to 90% cordierite are genetically associated with a cordierite monzogranite pluton and a larger body of porphyritic granodiorite. The petrogenesis of this association has been studied using petrographical, mineralogical, thermobarometric, geochemical, geochronological and isotope methods. The granitic magmas were formed by anatexis of mid-crustal metamorphic rocks formed earlier in the Pampean orogeny. The cordierites appear at the top of feeder conduits that connected the source region located at ~ 6 kbar with the pluton emplacement level at 3.7 ± 0.3 kbar. A fall in the liquidus temperature of the melt during emplacement was produced by a marked increase in fluid activity owing to rapid decompression and assimilation of surrounding hydrous metapelitic schists, followed by isobaric crystallization. High-Mg cordierite crystallized early on biotite–sillimanite restitic mineral assemblages of the assimilated schists or at the wall of the feeder conduits. Strong convection in the small magma chamber caused flow segregation of cumulate cordierite and restite, developing leucogranites and highly evolved*

pegmatoids that are in isotopic equilibrium. Rapid ascent of highly peraluminous magmas might explain why emplacement of these granites was simultaneous with the metamorphic peak registered in neighbouring high-grade migmatite and granulite terranes.

KEY WORDS: *cordierite; anatexis; granite; geochemistry; Ordovician*

INTRODUCTION

Cordierite is a low-pressure mineral that appears above the granite solidus in many peraluminous felsic magmas and as a metamorphic (subsolidus) phase in pelitic rocks (Clarke, 1995). Both occurrences are typical of low-pressure (*P*), high-temperature (*T*) terranes that underwent extensive crustal melting in the late thermal stages of continental collision and terrane amalgamation. Examples are common in the Late Palaeozoic Variscan belt of Europe, the Cretaceous–Miocene Ryoke belt of Japan and the Cambrian Pampean belt of SW

South America (Gardien *et al.*, 1997; Brown, 1998; Rapela *et al.*, 1998a).

The critical parameters controlling formation of cordierite in magmas are relatively low P , and high ($\text{Mg} + \text{Fe}^{2+}$), Mg/Fe^{2+} , alumina saturation index [$\text{ASI} = \text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$ molar], $a\text{Al}_2\text{O}_3$, and $f\text{O}_2$ (Clarke, 1995). Cordierite is usually an accessory phase; in cordierite-bearing granites and rhyolites its abundance rarely exceeds 10% of the mode. Cordierites, in which cordierite is a major mineral phase with >30 vol. %, are an extreme member of this rock family, and exceptionally approach an almost monomineralic composition with ~90% cordierite. In the case of a magmatic origin, such extreme compositions could be achieved only by some type of accumulation process after crystallization, and cannot be produced by metamorphism of a normal sedimentary protolith. If cordierites are uncommon, orbicular cordierites that share many of the field and fabric characteristics of orbicular granites are even rarer. Although they are curiosities in themselves, the petrogenesis of such rocks can shed light on many crucial aspects of granite magmatism, such as the composition of the source, the water content and the mechanism of emplacement of highly peraluminous magmas in low- P , high- T metamorphic belts. This is not a new idea; more than 70 years ago petrologists were surprised by the fact that in orbicular granites they faced many of the main problems of granite petrology 'almost literally, in a nutshell' (Sederholm, 1928).

The Cambrian granite complex of El Pílon in southern South America is composed of highly peraluminous igneous rocks and associated cordierite bodies, emplaced during low- P , high- T metamorphism (Rapela *et al.*, 1998a). In particular, exceptionally fresh and well-exposed bodies of massive and orbicular cordierite are closely associated with a small cordierite-bearing monzogranitic body. This paper focuses on the relationship between highly peraluminous granites and cordierites in this setting. New field, mineralogical, chemical and isotopic data are presented to (1) constrain the P - T conditions of the source and emplacement of the granites, (2) determine the source of the highly peraluminous magmas and the roles of high-level partial melting and contamination, (3) identify the mechanism of magma ascent, and (4) evaluate the fractionation mechanism at the emplacement level that produced the observed accumulation of cordierites and chemical variations within the granite. Mineral abbreviations are those of Kretz (1983).

GEOLOGICAL SETTING

Palaeozoic basement rocks at 27–33°S (see insert, Fig. 1) may be subdivided into those related to Early to Middle

Cambrian subduction and terrane collision (the Pampean mobile belt), and those associated with Ordovician subduction (the Famatinian mobile belt) and accretion of an exotic terrane (the Precordillera terrane) (see Pankhurst & Rapela, 1998). The Pampean mobile belt includes the Eastern Sierras Pampeanas and Eastern Cordillera geological provinces. It is mostly composed of metamorphic rocks (both high-grade and low- to medium-grade) and anatectic granites, partially remobilized and intruded by Ordovician–Carboniferous granitoids. The El Pílon granitic complex and associated cordierites are located in the Sierras de Córdoba, in the southern part of the Pampean belt (Fig. 1), where the Cambrian events are well established (Rapela *et al.*, 1998b; Sims *et al.*, 1998, and references therein).

The Sierras de Córdoba are largely composed of metamorphic rocks, Cambrian to Devonian granitoid plutons emplaced at various levels, and subordinate basic and ultrabasic rocks (Fig. 1; Gordillo, 1984; Martino *et al.*, 1995; Baldo *et al.*, 1998; Rapela *et al.*, 1998b; Otamendi *et al.*, 1999). Cambrian metamorphic rocks of middle to high amphibolite facies are the main and most widespread component of the basement, in which large migmatitic masses are characteristic (see Rapela *et al.*, 1998b, fig. 1). Low-grade metapelites appear only along the western side of the sierras, whereas metabasic rocks crop out discontinuously in the central and southeastern areas. Garnet–cordierite migmatites dominate the lithology in most of the high-grade migmatitic massifs (Gordillo, 1984), a remarkable exception to which is that of El Pílon in the northwestern sector of the Sierras de Córdoba (Figs 1 and 2). Migmatites and granitoid rocks in this area define a large medium- to low-pressure, garnet-absent basement block, separated by major faults from other medium-pressure, garnet-bearing high-grade rocks to the south and east.

The history and timing of the local Early Palaeozoic events was established by Rapela *et al.* (1998b), whose conclusions are summarized here. Emplacement of a suite of metaluminous calc-alkaline granitoids at 530 ± 4 Ma (U–Pb on abraded zircons from three units) represents an active margin environment along the eastern edge of the Sierras Pampeanas. This magmatism was followed by crustal thickening that resulted in granulite facies conditions ($P = 8.6 \pm 0.8$ kbar, $T = 810 \pm 50^\circ\text{C}$). A clockwise P - T - t path was inferred, producing regional migmatitic massifs during peak thermal conditions (M_2 metamorphic stage) at $P = 5.7 \pm 0.4$ kbar, $T = 820 \pm 25^\circ\text{C}$; a monazite U–Pb SHRIMP age of 522 ± 8 Ma was thought to date the M_2 event. The P - T conditions of an earlier metamorphic stage (M_1) inferred from relict fabric in garnet cores could not be determined because of garnet homogenization during M_2 . In the southern part of the Sierras de Córdoba, peak metamorphism occurred at essentially constant pressure of

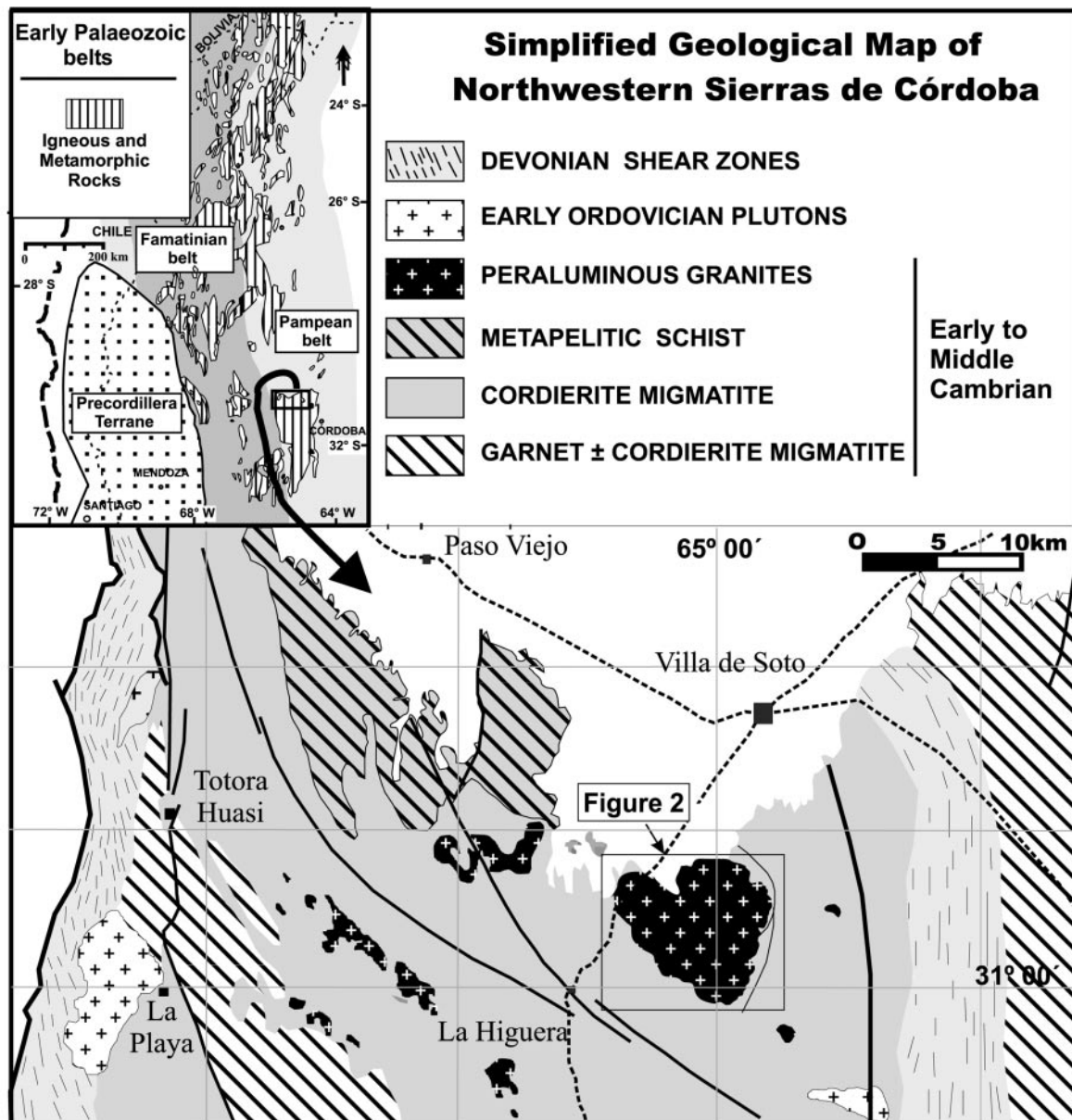


Fig. 1. Simplified geological map of the northwestern sector of Sierras de Córdoba [modified after Sims *et al.* (1998)]. Inset maps show the Early Palaeozoic belts of southern South America (Rapela *et al.*, 1998b) and the location of El Pilón granite complex.

7–8 kbar, with temperatures of $\sim 800^{\circ}\text{C}$ for the migmatites and $\geq 900^{\circ}\text{C}$ for the granulites (Otamendi *et al.*, 1999). Strongly peraluminous cordierite–sillimanite granites, sometimes associated with cordierites, as in the El Pilón complex, were emplaced coevally with the M_2 event at higher levels in the crust ($P = 3.9 \pm 0.6$ kbar, $T = 684 \pm 60^{\circ}\text{C}$, Rapela *et al.*, 1998b). An undated M_3 event recorded in the migmatitic rocks ($P = 4 \pm 0.5$ kbar, $T = 715 \pm 15^{\circ}\text{C}$, Rapela *et al.*, 1998b), presumably corresponds to a stage during the exhumation of the high-grade rocks.

The igneous and metamorphic evolution of the Pampean belt has been interpreted in terms of collision between a continental block (the Pampean terrane) and Gondwana during early to mid-Cambrian times (Rapela *et al.*, 1998a, 1998b). The accreted terrane is envisaged as parautochthonous, related to the break-up scenario pertaining at the Precambrian–Cambrian boundary. Inherited zircon from the metapelitic high-grade migmatites as well as from the strongly peraluminous granites gives ages between 600 and 1400 Ma, suggesting provenance from a Mesoproterozoic to Neoproterozoic basement.

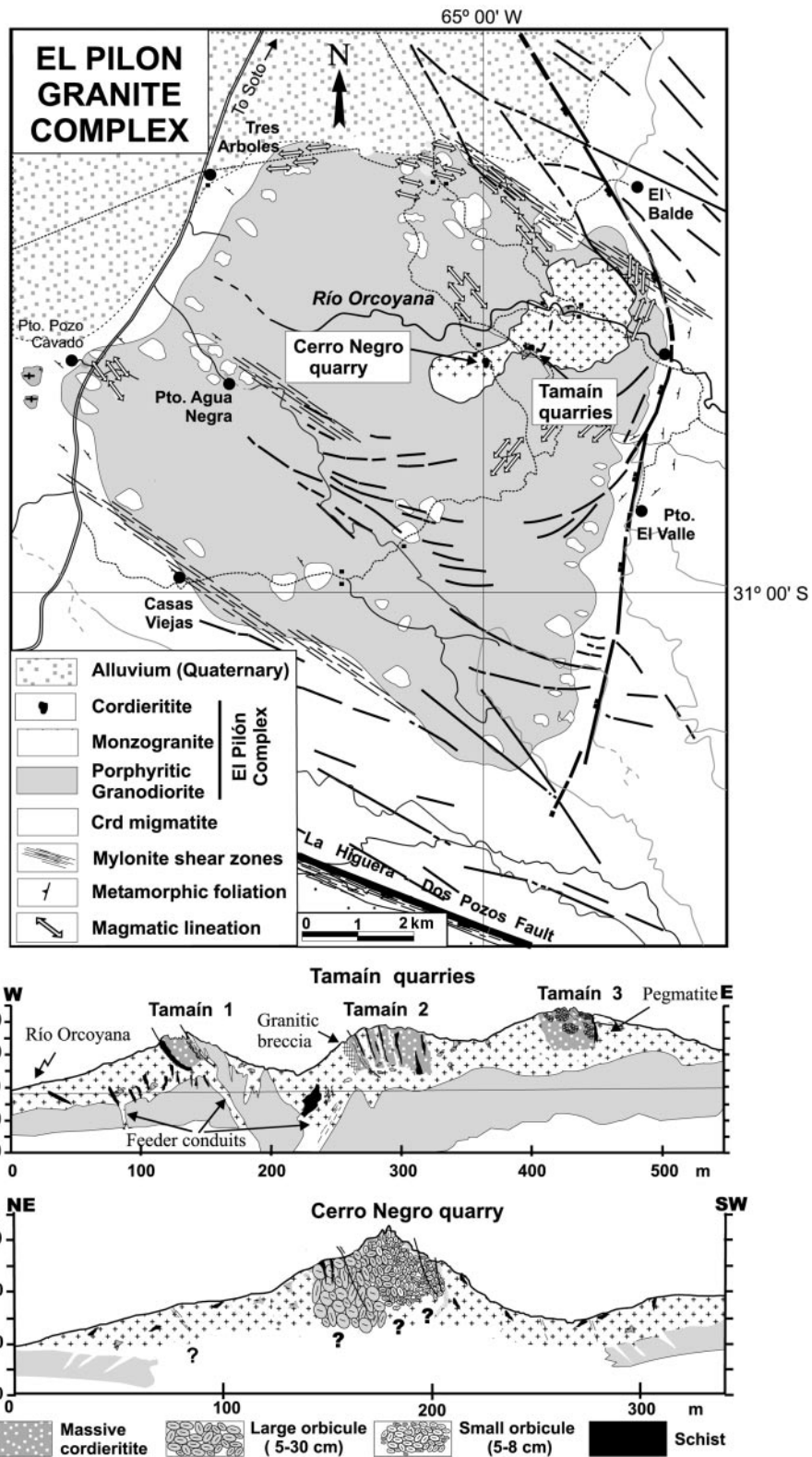


Fig. 2. Geological sketch map of El Pílon granite complex and cross-sections of the cordierite bodies at the Tamain and Cerro Negro quarries.

