

Petrogenesis of cordierite-bearing S-type granitoids in Sierra de Chepes, Famatinian orogen, Argentina

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Abstract

During the Lower Paleozoic Famatinian orogeny in the Sierra de Chepes, NW Argentina, emplacement of a major metaluminous igneous suite in the middle crust caused high-temperature ($>700\text{ }^{\circ}\text{C}$) and low-pressure (2–3 kbar) metamorphism. Heating was sufficient to induce local anatexis of the surrounding metasediments. Combined petrology, chemistry/mineralogy, and whole-rock geochemistry studies indicate that the cordierite-bearing granitoids of the Tuaní Granite unit (479 Ma) were mostly produced by in situ partial melting of the surrounding metasedimentary rocks and represent a primary melt. Major (CaO, Na₂O) and trace (Rb, Sr, Ba) element contents in the Tuaní Granite unit strongly suggest anatexis of immature continental platform material. The granitic bodies in the unit are typical S-type granitoids, and the petrogenetic model established here contributes to a better understanding of the transition from high-grade metamorphic to igneous rocks and the link between peraluminous melts and source rocks.

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1. Introduction

The Famatinian orogen formed during the Lower Paleozoic on the proto-Andean margin of Gondwana (Fig. 1; Pankhurst et al., 1998, 2000; Rapela et al., 1998; Rapela, 2000). The Sierra de Chepes, which occurs within the Famatinian orogenic belt (Fig. 1), is mainly composed of Lower Ordovician granitoids that can be subdivided into two types: I-type and peraluminous (presumably S-type) (Fig. 2; Pankhurst et al., 1998). Metaluminous batholiths are located in the western region of the orogen, whereas slightly peraluminous batholiths are located in the eastern region and have been identified as S-type granites (e.g. Sierra de Capillitas, Sierra de Velasco of more than 6000 km²; Fig. 1; Rossi et al., 2002; Pankhurst et al., 2000). The granitoids of these batholiths do not seem to share a similar origin with the Tuaní Granite unit of the Sierra de Chepes (Figs. 1 and 2), which is formed by granitoids probably derived from metasedimentary rocks, namely, S-type granitoids. According to Pankhurst et al. (2000), the peraluminous

granitoids of the Sierra de Velasco could have crystallized from melts derived from a middle crustal source region, perhaps with minor hybridization of I-type granodioritic melts.

The likely S-type granitoids of the Tuaní Granite were emplaced almost synchronously with the metaluminous suite (Dahlquist and Baldo, 1996; Pankhurst et al., 1998, 2000), which constitutes a classic example of the generation of granitoids of this type, that is, produced from a sedimentary source rock, as originally conceived by White and Chappell (1977). Although their age and geochemical and isotopic characteristics are known (Pankhurst et al., 2000), no integrated field observations, petrography, mineral, or whole-rock geochemistry studies have been conducted on these granitoids.

In this article, we integrate field observations, petrography, mineral/chemistry, whole-rock geochemistry, and petrologic modeling to elucidate the petrogenesis of the Tuaní Granite, which we infer was derived from partial melting of the metasedimentary protoliths in the Sierra de Chepes. The petrogenetic model established here and a comparison with typical S-type granitoids in the Lachlan fold belt of SE Australia contribute to a better understanding of how shallow-level S-type granitoids are formed.

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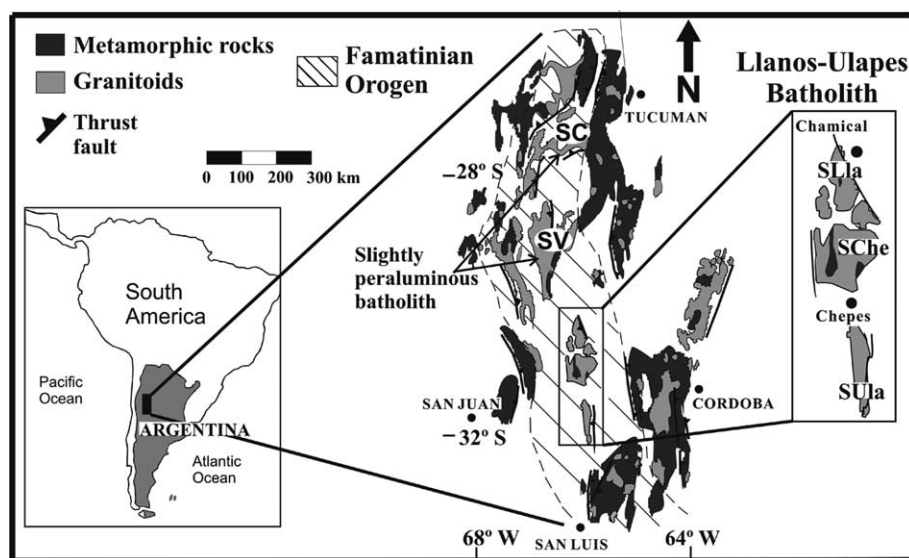


Fig. 1. Geological sketch map of the Sierras Pampeanas (Argentina), modified from Dahlquist (2002). The striped field shows the main belt of the Early–Mid-Ordovician Famatinian arc. SLla: Sierra de Los Llanos, SChe: Sierra de Chepes (Fig. 2), SULA: Sierra de Ulapes, SV: Sierra de Velasco, SC: Sierra de Capillitas.

2. Geologic background

The Sierra de Chepes occurs in the central sector of the Famatinian orogenic belt (Figs. 1 and 2) and is mainly composed of Lower Ordovician metaluminous, calc–alkaline granitoids (~84%), probable S-type granitoids that occur as small-scale bodies (~1%), and metamorphic host rocks (~15%), which form discontinuous outcrops (Fig. 2).

Metamorphosed wallrocks represent a metasedimentary sequence of mixed metapelitic and metapsammitic rocks (i.e. metagreywacke). The M_1 event is represented by fine-grained inclusions of biotites, very abundant magnetites, quartz, and muscovite preserved in cordierite porphyroblasts. Detailed studies of the M_2 event (Dahlquist and Baldo, 1996; Pankhurst et al., 1998; Dahlquist, 2000) reveal a strong metamorphic zonation in which the following can be distinguished: (1) phyllite in a biotite zone, (2) schist in a cordierite zone, (3) stromatic migmatite in an andalusite + K-feldspar zone, and (4) an anatectic zone (Fig. 3). The last zone is represented by the rocks of the Tuaní Granite, which represent local anatexis of the surrounding metasediments. The metamorphic zones produced during the M_2 event are characterized by (1) predominant cordierite, (2) andalusite above the stability limit of muscovite, and (3) the complete absence of garnet from the highest temperature zone. These characteristics imply a thermal event at pressures not greater than 3 kbar (Dahlquist and Baldo, 1996; Pankhurst et al., 1998).

The I-type granitoids in the Sierra de Chepes have been studied petrologically, geochemically, and isotopically by Pankhurst et al., 2000 and Dahlquist, 2000 2001a,b, 2002. The most important findings revealed by these studies include the following: (1) the intermediate composition of the parental magma was mainly produced by melting of old (~1700 Ma) continental lithosphere, probably with a partial contribution from the subcontinental lithospheric mantle; (2) the parental magma differentiated by fractional crystallization

(compositional range 60–75% SiO_2) in a largely closed magmatic system, which involved early segregation of the mafic microgranular enclaves; (3) the evolution of rare-earth elements (REE) was controlled by the accessory mineral assemblage; (4) the magmatic epidote-bearing granitoids were emplaced in low-pressure ($P=2.7\text{--}3.6\pm0.5$ kbar) and high-temperature ($T=780\text{--}850\pm30$ °C) conditions; and (5) metamorphism at low- P and high- T conditions was associated with the emplacement of the I-type granitoids.

The I-type granitoids are dominated by granodiorites and tonalites, with less abundant monzogranites and leucogranites (Pankhurst et al., 1998; Sims et al., 1998; Dahlquist, 2000; Dahlquist et al., 2005). Two main magmatic units are recognized in Sierra de Chepes: the Chepes and Chepes porphyritic granodiorites.

The Chepes granodiorite unit is the largest (Fig. 2), equigranular, and medium grained (1.5 cm) with a typical presence of mafic microgranular enclaves. The magmatic mineral assemblage is microcline (Mc), plagioclase (Pl), biotite (Bt), and hornblende (Hbl); the accessory minerals are epidote (Ep), allanite (Aln), titanite (Ttn), apatite (Ap), zircon (Zrn), and opaque minerals (Opq) (abbreviations from Kretz, 1983). The Chepes porphyritic granodiorite unit is coarse grained (2–2.5 cm) and characterized by large alkali feldspar megacrysts (4 cm) and scarce or absent mafic microgranular enclaves. Its mineral paragenesis is similar to that of the Chepes granodiorite, except for a higher abundance of some felsic phases such as K-feldspar, quartz, and conspicuous allanite. Major element geochemistry indicates that both units are metaluminous to slightly peraluminous (alumina saturation index = 0.92–1.1), with a typical content of K_2O between 1.5 and 3.5% and a Peacock index of 63.5, which indicates a calcic association. The Chepes granodiorite unit ranges between 60 and 67% (average = 65%) SiO_2 , whereas the Chepes porphyritic granodiorite unit has 66–70% (average = 68%) SiO_2 . Detailed petrological and geochemical information about the

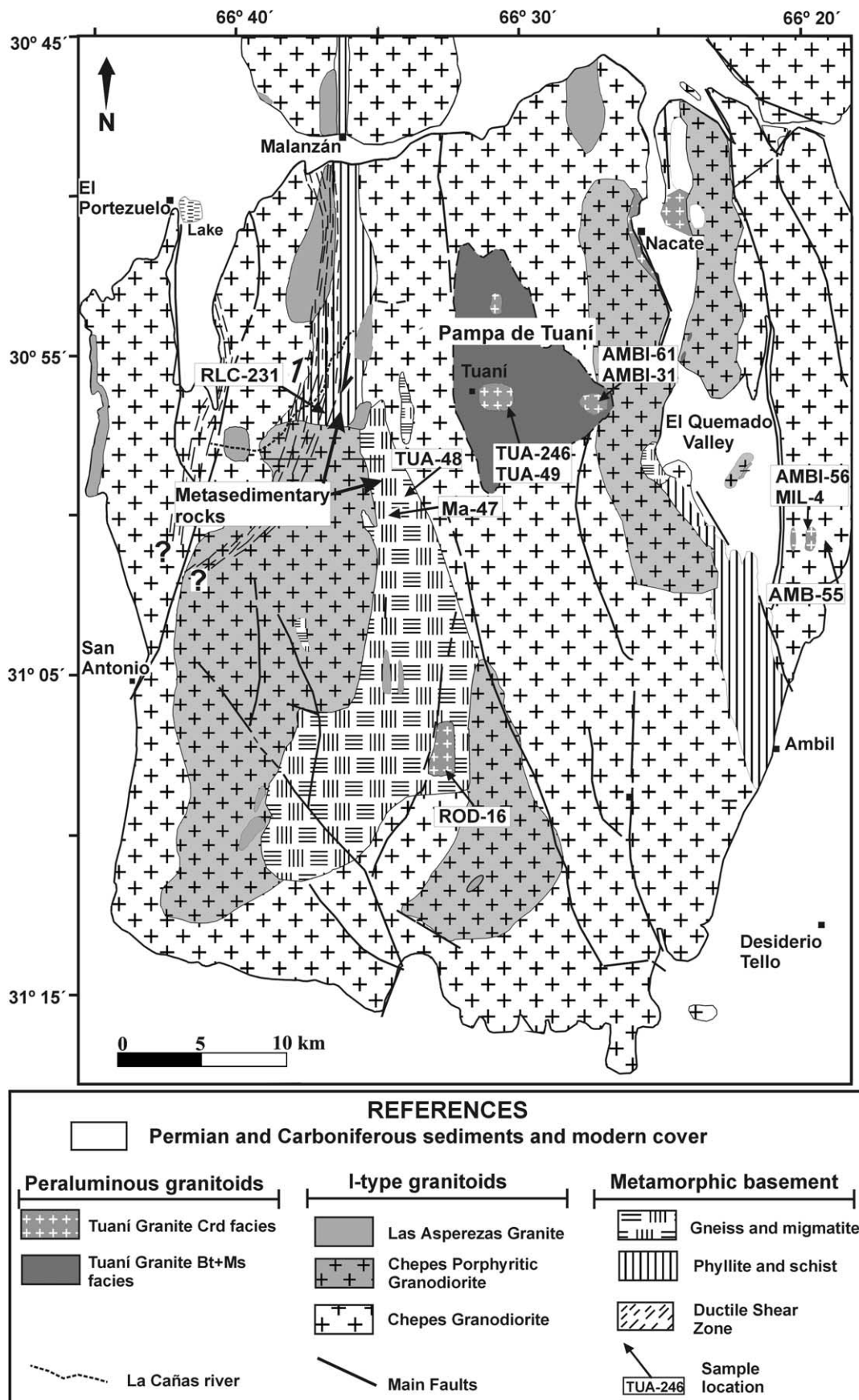


Fig. 2. Simplified geological map of Sierra de Chepes, with sample locations (modified from Pankhurst et al., 1998; Dahlquist, 2000). Granitic rocks of the Tuani Granite around Nacate were inferred from LANDSAT images.