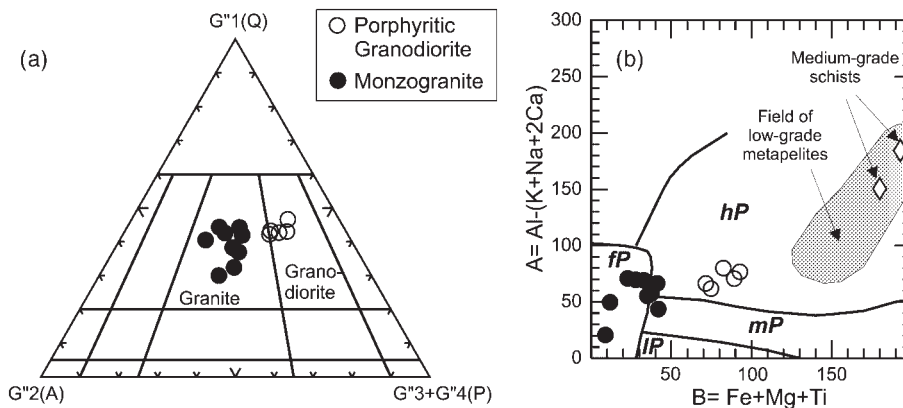


Fig. 3. Classification of the Cambrian granitic rocks of El Pilón complex. Chemical classifications relating to analysis of large samples (6–10 kg) are preferred, as in many cases the heterogeneous flow-fabric and coarse grain size prevent accurate modal measurements. (a) Multi-cationic homologue of the modal QAP triangle, after La Roche (1992). (b) Chemical classification of peraluminous granitoids (Villaseca *et al.*, 1998a): *hP*, highly peraluminous; *mP*, moderately peraluminous; *IP*, low peraluminous; *fP*, highly felsic peraluminous. Parameters are expressed as gram-atoms $\times 10^3$ of each element in 100 g of rock.

The rock and mineral associations at El Pilón were first described by Gordillo (1974, 1979), and his work is a tribute to his pioneering research investigations in the cordierite-bearing rocks of the Sierras de Córdoba. Chemical analyses of the cordierites and granites of this area were performed and reported by Gordillo (1974, 1979), including a more focused study of sodian–beryllian cordierite (Schreyer *et al.*, 1979). New results at El Pilón reported in this study included mapping, major and trace element whole-rock geochemistry, mineral microprobe analysis, and Nd and Sr isotope determinations.

The 70 km² granitic complex of El Pilón is located in the central part of a middle- to low-pressure basement block defined by abundant cordierite–sillimanite migmatites, gneisses and schists with conspicuous cordierite and a lack of garnet in the high-grade rocks. The complex is subcircular, ~ 10 km in diameter, and contains two main granitoid bodies (Figs 2 and 3): (1) a large porphyritic cordierite–sillimanite granodiorite pluton; (2) a small cordierite monzogranite body located in the NE sector of the complex. The latter encloses and is genetically associated with subcircular bodies of cordierites. Subordinate tourmaline–cordierite pegmatoids are also spatially associated with the monzogranite.

THE METAMORPHIC ENVELOPE

Schists

Metapelitic muscovite schists located to the NW of the complex (Fig. 1) are the lowest-grade metamorphic rocks in the low-pressure basement block. The continuous outcrop is composed of medium- to low-grade schists dominated by pelitic layers having a mineral assemblage

of Na-Crd poikilitic porphyroblasts (Na₂O 0.9–1.2%), Ms, Bt, Pl and Qtz. Staurolite is a relic phase that occurs as small crystals together with Bt and Ms within the Na-Crd porphyroblasts. Sandstone protoliths and impure quartzites alternate with the pelitic bands, and in these Qtz, Pl and Ms dominate the assemblage and Crd and St are absent.

Schist enclaves of all sizes are also very common in the porphyritic granodiorite and the cordierite monzogranite. The fabric and protolith composition of the enclaves are very similar to those of the *in situ* schists. However, primary muscovite has disappeared in most cases, and the dominant assemblage is Qtz + Bt + Pl + Kfs \pm Sil \pm Ms, suggesting an increase in metamorphic grade towards the El Pilón complex (Fig. 1). A summary of the metamorphic phase assemblages and mineral compositions in all metamorphic and granitic units is shown in Table 1. Th–U–Pb SHRIMP analysis of monazites from a biotite–muscovite gneiss located in the north-western sector of the large schist outcrop gave an age of 526 ± 11 Ma, and U–Pb SHRIMP analysis of zircon rims from the same sample produced clusters at around 531 ± 10 Ma and 561 ± 10 Ma (Sims *et al.*, 1998). These data may be used to infer an age of 529 ± 7 Ma for the metamorphism in these rocks.

Migmatites

Cordierite migmatites are the dominant metamorphic lithology and are the host rocks of the peraluminous granites and the cordierite. Stromatolite and diatexite are the common types. The leucosome in the stromatolites is composed of Qtz + Crd + Kfs \pm Pl. The coarse-grained lepidoblastic melanosome contains Bt + Sil +

Table 1: Summary of metamorphic phase assemblages and mineral composition

	Schists	Migmatites	Cordierite	Leucogranite/ porphyritic granodiorite
	(1) Qtz + Ms1 + Bt2 + Pl ± St	(1) Leucosome: Qtz + Kfs + Crd ± Pl	(1) Orbicular facies, restitic core: Bt + Sil + Crd1 + Pl + (Zrn + Ap)	(1) Restitic assemblages: (a) Bt1 + Sil + Crd1 + Grt (b) Bt1 + Sil + Crd1
	(b) Crd2 + Bt2 + Ms2 ± And + Ilm	(2) Mesosome: Qtz + Pl + Kfs + Bt + Sil + Ilm ± Crd	(2) Orbicular facies, granitic matrix: Qtz + Kfs + Pl	(2) Magmatic assemblages: Qtz + Pl + Kfs + Crd2 + Bt-2
	(2) Qtz + Ms + Bt + Pl	(3) Melanosome: Bt + Sil + (Ap + Tur)	(3) Massive facies: (a) poikilitic Grt with Bt1 + Qtz + Ap inclusions and (b) Crd2 + Bt2 + Pl corona	(1) (2)
	(3) Qtz + Bt + Pl + Kfs ± Sil ± Ms	(1) (2) (3)	(1) (2) (3)	(1) (2)
mg-no. Crd1		61-63	69-72	59-61
mg-no. Crd2			65-67	50-62
mg-no. Bt1	43-44		66-67	44-50
mg-no. Bt2		49-51 44	50-52	42-44
mg-no. St				49-50
mg-no. Grt core				22-23
mg-no. Grt rim				13-14
An Pl core	23	20	16-20	9-11
An Pl rim	27	18	18	20-24 19-19

Tur + Ap, with fibrolite along the leucosome–melanosome interface. A hexagonal granoblastic aggregate of Pl + Kfs + Bt + Sil + Ilm ± Crd is typical of the mesosome.

Heterogeneous diatexites with nebulitic and agmatitic structures have nodular cordierite (5–10 cm), and in some cases grade into porphyritic Sil + Crd granite. The granoblastic texture of the diatexites, which are composed of Qtz + Pl + Bt + Crd + Sil ± Kfs (secondary Ms + Chl), is sometimes modified by ductile shear deformation that also affected the peraluminous granites. Cordierite + tourmaline-bearing pegmatoids and tourmaline pegmatites are common near the El Pilón complex.

EL PILÓN GRANITE COMPLEX

The porphyritic granodiorite

The largest granitic intrusion at El Pilón is a 63 km² porphyritic granodiorite pluton characterized by an abundance of enclaves of the country rock migmatites and schists, which range from a few centimetres to >50 m (Fig. 2). On the regional scale the contact of the granodiorite with the country rock migmatites is sharp, but at outcrop scale it is transitional over a few metres, with an increasing proportion of country rock enclaves in the granite. Small cordierite-bearing pegmatoids occasionally cut the porphyritic granodiorite. K-feldspar phenocryst, biotite-rich schlieren and metamorphic enclaves orientated subparallel to the contact suggest local flow of the granodiorite magma. There is no thermal contrast between the granodiorite and the high-grade country rocks, and the abundance of metamorphic enclaves suggests that the present level of erosion was near the roof of the granite pluton (Gordillo, 1974). K-feldspar phenocrysts (Or₉₀, length 1–7 cm, average 2 cm) are poikilitic, carrying euhedral plagioclase, biotite, and quartz, or occasionally only sillimanite. Plagioclase, biotite, prismatic sillimanite and subhedral altered cordierite are the remaining dominant mineralogy, with apatite and zircon as accessory minerals. Cordierite is very abundant and appears as either anhedral crystals included in Kfs phenocrysts associated with Sil, Bt and Qtz, or as isolated, inclusion-free, partially pinnitized individuals, indicating that the porphyritic granodiorite is mineralogically a strongly peraluminous granite (Miller, 1985). Occasionally cordierite also occurs as nodules up to 10 cm in diameter. Microscopic clusters of Bt + Sil + Grt + Crd ± Qtz are characteristic; they have a lepidoblastic fabric and are hence interpreted as restitic rather than glomerocystic. Migmatitic enclaves in the porphyritic granodiorite show garnet-absent restitic melanosomes (Bt + Sil + Crd).

A precise emplacement age of 523 ± 2 Ma for the porphyritic granodiorite facies was obtained by conventional U–Pb analyses of zircon, whereas discordant fractions suggest Proterozoic inheritance (Rapela *et al.*, 1998a).

The cordierite monzogranite

A NE-trending monzogranitic body clearly intrudes the porphyritic granodiorite in the NE sector of the complex (Fig. 2). This small body of ~4 km² is composed of two small lenses, each displaying a subcircular shape in plan view, connected by a narrow zone of 200 m width. Despite the relatively reduced scale of the vertical exposures at El Pilón, the three-dimensional shape of the bottom of the monzogranite body and the associated cordierite bodies can be reasonably inferred as a result of two fortuitous circumstances. The present erosion level is near the floor of the body, so that river sections, especially along the Río Orcoyana, allow direct observations. Moreover, spatial relationships at this level are exceptionally well exposed, as all the cordierite bodies and several sites in the monzogranite have been intensively quarried for ornamental purposes. Erosional windows in small creeks and dry gullies show that the porphyritic granodiorite is always present at the floor of the monzogranite. From these observations, especially in the cross-section at Tamain 2 quarry (Fig. 2), it is clear that the floor of the monzogranite is nearly flat, and extended laterally over the granodiorite during emplacement. The top of the body was located above the present level of erosion so that its thickness cannot be directly measured. However, the abundance of large schist enclaves, similar to those cropping out 14 km NW of the complex, in both the monzogranite and the cordierites, suggests that the roof of the body was close and the monzogranite was emplaced as relatively thin, subhorizontal intrusion between the porphyritic granodiorite and the schists. Fabric evidence suggests that the underlying granodiorite was still ductile at the time of intrusion, although irregular-shaped 'xenoliths' of the granodiorite in the monzogranite often found near the contact clearly indicate that the latter was a late intrusive event within the granitic complex.

The grain size of the monzogranite is fine to medium, rarely exceeding 4 mm. Anhedral K-feldspar (Or₉₀) with abundant sillimanite and pinnitized cordierite inclusions, small amounts of biotite, and cordierite partially retrogressed to biotite + sillimanite are the main minerals. Common accessories are zircon and apatite. Small (5–7 cm) restitic ovoid clusters of Bt + Sil + Grt + Crd ± Qtz are common, as well as pegmatoid patches and veins (Table 1). The restitic almandine-rich garnets contain orientated inclusions of Bt, Qtz and Ilm, and are often rimmed by Crd and Bt, indicating retrograde

adjustment. Whereas modal biotite varies from 8 to 15% in the main facies of the body, there is sometimes a local decrease to <5%, noticeable for example in the colour index of the leucogranites and pegmatoids spatially associated with the cordierites of the Cerro Negro quarry (Fig. 2). Close to the southern contact of the body, the country rock migmatites and schists desegregate into the monzogranite, leaving subcircular melanosome clusters of Bt + Sil.

The cordierites

At the tops of small hills there are four outcrops, each up to 40 m × 80 m in length, of a cordierite-rich rock enclosed within the monzogranite body (Fig. 2). Three of these (Tamaín quarries 1, 2, and 3) occur in the southern part of the eastern subcircular lens of the body, and the remaining outcrop is in the western monzogranite lens (Cerro Negro quarry). This exceptional rock, consisting of 70–95% cordierite, has been called *cordierite* (Gordillo, 1979; Schreyer *et al.*, 1979). Because of its beautiful pale blue colour, the cordierite outcrops have been intensively quarried as ornamental stone and exported to Europe since the early 1950s (Gordillo, 1974).

Two main facies—orbicular and massive—are recognized, called respectively ‘dark’ and ‘light’ varieties by Schreyer *et al.* (1979). The Cerro Negro quarry is made up entirely of a remarkable orbicular cordierite consisting of 5–30 cm egg-shaped orbicules, often rimmed by a thin aggregate of biotite and fibrolite. Orbicules are composed of a light-coloured shell and a dark core [Fig. 4a; terminology for the orbicule structure follows that of Leveson (1966)]. The shell is essentially monomineralic, consisting of a polycrystalline aggregate of polygonal, fresh cordierite, with chlorite and fibrolite surrounding individual crystals, and with minor quartz, plagioclase, dumortierite, apatite and zircon. The largest orbicules (>20 cm) have high shell/core ratios and the shells display a grain-size zonation in which the individual cordierite crystals decrease from 1–7 mm around the core to a fine-grained outer layer (Fig. 4c). Outer parts of the core are often irregular and partially digested into the innermost layer of the shell. Small orbicules (<5–8 cm) usually show unzoned, uniform cordierite shells, and lower shell/core ratios.

The dark core of the orbicules is mainly composed of oriented biotite, sillimanite, and cordierite, with subordinate amounts of feldspar, quartz, ilmenite and secondary muscovite and chlorite. Despite the appropriate aluminous composition, garnet has never been found in the orbicule cores. The fabric and mineralogy of the orbicular cores in the Cerro Negro outcrop are indistinguishable from the melanosome of the regional cordierite migmatites. Restitic cores are usually elongated,

but rounded, semi-rectangular or irregular shapes are also observed, in which cases the external cordierite mantles reflect the shape of the core. The space between orbicules is occupied by small patches of a leucogranitic matrix composed of quartz, perthitic K-feldspar and plagioclase (Fig. 4a and b).

In the Cerro Negro quarry, large orbicules in a ‘matrix’ of smaller orbicules (Fig. 4c) are observed in the lower part of the 30 m cross-section, in contact with the monzogranite. There is an upward decrease in size equivalent to ‘graded bedding’ (Fig. 5). The lower zone is dominated by large orbicules (long axis 8–15 cm) although smaller and larger ones are also present. In the middle zone there is a general decrease in the size, and the mode is between 7 and 8 cm. The top of the section is composed solely of small oriented orbicules (all <11 cm, >50% in the range 4–6 cm). At the very bottom of the section, the leucogranitic matrix increases in proportion towards the contact with the granite, resulting in orbicules ‘swimming’ in the enclosed leucogranite (Fig. 4b). Isolated orbicules are found in the local leucogranite up to 4 m away from the contact, but they have never been observed in other parts of the monzogranitic body.

In the Tamaín quarries 2 and 3, small orbicules are single crystals with a small, limpid cordierite core, surrounded by a cordierite shell with concentrically arranged deformed inclusions, suggesting growth of the latter in a partially molten host (Gordillo, 1979). Microprobe analysis of the inclusions indicates that they consist of apatite. The fabric of the orbicules suggests that they grew epitaxially following nucleation around either partially melted biotite-rich restite or large idiomorphic crystals of cordierite. Accumulation of orbicules that seem to have been deformed and accommodated to each other in a ductile way, presumably in a fluid matrix, is typical of the orbicular facies (Fig. 4). The outer rims of large orbicules are sometimes digested and deformed by ‘impacts’ of small orbicules during the process of accumulation (Fig. 4c).

The Tamaín 1 and Tamaín 2 quarries are dominated by a massive cordierite facies, which approaches a composition of almost monomineralic cordierite (85–90%) with Bt, Pl, Kfs and Qtz making up the remaining 10–15%. Coarse- and fine-grained varieties, with sharp contacts between them, are typical of the massive facies. In some sectors the massive cordierite shows a gradual transition to darker varieties with up to 40% of modal biotite. The cordierite is fresh, and in the coarse variety forms a polycrystalline aggregate of 1–3 cm phenocrysts, with cyclic twins set in a groundmass of small crystals (0.5–2.5 mm), and with fibrolite and biotite at the crystal edges. Rare porphyroblastic garnet was observed only in the fine-grained variety of the Tamaín 2 quarry (see below), whereas staurolite appears in the more biotitic variants. Apatite is very abundant in the fine-grained

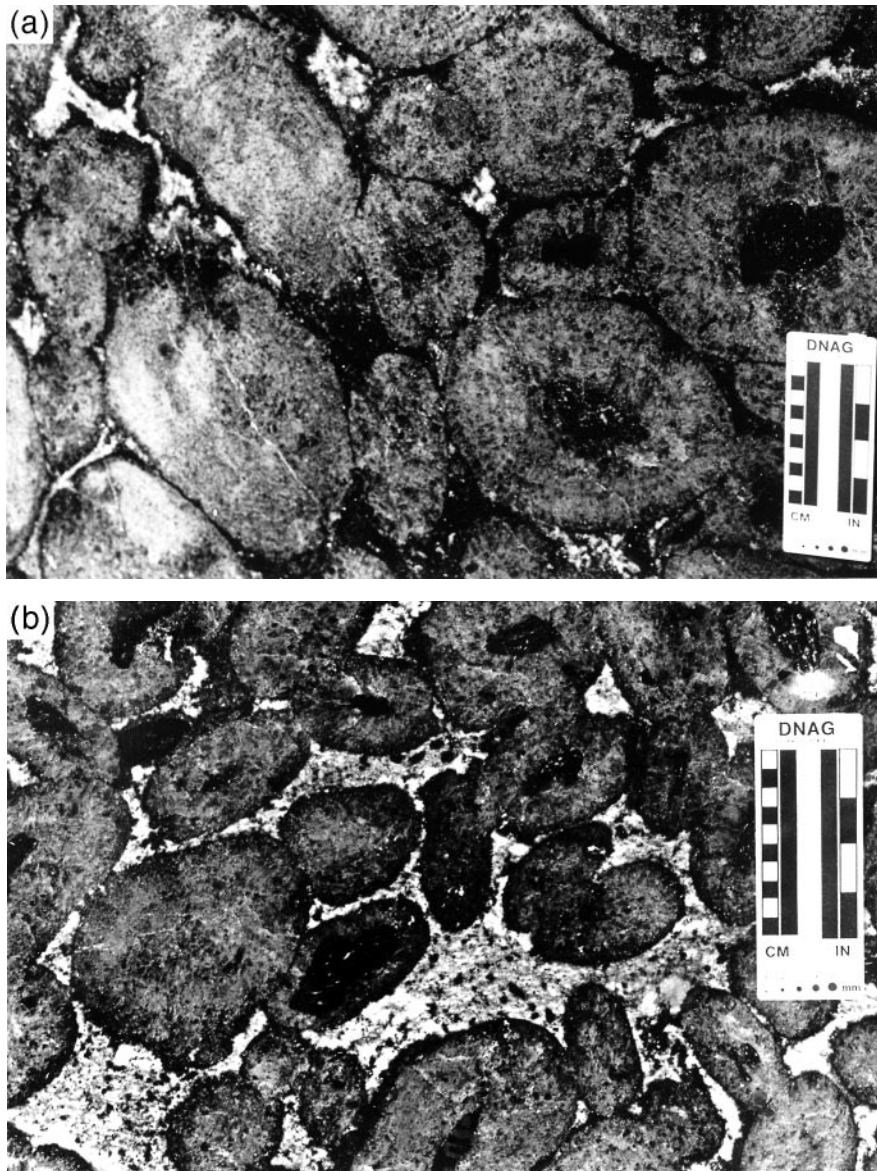


Fig. 4.

massive cordierite; tourmaline, zircon and less frequently piemontite, dumortierite and pyrite are also present. In the Tamaín 3 quarry, the fine-grained massive cordierite is in sharp contact with the orbicular facies, consisting here of small orbicules with cordierite cores. The massive cordierite of Tamaín 2 displays sharp magmatic-style contacts against both the granite and screen-like exposures of schist (Bt + Qtz + Pl + Kfs). This facies also contains a large (1 m × 1.5 m) xenolith of the porphyritic granodiorite, indicating that the massive cordierite was ductile enough to be mobilized together with the monzogranite melt. A breccia facies seen in the Tamaín 2 quarry has angular xenoliths of the granodiorite, schists and subordinate cordierite set in the

monzogranite matrix, suggesting that local fluid-rich turbulent flow of the monzogranite melt affected both the cordierite and the host granitic and metamorphic rocks. Although the exposures in the Tamaín quarries are small, the observed relations suggest that the massive cordierite was not formed by an *in situ* accumulation as is deduced for the orbicular variety of the Cerro Negro quarry.

Cross-sections of the cordierite bodies show that both types have restricted vertical continuity and are spatially associated with funnel-shaped vertical dykes of the monzogranite that terminate at the floor of the body (Fig. 2). An obvious interpretation of these spatial relationships, further discussed below, is that these dykes were feeder conduits of the monzogranite lenses.

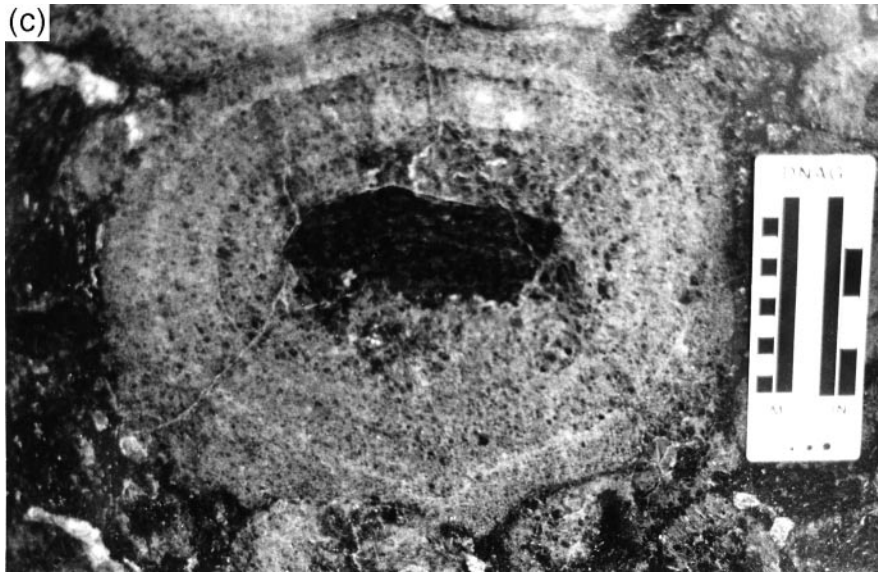


Fig. 4. Photographs of slabbed surfaces of orbicular cordierite from Cerro Negro, El Pilón granite complex. (a) Ellipsoidal orbicules composed of a cordierite shell and a dark core of Bt + Sil + opaque minerals. The slab surfaces do not always intersect the orbicule cores, which are, however, present in all cases. A leucogranitic matrix of K-feldspar, quartz and plagioclase fills the space between orbicules, which (b) increases towards the contact with the host monzogranite. (c) A 30 cm orbicule set in a matrix of smaller orbicules at the base of the Cerro Negro section. The following features should be noted: (1) the indentation of the shell structure by neighbouring orbicules; (2) the decreasing size of the cordierite crystals towards the edge of the shell of the large orbicule; (3) the partially digested outer part of the core.

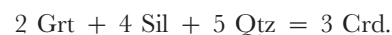
***P*–*T* CONDITIONS AT THE EMPLACEMENT LEVEL AND IN THE SOURCE REGION OF THE CORDIERITITE PARENTAL MAGMAS**

The porphyritic granodiorite of the El Pilón granitic complex is emplaced in stromatitic and diatexitic Crd migmatites, whereas the monzogranite, which has abundant schist enclaves, was emplaced between the medium-grade schists and the migmatites. The emplacement depth of the monzogranite and associated cordierites, as well as the *P*–*T* conditions in the source region of the granitic magmas, have been estimated from thermobarometric calculations in the cordierite and in Bt–Sil–Grt restitic assemblages in the monzogranite (samples PIL-375 and PIL-202, Table 1).

Although garnet is a common mineral in the restitic assemblages, it was never found in the restitic cores of the Cerro Negro orbicular cordierites, indicating that the latter are partial melting residues formed above the garnet stability field, probably remaining from assimilation reactions at the level of emplacement. The only exception is a resorbed garnet crystal discovered in the cordierite of the Tamaín 2 quarry (Fig. 2), where the association Grt–Crd–Sil–Bt–Qtz–(St–Ap–Tur–Ilm–Zrn–dumortierite) was found in an angular enclave of fine-grained cordierite set in a groundmass of orbicular cordierite with euhedral cores. A large enclave of the granodiorite also occurs here in the massive cordierite.

The studied sample (PIL-375) shows a granoblastic texture of euhedral 0.3–0.5 mm crystals of limpid cordierite (Crd1) with inclusions of fibrolite, and surrounded by smaller crystals of cordierite, plagioclase and quartz. An isolated 9 mm garnet crystal is partially resorbed at the edge by the growth of an anhedral and poikilitic cordierite (Crd2) (Fig. 6a), with inclusions of biotite, quartz and fluorapatite. Apatite is very abundant and occurs as inclusions in all major minerals, suggesting that Grt and Crd1 formed during the same process in contact with melt and apatite crystals.