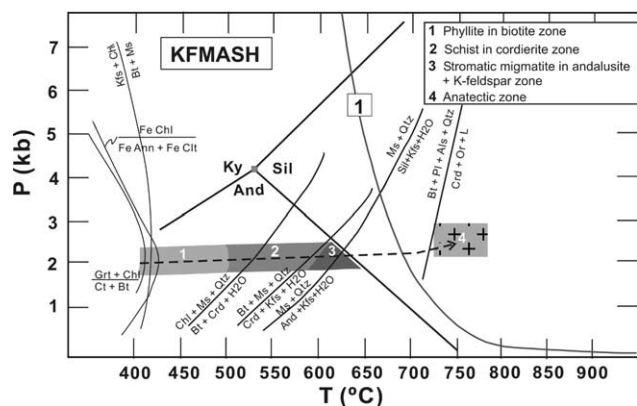


Fig. 3. Synthesis of P – T conditions for M_2 event and of the melt generation, showing univariant reactions selected for illustration. The P – T conditions for metamorphic rock (dark region) were estimated from mineral paragenesis, TWEEQU (Berman, 1991), and feldspar geothermometer (Dahlquist and Baldo, 1996; Dahlquist, 2000). Temperature of anatexis from Mirwald (1986) cordierite geothermometer. The broken arrow indicates metamorphic grade in the cross-section of Las Cañas River-Tuaní (Fig. 2, NW Sierra de Chepes; Dahlquist and Baldo, 1996; Pankhurst et al., 1998). The main reactions in the KFMASH system are after Spear (1993) and Pattison and Tracy (1991). Al_2SiO_5 phase relations according to Guowei et al. (1994). Gray box: triple point (530 ± 20 °C and 4.2 ± 0.3 kb), according to Bohlen et al. (1991). Square 1, haplogranitic water-saturated solidus.

Sierra de Chepes is given by Pankhurst et al. (1998) Dahlquist (2000, 2001a, 2001b, 2002) and Dahlquist et al. (2005).

A small-scale S-type pluton of the Tuaní Granite occurs in the roof zone of I-type granitoids or in the highest-grade, migmatitic rocks (Fig. 2) and is associated with the peak of the high- T , low- P (M_2) metamorphic event (Fig. 3).

Two main facies are recognized in the Tuaní Granite: a fine-grained (≤ 1 cm), equigranular, orange-brown, two-mica granitoid with conspicuous white mica and a fine-grained, equigranular, brown cordierite granitoid that also contains conspicuous white mica (Fig. 4a) and sometimes is rich in sillimanite or fibrolite, which contain nodules of cordierite, biotite, numerous xenoliths of metamorphic rocks, and very large quartz and K-feldspar crystals (4–6 cm) (Fig. 4b).

The cordierite facies has a magmatic phase assemblage of Qtz, Mc, Pl, Bt, Ms (primary and secondary white mica), and Crd (cordierite), with Opq, Zrn $\pm$ Tur (tourmaline), and Ap as accessory minerals. Sometimes the rock contains abundant sillimanite (Sil) or fibrolite. Andalusite was not observed in the Tuaní Granite rocks. Table 1 lists modal values for representative rocks.

In the eastern sector of Sierra de Chepes, the peraluminous Tuaní Granite (facies with cordierite, sample AMBI-56) shows a sharp contact with the metaluminous Chepes granodiorite (sample AMBI-55) (Fig. 2). There is no evidence of intrusion of the Tuaní Granite into the Chepes granodiorite unit, but the former develops a distinctive flow structure in a layer affected by a smooth fold, which leans on the rock of the Chepes granodiorite unit (Fig. 4c). Toward the central part of the Tuaní Granite pluton, the fabric becomes homogeneous and equigranular. In the contact area with the Chepes granodiorite unit, biotite is increasingly abundant, probably as a result of

local heating. However, the Tuaní Granite unit did not cross the Chepes granodiorite unit, which strongly suggests that both S- and I-type granitoids were emplaced almost synchronously (Dahlquist, 2000).

In the southern sector of the Sierra de Chepes, another pluton of the Tuaní Granite is housed in a migmatite (Fig. 2, sample ROD-16). These rocks have a stromatic migmatite structure in some places that changes in a few centimeters to a rock with equigranular texture typical of a granitoid (Fig. 4d). This change suggests that the rocks of the Tuaní Granite are the result of progressive heating of the metasedimentary sequence that culminates in local anatexis (Dahlquist, 2000).

These interpretations, based on field evidence, suggest a relationship between the M_2 event (developed during the emplacement of I-type granitoids) and the generation of the Tuaní Granite and recently have been confirmed by SHRIMP ages (U–Pb on zircon) that reveal similar ages for the Tuaní Granite (483 ± 12 and 479 ± 10 Ma; Rapela et al., 1999; Pankhurst et al., 2000) and the metaluminous suite. An age range of 478–486 Ma was determined by Sims et al. (1998) and Pankhurst et al. (2000) for the metaluminous rocks. In addition, Pankhurst et al. (2000) determined that the plutons of the Tuaní Granite have initial Sr and Nd isotope ratios very close to those of the adjacent metapelites and that a pluton of the Tuaní Granite has a fully developed pattern of zircon inheritance that is comparable to that of the Cambrian metasedimentary sequence (i.e. from the upper crust, deposited during the Pampean orogeny).

3. Analytical methods

Most of the analyses were obtained with an electron microprobe JEOL-JXA-8900M in the Luis Bru Electron Microscopy Centre, Complutense University, Madrid, Spain. The operating parameters were 15 kV accelerating voltage, 20 nA beam current, 10 s counting time, and 5 μ m beam size for all elements. Other analyses (samples TUA-49 and Ma-47) were obtained with an electron microprobe CAMECA SX-50 in the Department of Geology, Oviedo University, Spain. The operating parameters were 15 kV accelerating voltage, 15 nA beam current, 20 s counting time, and 2 μ m beam size for all elements. The ZAF correction procedures were employed, and calibration standards consisted of a combination of natural and synthetic silicate, pure metals, and oxide in both cases. More details of the measurement conditions can be found in Dahlquist (2000, 2001a) and González del Tánago (1997).

Whole-rock major and trace elements were analyzed on representative samples of the Tuaní Granite; the analytic methodology is given in Table 3.

4. Petrologic and geochemical characteristics of the Tuaní Granite unit

4.1. Petrography and mineral chemistry

This section provides the main mineralogical and textural characteristics and the mineral chemistry of the rocks of the

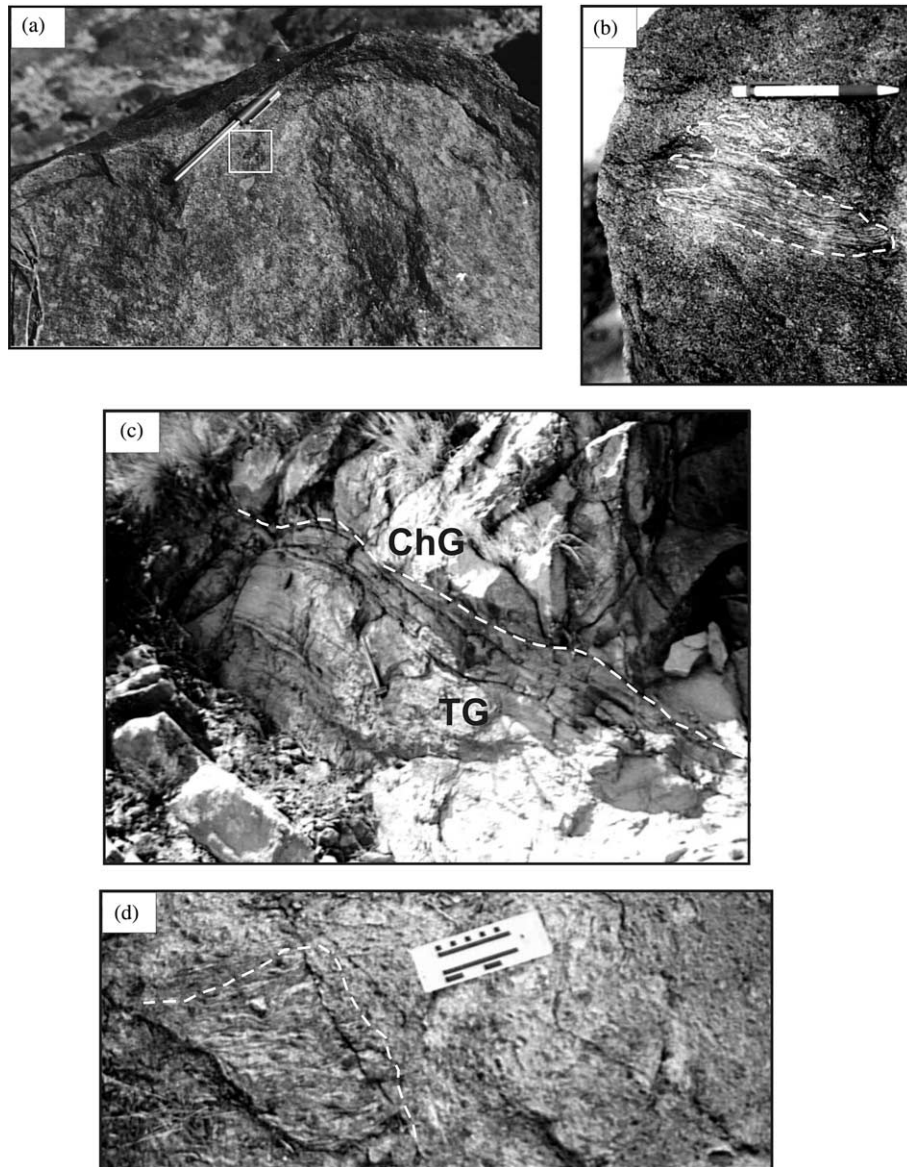


Fig. 4. Field characteristics of the Tuaní Granite. (a) Equigranular facies with homogeneously distributed muscovite megacrysts and cordierite nodule (boxed area). (b) Xenolith with gneissic structure (white dashed line). (c) Contact between the Tuaní Granite (TG) and metaluminous Chepes granodiorite (ChG). A dashed line marks the contact between igneous rocks. (d) Migmatite structure (left) and equigranular texture (right). A dashed line indicates the change. Sample ROD-16 (see Fig. 2). Leucosome bands parallel to the lower margin of the figure. Scale in the photographs: pencil (14 cm), hammer (40 cm), and scale card (10 cm).

Tuaní Granite cordierite facies. Proportion minerals and their modal classification appear in Table 1.

4.1.1. Feldspar

The alkali feldspar is microcline (Or_{61-93} , Ab_{39-7} , $An_{0-0.4}$) and varies in composition between core and rim. Cross-hatched (perthitic) twinning is common. Microcline forms subhedral-euhedral square crystals of two grain sizes: coarse-grained ($4-5\text{ mm} \times 2-3\text{ mm}$) and medium-grained ($3.5\text{ mm} \times 1.2\text{ mm}$). It is partly poikilitic with a few inclusions of quartz, biotite, magnetite, and white mica (Fig. 5a). It often shows well-developed myrmekites in contact with plagioclase. Most microcline contains albitic exsolution lamellae (perthitic crystals) that are homogeneously distributed.

A chemical profile of BaO% in the microcline reveals zoning similar to that reported for magmatic microcline by Long and Luth (1986) and Dahlquist (1998) (cross-section in Figs. 5a and 6a, data in Table 2a). In this profile, the Ab% in microcline is likewise zoned with higher concentrations of Ab in the core (Ab_{38-24}) and lower concentrations toward the rim (Ab_{9-7}) (Fig. 6a). Analysis 39, located in the core area, is an exception, with a value of $Ab_{9.9}$. This point probably supports the loss of Na_2O by exsolution (perthites). Thus, one point obtained on the profile is identified as an typical albitic exsolution, as recognized by its very high Ab (94%) and absence of BaO (0%) (Table 2a, Analysis 44).

Plagioclase is major phase, though considerably less abundant than microcline or quartz (Table 1). Two varieties

Table 1
Representative modal proportions of metaluminous suites and the peraluminous Tuaní Granite unit

Igneous unit Sample	MME Average of five samples	ChG Average of 15 samples	ChPG Average of eight samples	AG Average of six samples	TG TUA-246 (a)	(b)	TG AMBI-61	TG MIL-4
Average total points	1140	1216	1251	1118	1034	1300	1000	800
Qtz	25.0	32.0	32.0	34.0	12.0	42.0	33.0	35.0
Kfs	–	7.0	15.0	28.0	2.3	23.0	14.0	15.0
Pl	31.0	36.0	35.0	25.0	3.0	7.0	5.0	9.0
Bt	14.0	15.0	13.0	7.0	19.0	13.0	14.0	17.0
Ms	–	–	–	5.0	6.0	8.0	8.0	6.0
Hbl	20.0	4.0	0.2	–	–	–	–	–
Ap	0.8	1.2	3.0	0.2	–	–	tr	–
Zrn	0.4	0.5	–	0.3	0.8	0.5	0.7	0.6
Aln	0.3	–	–	–	–	–	–	–
Ep	1.0	1.7	3.0	–	–	–	–	–
Opq	1.3	1.6	3.0	0.6	7.2	2.0	4.0	2.8
Ttn	1.0	1.0	1.0	–	–	–	–	–
Crd	–	–	–	–	32.0	3.0	20.0	9.0
Sil/Fibrolite	–	–	–	–	17.0	0.5	–	5.0
QAP ^a	Tonalite	Granodiorite	Granodiorite	Monzogranite	Quartz-rich granitoids			

Notes: Sample TUA-246 presents different modal proportion of cordierite and sillimanite/fibrolite in two thin sections (a and b). Quartz (Qtz), K-feldspar (Kfs), plagioclase (Pl), biotite (Bt), muscovite (Ms), hornblende (Hbl), apatite (Ap), zircon (Zrn), allanite (Aln), epidote (Ep), opaque (Opq), titanite (Ttn), cordierite (Crd), sillimanite (Sil), and tr: traces. Abbreviation are taken from Kretz (1983). MME: mafic microgranular enclaves, ChG: Chepes granodiorite, ChPG: Chepes porphyritic granodiorite, AG: Las Asperzas Granite, TG: Tuaní Granite. Data from Dahlquist (2000). – indicates the mineral was absent.

^a QAP diagram according to Streckeisen (1976).

are identified: coarse-grained ($2.8\text{--}1.3 \times 1.2\text{--}0.8$ mm) and fine-grained ($0.8\text{--}0.6 \times 0.5\text{--}0.3$ mm). The coarse-grained plagioclase forms euhedral rectangular crystals, with polysynthetic twinning and normal zonation (Fig. 5b). Fine-grained plagioclase is anhedral, generally with polysynthetic twinning, and can sometimes show normal zoning. Both plagioclase types are homogeneously distributed in the crystalline rock in similar proportions. Occasionally, the fine-grained plagioclase (against the quartz and biotite) can constitute inclusions in the microcline and shows slightly curved twinning (Fig. 5c). Coarse-grained plagioclase shows normal zoning with a slight An-rich core (Table 2a). The plagioclases mostly are Ca-oligoclase. The Ab contents of plagioclase in the migmatites is 81.4% (six analyses), higher than the plagioclase of the Tuaní Granite (average Ab content = 75.5%; seven analyses; Dahlquist, 2000).