Chemical profiles of the garnet show compositional plateaux in the central part of the crystal and marked zonation at the edge, with an increase in Alm, Spl and the Fe/(Fe + Mg) ratio, and a decrease in Prp towards the rim (Fig. 6b). The unzoned core is a remnant of the original garnet, probably preserved because of the large size of the crystal (~10 mm). This type of rim zonation is usually ascribed to inward diffusion of Fe, Mg and Mn in retrograde reactions during decompression (Spear *et al.*, 1999). The main reaction consuming garnet to form the poikilitic Crd2 at the edge of crystal was



Although Ca distribution is less well defined, Ca decreases in the garnet at the garnet–plagioclase contacts, whereas it increases towards the edge in the plagioclase crystals (up 2% An), suggesting that partition of Ca between the two minerals was produced by the reaction

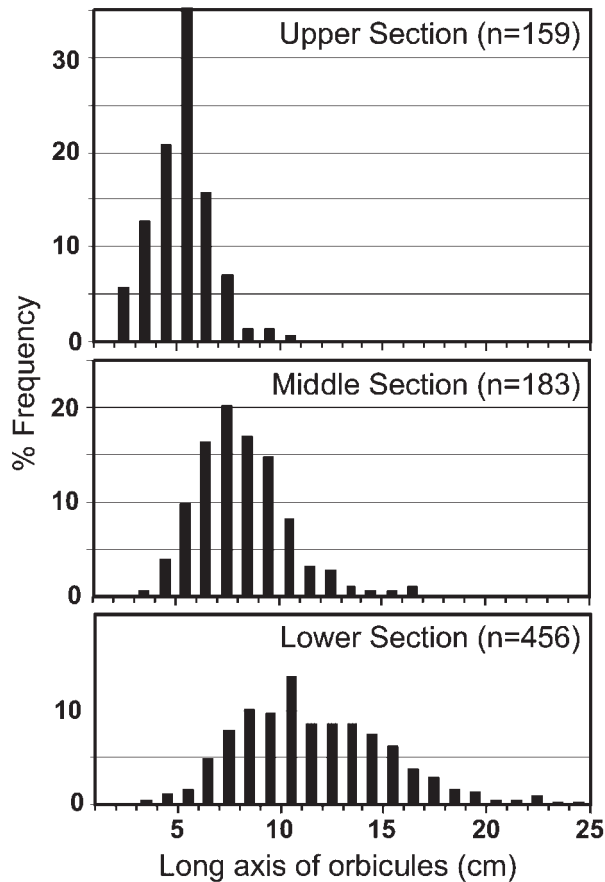
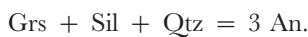


Fig. 5. Size distribution of orbicules through the vertical section in the Cerro Negro quarry.



Two paragenetic mineral associations were selected according to the above textural relationships and considerations, to infer the P - T conditions prevailing in the two stages of the evolution of the rock. The first is composed of the Grt core + Pl core + Crd1 (Paragenesis 1), and represents the equilibrium attained during the maximum P - T conditions. The second is composed of the Grt rim + Pl rim (in contact with Grt) + Crd2 + Bt (in contact with Grt) (Paragenesis 2), and represents local equilibrium during the formation of cordierite at lower P - T conditions. P - T conditions were calculated with version TWQ/102 of TEEWQ (Berman, 1991). Solid solution models are those from McMullin *et al.* (1991) for Bt, Berman (1991) for Grt, and Fuhrman & Lindsley (1988) for Pl, and an ideal model for Crd was assumed. The calculations for Paragenesis 1 were restricted to H_2O -conserving equilibria, thus constraining P - T conditions independently of water activity. However, it is clear that anatexis at 6–8 kbar in the Sierras de Córdoba took place in water-undersaturated conditions,

either with a small amount of free water or with dehydration melting of biotite (Otamendi & Patiño Douce, 2001). For estimating the P - T conditions of Paragenesis 2 at the emplacement level, a high water activity ($a\text{H}_2\text{O} \sim 1$) was assumed. This is consistent with the estimates in the restite of the monzogranite (sample PIL-202), where equilibrium in the reaction set is optimum only for the interval $a\text{H}_2\text{O} = 0.9$ – 1.0 . The mineral chemistry data on which these calculations are based are given in Appendix 1, available from the *Journal of Petrology* Web site (<http://www.petrology.oupjournals.org>). The two independent sets of calculated reactions intercept in tightly restricted P - T fields (Fig. 6c and d), suggesting that chemical equilibrium was attained in both textural assemblages. Estimated mean P - T values can be therefore considered representative of the physical conditions prevailing during formation of the respective paragenetic mineral association (Fig. 6c and d).

The values of 780°C and 5.9 kbar obtained for the restitic Paragenesis 1 in the massive cordierite indicate a first generation of Crd + Grt at ~20 km depth. These P - T estimates may be compared with those obtained by similar methods in other Crd + Grt migmatitic massifs formed during the M_2 episode in the Sierras de Córdoba (Fig. 7). Paragenesis 1 conditions are below those obtained in the southern sector (Otamendi *et al.*, 1999) and within the range, but close to the lower limit of those in the central–east sector (Rapela *et al.*, 1998b). Thus the P - T values obtained for the paragenesis of the massive cordierite suggest that the garnet-bearing restitic associations observed in the granitoids and the cordierites of El Pílon (Table 1) are samples from a deeper mid-crustal source region (Fig. 7).

P - T conditions inferred for Paragenesis 2 ($650 \pm 16^\circ\text{C}$, 3.7 ± 0.3 kbar) plot on the haplogranite water-saturated solidus, suggesting that crystallization ends during near water-saturation conditions (Fig. 7). The calculated pressure range most probably represents re-equilibration conditions at the emplacement level of the cordierite and the peraluminous granites (~10–15 km depth, Fig. 7). This range is consistent with that estimated in the country rock migmatites (3.9 ± 0.6 kbar, Rapela *et al.*, 1998a). Furthermore, the lack of primary magmatic muscovite in the monzogranite indicates that crystallization took place below the invariant point in the KFMASH system where the reaction products in the reaction $\text{Ms} + \text{Qtz} = \text{Sil} + \text{Kfs} + \text{coexist}$ with granitic melts (see Fig. 7).

The pressure of 3.3 ± 0.6 kbar estimated for a garnet-bearing restite in the monzogranite is slightly lower than that obtained for Paragenesis 2 (sample PIL-202, Fig. 6e). This association exhibits a lepidoblastic texture, with Bt and Sil orientated as a relict metamorphic foliation. The xenoblastic garnets are surrounded by Bt + Sil

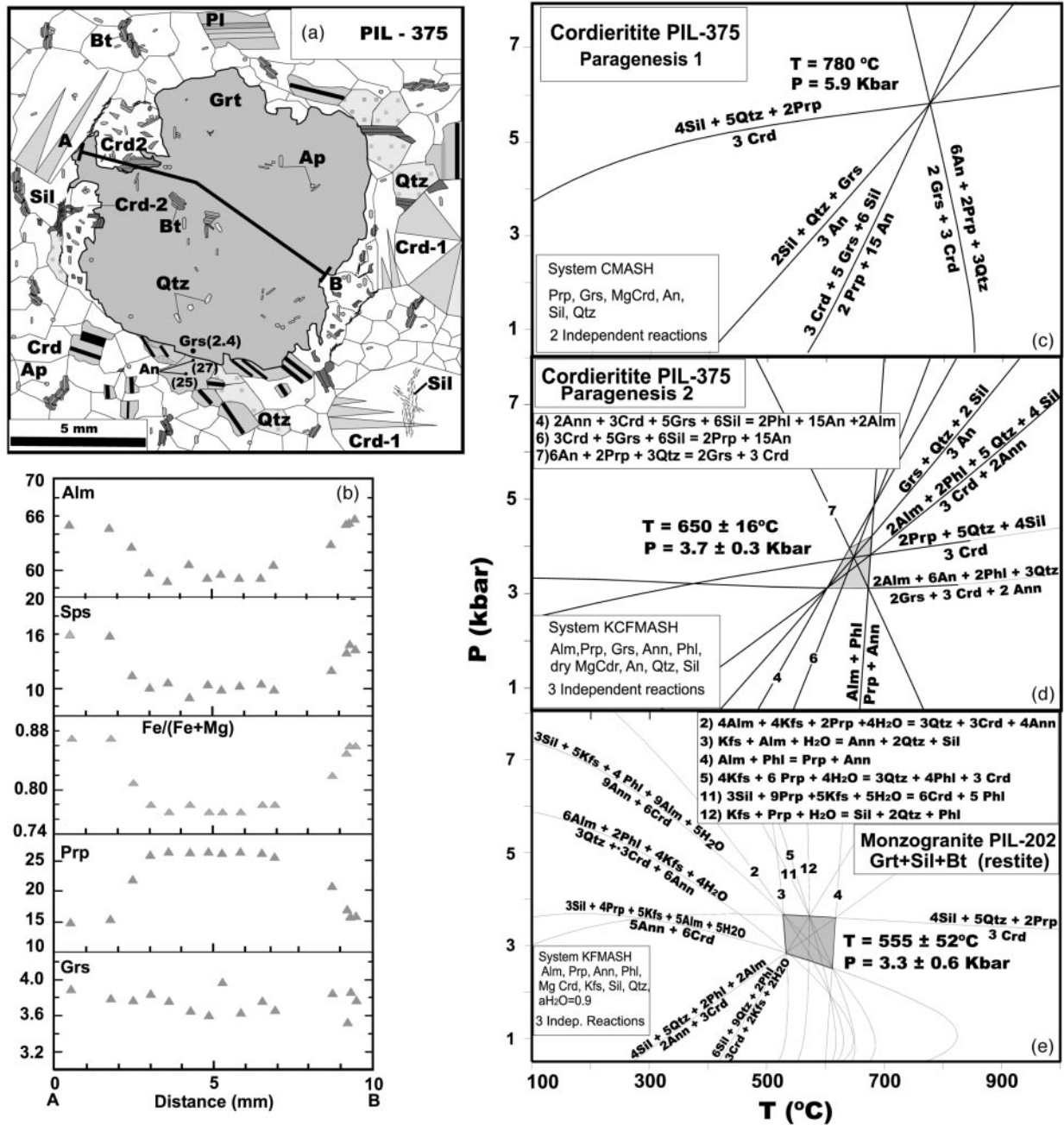
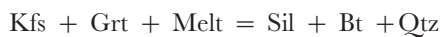


Fig. 6. (a) Restitic Grt-Crd in cordierite PIL-375. Large Grt crystal overgrown by xenoblastic Crd2, in a matrix composed of Qtz, limpid Crd1, Pl, Sil and Bt. (b) Electron microprobe traverse across Grt as shown in (a). See text for discussion. (c) *P-T* conditions for Grt core + Pl core + Cdr1 (Paragenesis 1) of cordierite PIL-375. (d) *P-T* conditions for Grt rim + Crd2 + Bt2 (Paragenesis 2) cordierite PIL-375. [See (a) for textural relationships.] (e) *P-T* conditions for the restitic association Grt (xenoblastic) + Crd + Bt + Sil in sample PIL-202 of the monzogranite.

and, eventually, Crd, suggesting that the main reactions consuming garnet were



and



The estimated temperature for the restitic association plots below the temperature of the wet haplogranitic solidus at the given pressure (Fig. 7), and probably

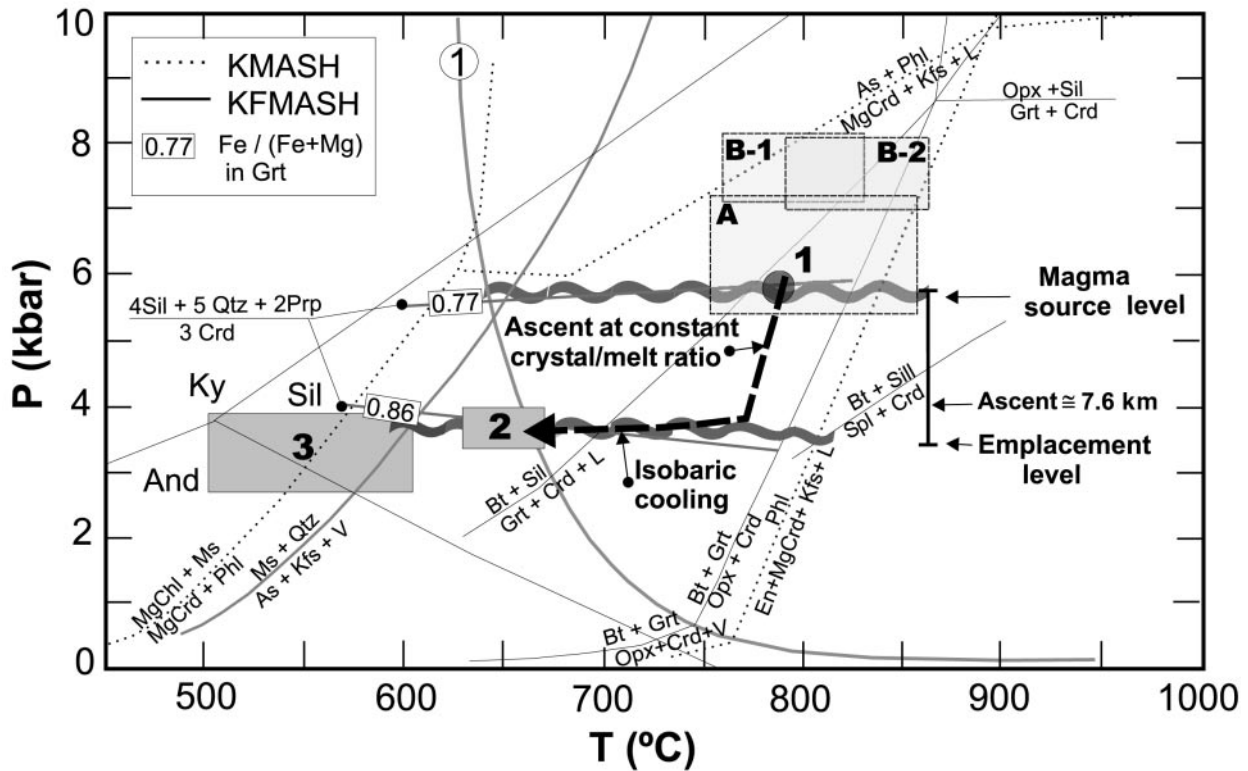


Fig. 7. Synthesis of P - T conditions for the Sierras de Córdoba. Dark shaded circle and boxes: representative samples of the cordierite and the monzogranite from El Pilón complex (this work). 1, P - T estimate for the source region of the highly peraluminous magmas; 2, P - T estimate for the emplacement level of the magmas and the final temperature of crystallization of the cordierites; 3, subsolidus adjustment of the restitic assemblage at the emplacement level. The bold dashed line with arrow shows the P - T ascent path of a granitic magma with a constant crystal/melt ratio and a starting melt fraction of 90%, followed by isobaric cooling at the emplacement level. Shaded boxes give estimates of the P - T conditions reached in different migmatitic massifs. A, Grt + Crd migmatites of Río Suquia (Rapela *et al.*, 1998a); B-1 and B-2, Grt and Grt + Crd migmatites of the Sierra de Comechingones (Otamendi *et al.*, 1999). The main melting reactions in the systems KFMASH and KMASH are after Spear *et al.* (1999). Aluminosilicate phase diagram as given by Berman (1991). Circled '1', haplogranitic water-saturated solidus.

represents a subsolidus, minimum temperature for the equilibrium exchange between Grt, Bt and Crd.