4.1.2. Micas

Black and white micas are recognized in the granitoids of the Tuaní Granite. Black mica is tabular, mainly subhedral, and present as either coarse grains homogeneously distributed in the rock (Fig. 5a–c) or fine-grained inclusions in Crd or microcline (Fig. 5a, d, and e). In the Al^{IV} versus $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg})$ diagram, black micas are classified as biotites. However, biotites of the Tuaní Granite (Table 2b) show different compositions than those of the igneous metaluminous unit in the Sierra de Chepes. The former is richer in Al^{IV} than biotite housed in the igneous metaluminous units (Fig. 6b).

White mica is the other sheet silicate present. Care was taken to determine if white mica is primary or secondary in

origin, because the presence of primary white mica is widely held as an indicator of peraluminous magmas (Speer, 1984). Petrographic observations suggest that both types are present. Miller et al. (1981) describe petrographic characteristics for determining if white mica is primary or secondary, including (1) coarse grain size, comparable to other primary magmatic phases, (2) subhedral or euhedral form, (3) enclosure by any mineral from which the mica may have formed through alteration, and (4) presence in a rock with clean, unaltered, igneous texture. The chemically analyzed white micas fulfill these petrographic criteria and are considered primary (Fig. 5e). The analyzed white mica reveals a phengitic composition, in which increasing Si (probable substitution of Al^{IV} in the tetrahedral sites) is accompanied by increasing Mg and Fe^{2+} (probable substitution for Al^{VI} in the octahedral sites) (Fig. 6c). The compositions considered primary white mica (phengite) are projected in the Mg–Ti–Na diagram (Fig. 6d), according to the divide established by Miller et al. (1981). The textural and chemical evidence therefore indicates a primary origin for some phengite of the Tuaní Granite.

4.1.3. Cordierite

Cordierite is coarse grained ($1.2\text{ mm} \times 1.0\text{ mm}$ to $3.0\text{ mm} \times 1.5\text{ mm}$) and euhedral to subhedral (Fig. 5c–e), exhibits the typical alteration to pinnate, and contains zircon inclusions with pleochroic halos. Cordierite generally is poikilitic, with inclusions of opaque minerals, white mica, biotite, and zircon (Fig. 5d and e) but occasionally is free of inclusions (Fig. 5c). Cordierite of the Tuaní Granite shows a different composition from that of the metamorphic rocks; in the discrimination

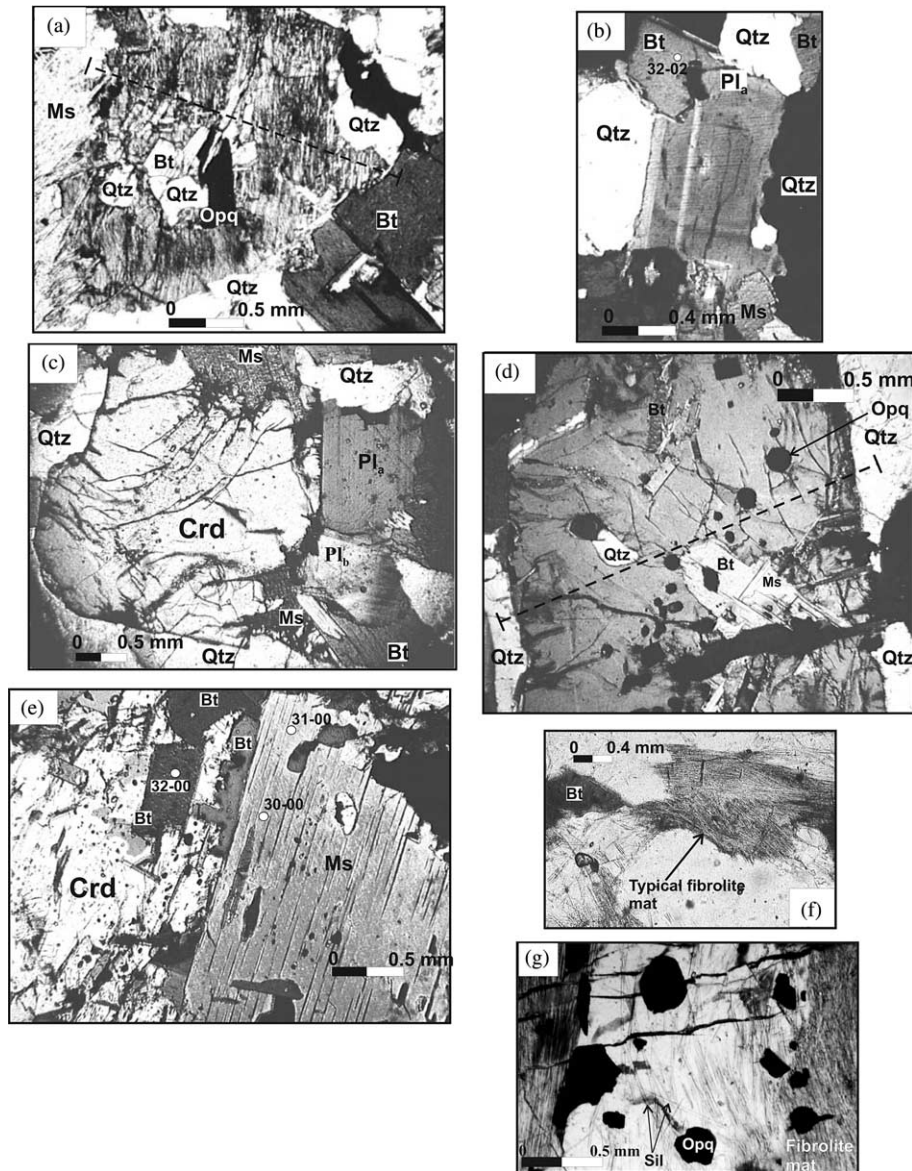


Fig. 5. Photomicrographs showing electron microprobe spot locations for analyzed minerals and textural relationships (see chemical analyses in Table 2). (a) Perthitic and poikilitic microcline with dashed line showing the path of the analyzed cross-section (see Table 2a, Fig. 6(a)). (b) Normal zonation in coarse-grained plagioclase. (c) Inclusion-free irregular shaped cordierite, euhedral crystal. Anhedral fine-grained plagioclase (lower crystal) showing the folded twinning. (d) Analyzed poikilitic and euhedral cordierite (dashed line shows analytical traverse; see Table 2c, Fig. 6 g). (e) Muscovite is considered primary. (a–e) Cross-polarized light photomicrographs. (f and g) Sillimanite prisms and mats of fibrolite needles. Plane-polarized light photomicrographs.

diagram of Pereira and Bea (1994), it plots in the field of magmatic cordierite, whereas the cordierite from the metamorphic rocks plots in the field of cordierite of solid-state growth (Fig. 6e). In addition, typical cordierite of the Tuaní Granite shows zoning in relation to an increase in X_{Mg} content (X_{Mg} = cations per formula unit) from the core to the rim of the crystal (Fig. 6f, Table 2c).

Cordierite with low MnO content is indicated by Deer et al. (1992) for metamorphic rocks, in contrast with cordierite from typical peraluminous cordierite-bearing granitoids (Secchi et al., 1991; Villaseca and Barbero, 1994) and associated pegmatite facies (Maillet and Clarke, 1985), in which the MnO

content reaches more than 1%. Similarly, high values of MnO are obtained for cordierite from the Tuaní Granite (Table 2c).

4.1.4. Oxide minerals

Eight analyses of oxide minerals (without secondary alteration) were obtained (Table 2e), revealing a complex composition without a straightforward interpretation. The dominant composition (five analyses) has a TiO_2 content varying between 11 and 22%, typical of titanomagnetites (Deer et al., 1992). Hematite (one analysis) and pseudobrookite composition (two analyses) are also observed (Table 2e). Total

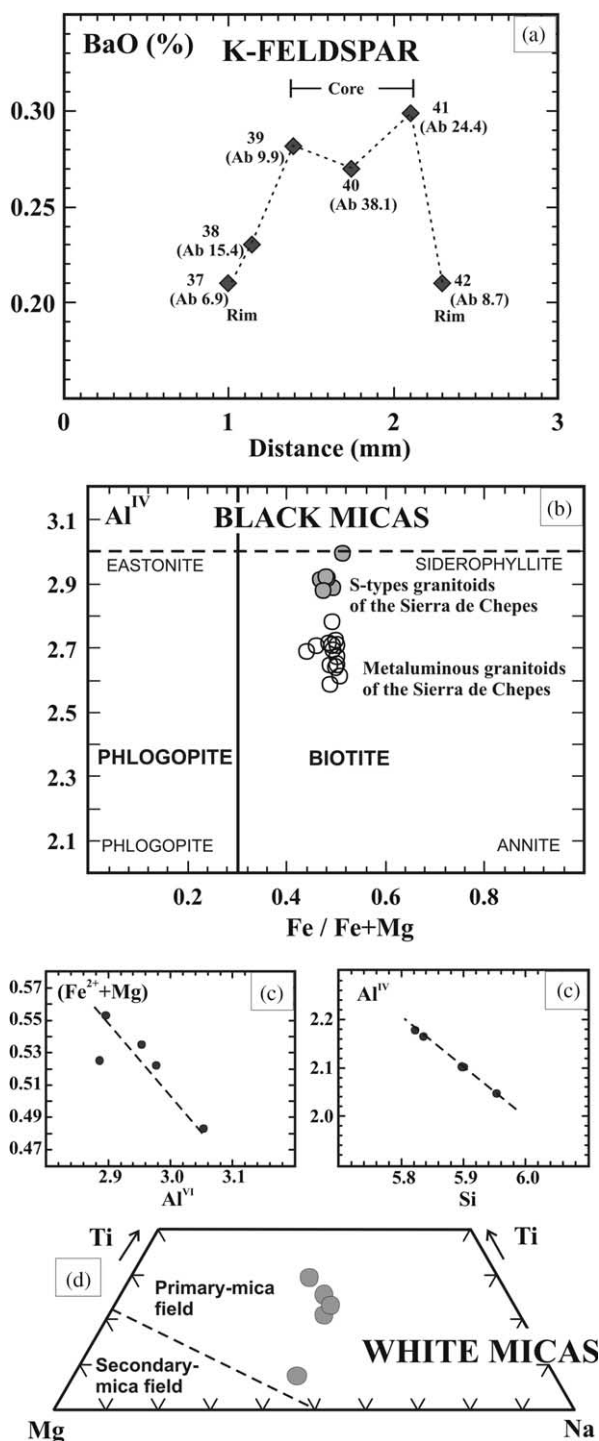


Fig. 6. (a) Compositional profile of BaO% in K-feldspar displays inverse zonation in the core. Location of electron microprobe compositional profile is shown in Fig. 5a. Number of analyses and Ab content indicated next to the analyses (data in Table 2a). (b) Classification diagram for black micas (Deer et al., 1966). Dashed line is the upper limit of the original diagram. Data from Dahlquist (2000) and Table 2c. (c) Diagrams illustrating the substitution for Si by Al^{IV} in tetrahedral sites accompanied by the substitution of Fe^{2+} plus Mg for Al^{VI} in octahedral sites in white mica. (d) Projected composition of white micas in the triangular Mg–Ti–Na diagram. The limit of fields between secondary and primary micas according to Miller et al. (1981). Data in Table 2b. Other white mica compositions from Dahlquist (2000). (e) Classification diagram for cordierite modified from Pereira and Bea (1994). The composition of cordierite in metamorphic and magmatic rocks from Dahlquist (2000) and Table 2c. (f) Compositional profile of X_{Mg} in cordierite displays increasing X_{Mg} toward the rims. Cordierite shown in Fig. 5d. Indicated analyses numbers in Table 2c. (g) Hypothetical formation of titanomaghemites from primary titanomagnetites by nonequilibrium oxidation (system $FeO-Fe_2O_3-TiO_2$ modified after Waychunas, 1991). Oxidation takes place along constant Fe/Ti lines (horizontal in the figure), which demonstrates that the titanomaghemites are formed by oxygen fugacity increases, not the removal of Fe. The formation of the titanomaghemites occurs in low-T (below 600 °C) and low-P conditions. Data in Table 2e. (h) Backscattered electron image of iron–titanium oxide showing titanomaghemite-bearing assemblage with (rutile–pseudobrookite) ss (sample TUA-246). Dashed line indicates the composition change.

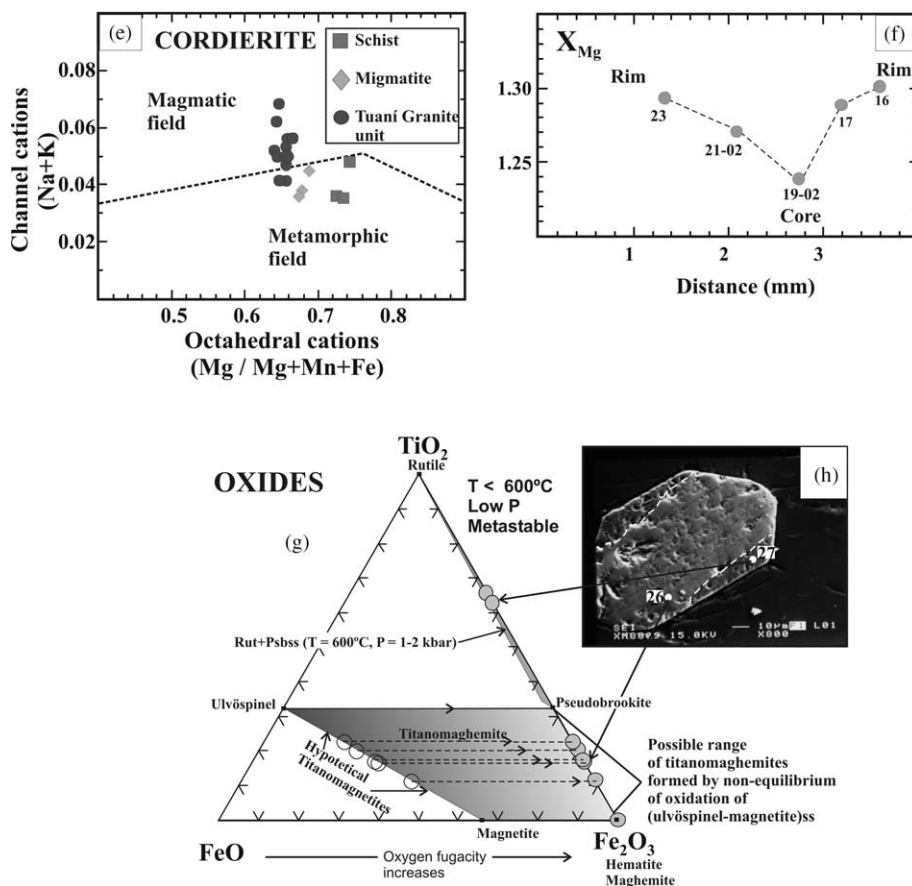


Fig. 6 (continued)

iron is expressed as Fe_2O_3 and results in an acceptable total summation of each analysis, which indicates that the rocks of the Tuaní Granite are highly oxidized. Most of the analyses plot on the TiO_2 – Fe_2O_3 axis in Fig. 6 g and h, which defines a titanomagnetite composition.