GEOCHEMISTRY

The granites of the El Pilón complex belong to the series with the highest peraluminosity in the classification of peraluminous granites (Fig. 3b). The porphyritic granodiorite is of the highly peraluminous type, which defines a trend from the most mafic varieties towards the field of metapelites. The monzogranite pluton mostly plots in the field of highly felsic peraluminous granites, but the main facies with >10% modal biotite is transitional to the highly and moderately peraluminous fields.

Selected major and trace element variations in the peraluminous granites, cordierites and metamorphic rocks of El Pilón are illustrated in Figs 8–11; representative whole-rock analyses are given in Appendix 2

(available from the *Journal of Petrology* Web site). Different symbols are used to differentiate the orbicular and massive facies of the cordierites, as well as single whole-rock analysis of an orbicule core and matrix from Cerro Negro. Two representative samples of the medium-grade metapelitic muscovite schists from NW of El Pilón complex (Fig. 2) illustrate the probable original composition of the partially digested schist enclaves observed in the monzogranite and the cordierites. The composition of these schists falls in the field of the regional low-grade metapelitic rocks of the Sierras de Córdoba, also shown in Fig. 8. Low-grade metapelitic rocks are located 50 km to the SW of El Pilón [for chemical and Sr–Nd isotopic analyses of these rocks, see Rapela *et al.* (1998a)].

Elements such as MgO, FeO and Na₂O define linear plots between the granites of El Pilón, with the cordierite monzogranite of El Pilón as the most acidic unit, and the orbicular cordierites, with the nuclei as the least evolved member (Fig. 8). Although the scatter is larger for other elements, a main feature of the Harker diagrams

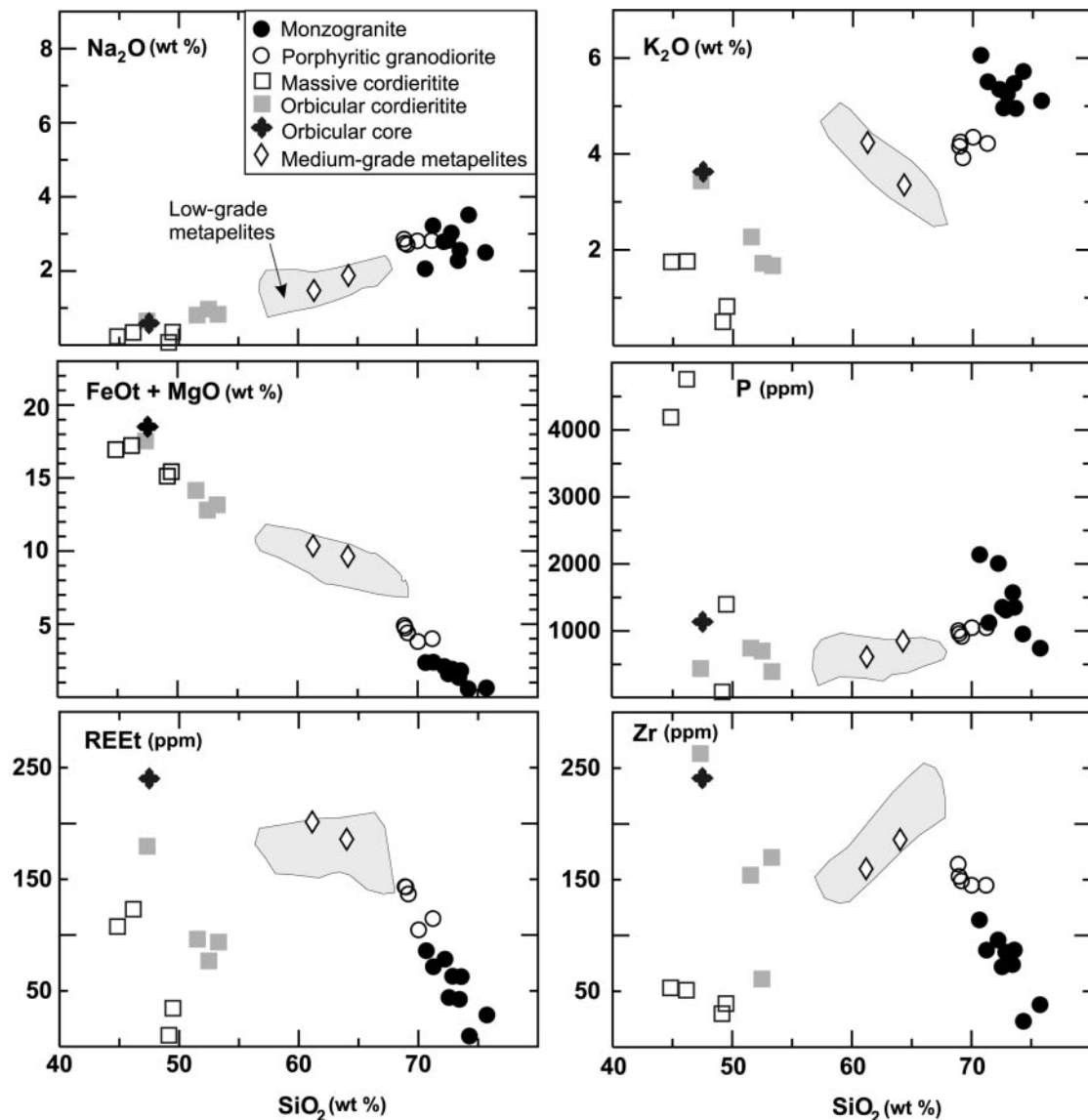


Fig. 8. Selected major and trace element Harker variation diagrams for granitoid and metamorphic rocks of the El Pilón complex. Samples of medium-grade metapelitic schists are from large outcrops located 15 km to the NW of the complex (see Fig. 1).

is that metapelites with 57–67% SiO_2 plot in an intermediate position between the cordierites and the granites.

The porphyritic granodiorite of El Pilón is characterized by $\text{SiO}_2 = 69\text{--}71\%$, $\text{ASI} = 1.26\text{--}1.38$, $\text{Na}_2\text{O} + \text{K}_2\text{O} = 6.7\text{--}7.2\%$, $mg\text{-number} = 46\text{--}49$, $\text{K/Rb} = 180\text{--}220$, REEt (total rare earth elements) = 110–150 ppm, $[\text{La}/\text{Yb}]_N = 7.5\text{--}10.5$ and $\text{Eu}/\text{Eu}^* = 0.52\text{--}0.63$. The monzogranitic pluton associated with the cordierites has a more evolved chemistry, and is distinguished by a high $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio (1.7–3.0) and high P_2O_5 content (0.2–0.5%). The normal facies in the central part of the pluton has $\text{SiO}_2 = 70.7\text{--}73.6\%$, $\text{ASI} =$

1.23–1.34, $\text{Na}_2\text{O} + \text{K}_2\text{O} = 7.4\text{--}8.2\%$, $\text{FeO} + \text{MgO} = 1.4\text{--}2.4$, $mg\text{-number} = 25\text{--}45$, $\text{K/Rb} = 185\text{--}240$, $\text{REEt} = 43\text{--}87$ ppm, $[\text{La}/\text{Yb}]_N = 4\text{--}5.5$ and $\text{Eu}/\text{Eu}^* = 0.42\text{--}0.63$. However, local monzogranites in association with the Cerro Negro and Tamain cordierite bodies are more leucocratic ($\text{FeO} + \text{MgO} = 0.5\text{--}1.5\%$, $\text{SiO}_2 = 73.5\text{--}75.7\%$), and are characterized by depleted REE patterns with positive Eu anomalies ($\text{REEt} = 8\text{--}28$ ppm, $\text{Eu}/\text{Eu}^* = 1.4\text{--}3.5$, Figs 9–11). Compared with typical felsic crustal granites such as the Himalayan and Hercynian leucogranites, the highly peraluminous monzogranites of El Pilón are depleted in Na_2O , enriched in K_2O and show distinctively high K/Rb ratios (Fig. 9). In

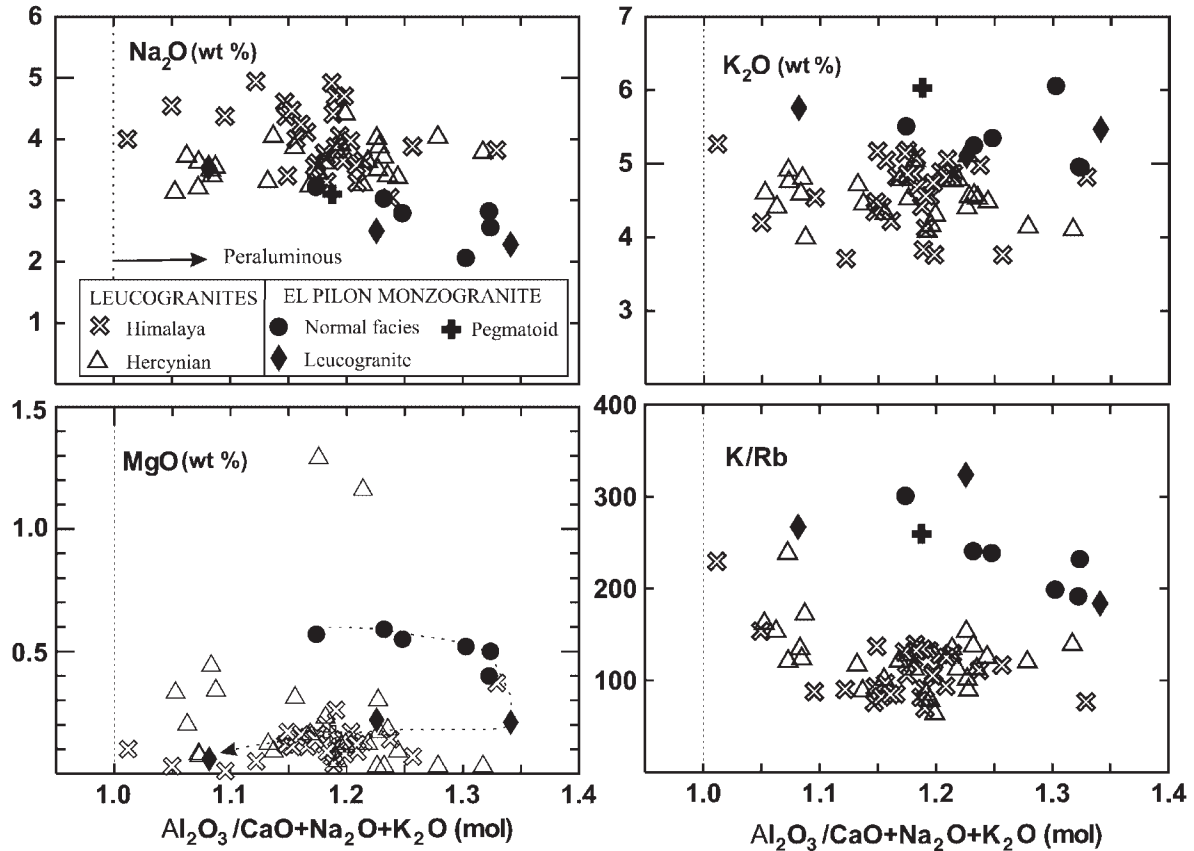


Fig. 9. Alumina saturation index ($ASI = \text{mol. Al}_2\text{O}_3/\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O}$) vs Na_2O , K_2O , MgO and K/Rb for El Pilón, Himalayan and Hercynian granites. Data sources: Dietrich & Gansser (1981), Le Fort *et al.* (1987), Crawford & Windley (1990) and Scaillet *et al.* (1990) for Himalayan leucogranites; Williamson *et al.* (1996), Villaseca *et al.* (1998b) and C. Villaseca (unpublished data, 2000) for Hercynian leucogranites from the Massif Central, France, and the Central System, Spain.

the normative plot Qtz–Ab–Or (not shown) the granites of El Pilón plot near the low-pressure cotectic, but displaced from the H_2O -saturated minima at 1–2 kbar towards the Qtz–Or side.

Cordierite- and tourmaline-bearing pegmatoids associated with the monzogranite form a more heterogeneous granitoid group, with $\text{SiO}_2 = 67.75\text{--}73\%$, $ASI = 1.19\text{--}1.21$, $\text{Na}_2\text{O} + \text{K}_2\text{O} = 9.1\text{--}9.2\%$, $mg\text{-number} = 30\text{--}40$, $\text{K/Rb} = 130\text{--}250$, $\text{REEt} = 10\text{--}22$ ppm, $[\text{La/Yb}]_N = 2.5\text{--}3.5$ and $\text{Eu/Eu}^* = 1.2\text{--}1.4$. Flat REE patterns with positive Eu anomaly are distinctive (Fig. 11).

The cordierites are distinguished from pure cordierites by high K_2O and low Al_2O_3 , as a result of the variable but ubiquitous presence of modal biotite. The massive cordierite approaches the composition of pure cordierite ($\text{SiO}_2 = 45\text{--}59\%$, $\text{FeO}_t + \text{MgO} = 15\text{--}17\%$, $\text{K}_2\text{O} = 0.5\text{--}1.7\%$, $mg\text{-number} = 61\text{--}67$, $\text{REEt} = 10\text{--}130$ ppm, $[\text{La/Yb}]_N = 1.5\text{--}3$, $\text{Eu/Eu}^* = 0.15\text{--}0.9$). Schreyer *et al.* (1979) reported the occurrence of a Na–Be cordierite ($mg\text{-number} = 62$, $\text{BeO} = 0.93\%$, $\text{Na}_2\text{O} = 1.25\%$),

but this is outside the typical range of $\text{Na}_2\text{O} = 0.25\text{--}0.49\%$ that we have found in our new microprobe analyses of the different facies of the cordierites. The whole-rock compositions of some orbicular cordierites from Cerro Negro have high SiO_2 and Na_2O , reflecting the minor modal quartz and plagioclase observed in their restitic cores (Fig. 8). Trace elements such as Rb, REE and Zr are also enriched in the orbicule cores, either because they occur mainly in accessory minerals (apatite, or zircon armoured in biotite), or as a result of replacement in biotite of K by Rb. The restitic orbicular nucleus is characterized by $\text{SiO}_2 = 47.5\%$, $\text{FeO}_t + \text{MgO} = 18.5\%$, $\text{K}_2\text{O} = 3.6\%$, $mg\text{-number} = 53.6$, $\text{K/Rb} = 195$, $\text{REEt} = 253$ ppm, $[\text{La/Yb}]_N = 10.6$ and $\text{Eu/Eu}^* = 0.27$.