4.1.5. Other minerals

Some samples of the Tuaní Granite contain mats of sillimanite and fibrolite (especially the migmatite of Sierra de Chepes), strongly suggesting that these minerals are refractory residues (restites) or xenocrysts. Chemical analyses of sillimanite reveal higher FeO contents (1.06–1.48%), which could extend its stability and explain its persistence in the melt.

Sillimanite occurs as individual prisms, whereas fibrolite shows a typical acicular habit (cf. Kerrick, 1990) (Fig. 5f and g). Tourmaline is occasionally observed in Tuaní Granite rocks as irregular subhedral crystal, with pleochroism that varies from green-olive to green-blue. Grain size varies from medium- to fine-grained (0.4×0.3 mm and 0.2×0.1 mm).

Zircon in the Tuaní Granite has been studied in detail by Rapela et al. (1999) and Pankhurst et al. (2000). This mineral shows magmatic overgrowths on older detrital cores.

Finally, very small grains of apatite are occasionally revealed by electron microprobe analysis, found to be

fluorine-rich apatite ($CaO=54.19\%$, $P_2O_5=40.50\%$, $F=2.44\%$) with high MnO contents (1.24%).

4.2. Whole-rock geochemistry of the Tuaní Granite unit

4.2.1. Major elements

The Tuaní Granite has a very high alumina saturation index (1.68–1.95; Table 3), in accordance with its strongly peraluminous mineralogy. Thus, according to Chappell and White (1992), the granitic rocks of the Tuaní Granite are typical S-type granitoids (alumina saturation index > 1.1).

The Tuaní Granite and metamorphic rocks plot outside the metaluminous main trend (as is evident in the relationship of CaO to SiO_2) and display a clearly distinct geochemistry. In contrast, metaluminous monzogranites in Sierra de Chepes (Las Asperzas Granite) plot in the evolved part of the metaluminous main trend (Fig. 7, Table 3; Pankhurst et al., 1998; Dahlquist, 2000). Remarkably, the concentrations of some major elements, such as TiO_2 , FeO' , and MgO , are enriched more in the Tuaní Granite than any typical metaluminous monzogranites in Sierra de Chepes (Fig. 7). Las Asperzas Granite unit is interpreted as the final product of differentiation of the metaluminous suite (Pankhurst et al., 1998; Dahlquist,

Table 2a
Representative compositions of feldspar

Igneous unit	TG	TG	TG	TG	TG	TG	TG
Sample	TUA-49	TUA-49	TUA-49	TUA-49	TUA-246	TUA-246	TUA-49
Analysis number	37	41	42	44	38	37	50
Mineral (wt%)	Kfs-rim	Kfs-core	Kfs-rim	Perthite on Kfs	Pl-core	Pl-rim	Pl-late rim
SiO ₂	64.50	64.51	64.01	85.02	61.43	62.01	63.39
TiO ₂	0.07	0.04	0.01	0.03	bdl	0.01	bdl
Al ₂ O ₃	18.10	18.38	18.19	9.51	24.17	24.32	22.55
FeO	0.09	0.04	bdl	0.10	0.02	0.03	0.06
MnO	bdl	bdl	bdl	0.06	0.03	0.01	0.04
MgO	bdl	bdl	0.03	bdl	0.02	bdl	bdl
BaO	0.21	0.30	0.21	bdl	0.01	bdl	bdl
CaO	0.01	0.05	0.01	0.60	5.33	5.15	4.27
Na ₂ O	0.78	2.82	1.00	5.76	8.76	8.80	9.52
K ₂ O	16.01	13.23	15.94	0.03	0.26	0.34	0.26
Total	99.77	99.37	99.40	101.11	100.03	100.67	100.09
<i>Structural formulae calculated on basis of 32 O</i>							
Si	11.98	11.94	11.95	14.08	10.90	10.92	11.23
Al	3.96	4.01	4.00	1.85	5.05	5.04	4.70
Ti	0.01	0.01	0.00	0.00	0.00	0.00	0.00
Fe ²⁺	0.01	0.01	0.00	0.01	0.00	0.00	0.01
Mn	0.00	0.00	0.00	0.01	0.01	0.00	0.01
Mg	0.00	0.00	0.01	0.00	0.01	0.00	0.00
Ba	0.02	0.02	0.02	0.00	0.00	0.00	0.00
Ca	0.00	0.01	0.00	0.11	1.01	0.97	0.81
Na	0.28	1.01	0.36	1.85	3.01	3.00	3.27
K	3.79	3.12	3.80	0.01	0.06	0.08	0.06
Ab	6.9	24.4	8.7	94.3	73.8	74.1	79.0
An	0.0	0.3	0.0	5.4	24.8	24.0	19.6
Or	93.1	75.3	91.3	0.3	1.4	1.9	1.4

Notes: Total iron measured as FeO. Structural formulae calculated from Richard (1995). Cross-section of K-feldspar grain in Fig. 5a. bdl: below detection limit, na: not analyzed. Kfs data from Dahlquist (2000).

2000), but it is difficult to envisage crystallization of the Tuaní Granite unit as a differentiation product of the metaluminous parent magmas. The lower limit of SiO₂ in the Tuaní Granite rock may be similar to, but never less than, that observed in the SiO₂-rich metapelitic rocks (Fig. 7). Finally, the whole-rock analyses reveal high MnO contents in both the metapelitic rocks and the Tuaní Granite rocks (Fig. 7).

The relationships between chemical composition and mafic mineralogy for common metaluminous and peraluminous granitoids may be shown in a triangular diagram in which the molar proportions of A ($A = \text{Al}_2\text{O}_3 - [\text{Na}_2\text{O} + \text{K}_2\text{O}]$), C ($C = [\text{CaO} - 0.0232 \times \text{P}_2\text{O}_5]$), corrected for apatite), and F ($F = \text{FeO} + \text{MgO}$) are plotted at the apices (Fig. 8a). The monzogranites and aplites continue the trend defined by the rocks of the metaluminous suite, showing a continuous and progressive decrease in F with enrichments in A and C for some samples. This trend reflects the removal of mafic minerals (hornblende and biotite) by fractional crystallization (Dahlquist, 2002). The Tuaní Granite plot outside the metaluminous main trend, showing a composition similar to that of the Cooma granodiorite (Fig. 8a), a classical S-type granitoid of the Lachlan fold belt of SE Australia that is enriched in A and F and poor in

C (A and F are manifested mainly in the growth of cordierite, which are absent in the monzogranites of Las Asperzas Granite unit and aplites).

Villaseca et al. (1998) demonstrate that the complex diversity of peraluminous magmatism may be best classified by the use of Debon and Le Fort's (1983) multicationic plot. In this diagram (Fig. 8b), the granitoids of the Tuaní Granite are clearly peraluminous and follow a trend of increasing peraluminosity with the mafic index (due to the crystallization of cordierite, biotite, and phengite), which approaches a trajectory similar to that of the Cooma granodiorite (Fig. 8b). The increasing peraluminosity in the more mafic compositions (Fig. 8b) is a typical S-type granite trend (White and Chappell, 1988).

Granitoids located in the *h-p* field, which defines a positive trend in the A–B diagram (Fig. 8b), are characterized by aluminous mineral phases other than biotite, usually the most abundant mafic phase. Cordierite and garnet are the most typical aluminous phases, but it is not unusual to find accessory sillimanite (Villaseca et al., 1998). In contrast, the intermediate to acidic metaluminous suites of Sierra de Chepes are located in the I-type granitoids field of the A–B diagram (Fig. 8b), thus defining a typical trend for metaluminous I-type suites (Villaseca et al., 1998).

Table 2b
Representative compositions of micas

Igneous unit	TG	TG	TG	TG	TG	TG
Sample	TUA-49	TUA-246	TUA-246	TUA-246	TUA-246	TUA-49
Analysis number	36	32-00	32-02	30-00	31-00	33
Mineral (wt%)	Bt	Bt	Bt	Phg	Phg	Phg
SiO ₂	35.15	35.59	34.68	44.84	45.10	45.96
TiO ₂	2.48	2.49	2.42	1.09	0.86	0.24
Al ₂ O ₃	19.54	19.99	19.67	33.17	33.58	32.93
Cr ₂ O ₃	bdl	0.05	0.02	0.02	bdl	bdl
FeO	16.77	17.12	16.64	3.74	3.54	3.38
MnO	0.49	0.58	0.56	0.06	bdl	0.08
MgO	10.45	9.80	10.11	0.76	0.79	0.81
BaO	na	0.02	na	0.02	0.01	bdl
CaO	0.01	0.02	0.03	bdl	0.01	bdl
Na ₂ O	0.23	0.22	0.17	0.65	0.67	0.54
K ₂ O	8.25	9.52	9.00	10.54	10.31	10.92
NiO	0.04	0.05	0.06	na	na	na
F	0.18	0.10	0.37	0.06	0.04	na
Cl	bdl	0.01	bdl	0.013	0.01	na
–O=F+Cl	0.00	0.11	0.00	0.03	0.00	–
Total	93.60	95.45	93.73	94.93	94.92	94.86
<i>Structural formulae calculated on the basis of 22 O and 2 OH</i>						
Si	5.12	5.12	5.08	5.82	5.84	5.95
Al ^{IV}	2.88	2.89	2.92	2.18	2.16	2.05
Sum T	8.00	8.00	8.00	8.00	8.00	8.00
Al ^{VI}	0.47	0.50	0.14	2.90	2.95	2.98
Ti	0.27	0.27	0.31	0.12	0.08	0.02
Fe	2.04	2.06	2.23	0.41	0.38	0.37
Cr	0.00	0.01	0.00	0.00	0.00	0.00
Mn	0.06	0.07	0.08	0.01	0.00	0.01
Mg	2.27	2.10	2.41	0.15	0.15	0.16
Sum VI	5.11	5.01	5.17	3.59	3.56	3.54
Ba	na	0.00	na	0.00	0.00	na
Ca	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.07	0.06	0.05	0.16	0.17	0.14
K	1.53	1.75	1.74	1.75	1.70	1.81
Sum A	1.60	1.81	1.79	1.91	1.87	1.95
F	0.17	0.21	0.35	0.049	0.01	–
Cl	0.00	0.02	0.00	0.006	0.00	–
Fe/(Fe+Mg)	0.47	0.50	0.48	0.73	0.71	0.70

Notes: Total iron measured as FeO. Structural formulae calculated from Richard (1995). bdl: below detection limit, na: not analyzed, Phg: phengite.

4.2.2. Trace elements and REE

Trace elements and REE were studied to establish the relationship of the Tuaní Granite and associated metamorphic rocks. Cs, Rb, Sr, and Ba are more concentrated in metamorphic rocks than in the Tuaní Granite, whereas Zr is more strongly concentrated in the latter (Table 3). U, Th, Y, Nb, Hf, Ta, Ga, and Cr have similar concentration in the Tuaní Granite and metamorphic rocks.

The chondrite-normalized REE patterns for the Tuaní Granite (average of data in Table 3; Fig. 9) are characterized by relatively high REE (LREE 18–150 times chondritic; HREE 15–26 times chondritic). All bodies of the Tuaní Granite display pronounced and distinctive negative Eu anomalies (Fig. 9), and the REE patterns are almost indistinguishable from those of the metamorphic rocks, with only slight differences (Fig. 10). The LREE pattern (up to Eu and Gd) of the Tuaní Granite

is very similar those of hypothetical primary undifferentiated melts in the Turku area of Finland (Johannes et al., 2003), though it differs remarkably from Tb onward (Fig. 9). According to Johannes et al. (2003), the small-scale granite bodies of Turku were differentiated from a hypothetical primary melt derived from migmatites, and the migmatite leucosome corresponds to a segregated cumulate (Fig. 9).

5. Emplacement temperature of the Tuaní Granite unit

In this work, the Na-in-cordierite thermometer of Mirwald (1986) [$T(\pm 30\text{ }^{\circ}\text{C}) = -2744.8 \times X_{\text{Na}} + 897.4$, with X_{Na} = cations per formula unit] was used to obtain preliminary estimates of the temperature of crystallization of the Tuaní Granite from 15 analyses. Calculated temperatures, as given in Table 2c, yield a mean value of 755 °C, consistent with the

Table 2c
Representative and average compositions of magmatic cordierite from different samples

Igneous unit Sample	TG TUA-246	TG TUA-246	TG TUA-246	TG TUA-246	TG TUA-246	TG TUA-49	TG Average from 15 analyses
Analysis number	23	21-02	19-02	17	16	31	
Mineral (wt%)	Crd-rim	Crd	Crd-core	Crd	Crd-rim	Crd-core	Crd
SiO ₂	47.65	48.02	47.62	47.07	48.18	48.82	48.18
TiO ₂	bdl	bdl	bdl	bdl	bdl	bdl	0.01
Al ₂ O ₃	33.00	33.03	32.94	32.52	33.33	31.58	32.77
FeO	6.40	6.81	6.29	6.39	6.81	6.81	6.54
MnO	1.25	1.09	1.37	1.12	1.03	2.06	1.57
Cr ₂ O ₃	bdl	0.02	0.02	0.02	bdl	na	0.01
NiO	0.01	0.13	bdl	0.02	0.07	na	0.00
MgO	8.26	8.19	7.90	8.13	8.46	8.87	8.52
ZnO	bdl	0.01	0.04	bdl	0.10	na	0.00
CaO	0.04	0.02	0.10	0.32	0.02	0.02	0.05
Na ₂ O	0.26	0.20	0.32	0.27	0.24	0.26	0.26
K ₂ O	0.01	bdl	0.03	bdl	bdl	bdl	0.00
Total	96.88	97.52	96.63	95.87	98.28	98.42	97.92
<i>Structural formulae calculated on the basis of 18 O</i>							
Si	4.98	5.00	5.01	4.99	4.97	5.04	4.99
Al ^{IV}	1.02	1.01	0.99	1.01	1.03	0.96	1.01
Sum T	6.00	6.01	6.00	6.00	6.00	6.00	6.00
Al ^{VI}	3.04	3.04	3.09	3.05	3.02	2.88	2.99
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺	0.56	0.59	0.55	0.57	0.59	0.59	0.57
Mn	0.11	0.10	0.12	0.10	0.09	0.18	0.14
Mg	1.29	1.27	1.24	1.29	1.30	1.36	1.32
Sum (VI)	5.00	5.00	5.00	5.01	5.00	5.01	5.02
Ca	0.01	0.00	0.01	0.04	0.00	0.00	0.01
Na	0.05	0.04	0.06	0.06	0.05	0.05	0.05
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum A	0.06	0.04	0.07	0.06	0.05	0.05	0.06
Mg/(Mg + Mn + Fe ²⁺)	0.66	0.65	0.65	0.66	0.66	0.64	0.65
Cat. Hexag. (A)	0.05	0.04	0.07	0.06	0.05	0.05	0.06
T (°C) ^{Na}							755

Notes: Total iron measured as FeO. Structural formulae calculated from Richard (1995). T (°C)^{Na} is calculated temperatures from Na-in-cordierite thermometer (Mirwald, 1986). Errors for the Na-in-cordierite temperatures in the high-temperature range are between ± 18 and ± 30 °C (Kalt et al., 1998). Cross-section of cordierite grain (TUA-246) in Fig. 5d. bdl: below detection limit.

emplacement of parental peraluminous magmas in the upper crust.

6. Discussion

6.1. Interpretation of the petrographic and chemical mineral data

Mineral chemistry strongly suggests a magmatic origin for the analyzed minerals. The chemical profile in Fig. 6a indicates crystallization directly from a melt (Long and Luth, 1986; Dahlquist, 1998). In addition, the Ab content of alkali feldspars is a function of the temperature of crystallization; those alkaline feldspars that crystallized at higher temperatures have the highest Ab contents (Stormer, 1975; Whitney and Stormer, 1977). In this way, the chemical profile in Fig. 6a strongly suggests progressive crystallization of the microcline, together with cooling of the peraluminous magma.

In general, the core compositions of coarse-grained plagioclase and microcline in the Tuaní Granite (Table 2a) are similar to those obtained for coexisting feldspars in crystallization experiments of two-mica leucogranites at a fixed temperature of 749 °C (Ab_{70–74} for plagioclase, Ab_{27–44} for alkali feldspar; Scaillet et al., 1995). Thus, the experimental data suggest that at least the core areas of feldspars were in high-T equilibrium.

The biotite composition establishes that it is a primary igneous mineral in equilibrium with a peraluminous magma. Biotite in the Tuaní Granite is richer in Al^{IV} than that in the metaluminous units (Fig. 6b). This difference may depend on the crystallizing mineral association (Albuquerque, 1973; Speer, 1984; Clarke et al., 2005). Biotite in the metaluminous unit has an Al^{IV} composition similar to that of biotite in equilibrium with hornblende (Albuquerque, 1973), whereas biotite in the Tuaní Granite shows a composition akin to biotite in equilibrium with cordierite in the Cloud Creek pluton, South

Table 2d
Representative compositions of metamorphic cordierite

Igneous unit	TG	TG	TG
Sample	Ma-47	Ma-47	Ma-47
Analysis number	19	20	21
Mineral (wt%)	Crd	Crd	Crd
SiO ₂	49.13	49.46	49.39
TiO ₂	bdl	bdl	0.04
Al ₂ O ₃	32.53	32.24	32.93
FeO	7.19	7.37	6.93
MnO	0.87	0.76	0.82
MgO	9.52	9.42	9.56
CaO	0.01	0.18	0.23
Na ₂ O	0.19	0.18	0.22
K ₂ O	bdl	0.02	0.01
Total	99.43	99.47	99.91
<i>Structural formulae calculated on the basis of 18 O</i>			
Si	5.00	5.03	4.99
Al ^{IV}	1.00	0.97	1.01
Sum T	6.00	6.00	6.00
Al ^{VI}	2.90	2.89	2.91
Ti	0.00	0.00	0.00
Fe ²⁺	0.61	0.63	0.59
Mn	0.08	0.07	0.07
Mg	1.44	1.43	1.44
Sum (VI)	5.03	5.02	5.01
Ca	0.00	0.00	0.00
Na	0.04	0.04	0.04
K	0.00	0.00	0.00
Sum A	0.04	0.04	0.04
Mg/(Mg + Mn + Fe ²⁺)	0.68	0.67	0.69
Cat. Hexag. (A)	0.04	0.04	0.05

Notes: Total iron measured as FeO. Structural formulae calculated from Richard (1995). bdl: below detection limit.

Carolina (Speer, 1984); with muscovite in the Al-rich granitoids of the Aregos region, Portugal (Albuquerque, 1973); and with andalusite in peraluminous felsic rocks (Clarke et al., 2005). Thus, biotite in the Tuaní Granite has compositions typical of equilibrium crystallization from a peraluminous magma.

The textural and chemical evidence indicates a primary origin for some phengite of the Tuaní Granite (Figs. 5e and 6d). The generally accepted intersection of the granite solidus curve with the experimental curves for the reaction $Ms + Qtz = Kfs + Al\text{-silicates} + H_2O$ (Fig. 3) suggests a depth of crystallization for muscovite housed in granitic magmas of at least 10–14 km at approximately 3–4 kb, which contradicts the evidence of late magmatic muscovite in many shallow-level (~1–2 kb) intrusions (Zen, 1988). D'Amico et al. (1981) affirm that the natural applicability of the muscovite-out reaction in peraluminous granitoids must be reexamined and that the muscovite field can be extended toward lower pressures and higher temperatures. A similar interpretation was proposed by Miller et al. (1981) and Anderson and Rowley (1981), who suggest that the discrepancy between the experimental data and the natural observations may be caused by the deviation of the natural muscovite (e.g. celadonitic content) composition from the ideal. D'Amico et al. (1981) propose, on the basis of petrographic and geologic data, an empirical extension of the muscovite stability field in water-undersaturated peraluminous granitic melts. This extended muscovite stability field would allow muscovite crystallization at low pressure (<3 kb) and higher temperatures (>700 °C). Similarly, Miller et al. (1981) suggest that muscovite can crystallize from magmas at relatively shallow depths (<10 km). The analyzed samples reveal distinctive Fe-rich white micas similar to those reported

Table 2e
Representative compositions of oxides

Igneous unit	TG	TG	TG	TG	TG	TG	TG	TG
Sample	TUA-246	TUA-246	TUA-246	TUA-246	TUA-246	TUA-246	TUA-246	TUA-246
Analysis number	11	12	15	26	36-02	13	14	27
Mineral (wt%)	Titanomag-hemite	Titanomag-hemite	Titanomag-hemite	Titanomag-hemite	Titanomag-hemite	Hematite	(Rut + Psb)ss	(Rut + Psb)ss
SiO ₂	0.08	0.04	0.03	0.02	0.02	0.07	1.46	2.89
TiO ₂	19.52	11.08	22.42	16.54	16.59	bdl	61.43	51.60
Al ₂ O ₃	0.16	0.11	0.08	0.12	0.17	0.13	0.90	1.35
Cr ₂ O ₃	0.05	0.15	bdl	0.21	0.16	0.31	bdl	0.09
Fe ₂ O ₃ ^a	76.19	86.53	76.13	80.50	79.08	99.11	32.04	30.32
MnO	1.45	0.17	0.04	0.38	0.60	0.10	0.56	6.71
NiO	bdl	0.05	0.14	0.02	0.02	0.03	bdl	0.10
MgO	0.14	0.04	0.02	0.04	0.10	0.02	0.20	1.58
ZnO	bdl	0.10	0.03	0.01	bdl	bdl	bdl	0.06
CaO	0.13	0.04	0.06	0.03	0.02	0.04	0.27	0.12
Na ₂ O	0.04	0.11	0.03	0.06	0.39	bdl	0.06	0.04
K ₂ O	bdl	bdl	bdl	bdl	0.01	bdl	0.05	0.04
P ₂ O ₅	0.03	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Total	97.79	98.42	98.97	97.92	97.16	99.80	96.95	94.90

Notes: bdl: below detection limit, na: not analyzed, Psb: pseudobrookite, ss: solid solution.

^a Total iron measured as FeO and expressed as Fe₂O₃.

Table 3
Major and trace element concentrations in peraluminous igneous and metamorphic rocks studied

Analyzed rocks	Tuaní granite					Metamorphic rocks		
Sample	TUA-246	ROD-16	MIL-4	AMBI-31	ELE-209 Bt zone	RLC-231 Crd zone	TUA-48 And + Kfs zone	GAR-33 psammite
(wt%)								
SiO ₂	67.38	73.64	67.58	64.24	60.10	60.05	62.60	84.55
TiO ₂	0.80	0.60	0.85	0.80	0.90	0.88	0.93	0.32
Al ₂ O ₃	15.47	12.71	15.05	16.05	18.71	19.66	16.8	6.86
Fe ₂ O ₃	2.34	2.06	3.25	2.73	4.24	2.57	4.55	1.57*
FeO	3.16	1.84	2.38	3.39	3.42	4.00	2.61	na
MnO	0.29	0.10	0.17	0.25	0.10	0.25	0.14	0.02
MgO	2.32	1.41	2.34	2.90	2.81	2.72	2.40	0.43
CaO	1.11	0.88	1.10	0.81	0.77	0.56	0.60	0.29
Na ₂ O	2.04	1.68	2.00	1.98	1.74	1.41	1.85	1.15
K ₂ O	3.79	3.56	3.82	3.56	4.22	5.20	4.08	2.40
P ₂ O ₅	0.12	0.14	0.03	0.14	0.17	0.12	0.17	0.08
H ₂ O +	1.22	0.85	1.20	1.48	2.87	2.74	1.20	na
H ₂ O –	0.33	0.18	0.33	0.35	0.18	0.20	0.23	na
LOI	na	na	na	na	na	na	Na	0.57
Total	100.37	99.65	100.10	98.68	100.23	100.36	98.16	98.24
(ppm)								
Cs	4.1	6.1	6.7	8.9	5.3	11.6	5.0	2.56
Rb	125	134	131	169	161	217	138	92
Sr	139	105	118	128	118	101	132	62
Ba	396	471	473	490	599	491	588	302
La	38.5	41.1	63.0	53.3	45.7	42.4	62.6	27.4
Ce	82.0	84.5	119.0	105.0	93.0	90.0	115.0	63.4
Pr	na	9.04	14.19	11.74	na	na	12.98	5.12
Nd	33.0	34.1	52.6	44.2	40	38.0	48.3	22.2
Sm	6.7	6.9	10.4	8.6	7.5	7.2	9.3	4.84
Eu	1.27	1.14	1.61	1.48	1.41	1.24	1.59	0.91
Gd	na	5.34	8.55	6.6	na	na	7.19	4.15
Tb	1.10	1.03	1.59	1.20	1.41	1.00	1.26	0.71
Dy	na	5.82	8.87	6.73	na	na	7.05	4.11
Ho	na	1.20	1.82	1.38	na	na	1.37	0.77
Er	na	3.59	5.51	4.09	na	na	4.08	2.45
Tm	na	0.55	0.85	0.62	na	na	0.60	0.41
Yb	4.23	3.65	5.61	3.92	3.42	3.62	3.84	2.35
Lu	0.64	0.55	0.77	0.59	0.51	0.65	0.57	0.38
U	2.60	3.03	5.00	3.63	2.5	2.40	2.22	3.08
Th	13.8	13.9	21.5	16.8	14.6	17.6	17.9	13.58
Y	39	35	51	38	41	40	41	21
Nb	15.0	34.1	19.0	20.0	13	15.0	20.0	9.0
Zr	219	255	269	210	192	171	203	265
Hf	5.4	7.3	8.0	6.0	43	4.6	5.7	7.9
Ta	1.40	4.26	3.18	3.77	19	1.50	2.03	0.81
Ga	18	16	21	22	25	26	25	bdl
Cr	75.7	43.0	112.0	79.0	79.4	85.9	89.0	60.6
ASI	1.68	1.61	1.61	1.95	nc	nc	nc	nc

Notes: Total Fe as Fe₂O₃. Samples TUA-246, ELE-209, and RLC-231 by XRF on fusion pellets (major elements), INAA (REEs and trace elements plus Cr); Y, Nb, Zr, and Ga by XRF, all at ACTLABS (Canada). Rb and Sr were determined by X-ray fluorescence on pressed powers at NIGL, Keyworth, UK. Samples AMBI-61, ROD-16, MIL-4, and TUA-48 analyzed by ICP and ICP-MS. Fe²⁺ determined volumetrically, all at Centro de Investigaciones Geológicas, La Plata (Argentina). ASI: alumina saturation index, LOI: loss on ignition, nc: not calculated, na: not analyzed. All data from Dahlquist (2000).

by Clarke et al. (2005) as white micas coexisting with aluminous minerals.