Sr AND Nd ISOTOPE DATA

Rapela *et al.* (1998b) presented Rb–Sr analyses of the massive cordierite, the biotite + sillimanite orbicular

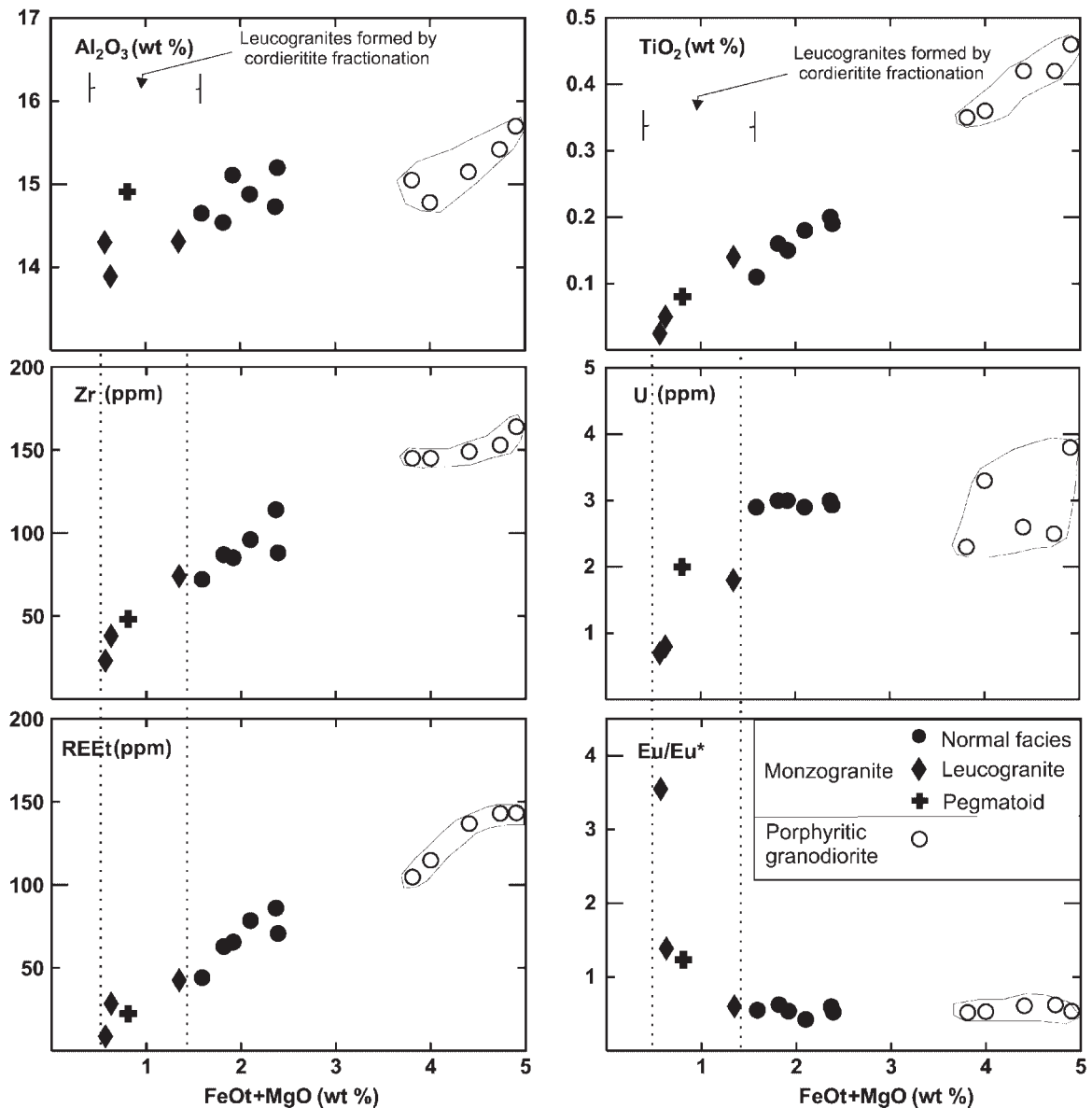


Fig. 10. FeO_t + MgO vs Al₂O₃, TiO₂, Zr, U, REEt and Eu/Eu* for the granitoid units of El Pílon complex. The sharp decrease in U, Zr and REEt, and the development of positive Eu anomalies in the leucogranites are produced by apatite and zircon fractionation armoured in cordierite and restitic clusters of Bt + Sil.

nuclei and the leucogranite and pegmatitic facies that defined a Rb–Sr isochron corresponding to 523 ± 4 Ma [mean square weighted deviation (MSWD) = 2.3, $n = 18$]. Together with the uniform initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7136 ± 0.0005 , this is taken to demonstrate that all these rock-types were coeval and genetically linked. Moreover, the Rb–Sr age is concordant with the U–Pb zircon age of 523 ± 2 Ma obtained from the main porphyritic granodiorite, demonstrating that all facies of El Pílon complex were emplaced during the same Early Cambrian

episode. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ of the porphyritic granodiorite is, however, slightly lower: the weighted mean for six samples of Rapela *et al.* (1998b), calculated at 523 Ma, is 0.7126 ± 0.0005 . Nevertheless, both values are within the ranges for the high-grade migmatites and gneisses of the Sierras de Córdoba (0.7137 – 0.7165) and for the low- to medium-grade schists and phyllites (0.7109 – 0.7163), both calculated at 530 Ma (Rapela *et al.*, 1998b). It is clear that the magmatic rocks of the El Pílon complex have been derived from sources comparable with these

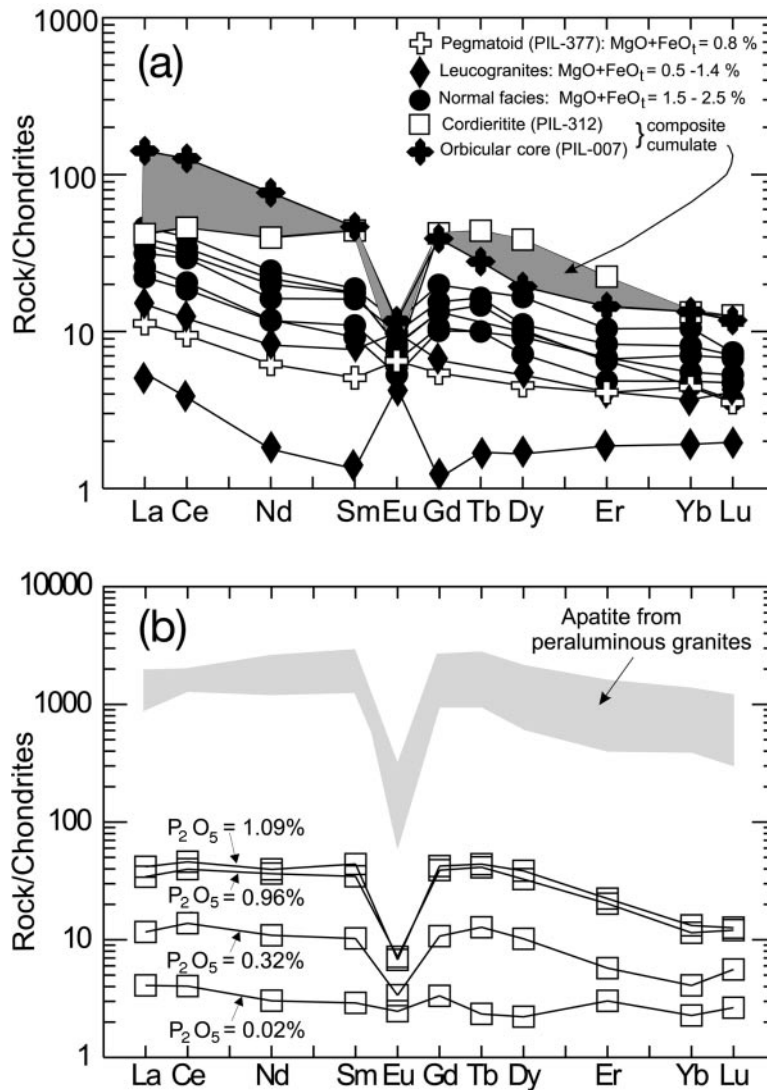


Fig. 11. (a) Representative REE patterns of the monzogranite, the massive cordierite and the orbicular core. (b) REE pattern of the massive cordierites showing the increase in total REE and negative Eu anomaly with increasing P₂O₅ content. The field for apatite in peraluminous granites is from Bea (1996).

local crustal metamorphic rocks, or at least that they incorporated a substantial component from them.

A more detailed isotopic treatment of the petrogenetic relationships is not possible with Rb–Sr data, as the highly peraluminous granites and, especially, the cordierites have very high Rb/Sr ratios, leading to significant errors in the calculation of Sr-isotope compositions in Cambrian times. Moreover, the mobility of these elements in fluid-present systems is well known and leads to uncertainty in interpretations. We prefer therefore to rely on more robust Sm–Nd data and have more than doubled the number of samples analysed by Rapela *et al.* (1998b), including some duplicate analyses. These data are presented in Appendix 3 (available from

the *Journal of Petrology* Web site) and the initial compositions are displayed graphically in Fig. 12.

The εNd₅₂₃ values of the monzogranite, pegmatites, restite and massive cordierites are very consistent (–5.5 to –6.7, mean of 16 values –6.1 ± 0.2), indicating attainment of a high degree of isotopic equilibrium during the melt segregation process. The values for the country rocks are more variable, as might be expected, reflecting considerable inhomogeneity at 523 Ma (–3.0 to –7.8). If the few extreme values above –3.0 and below –7.0 are excluded, the high-grade gneisses have a mean of –5.4 ± 0.7, and the low- to medium-grade schists and phyllites a mean of –6.5 ± 0.9. Thus both could have contributed to the anatexic melt that formed the

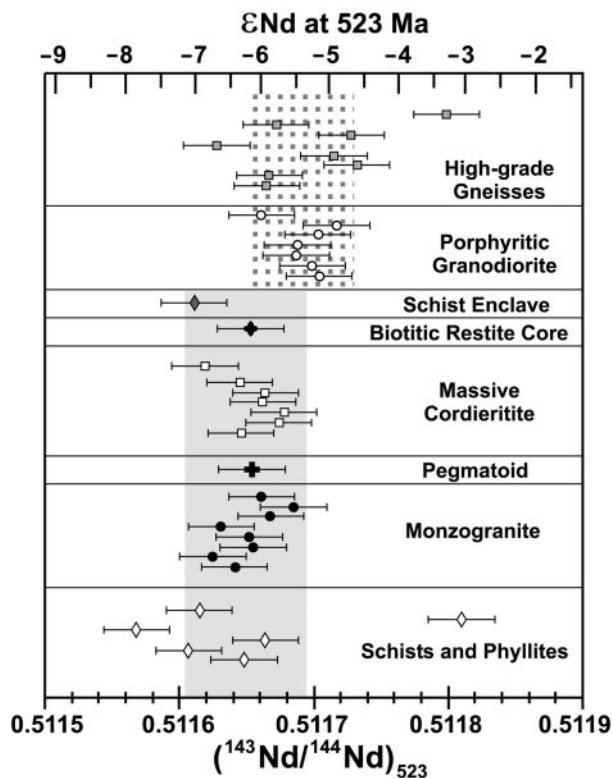


Fig. 12. Plots of initial Nd isotope compositions for samples from the El Pilón complex and country rocks. The shaded and dotted columns represent the effectively different compositions of the monzogranite (closely similar to the phyllites and low-grade schists), and the porphyritic granodiorite (more similar to the high-grade country rocks), respectively.

monzogranite magma. Seven analyses of the porphyritic granodiorite give a mean ϵNd_{523} value of -5.3 ± 0.3 , indistinguishable from that of the high-grade gneisses and confirming the impression obtained from the Sr data that its source was slightly more primitive in terms of isotopic evolution than that of the monzogranite–cordierite–restite association. Crust-derived Sm–Nd model ages (De Paolo *et al.*, 1991) of all rocks of the El Pilón complex are consistently Mesoproterozoic; averaging ~ 1700 Ma for the highly peraluminous association and the schists, and ~ 1650 Ma for the porphyritic granodiorite and the gneisses. Interpretation of these observations in terms of the magmatic history is considered more fully below.

DISCUSSION

Geological environment of the cordierites

The high dT/dP gradient of the Middle Cambrian M_2 metamorphism during which the cordierites and highly peraluminous granites of El Pilón were emplaced has been ascribed to (1) isothermal uplift following crustal

thickening, ophiolite obduction, compression and high-grade metamorphism (Rapela *et al.*, 1998a) or (2) ridge subduction under the accretionary prism (Fantini *et al.*, 1998). Orbicular cordierites similar to the well-preserved facies of Cerro Negro are extremely rare. To our knowledge, the only other described example of orbicular cordierite is that of Minedera-yama, Tsukuba, Japan, consisting of ellipsoidal orbicules with cordierite shells and schistose biotite–plagioclase cores set in a granular granitic matrix (Kawano, 1933; Yoshiki, 1933). The field association with porphyritic granites, the fabric of the orbicular rock, the mineralogy (including abundant accessory apatite), and the chemical composition, all resemble features of El Pilón. In Minedera-yama the orbicular cordierite occurs as a dyke in a porphyritic biotite granodiorite–monzogranite of Latest Cretaceous–early Palaeogene age (59–63 Ma), which intrudes a low P/T shale and sandstone sequence considered to be an eastern extension of the Ryoke metamorphic belt of SW Japan (S. Ishihara, personal communication, 2000). A tectonic model for the Ryoke belt involving ridge subduction followed by terrane amalgamation of the high- P/T rocks of the Sanbagawa belt has been recently proposed (Brown, 1998).