In agreement with Clarke (1995), the textural characteristics of cordierite in the Tuaní Granite (euhedral, grain size compatibility with host rock, few inclusions) indicate that they have a magmatic cotectic origin. Changes in the

composition of cordierite (in the absence of garnet) have been experimentally evaluated by Holtz and Johannes (1991), who observe that magmatic cordierite is usually zoned, with increasing Mg from the core to the margin of the crystal. The rims of cordierite become slightly richer in Mg with increasing temperatures (constant pressure and melt fractions). A similar

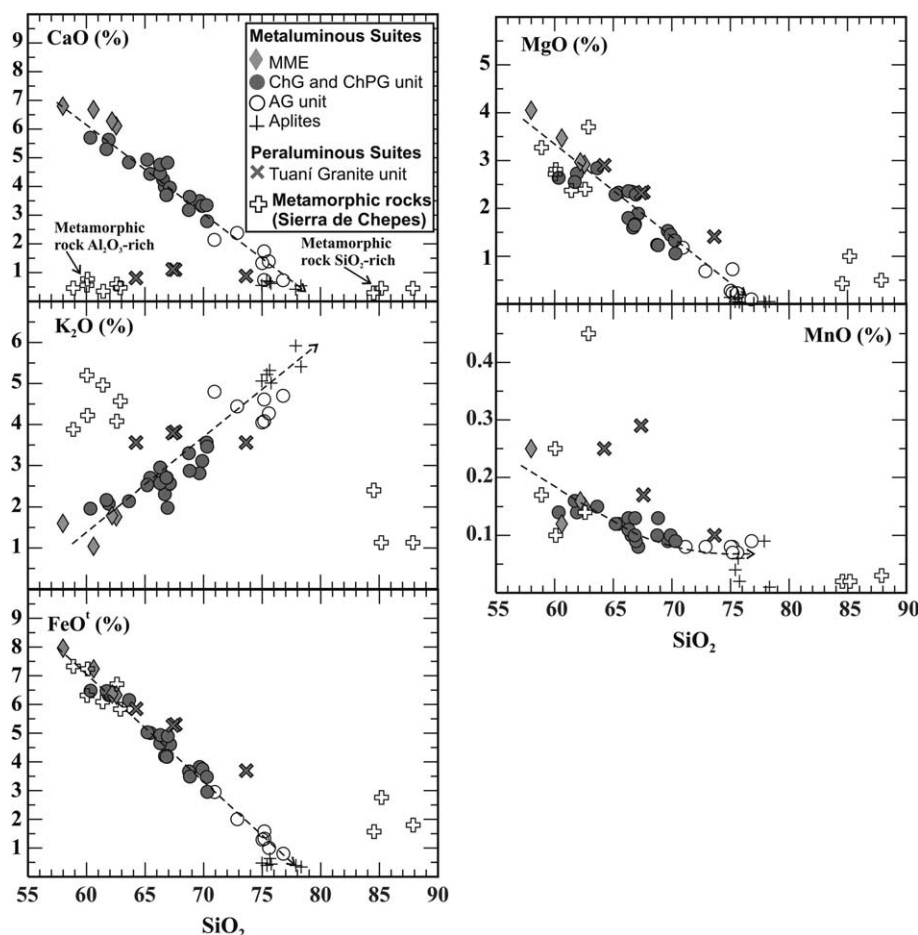


Fig. 7. Harker variation diagrams for granitic units of Sierra de Chepes showing the main trend defined by metaluminous units (Pankhurst et al., 1998; Dahlquist, 2000). The Tuaní Granite data systematically plot in an intermediate position between Al_2O_3 - and SiO_2 -rich metamorphic rocks and outside the metaluminous main trend. MME: mafic microgranular enclaves, ChG: Chepes granodiorite, ChPG: Chepes porphyritic granodiorite, AG: Las Asperiza Granite. Broken arrow: main trend of the metaluminous suite. Representative samples of psammitic rocks in Table 3. More data of psammitic rocks reported by Pascua (1998).

increase in Mg in the rim of the cordierite is also observed with increasing melt fractions (constant pressure and temperature but variable H_2O). Cordierites of the Tuaní Granite show zoning with an increase in X_{Mg} from the core to the rim of the crystal (Fig. 6f), strongly suggesting a magmatic origin.

The high MnO content of cordierite from the Tuaní Granite (Table 2c) suggests that it is magmatic in origin (see Section 4.1.3). However, the whole-rock analyses reveal high MnO contents in both the metapelitic rocks and the rocks of the Tuaní Granite (Fig. 7), which suggests the Tuaní Granite unit may have 'inherited' the high MnO content from the melting of a metasedimentary sequence and could explain the low MnO contents (0.08–0.34%) from other cordierites of supposed magmatic origin (e.g. Schreyer et al., 1990; Pereira and Bea, 1994; Barbey et al., 1999). Therefore, the MnO content in cordierites probably depends on the bulk rock composition. Analytical totals of metamorphic cordierites are near 100% (Table 2d), which suggests these cordierites do not contain fluid phases such as H_2O or CO_2 in their channels. In contrast, the total analyses of cordierites housed in the Tuaní Granite are approximately 98%, which indicates they do contain such fluid phases.

Titanomaghemite has been defined by Lindsley (1976) as any Fe–Ti spinel lying off the Fe_3O_4 – Fe_2TiO_4 joint, that is, magnetite-ulvöspinel solutions with an additional component of Fe_2O_3 or FeTiO_3 , which makes them cation-deficient, nonstoichiometric spinels. These spinels are usually formed by the oxidation of precursor titanomagnetites (Waychunas, 1991). The oxygen fugacity increases from left to right in Fig. 6g, and the hypothetical primary mineral phases (titanomagnetite) lose FeO and gain Fe_2O_3 , which produces the titanomaghemite composition (Table 2e, Fig. 6g). The texture of oxide minerals, as analyzed by electron microprobe (Fig. 6g and h), shows that the rutile-pseudobrookite_{solid solution} (Analysis 27, Table 2e) domain occurs at the rim of titanomaghemite grains, in support of a late exsolution process (Lindsley, 1991).

Mats of fibrolite/sillimanite needles found in the Tuaní Granite (Fig. 5f and g) are interpreted as a relic from the migmatitic source rock. Chemical analysis of fibrolite/sillimanite in the migmatitic rocks reveals higher FeO (wt%) content (1.06–1.48) ($\text{SiO}_2=36.56$ – 37.27% , $\text{Al}_2\text{O}_3=61.89$ – 62.38%), thus showing a discrepancy between the ideal formulae and natural sillimanite. Miller et al. (1981) and Zen

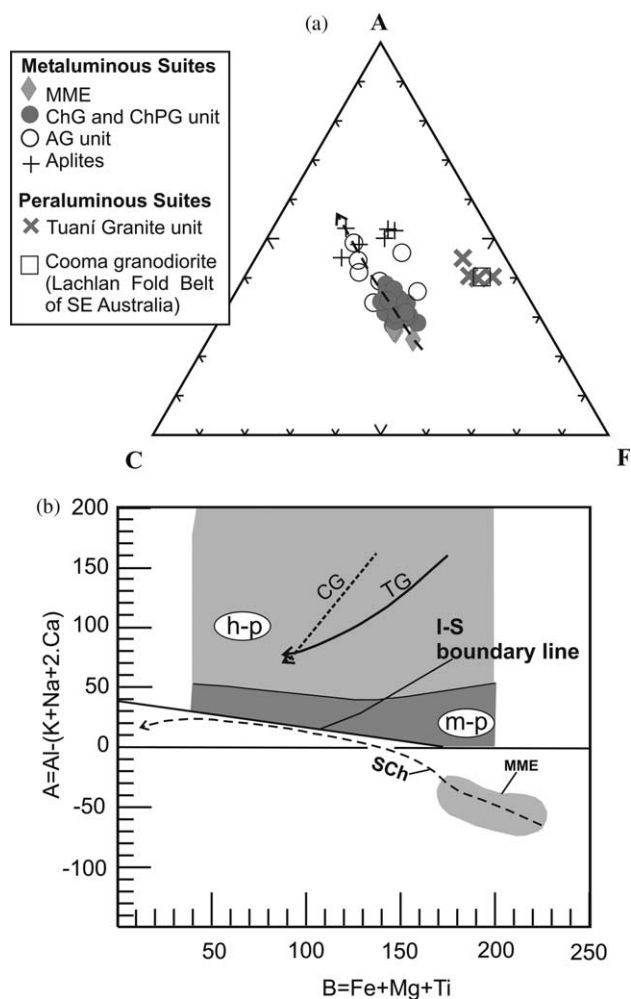


Fig. 8. (a) Granitoids plotted in terms of A ($A = [Al_2O_3 - (Na_2O - K_2O)]$), C ($C = [Ca - (P_2O_5 \times 0.0232)]$), and F ($F = FeO' + MgO$) showing the difference in chemical composition between hornblende and biotite granitoids (metaluminous suite) and cordierite-bearing granitoids (peraluminous suite). Broken arrow marks the main trend defined for the metaluminous suite of Sierra de Chepes (Table 3; Pankhurst et al., 1998; Dahlquist, 2000). $FeO' = Fe_2O_3 \times 0.899 + FeO$. Chemical data of Cooma granodiorite from Chappell and White (1992). (b) A-B diagram after Debon and Le Fort (1983) and Villaseca et al. (1998) showing overall major element variation in the I- and S-type suites of Sierra de Chepes and Cooma granodiorite, a classic S-type of the Lachlan fold belt. I-S boundary line is defined from I- and S-type data from Lachlan fold belt, dotted line shows the evolution trajectories of Cooma granodiorite (CG), and different areas in the diagram according to Villaseca et al. (1998). h-p: highly peraluminous, m-p: moderately peraluminous. Sch: Sierra de Chepes metaluminous trend, MME: mafic microgranular enclaves, TG: Tuaní Granite unit.

(1988) indicate that celadonitic or other impurities in muscovite would enlarge the stability field of this mineral. Similarly, we suggest tentatively that the impurities in sillimanite may increase their stability and explain their persistence in the melt. This interpretation is supported by the textural characteristics exhibited by the adjacent migmatites, which generally contain abundant fibrolite associated with andalusite. In this way, cordierite with a core of matted fibrolite needles has been interpreted as a typical restitic core from the source rock (Chappell et al., 1987, fig. 2A).

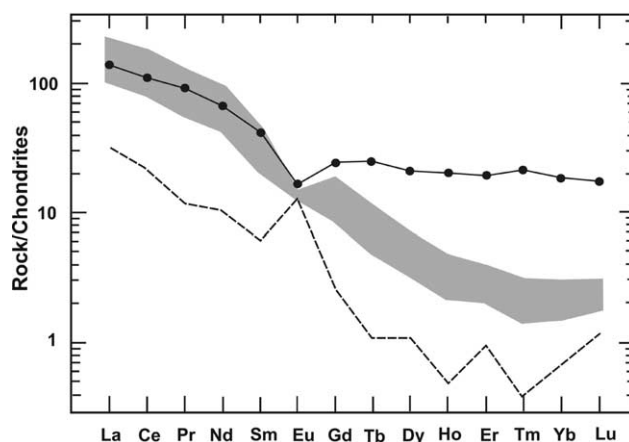


Fig. 9. Modified from Johannes et al. (2003, Fig. 12). Dark field defines the hypothetical primary undifferentiated melt composition derived from partial melting of metasedimentary rocks during the metamorphic peak (830 °C, 6 kbar, garnet in the source rock) in Turku, Finland. The lower broken line represents the REE patterns of the leucosomes in migmatites of Turku, interpreted as a segregated cumulate from the primary undifferentiated melt (Johannes et al., 2003). The low normalized Tm and Ho values are due to analytical uncertainties (Johannes et al., 2003). The solid line and black circle define the average REE pattern of the Tuaní Granite (Table 3). The chondrite-normalized REE for the Tuaní Granite is according to Nakamura (1974). Tb, Ho, and Tm are according to Boynton (1984).

Many mineralogical and textural characteristics present in the Tuaní Granite have been reported in other S-type granitoids (e.g. Flood and Vernon, 1978; Vernon et al., 2001). In the S-type granitoids of the Lachlan fold belt of SE Australia, the typical mineralogy of the restite comprises cordierite with inclusions of matted fibrolite, gneiss fragments with relatively refractory minerals (e.g. Crd + Sil + Grt + Bt), and zircon inherited from the source rock (White and Chappell, 1977; Chappell et al., 1987). Some minerals of the Tuaní Granite are xenocryst (i.e. phases derived from the metamorphic rocks), such as sillimanite-fibrolite, old cores of detrital zircon, and plastically deformed, fine-grained plagioclase (Fig. 5c).

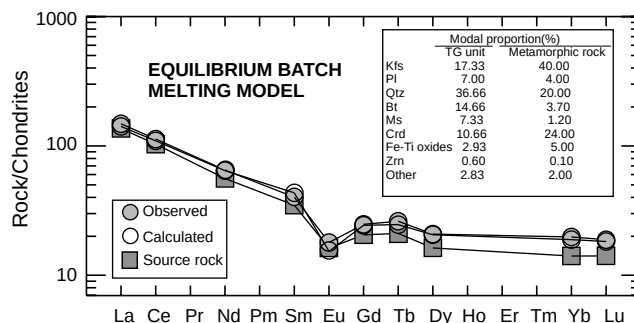


Fig. 10. Equilibrium batch melting model. Square's represent source rock, resulting from an average between Al₂O₃- and SiO₂-rich metasediments rocks (Table 3). Observed composition result is average between representative granitoids of the Tuaní Granite (Table 3). Calculated melt composition in Table 4. Observed and calculated compositions are close and show similar REE concentrations to the source rock, in support of an equilibrium partial melting origin. The chondrite-normalized REE for the Tuaní Granite is according to Nakamura (1974). The Tb is according to Boynton (1984).

According to Malaroda (1994), this deformation in plagioclase is especially common in the paleosomes of migmatites and is produced by crystallization of new minerals during their passage from the molten to the solid state (Malaroda, 1994, figs. 22, 24).