The cordierite–sillimanite-bearing granitic rocks of El Pilón also show many similarities with widespread granitic massifs formed during the late thermal evolution of the Hercynian domain in western Europe and northwestern Africa (Gardien *et al.*, 1997; Escuder Viruete *et al.*, 1998). Central Iberian massive cordierites with 60–80% cordierite have been related to assimilation of restitic meta-sedimentary material by the granitic magmas (Ugidos, 1988; Ugidos & Recio, 1993). A high-level pluton in Morocco contains cordierite enclaves (80% Crd) inferred to be partly digested pelitic xenoliths picked up by the ascending magma (Boulton, 1992). Another well-studied example of these low- P , high- T terranes associated with highly peraluminous cordierite-bearing granites is the Velay dome in the French Massif Central (Barbey *et al.*, 1999, and references therein), although no cordierites have been found in this case. The high dT/dP gradient in the Velay dome cannot be explained by post-tectonic uplift alone as deduced from calculated uplift rates, but several lines of evidence suggest heat supplied by hot mantle-derived magmas at the base of the crust during the extensional D_4 deformation phase (Montel *et al.*, 1992). The El Pilón peraluminous granites show no evidence of coeval mantle-derived rocks, but Cambrian uplift rates have not been yet accurately estimated in the Sierras de Córdoba, and therefore underplating by mafic magmas during the later stages of the M_2 event cannot be ruled out. The common environmental links between the cordierites of El Pilón, Minedera-yama and the Hercynian belt are the high dT/dP metamorphic gradient and an association with peraluminous granites containing

fertile pelitic enclaves. The orbicular cordierites of El Pilón and Minedera-yama appear to be closely related to dykes or conduits. Despite this general coincidence in the geological environment, cordierites are scarce even in large low- P , high- T domains such as the Velay dome. This indicates that other local factors such as availability of sufficient water to allow local fluid-present melting of metapelites, high temperatures, and cordierite accumulation by flow segregation, are needed to form relatively large cordierite outcrops such as in El Pilón (see below).

Cordierites are not restricted to the localities mentioned above, and the following examples, not intended as a thorough compilation, illustrate the scattered occurrence of cordierite-rich rocks in orogenic belts of different ages and continents, although in some cases the modern petrological studies are lacking. Read (1923, 1935) first described cordierite-rich rocks of igneous aspect from the Dalradian Series of NE Scotland, the classic area for 'Buchan type' low- P (1–3 kbar), high- T (500–550°C) regional metamorphism, analogous to the Ryoke belt of Japan. Massive layered gabbros were emplaced at, or soon after, the peak of metamorphism, and are associated with quartz–cordierite norites and quartz–cordierite–garnet–feldspar rocks with cordierite up to 20–35% of the mode, both containing metapelitic xenoliths. Petrological arguments, field relations, and isotopic data are consistent with melting of the host pelitic schists in the roof zone of the gabbros (Gribble & O'Hara, 1967; Gribble, 1968; Pankhurst, 1969). Mathias (1952) described and analysed an 'unusual' rock, composed of 63% of porphyroblastic cordierite, associated with granites at Upington, South Africa, that are most probably part of the 1000–1200 Ma Namaqualand metamorphic complex (R. Armstrong, personal communication, 2000). In the Strathbogie batholith, a subvolcanic S-type body of the Lachlan Fold Belt (Phillips *et al.*, 1981), a cumulate layer probably formed by a flow segregation is found near the edge of a pluton lobe. This contains ~30% euhedral cordierite, biotite booklets, plagioclase, a little interstitial quartz and relatively high concentration of the usual accessory minerals (J. D. Clemens, personal communication, 2000).

Magma sources and ascent mechanism of El Pilón magmas

The highly peraluminous mineralogy and geochemistry of these granites, coupled with the radiogenic Sr and unradiogenic Nd isotopic signatures, demonstrate major involvement of a mature metasedimentary component in their source (Figs 3 and 12). The mid-crustal high-grade Grt + Crd migmatitic massifs of the Sierras de Córdoba, formed during the M_2 metamorphic peak

(Rapela *et al.*, 1998a; Otamendi *et al.*, 1999), are an obvious potential candidate for this source. The protolith of the high-grade rocks is inferred to be Bt + Grt gneisses derived from metaluminous greywackes with $\text{SiO}_2 = 69.8\text{--}72.5\%$, $\text{Al}_2\text{O}_3 = 12.0\text{--}13.6\%$, $\text{MgO} = 2.2\text{--}2.7\%$, $\text{K}_2\text{O} = 2.0\text{--}2.6\%$ and $\text{Na}_2\text{O} = 2.0\text{--}2.6\%$, with very little if any shale intercalations (Otamendi & Patiño Douce, 2001). It is very likely that such high-grade rocks underlie the lower-pressure Crd migmatites that host the El Pilón complex. The presence or absence of garnet is the only difference between these two types of migmatite, which are separated by a ductile shear zone to the east of El Pilón (Fig. 1). Another potential metasedimentary source is the low- to medium-grade phyllites and schists of the Sierras de Córdoba, and equivalent Cambrian supracrustal sequences in other parts of the Sierras Pampeanas (Rapela *et al.*, 1998a; Pankhurst *et al.*, 2000). Schists cropping out to the NE of El Pilón, and abundant enclaves in the monzogranite, are representative of this sequence, in which metapelite protoliths commonly contain 57–67% SiO_2 , 14.2–19.0% Al_2O_3 , 2.6–5.3% MgO , 2.6–5.0% K_2O and 0.6–2.2% Na_2O (Fig. 8). Initial Sr and Nd isotope ratios indicate that the garnet-bearing, high-grade metasedimentary rocks are slightly but consistently less evolved isotopically than the low- to medium-grade rocks (Fig. 12). This shows that the protoliths of the two metamorphic sequences are not identical in composition. The porphyritic granodiorite of the El Pilón complex has isotopic compositions similar to those in the high-grade rocks. In contrast, the monzogranite is isotopically more evolved and displays a range of initial ratios transitional to the field of low- to medium-grade metamorphic rocks (Fig. 12). This, and the large number of schist enclaves found in both the monzogranite and the cordierites, is consistent with an important contribution from a relatively mature metasedimentary source similar to the low- to medium-grade regional schists and phyllites.

On the other hand, the abundant Grt + Bt enclaves in both the porphyritic granodiorite and the monzogranite show that, although contaminated at emplacement level by *in situ* segregations and/or assimilation of garnet-absent host rocks, the primary source of the peraluminous magmas was located at a deeper level. The pressure of 5.9 kbar calculated from the core of a restitic garnet in the cordierite (Figs 6 and 7) is taken as an indication of the depth of the magma sources. This is consistent with coeval generation of extensive migmatitic massifs at the same depth during the thermal peak of the M_2 metamorphism in the Sierras de Córdoba, dated at 522 ± 8 Ma (Rapela *et al.*, 1998b). Vertical migration through ~6–8 km is implied if a melt segregated from a magmatic source at ~6 kbar was finally emplaced at 3.5–4 kbar. Peak P – T condition estimations in Crd + Grt migmatitic massifs of the Sierras de Córdoba formed during the M_2 episode decrease towards the north (Fig. 7), suggesting

exposure of progressively higher levels of the Cambrian crust, at which peraluminous magmas started to accumulate. On the basis of the field relations of the monzogranite and cordierite, and the illustrative cross-sections (Fig. 2), we argue that the monzogranite melt migrated by a dyke mechanism (e.g. Clemens, 1998; Petford *et al.*, 2000, and references therein), and that cordierites were locally formed at the top ends of feeder conduits during the laccolithic emplacement of the monzogranite body. Given the small size of El Pilón monzogranite, emplacement in <100 years may be inferred from the estimated filling times for tabular disc-shaped plutons (Petford *et al.*, 2000, fig. 4). Consequently, the time interval between the P - T conditions inferred for magmatic segregation and the lower pressure readjustment registered in the restitic association of the cordierites (Figs 6 and 7) was probably of the same order of magnitude. This is consistent with the fact that the ages of the granites and migmatites are indistinguishable, and implies extremely rapid ascent of the highly peraluminous melts at the start of the decompression stage of the Pampean orogen in the Sierras de Córdoba.

From the Cerro Negro and Tamaín conduits the monzogranite melt extended laterally over the porphyritic granodiorite forming two interconnected subcircular granitic lenses. The three-dimensional shape of this small-scale laccolith resembles the 'pinch and swell' type geometry of multiple laccolith formation in the Himalayas, which may represent a common emplacement mechanism in extending collisional belts (Scaillet *et al.*, 1995a). As in the Himalayan laccoliths, the two-lens boudin geometry of the El Pilón monzogranite seems to be more obviously related to melt supply from two different conduit feeders (Cerro Negro and Tamaín, Fig. 2), rather than to regional deformation. Recognition of feeder dykes is difficult, so that the association of orbicular facies and conduit feeders found at El Pilón might be profitably sought in large batholiths, where the orbicular facies are usually restricted to structural traps into which upward-migrating solute-rich water was channelled (e.g. the Sierra Nevada batholith, Moore & Lockwood, 1973).

Both the monzogranite and the porphyritic granodiorite were emplaced at or near the contact between the Crd migmatites and the schists. This limit, located at ~ 3.5 – 4 kbar, represented an important subhorizontal anisotropy in the crustal section at El Pilón; peraluminous granites formed during the anatexis stage were not emplaced in the phyllites and low-grade schists above this level. An exposure of medium-grade schist with Crd porphyroblasts 14 km from the complex suggests that the emplacement of peraluminous plutons beneath the schist unit extended to this distance. During extensional regional stress, magma driving pressure may greatly exceed the lithostatic load, resulting in subhorizontal

sheet-like intrusions (Hogan *et al.*, 1998). In the case of El Pilón complex, the boundary between two different metasedimentary units seems to have behaved as an effective magma trap.

Compared with the monzogranite, there is no field evidence from which to infer a feeder-like mechanism for emplacement of the porphyritic granodiorite, as the floor of the pluton is not exposed. Nevertheless, as for the monzogranite, garnet–biotite restitic enclaves in the granodiorite indicate that the source of the melt was at least 6 km below the intrusion level, and U–Pb and Rb–Sr geochronological data indicate that both units were intruded during the same event (Rapela *et al.*, 1998b). We argue that the absence of thermal contrast between the granodiorite and the country rock may reflect thermal equilibrium between a large batch of accumulated melt and the metamorphic envelope at 3.7 kbar. A slow ascent mechanism, such as diapirism, for the granodiorite pluton and a fast feeder emplacement for the monzogranite are mutually exclusive. If the ascent of the porphyritic granodiorite was by feeder-dyke mechanism similar to that for the monzogranite, the rapid intrusion of large amounts of hot highly peraluminous magmas into the upper crust would have been critical in developing the high dT/dP gradient during the later stages of the M_2 metamorphism. We suggest that it triggered widespread partial melting and led to formation of cordierite-bearing migmatites, which also acted as a rheological screen.

Partial melting and the role of fluids at the emplacement level

The remarkably fresh and well-developed orbicular cordierites of Cerro Negro share many, if not all, of the features of fabric, rheological behaviour and setting with the orbicular granite facies (Elliston, 1984). An important characteristic common to many orbicular granites is their restriction to small lenses, pipes and water-rich marginal facies of the magma from which they crystallized (Elliston, 1984). Their development seems to require an absence of nuclei in the magma accompanied by a fall in the liquidus temperature of the melt, forcing crystallization to occur only on solid objects (Vernon, 1985). An effective way to cause a drop in the liquidus temperature of an H_2O -undersaturated magma is by introduction of H_2O into the melt (Vernon, 1985). At El Pilón, the local concurrence of cordierites, tourmaline-bearing pegmatoids and hydrothermal alteration is consistent with intense fluid activity associated with the feeder conduits represented by the cordierite pipes. Nevertheless, the most likely source of the highly peraluminous granites of El Pilón is Grt + Crd migmatites formed at ~ 6 kbar.

The peraluminous magmas of the Sierras de Córdoba are H_2O -undersaturated melts formed by partial melting,

either in the presence of a small amount of free water (H_2O -fluxed melting) or by dehydration melting of biotite (Otamendi & Patiño Douce, 2001). The initial temperature of the monzogranite melt at the emplacement level has been inferred from the temperatures estimated for the source (5.9 kbar, 780°C), and by assuming an ascent path with a constant and very low crystal/melt ratio. This steep path is akin to those followed by melts that remain isothermal and H_2O undersaturated, with a minimal chemical and thermal exchange between magma and country rocks, as in dyke ascent (dashed line in Fig. 7; Johannes & Holtz, 1996; Petford *et al.*, 2000). A very slight fall in temperature of $\sim 10^\circ\text{C}$ is inferred for the ascent of a melt from 5.9 kbar to the emplacement level at 3.7 kbar. Taking the temperature of Paragenesis 2 in the cordierite (PIL-375, 650°C) as representative of the final temperature after isobaric cooling, this yields a crystallization interval of $\sim 110^\circ\text{C}$ (Fig. 7). This interval is consistent with those observed for peraluminous leucogranites under water-saturated conditions at 4 kbar (70–120°C), which increase with decreasing aH_2O (Scaillet *et al.*, 1995b). The initial temperature of $\sim 770^\circ\text{C}$ inferred for the water-undersaturated peraluminous melt is within the range of liquidus temperature for Bt + Ms leucogranites at 4 kbar with $H_2O_{\text{melt}} > 5\%$ (770–800°C, Scaillet *et al.*, 1995b), and is well above that of the relict St + Bt1 + Ms1 association observed in the pelitic schists close to the El Pilón complex (Fig. 1, Table 1). The abundant restites of assimilated schists, including those at the core of the orbicular cordierite and the poikilitic Crd–Bt2–Ms2 association developed in the schists to the NE of the complex, indicate that significant thermal disequilibrium must have initially existed at the magma emplacement level.

Ascending magmas with constant crystal/melt ratio produce an increase in aH_2O with decreasing pressure (Johannes & Holtz, 1996), which in the case of El Pilón complex would have been accentuated at the top of the feeder conduits as a result of water released by partial melting of the hydrous country rock schists. The schists contain 16.3–18.1% Al_2O_3 , 3.2–3.4% MgO and ~ 2 wt% H_2O^+ (see Appendix 1), whereas the probable unmelted source rocks are biotite–garnet gneisses with 12.0–13.6% Al_2O_3 and 2.2–2.7% MgO (see Table 2; Otamendi & Patiño Douce, 2001). Water-saturated melting experiments on peraluminous rocks at 2–5 kbar have shown that the amount of cordierite formed increases with increasing Al_2O_3 excess at constant pressure, whereas the stability field of biotite decreases as a result of preferential partitioning of Mg into cordierite (Puziewicz & Johannes, 1988). This is relevant for the El Pilón case, as fluid-present melting of the pelitic schist enclaves leaving garnet-absent Bt–Sil restites at 3.5–4 kbar would have increased the Al, K, P, Fe and Mg contents and

mg -number in the melt ($mg\text{-number}_{\text{biotite}} = 49\text{--}56$). Although the solubilities of ferromagnesian components in H_2O -undersaturated felsic melts are very low (e.g. Johannes & Holtz, 1996), at constant temperature and pressure MgO and FeO concentrations in granitoid melts vary directly with H_2O content (Patiño Douce, 1996, and references therein). Ca-poor peraluminous melts incorporate up to 0.6–0.7% MgO, in contrast to $\leq 0.15\%$ MgO in subaluminous melts, which also have significantly lower Mg/Fe ratios (Holtz *et al.*, 1992). The normal facies of the monzogranite contains 0.4–0.6% MgO and has very high ASI compared with Hercynian and Himalayan granites (Fig. 9). Early crystallizing cordierite from this melt would therefore be expected to have a high mg -number, suggesting that the massive cordierite ($mg\text{-number} = 65\text{--}70$) started to crystallize in the fluid-rich environment associated with the cordierite pipes, when the melt became saturated in MgO. An early crystallizing high-Mg cordierite is in accord with experimental evidence indicating that some Al forms complexes with Mg in Mg-bearing highly peraluminous melts (Holtz *et al.*, 1992).