6.2. Interpretation of the geochemical data

6.2.1. Nonmodal equilibrium batch melting calculation

The Tuaní Granite has close chemical, isotopic ratio, and mineralogical relationships with the adjacent low-P metamorphic rocks. The Cooma granodiorite, the most typical S-type of the Lachlan fold belt, reveals similar features. Many works have suggested that the Cooma granodiorite was formed by either partial melting in situ or intrusion of a magma that moved only a short distance from a similar source (e.g. Flood and Vernon, 1978; Vernon et al., 2001). In addition, Sawyer (1987) uses mathematical modeling to suggest that REE patterns in different layers of migmatites may be helpful, particularly for investigations of whether the leucosomes represent pure melts or segregated cumulates. The granitoids of the Tuaní Granite have REE patterns (relatively high REE and negative Eu anomalies, Fig. 9) similar to those reported by Sawyer (1987) and Johannes et al. (2003) for rocks that have been interpreted as melt derived from migmatitic rocks.

The geochemistry of the Tuaní Granite is consistent with derivation by partial melting of the metasedimentary rocks in situ (or minor displacement of melt) akin to the Cooma granodiorite. To test this hypothesis, we use a numerical model to compare the observed composition of the Tuaní Granite with compositions obtained by calculation. Batch melting (also known as equilibrium fusion or equilibrium partial melting) describes the formation of a partial melt in which the melt continually reacts and reequilibrates with the solid residue at the site of melting until mechanical conditions allow it to escape as a single magma 'batch'. Melt formed by large-degree

partial melting in situ or intrusion of a magma that moved only a small distance would have a similar composition to that of its source rock.

The following equation to describe partial melting was originally formulated by Shaw (1970) for nonmodal equilibrium melting, which has been considered the most geologically realistic in plutonic conditions:

$$C_L = C_o / [D_o + F(1 - P)] \quad (1)$$

where D_o is the bulk distribution coefficient for the starting assemblage, given by $D_o = \sum X_{oi} K_i$, where X_{oi} is the initial mass fraction of mineral i in the solid and $K_{i/l}$ is the mineral-melt partition coefficient for a given trace element for mineral i ; P is given by $P = \sum p_i K_i$, where p_i is the fractional contribution of the mineral i to the melt; C_o is the initial element concentration in the solid that results in an average of representative pelitic and psammitic rocks (Table 3); and C_L is the concentration of an element in the melt that remains continually in equilibrium with a residual solid of concentration C_s after a fraction F has melted. The degree of melting ($F=0.28$) was chosen to provide the best fit to actual data. The Tuaní Granite comprises only approximately 1% of the exposed area of Famatinian granitoids in Sierra de Chepes, which is consistent with a low degree of melting.

Eq. (1) was applied with the assumptions that p_i and K_i are constant during the melting process. The partition coefficients (K_i) used and other details appear in Table 4.

The chondrite-normalized REE concentrations for the observed and calculated values are essentially identical, as we show in Fig. 10. Therefore, an equilibrium batch partial melting appears to be an acceptable process for generating the granitoids of the Tuaní Granite. La, Ce, and Eu have higher partition coefficients when peraluminous migmatites melt in low-pressure conditions (Bea et al., 1994), which results in little difference between REE concentrations of the metamorphic rocks and the calculated melt (Table 4). The REE

Table 4
Non-modal equilibrium batch melting for the TG unit

REE	Source rock (C_o)	D_o	P	Calculated $C_{L\text{Calc.}}$	Observed $C_{L\text{Obs.}}$	Minerals	Modal proportions (%) PRO-18 ^a
La	45.00	0.902	0.779	46.70	48.98	Kfs	40.0
Ce	89.17	0.878	0.770	94.66	97.63	Pl	4.0
Nd	35.25	0.772	0.649	40.52	41.00	Bt	3.7
Sm	7.07	0.684	0.574	8.80	8.15	Ms	1.2
Eu	1.25	0.941	0.610	1.19	1.38	Qtz	20.0
Gd	5.67	0.741	0.628	6.71	6.83	Crđ	24.0
Tb	0.99	0.795	0.779	1.15	1.23	Opq	5.0
Dy	5.58	0.738	0.808	7.05	7.14	Zrn	0.1
Yb	3.10	1.091	2.230	4.15	4.35	Sil + And	2.0
Lu	0.48	2.291	6.415	0.62	0.64		

Notes: Partition coefficients from peraluminous and silicic magmas. Data are from Bea et al. (1994), Fe–Ti oxides from Rollinson (1993, table 4.3), quartz from Nash and Crecraft (1985, sample 20), and white micas from du Bray (1994, sample 169635 from La–Nd and 184435L from Sm–Lu). The partition coefficient of Gd for the Fe–Ti oxide is equal to the Tb values using data from Rollinson (1993), table 4.3). The modal proportion of the TG unit results from the average of values in Table 1 (samples TUA-246b, AMBI-61, and MIL-4), as shown in Fig. 10. Source rock (C_o) = average of TUA-48 and GAR-33 samples, and trace element concentration in TG unit ($C_{L\text{Obs.}}$) = average of TUA-246, ROD-16, MIL-4, and AMBI-31 samples (Table 3).

^a PRO-18 = modal proportions from representative migmatite (total counting points = 762).

patterns are consistent with the presence of plagioclase in the source, as is noted in the next section.

6.2.2. Geochemical constraints on the sedimentary source of the Tuaní Granite

The CaO and Na₂O concentrations in the Tuaní Granite deserve some comment. The CaO/Na₂O ratio increases in the melt relative to the protolith. Thus, [Sylvester \(1998\)](#) argues that CaO and Na₂O concentrations in S-type peraluminous granitoids are controlled by the original proportion of plagioclase in the source rock. S-type peraluminous granitoids melts produced from clay-rich (plagioclase-poor) sources tend to have lower CaO/Na₂O ratios (<0.3) than melts derived from sources that are clay poor (plagioclase rich, CaO/Na₂O ratios >0.3). The Tuaní Granite data systematically plot in an intermediate position between Al₂O₃- and SiO₂-rich metamorphic rocks ([Fig. 7](#)), with CaO/Na₂O = 0.51 (average, [Table 3](#)), which suggests a metagreywacke source. The discrimination diagram for sources of peraluminous melt ([Sylvester, 1998](#)) indicates a clay-poor source for the Tuaní Granite ([Fig. 11](#)). Furthermore, S-type peraluminous granitoids of the Lachlan fold belt and the Tuaní Granite define similar fields in [Sylvester \(1998\)](#) discrimination diagram, which indicates that both were derived mostly from clay-poor sources. In contrast, Himalayan S-type granitoids seem to have been derived mostly from clay-rich sources ([Fig. 11](#)).

6.3. Anatectic reaction and crystallization of cordierite

6.3.1. Anatectic reaction

The anatectic reaction that generated the Tuaní Granite is deduced from the prograde reactions reported by [Dahlquist and](#)

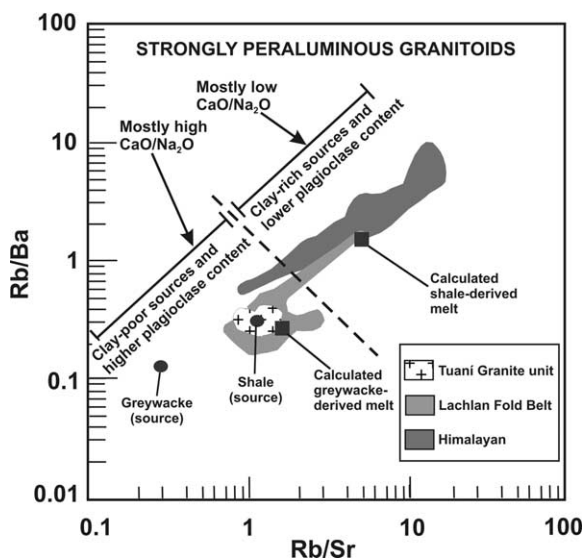


Fig. 11. Rb/Sr and Rb/Ba ratios for S-type, strongly peraluminous granitoids modified from [Sylvester \(1998\)](#). The dark fields, dashed line, and calculated melt from [Sylvester \(1998, Fig. 7\)](#). Chemical data of the Tuaní Granite from [Table 3](#).

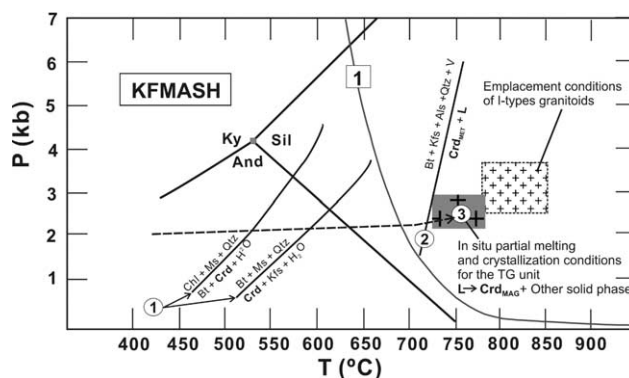
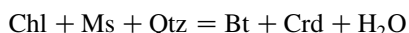


Fig. 12. Simplified P - T grid showing (1) crystallization of metamorphic cordierite, (2) anatectic reaction, (3) crystallization of magmatic cordierite, and inferred P - T path (dashed arrow). The main reactions in the KFMASH, Al_2SiO_5 phase relations, and triple point (gray box) equal to [Fig. 3](#). Equation 2 from [Ellis and Obata \(1992\)](#) and Equation 3 from [Clarke \(1995\)](#). Emplacement conditions of I-type granitoids according to [Dahlquist \(2001b\)](#). In situ partial melting conditions for the Tuaní Granite are discussed herein. Square 1, haplogranitic water-saturated solidus.

[Baldo \(1996\)](#). Metamorphic cordierites crystallized before anatexis by the following reactions ([Fig. 12](#))



and



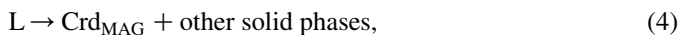
In the KFMASH system, a likely low- P anatectic reaction is as follows ([Fig. 12](#)):



The same reactions have been proposed by [Ellis and Obata \(1992\)](#) for the Cooma granitic Complex in the Lachlan fold belt.

6.3.2. Crystallization of cordierite from the peraluminous melts

The textural characteristics of magmatic cordierite (euhedral, coarse-grain size compatibility with host rocks, few inclusions) indicate that it has a magmatic cotectic origin. According to [Clarke \(1995\)](#), nucleation of cordierite in the magmatic cotectic environment occurs when silicate melt becomes saturated in cordierite through changes in temperature, pressure, or composition. With cordierite stable down to the solidus temperature in most cases, the reaction must approximate ([Fig. 12](#))



with the solid phases in equilibrium, according to [Clarke \(1995\)](#).

Only the Crd_{MAG} was observed in the Tuaní Granite, which could mean that Crd_{MET} produced by the reaction described by Eq. (2) remained in the migmatite.

7. Conclusions: a summary of the petrogenetic model for Tuaní Granite unit

All available data, including field and petrographic relationships, mineral chemistry, and bulk major and trace

element compositions, as supported by an equilibrium batch melting model, indicate that the Tuaní Granite is a typical S-type granitoid. The granitic melt presumably represents a primary melt formed mostly in situ by partial melting of a plagioclase-rich metasedimentary source (metagreywacke rocks) located in the upper crust (~ 10 km) and exposed as a migmatite complex. A synthesis of P – T conditions during the M_2 event and partial melting conditions for the generation of the Tuaní Granite appear in Fig. 12. During the metamorphic peak of the M_2 event (low- P and high- T , high geothermal gradient; Dahlquist and Baldo, 1996), which occurred synchronously with the emplacement of the metaluminous suite, partial melts would have been generated according to the reaction in Eq. (2). This claim is supported by petrographic evidence, which suggests that not all sillimanite/fibrolite was consumed and some was preserved as a relict phase (xenocryst or restite). The textural characteristics and chemical compositions of magmatic cordierite indicate that it has a magmatic cotectic origin, in agreement with Eq. (3).

The REE patterns in the Tuaní Granite also support the hypothesis that it represents a primary melt, as described by the equilibrium batch melting model. The HREE pattern indicates that garnet was absent from the source rock during the generation of the primary magma. Textural studies and the chemical composition of minerals of the Tuaní Granite indicate crystallization from peraluminous magma. Consistently, the major element concentrations, such as FeO^f , TiO_2 , and MgO , would have resulted from the crystallization of biotite, phengite, and cordierite minerals.

Notably, the P – T conditions and petrological and geochemical features are very similar to those described by Flood and Vernon (1978) and Vernon et al. (2001) for the generation of the Cooma granodiorite, a classic S-type granitoid located in the Lachlan fold belt of SE Australia. In addition, the Tuaní Granite and the strongly peraluminous S-type granitoids of the Lachlan fold belt show similar greywacke source rocks. The predominance of greywacke source rocks for the Tuaní Granite may suggest anatexis of an immature continental platform material, possibly in the context of an immature arc.

Finally, the small exposed area of the Tuaní Granite ($\sim 1\%$) relative to the metaluminous granitoids indicates that significant heat input from a major batholith is required to generate a small amount of peraluminous magma at high levels of the crust.