Provided that equilibrium were attained in the partial melting of schists at the emplacement level, a melt with a high K/Rb ratio would be expected, as biotite was the main rock-forming mineral in the residue and the $Kd^{\text{biotite/melt}}$ for Rb is very high. Fluid-present partial melting of hydrous country rocks near magma conduits provides a suitable model to explain the massive occurrence of magmatic cordierite in very restricted environments, as well as the high MgO content, high ASI, and high K/Rb ratio of the consanguineous melts (Fig. 9).

Even without reaching H_2O saturation, an increase in the H_2O and fluid content of the highly peraluminous melt as a result of rapid decompression and partial melting of hydrous Al-rich country rocks may have produced an important drop in the liquidus temperature and changes in the composition of the magma. Another consequence of fluid-present melting is depression of the Pl + Qtz solidus, so that residues formed by H_2O -fluxed melting contain significantly less plagioclase (and quartz) than those formed by dehydration melting (Patiño Douce & Harris, 1998). Hence, with preferential partition of quartz and feldspar into melt, biotite-rich residues are expected to be a common product of medium- to low-pressure, fluid-present melting of biotite-bearing metasedimentary rocks. Mass balance calculations between the low- and medium-grade metapelites (see the compositional field of these rocks in Figs 3 and 8) and the normal facies of the monzogranite indicate that residues with a silica composition akin to that of the restitic core of the orbicule (sample PIL-007) would be achieved if the melt fraction were at least 50–60% (Table 2a). Although the quantitative

Table 2: Mass balance calculations

(a) Calculated residues after 40–60% extraction of monzogranite from average metapelite						
(wt %)	Average metapelite	Average monzogranite	Calculated residues			Observed residue (PIL-007)
			40%	50%	60%	
SiO ₂	61.50	72.37	54.25	50.63	45.20	47.51
TiO ₂	0.80	0.16	1.23	1.44	1.76	1.53
Al ₂ O ₃	18.00	14.77	20.15	21.23	22.85	25.62
FeO(t)	6.50	1.45	9.87	11.55	14.08	11.23
MnO	0.09	0.04	0.12	0.14	0.17	0.26
MgO	3.15	0.48	4.93	5.82	7.16	7.28
CaO	0.95	0.76	1.08	1.14	1.24	0.31
Na ₂ O	1.55	2.68	0.80	0.42	−0.15	0.59
K ₂ O	4.10	5.36	3.26	2.84	2.21	3.63
P ₂ O ₅	0.16	0.35	0.03	−0.03	−0.13	0.26
Total	96.8	98.42	95.72	95.18	94.37	98.22

(b) Least-squares fractionation model for monzogranite and cordierite				
(wt %)	Parental magma (average monzogranite)	Fractionated magma (average leucogranite)	Composite cumulate (PIL-303 (cordierite))	Difference obs.–calc. parent (wt %)
	SiO ₂	72.37	75.00	47.33
TiO ₂	0.16	0.04	0.21	0.11
Al ₂ O ₃	14.77	14.01	25.49	−0.05
FeO(t)	1.45	0.46	10.37	0.19
MnO	0.04	0.01	0.21	0.01
MgO	0.48	0.14	7.17	−0.24
CaO	0.76	0.79	0.14	0.03
Na ₂ O	2.68	3.02	0.65	−0.13
K ₂ O	5.36	5.58	3.44	−0.01
P ₂ O ₅	0.35	0.20	0.10	0.16
Total	98.42	99.25	95.11	

Sum of square of residuals = 0.150; percent of cumulate assemblage = 7.9%.

comparison is limited by unmeasured variations in the modal proportions of Bt, Sill and Crd in the core of the orbicules, the high colour index and concentration of refractory minerals observed in most cores (see Fig. 4) indicate a high degree of partial melting of the schist enclaves. Negative values of P₂O₅ and CaO for calculated residues at 50–60% melting (Table 2a) are related to the preferential partition of apatite in the cordierites and highly peraluminous melts subsequently

formed (see Fig. 11 and below). Melts produced by anatexis of the metapelitic enclaves mixed at the final emplacement level of the body with the monzogranitic melts formed at greater depth in the garnet stability field. Such strong upper-crustal contamination may have not significantly changed the highly peraluminous chemistry of the magma, as a metasedimentary source was probably involved at depth. However, the more evolved Sr and Nd isotopic compositions of the

monzogranite clearly indicate the influence of an evolved crustal component, such as the low- and medium-grade rocks of the Sierras de Córdoba (Fig. 12).

Orbicular cordierite: an *in situ* cumulate rock formed from highly peraluminous melts

The zoning and radial arrangement of cordierite crystals that decrease in size towards the outer edge of the shells of the large orbicules suggests static growth in a liquid environment (Fig. 4). There is no genetic difference between this cordierite and that of the massive variety, as cordierite crystallized from magma on any available solid object: (1) Sil + Bt schist restites; (2) euhedral first-formed crystals of cordierite; or (3) the sides of the conduits and/or the magma chamber. Crystallization types (1) and (2) led to formation of orbicular cordierite whereas crystallization type (3) developed the massive variety. Crystallizing directly from the magma under fluid-present conditions, the cordierite of the cordierites is a magmatic mineral growing in an environment close to that found in pegmatitic systems (Clarke, 1995). Melt supply through the feeder conduits was probably pulsed or intermittent, as inferred from the fabric of the orbicular cordierite. The static growth of large orbicules during the initial stage of crystallization of the monzogranitic magma was followed by periods of transport, accumulation and deformation of the orbicules at the funnel-shaped end of the feeder dyke. Breccia facies, angular enclaves and disrupted outcrops associated with the massive cordierites also reflect rapid and turbulent flow, probably produced by a sudden release of pressure during the filling of the laccolith by a fluid-rich melt. The decreasing size of the orbicules towards the top of the Cerro Negro section suggests that flow segregation along the upper section of the feeder conduit produced a magmatic analogue of graded bedding in sedimentary rocks (Fig. 2).

The leucogranitic orbicular matrix, which is transitional to the local facies of the monzogranite, is interpreted as a solidified remnant of the magma from which the orbicules crystallized. Initial Sr and Nd ratios of the orbicule cores, the massive cordierite and the monzogranite are all indistinguishable, indicating that near isotopic equilibrium was attained during the crystallization of the orbicules at high temperature (Fig. 12). This remarkable isotopic homogeneity for a melt derived from a heterogeneous sedimentary source can only be explained by effective mixing of the melt after the emplacement and contamination by *in situ* partial melting of metapelitic enclaves. Effective mixing is best explained by strong convection within the laccolith body. Thus,

the combined field, fabric and isotopic evidence indicates that the orbicular cordierites are mafic cumulate rocks that crystallized from an isotopically homogeneous peraluminous magma. The contemporaneous leucogranitic melt was trapped between the orbicules and solidified as intercumulus material (Fig. 4). These features are common in basic plutonic complexes but extremely rare in granitic rocks.

Massive crystallization of cordierite on restitic cores followed by flow-driven accumulation of orbicules at shallow levels depleted the liquid in MgO, FeO, Al₂O₃ and MnO and increased the silica content to 74–76% (Figs 8 and 10). The decrease in the colour index of the normal facies of the monzogranite (FeO_t + MgO ~ 2%) to form leucogranite (FeO_t + MgO ~ 0.6%) is ascribed to cordierite segregation from the granitic melt (Fig. 10). Crystallization of high-Mg cordierite reduced the ASI and depleted the MgO of the residual leucogranite melt (Fig. 9). It should be noted that the average CaO, Na₂O and K₂O of the leucogranite and the normal facies of the monzogranite are similar (Table 2b), indicating that feldspar fractionation was not significant. Quantitative evaluation of the cordierite fractionation must take into account the fact that orbicular cordierites are complex cumulates composed of magmatic cordierite and metapelitic restitic cores. Leucogranites may thus be formed by a single process that simultaneously involved (1) separation of an early formed hydrous mafic mineral by fractional crystallization and (2) separation of a restitic assemblage from the magma by a type of restite unmixing process (White & Chappell, 1977).

A least-squares fractionation model using the orbicular cordierite as a cumulate assemblage provides a useful quantitative framework for this process (Table 2b). The modelled fractionation of this 'natural' composite cumulate involved the combined extraction of pure cordierite [parental magma = x leucogranite (1) + (1 - x) cordierite] and restite [parental magma = x leucogranite (2) + (1 - x) orbicular core] from a parental magma similar in composition to the average monzogranite (Table 2b). The main differences between the cumulate cordierite and restite end-members are in K₂O, TiO₂, P₂O₅ and CaO, as biotite, zircon and opaque minerals concentrate in the orbicular core and apatite in the cordierites, respectively (Table 2). The proportion of shell/core is variable in the orbicules (Fig. 4), and therefore a typical orbicular cordierite has been selected for modelling purposes (sample PIL-303). Despite these uncertainties, the least-squares calculations show that the parent monzogranitic magma can be well reproduced after ~8% extraction of the composite cumulate. Cordierites therefore represent only ~8% of the monzogranitic magma.

Trace elements such as REE, Zr, Hf, Th and U that are concentrated in apatite and zircon—the main

accessory minerals of the cordierite and biotitic restite, respectively—are also strongly depleted in the fractionated leucogranites (Fig. 10, Table 2). Zircon crystals largely occur armoured in the restitic biotite, so that Zr, U, Th and Hf are depleted in the fractionated leucogranites as a result of the coupled restite unmixing process that accompanied cordierite formation. The high P_2O_5 content of the cordierites is most probably related to the high solubility of apatite in peraluminous melts (Pichavant *et al.*, 1992), from which cordierite crystallized. The depleted REE patterns of the leucogranites, with positive Eu anomalies, can be explained by the combined extraction of the P_2O_5 -rich cordierite facies and restite as shown in Fig. 11a. Both the cordierite and the biotite restite have higher light REE (LREE) and heavy REE (HREE) than the monzogranite. None the less, as the Eu content is similar in both melt and composite cumulate, the positive Eu anomaly in the leucogranitic liquid is developed by depletion of the remaining REE, which are partitioned in the composite cumulate. The REE pattern in the cordierites is in turn directly related to the whole-rock P_2O_5 content (Fig. 11b). Coarse-grained cordierites with low P_2O_5 contents show flat and depleted patterns without Eu anomalies, similar to those observed in purely magmatic cordierite (Bea, 1996). The total REE contents and the negative Eu anomalies of the cordierites increase with the P_2O_5 content, from 0.02% P_2O_5 (0.05% normative apatite) in the coarse-grained cordierites to a maximum of 1.1% P_2O_5 (2.5% normative apatite) in the fine-grained massive facies (Fig. 11b). The observed change of REE patterns in cordierites corresponds to that from pure cordierite to an end component of pure apatite, which occurs in peraluminous granites (Fig. 11b). The large amount of modal apatite in the cordierites is the main factor controlling the REE distribution during cordierite extraction from peraluminous melts. Lensoid pegmatitic patches in the main monzogranite facies also developed depleted REE patterns with positive Eu anomalies (Fig. 11a) and plot on the Rb–Sr isochron (Rapela *et al.*, 1998b). This suggests that some fractionation occurred in the latest stages of crystallization of the monzogranitic magma, during which highly evolved melts segregate from crystal mush by a mechanism such as gas-driven filter pressing (Sisson & Bacon, 1999).

CONCLUSIONS

The El Pilón granite complex illustrates the rapid emplacement of highly peraluminous magmas in the upper crust at the start of the decompression stage of the Pampean orogeny. Field and petrological evidence indicates that the ascent of monzogranitic magmas was produced by feeder conduits that connected a source

region located at ~ 6 kbar, with the final emplacement level at 3.7 kbar. Fast injection of large amounts of highly peraluminous magmas at high level in the crust was critical for developing the late M_2 high dT/dP gradient that formed the cordierite diatexites and stromatolites of the El Pilón complex. The conclusion that melts were able to migrate rapidly over long distances and accumulate at higher levels in the crust explains why granitic plutons have not been found in the neighbourhood of other melt-depleted migmatitic and granulitic terranes in the Sierras de Córdoba (Otamendi & Patiño Douce, 2001). This mechanism sharply contrasted with the slow diapiric ascent proposed for granites and migmatites in other high- T , low- P complexes (e.g. Barbey *et al.*, 1999).

Cordierites appear at the top of conduits feeding into the floor of a laccolith-like body of a cordierite monzogranite. This hot, H_2O -undersaturated, highly peraluminous magma reached fluid-saturation conditions at the emplacement level, probably as a result of a rapid decompression and extensive assimilation of metapelitic country rock enclaves. This produced a marked fall in the liquidus temperature of the melt, which in turn destroyed crystallization nuclei, forcing crystallization to occur only on solid objects (Vernon, 1985), and provoked strong convection in the small magma chamber. High-Mg cordierite crystallized first in the magma, either on Bt + Sil schist restites (forming orbicular cordierites) or at the side of the conduits as massive cordierite. During the isobaric cooling, flow segregation of cumulate cordierite and restite decreased the colour index of the residual magma, developing leucogranites and highly evolved pegmatoids that are all in isotopic equilibrium (Nd and Sr). Again, this situation seems to be the antithesis of other water-undersaturated crust-derived granites emplaced by dykes, such as the Himalayan granites, in which heterogeneous initial isotopic ratios indicate that no significant magma mixing occurred during emplacement (Scaillet *et al.*, 1990).

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