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References

- Albuquerque, C.A.R., 1973. Geochemistry of biotites from granitic rocks, Northern Portugal. *Geochimica et Cosmochimica Acta* 37, 1179–1802.
- Anderson, J.L., Rowley, M.C., 1981. Synkinematic intrusion of peraluminous and associated metaluminous granitic magmas, Whipple Mountains, California. *Canadian Mineralogist* 19, 83–101.
- Barbey, P., Marignac, C., Montel, J.M., Macaudière, J., Gasquet, D., Jabori, J., 1999. Cordierite growth textures and the conditions of genesis and emplacement of crustal granitic magmas: the Velay Granite Complex (Massif Central, France). *Journal of Petrology* 40, 1425–1441.
- Bea, F., Pereira, M.D., Stroh, A., 1994. Mineral/leucosome trace-element partitioning in a peraluminous migmatite (a laser ablation-ICP-MS study). *Chemical Geology* 117, 291–312.
- Berman, R.G., 1991. Termobarometry using multi-equilibrium calculations: a new technique with petrological applications. *The Canadian Mineralogist* 29, 833–855.
- Bohlen, S.R., Montana, A., Kerrick, D.M., 1991. Precise determinations of equilibria kyanite-sillimanite and kyanite-andalusite and revised triple point for Al_2SiO_5 polymorphs. *American Mineralogist* 76, 677–680.
- Boynnton, W.V., 1984. Geochemistry of the rare earth elements: meteorites studies. In: Henderson, P. (Ed.), *Rare Earth Element Geochemistry*. Elsevier, Amsterdam, pp. 63–114.
- Chappell, B.W., White, A.J.R., Wybron, D., 1987. The importance of residual source material (restite) in granite petrogenesis. *Journal of Petrology* 28, 1111–1138.
- Chappell, B.W., White, A.J.R., 1992. I- and S-type granites in the Lachlan Fold Belt. *Transactions of Royal Society of Edinburgh: Earth Sciences* 83, 1–26.
- Clarke, D.B., 1995. Cordierite in felsic igneous rocks: a synthesis. *Mineralogical Magazine* 59, 311–325.
- Clarke, D.B., Dorais, M., Barbarin, B., Barker, D., Cesare, B., Clarke, G., el Baghdadi, M., Erdmann, S., Förster, H.J., Gaeta, M., Gottesmann, B., Jamieson, R.A., Kontak, D.J., Koller, F., Gomes, C.L., London, D., Morgan Vi, G.B., Neves, L.J.P.F., Pattison, D.R.M., Pereira, A.J.S.C., Pichavant, M., Rapela, C.W., Renno, A.D., Richards, S., Roberts, M., Rottura, A., Saavedra, J., Sial, A.N., Toselli, A.J., Ugidos, J.M., Uher, P., Villaseca, C., Visonà, D., Whitney, D.L., Williamson, B., Woodard, H.H., 2005. Occurrence and origin of andalusite in peraluminous felsic igneous rocks. *Journal of Petrology* 46, 441–472.
- Dahlquist, J.A., 1998. Evolución textural en la granodiorita Chepes, Batolito de Los Llanos-Ulapes, Sierras Pampeanas. *Actas, 10° Congreso Latinoamericano de Geología y 6° Congreso Latinoamericano de Geología Económica*. Buenos Aires 2, 224–229.
- Dahlquist, J.A., 2000. Geología, petrología y geoquímica de las rocas de la Sierra de Chepes, La Rioja, Argentina. PhD Thesis, Universidad Nacional de Córdoba (unpubl). Argentina, 464 p.
- Dahlquist, J.A., 2001a. REE fractionation by accessory minerals in epidote-bearing metaluminous granitoids from the Sierras Pampeanas, Argentina. *Mineralogical Magazine* 65, 463–475.
- Dahlquist, J.A., 2001b. Low-Pressure emplacement of epidote-bearing metaluminous granitoids in the sierras de Chepes (famatina Orogen, Argentina) and relationships with the source. *Revista Geológica de Chile* 28, 147–161.
- Dahlquist, J.A., 2002. Mafic microgranular enclaves: early segregation from metaluminous magma (Sierra de Chepes), Pampean Ranges, NW Argentina. *Journal of South American Earth Science* 15, 643–655.

- Dahlquist, J.A., Baldo, G.E., 1996. Metamorfismo y deformación Famatinianos en la Sierra de Chepes, La Rioja, Argentina. *Actas, 13° Congreso Geológico Argentino y 3° Congreso de Exploración de Hidrocarburos*. Buenos Aires 5, 393–409.
- D'Amico, C., Rottura, A., Bargossi, G.M., Nannetti, M.C., 1981. Magmatic genesis of andalusite in peraluminous granites. Examples from Eisgarn type granites in Moldanubikum. *Rediconti Società Italiana di Mineralogia e Petrologia* 38 (1), 15–25.
- Debon, F., Le Fort, P., 1983. A chemical-mineralogical classification of common plutonic rocks and associations. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 73, 135–149.
- Deer, W.A., Howie, R.A., Zussman, J., 1966. *An Introduction to the Rock Forming Minerals*, first ed. Longman, London, 528 p.
- Deer, W.A., Howie, R.A., Zussman, J., 1992. *An Introduction to the Rock Forming Minerals*, second ed. Longman, London, 696 p.
- du Bray, E.A., 1994. Compositions of micas in peraluminous granitoids of the eastern Arabian Shield. *Contribution to Mineralogy and Petrology* 116, 381–397.
- Ellis, D.J., Obata, M., 1992. Migmatite and melt segregations at Cooma, New South Wales. In: Brown, P.E., Chappell, B.W. (Eds.), *The Second Hutton Symposium on the Origin of Granites and Related Rocks*, *Proceedings Geological Society of America Special Paper* 272, pp. 95–106.
- Flood, R.H., Vernon, R.H., 1978. The Cooma granodiorite, Australia: an example of in situ crustal anatexis? *Geology* 6, 81–84.
- González del Tánago, J., 1997. Allanite-(Nd) y minerales de elementos raros en las pegmatitas graníticas de La Cabrera, Madrid (Sistema Ibérico Central). *Revista de la Sociedad Geológica de España* 10, 83–105.
- Guo, Wei, Xu, Will, T.M., Powell, R.A., 1994. Calculated petrogenetic K_2O – FeO – MgO – Al_2O_3 – SiO_2 – H_2O , with particular reference to contact metamorphosed pelites. *Journal of Metamorphic Geology* 12, 99–119.
- Holtz, F., Johannes, W., 1991. Genesis of peraluminous granites I. Experimental investigation of melt composition at 3 and 5 kb and various H_2O activities. *Journal of Petrology* 32, 935–958.
- Johannes, W., Ehlers, C., Kriegsman, L.M., Mengel, K., 2003. The link between migmatites and S-type granites in the Turku area, southern Finland. *Lithos* 68, 69–90.
- Kalt, A., Altherr, R., Ludwig, T., 1998. Contact metamorphism in pelitic rocks on the Island of Kos (Greece, eastern Aegean Sea): a test for the Na-in-cordierite thermometer. *Journal of Petrology* 39, 663–668.
- Kerrick, D.M., 1990. The Al_2SiO_5 polymorphs. *Reviews in Mineralogy, Mineralogical Society of America* 22, 406.
- Kretz, R., 1983. Symbols for rock-forming minerals. *American Mineralogist* 68, 277–279.
- Lindsley, D.H., 1976. The crystal chemistry and structure of oxide minerals as exemplified by the Fe–Ti oxides. *Reviews in Mineralogy, Mineralogical Society of America* 3, L1–L60.
- Lindsley, D.H., 1991. Experimental studies of oxide minerals. *Reviews in Mineralogy, Mineralogical Society of America* 25, 69–106.
- Long, P.E., Luth, W.C., 1986. Origin of K-feldspar megacryst in granitic rocks: implications of partitioning model for barium. *American Mineralogist* 71, 367–375.
- Maillet, L.A., Clarke, D.B., 1985. Cordierite in the peraluminous granites of the Megana Zone, Nova Scotia, Canada. *Mineralogical Magazine* 49, 695–702.
- Malaroda, R., 1994. The microscopic structures of migmatites (genetic inferences and atlas). *Bollettino Regionale di Scienze Naturali-Torino* 12, 5–30.
- Miller, C.F., Stoddard, E.F., Bradfish, L.J., Dollase, W.A., 1981. Composition of plutonic mucovite: genetic implications. *Canadian Mineralogist* 19, 25–34.
- Mirwald, P.W., 1986. Ist cordierit ein geothermometer? *Fortschritte der Mineralogie* 64/1, 119.
- Nakamura, N., 1974. Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. *Geochimica et Cosmochimica Acta* 38, 757–775.
- Nash, W.P., Crecraft, H.R., 1985. Partition coefficients for trace elements in silicic magmas. *Geochimica et Cosmochimica Acta* 49, 2309–2322.
- Pankhurst, R.J., Rapela, C.W., Saavedra, J., Baldo, E., Dahlquist, J., Pascua, I., Fanning, C.M., 1998. The Famatinian magmatic arc in the central Sierras Pampeanas: an early to Mid-Ordovician continental arc on the Gondwana margin. In: Pankhurst, R.J., Rapela, C.W. (Eds.), *The Proto-Andean Margin of Gondwana Geological Society of London, Special Publications* 142, pp. 343–367.
- Pankhurst, R.J., Rapela, C.W., Fanning, C.M., 2000. Age and origin of coeval TTG, I- and S-type granites in the Famatinian belt of NW Argentina. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 91, 151–168.
- Pascua, M.I., (1998). *Petrología y geoquímica de la sierra de Los Llanos, provincia de La Rioja, República Argentina*. PhD Thesis, Universidad de Salamanca (unpubl), Spain, 236 p.
- Pattison, D.R.M., Tracy, R.J., 1991. Phase equilibria and thermobarometry of metapelites. In: Kerrick, D.M. (Ed.), *Contact Metamorphism Reviews in Mineralogy, Mineralogical Society of America*, vol. 26, pp. 105–206.
- Pereira, M.D., Bea, F., 1994. Cordierite-producing reactions in the Peña Negra Complex, Avila Batholith, Central Spain: the key role of cordierite in low pressure anatexis. *Canadian Mineralogist* 32, 763–780.
- Rapela, C.W., 2000. Accretionary history and magma sources in the Southern Andes. 31° International Geological Congress. Abstract Volume (CD-ROM), Rio de Janeiro, Brasil.
- Rapela, C.W., Pankhurst, R.J., Casquet, C., Baldo, E., Saavedra, J., Galindo, C., 1998. Early evolution of the proto-Andean margin of South America. *Geology* 26, 707–710.
- Rapela, C.W., Pankhurst, R.J., Dahlquist, J., Fanning, C.M., 1999. U–Pb SHRIMP ages of famatinian granitoid: new constraints on the timing, origin and tectonic setting of I- and S-type magmas in an ensialic arc. *Actas, 2° South American Symposium on Isotope Geology*, Carlos Paz, pp. 264–267.
- Richard, L.R., 1995. Mineralogical and petrological, data processing system for Window, V. 2.02. Minpet Geological Software-Logiciel Geologique Minpet, Que., Canada.
- Rollinson, H.R., 1993. *Using Geochemical Data: Evaluation, Presentation, Interpretation*. Longman Scientific & Technical Editions, Singapore, p. 352.
- Rossi, J.N., Toselli, A.J., Saavedra, J., Sial, A.N., Pellitero, E., Ferreira, V.P., 2002. Common crustal source for constraining peraluminous facies in the early Paleozoic Capillitas Batholith, NW Argentina. *Gondwana Research* 5, 325–337.
- Sawyer, E.W., 1987. The role of partial melting and fractional crystallization in determining discordant migmatite leucosome compositions. *Journal of Petrology* 28, 445–473.
- Scailliet, B., Pichavant, M., Roux, J., 1995. Experimental crystallization of leucogranite magmas. *Journal of Petrology* 36, 663–705.
- Schreyer, W., Maresh, W.V., Daniels, P., Wolfsdorff, P., 1990. Potassic cordierites: characteristic mineral high-temperature, very low-pressure environments. *Contribution to Mineralogy and Petrology* 105, 162–172.
- Secchi, F.A., Brotzu, P., Callegari, E., 1991. The Arburese igneous complex (SW Sardinia, Italy)—an example of dominant igneous fractionation leadings to peraluminous cordierite-bearing leucogranites as residual melts. *Chemical Geology* 92, 213–249.
- Shaw, D.M., 1970. Trace element fractionation during anatexis. *Geochimica et Cosmochimica Acta* 34, 237–243.
- Sims, J.P., Ireland, T.R., Camacho, A., Lyons, P., Pieters, P.E., Skirrow, R.G., Stuart-Smith, P.G., Miró, R., 1998. U–Pb, Th–Pb and Ar–Ar geochronology from the southern Sierras Pampeanas, Argentina: implications for the Palaeozoic tectonics evolution of the western Gondwana margin. In: Pankhurst, R.J., Rapela, C.W. (Eds.), *The Proto-Andean Margin of Gondwana Geological Society of London, Special Publications* 142, pp. 259–281.
- Spear, F.S., 1993. *Metamorphic phases equilibria and pressure-temperature-time paths*. Mineralogical Society of America, Monograph, Washington, USA, 779 p.
- Speer, J.A., 1984. Micas in igneous rocks. *Reviews in Mineralogy, Mineralogical Society of America* 13, 357–368.
- Stormer, J.C., 1975. A practical two-feldspar geothermometer. *American Mineralogist* 60, 667–674.

- Streckeisen, A., 1976. To each plutonic rock its proper name. *Earth-Sciences Reviews* 12, 1–33.
- Sylvester, P.J., 1998. Post-collisional strongly peraluminous granites. *Lithos* 45, 29–44.
- Vernon, R.H., Richards, S.W., Collins, W.J., 2001. Migmatite–granite relationships: origin the Cooma Granodiorite magma, Lachlan Fold Belt, Australia. *Physics and Chemistry of the Earth (A)* 26, 267–271.
- Villaseca, C., Barbero, L., 1994. Chemical variability of Al–Ti–Fe–Mg minerals in peraluminous granitoids rocks from central Spain. *European Journal of Mineralogist* 6, 691–710.
- Villaseca, C., Barbero, L., Herreros, V., 1998. A re-examination of the typology of peraluminous granite types in intracontinental orogenic belts. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 89, 113–119.
- Waychunas, G.A., 1991. Crystal chemistry of oxides and oxyhydroxides. *Reviews in Mineralogy, Mineralogical Society of America* 25, 11–68.
- White, A.J.R., Chappell, B.W., 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics* 43, 7–22.
- White, A.J.R., Chappell, B.W., 1988. Some supracrustal (S-type) granites of the Lachlan Fold belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 79, 169–181.
- Whitney, J.A., Stormer, J.C., 1977. The distribution of $\text{NaAlSi}_3\text{O}_8$ between coexisting microcline and plagioclase and its effects on geothermometric calculations. *American Mineralogist* 62, 687–691.
- Zen, E-an, 1988. Phase relations of peraluminous granitic rocks and their petrogenetic implications. *Annual Review of Earth and Planetary Science* 16, 21–51.